Validity and Value of Wave Energy Generation as Blackout Risk Mitigation for the Central Oregon Coast

Marine Renewable Energy NRT Group
Transdisciplinary Report

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Executive Summary

Energy security is a vitally important but often overlooked vulnerability in communities. Electricity availability is essential to the functioning of the economy, individual households, and the collective essential services that provide health, safety, and the basic human needs to sustain life. Coastal communities in Oregon face special vulnerability because they are almost entirely dependent on outside sources of electricity generation routed via a limited number of transmission lines as shown in Figure ES-1. If enough of these lines fail, as occurred during a winter storm in 2007, the coast would be electrically stranded from the regional grid network. This vulnerability raises a question whether this risk to coastal community energy resilience could be mitigated through utilization of a local and abundant renewable energy source: ocean wave energy.

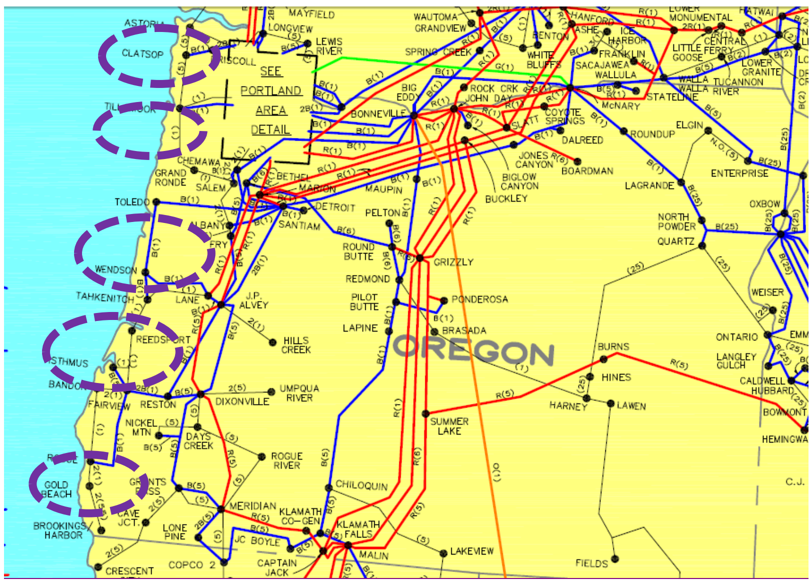

Figure ES-1. Electrical Transmission Lines to the Oregon Coast circled in purple.
Red lines represent 500kV transmission lines. Blue represents 230kV lines. (Source: WECC)

This transdisciplinary report assesses key *technical*, *natural system*, *socio-economic*, and *regulatory* considerations surrounding the validity and value of Wave Energy Converters (WECs) as an emergency power generation resource for the example community of Newport, Oregon. The work was performed by a collaborative, multi-disciplinary team of graduate researchers as part of the National Science Foundation National Research Traineeship in Risk and Uncertainty Quantification and Communication in Marine Sciences at Oregon State University. The team was composed of two Mechanical Engineering students, one Electrical Engineering student, and one student in Marine Resource Management.

This report imagines a scenario in which an event such as a winter storm causes a regional transmission line outage in the example community of Newport, Oregon for a hypothetical duration of two weeks. We propose a system of rapidly deployed WECs connected to the local electrical grid to allow conversion of the Central Lincoln PUD service area into an "islanded microgrid" that can provide locally for the community's critical infrastructure services (e.g., water, fuel, wastewater sanitation, heating and cooling, food preservation, communication capabilities, and emergency services such as medical care, police, and fire protection). In this context, the goal of having an islanded microgrid is to be able to use local sources to supply the community's electrical needs.

We determine that marine renewable energy (MRE) may be a valid risk mitigation alternative from a technical and regulatory standpoint with the proper consideration of grid integration needs and support for emergency MRE options on a policy level. Based on the findings in this report, it appears that the temporary emergency WEC use case would be economically infeasible given the estimated power demand of critical services and the generation capabilities of currently available WEC devices. However, our research shows that there are significant gaps in knowledge regarding how we value critical services in a long emergency, and advancements in this field may change the value proposition of an emergency WEC use case. Additionally, advancements in wave energy technology or emergency power demand management may reduce the total size requirements for an emergency WEC array, or the logistical ability to deploy the WEC system, changing the feasibility and cost of the system in the future. Moreover, there is additional uncertainty regarding the recurrence interval of an outage of sufficient scale to warrant investment.

Based on a selected suite of critical infrastructure for Newport, Oregon, this report determines that an emergency power system would need to satisfy a total energy demand of approximately 4.5 MW of instantaneous power (Section 2.4). The total number of WECs required to meet this demand was modeled for two different device types: the Archimedes Wave Swing, using performance estimates from 2004 and reference wave climate data from southern Oregon; and a generic 10-m diameter floating point absorber modeled with the software mWave using NOAA buoy data from the aftermath of a winter storm in 2012.

The results concluded that a total of 14 Wave Swing devices would be required to meet critical infrastructure demand, or 37 of the modeled generic point absorber devices (without considering the potential efficiency gains from device shape enhancements or advanced control systems). This discrepancy in number of devices required to meet emergency power demand is due to differences in device type (how they convert wave energy to electricity), size of the devices, and efficiency of those devices. A deployment of a system including 14 Wave Swings would cost an estimated $117 million, mostly driven by capital costs. The cost of the generic array was not estimated but is likely to be significantly higher based on the larger number of devices.

Using currently available methods of valuing the loss of electricity for critical services alone, we estimate a value of $469,000 to $2.34 million for a hypothetical two-week outage. These results are highly uncertain due to the relatively sparse body of research regarding the specific value of critical services to communities and a lack of research into the perceived social and safety costs of blackouts lasting longer than 24 hours. Furthermore, the estimate does not account for the value of potential lives saved, due to an inability to quantify the likelihood of occurrence with any reasonable certainty.

Alternatively, if the WEC array was scaled larger to provide electricity for all needs of the community (not just critical service needs), including continued economic production (approximately 11-16 MW of generation capacity), the WEC array could aid in avoiding economic losses. In this case, the WEC array would increase in value to anywhere between $16 million to $1.5 billion for a two-week outage. This wide range of estimates further emphasizes the uncertainty associated with valuing the losses from long-duration power outages. Despite this uncertainty, the technical feasibility of a WEC system deployed off the Oregon coast, and the high associated costs with that installation prompts another an idea: worth further exploration regards how might the value of blackout risk mitigation change if the WEC array were to be for a pre-existing permanent, installed prior to an emergency and used for local, nominal electricity needs, rather than be a deployable system that sits idle most of its life?

This report found that the local electrical grid in Newport, Oregon would be able to make use of the provided electricity from a WEC system to satisfy the energy needs of critical infrastructure without causing any major problem to the energy network. However, integrating a WEC array into the grid would likely require upgrades to several of the protective devices spread throughout the local electrical grid network. Furthermore, issues surrounding the inherent variability of ocean wave energy would need to be addressed. One potential solution would be to use energy storage devices or other power smoothing technology. Additionally, rapid deployment of WECs as an emergency resource would lead to additional logistical challenges such as transmission line laying, mooring requirements, space requirements for on-land device storage, and safe installation of devices at sea.

In comparison with diesel emergency generators, it appears that an MRE solution might surpass a diesel-powered solution on both a cost basis and, arguably, on a resiliency basis as well. Our calculations estimate the cost of providing electricity for critical infrastructure in Newport via diesel generators could be as high as $5.5 billion. Furthermore, the cost and logistical feasibility of delivering and managing that amount of fuel would be significant. Diesel generators may make sense for individual buildings for limited periods of time, but they are a poor solution for larger energy system support or for long-duration outages given their reliance on fuel resupply and propensity for mechanical failure.

While there is currently no explicit regulatory path to enable the emergency use of a WEC system, there may be a system that could provide rapid approval in an emergency. A review of existing laws and recent historical precedents, coupled with qualitative interviews of current marine renewable energy permitting process participants in the US, suggests that in the event of a natural disaster, legal and political will favors actions to preserve human life and property over environmental protection regulations. If one considers the relative risk posed by a temporary moving structure in the ocean against the loss of critical human infrastructure needs, emergency provisions and management structures under existing law may favor MRE. Alternatively, a preemptive emergency MRE permit use case may be a viable alternative worth pursuing on the state and federal policy level.

The creation of microgrid-capable MRE “resilience zones” along the coast could potentially improve coastal energy infrastructure for use as a nominal energy provider under normal circumstances and as a primary energy supply for emergency situations. The proposed Pacific Marine Energy Center South Energy Test Site (PMEC-SETS) in Newport has the potential to act as one such resilience zone. This may represent a previously undervalued additional benefit to the installation of this facility. The electricity generated from SETS will be integrated into the grid at Seal Rock, south of Newport Bay, and would require routing through Toledo to be used by Newport in the event of an emergency.

1 Purpose and Need for Transdisciplinary Study

The purpose of this feasibility study is to evaluate the potential validity and value of marine renewable energy (MRE) as a method to mitigate the risk to coastal communities associated with long-duration power outages. It is intended to inform energy investment managers and emergency management planners within multiple scales of government. The analysis considers multiple aspects of the potential risk and the proposed solution from multiple disciplinary perspectives. Additionally, the report imagines a new use case for MRE specifically focused on emergency response. Finally, the report characterizes remaining uncertainties affecting the results of the analysis and proposes directions for future research.

1.1 Transmission Disruption Events on the Pacific Coast

Access to sufficient, consistent, and affordable energy supplies is a keystone in community functions and individual quality of life. Often, however, this electricity security is overlooked as a source of community vulnerability. Events in recent history such as the Northeastern US blackout of 2003 and outages following Hurricanes Katrina (2005), Sandy (2012), and Irma (2017) have increased awareness among electric utilities and governments, underlining the importance of investing in system improvements that bolster community resilience to and prevent or mitigate effects of these outages.

The detrimental effects of a sustained power outage on a community are significant and multi-faceted. All local economic production halts without energy to support businesses, from hotels and stores to industrial plants that enable resource-based economic activities. The effects of outages can be potentially disastrous for those at home as well. As Rouse (2011) stressed:

> In addition to the inconvenience experienced by consumers during prolonged periods without electricity service, a power outage can literally mean the difference between life and death. From specialized care equipment such as dialysis machines to everyday heating and cooling devices like air conditioners or furnaces, the impact of a power interruption on consumers can be significant. Interruptions can result in fatalities, injuries, days of lost productivity and thousands of dollars in production losses and equipment repairs. (Rouse 2011)

Households and grocery stores can experience food spoilage, further exacerbating community risk and potentially leading to increases in accidental human poisoning, as occurred during the 2003 blackout on the US East Coast (Lin et al., 2011) or carbon monoxide poisoning from unsafe in-home heating (Anderson and Bell, 2011). Other potential risks for injury or mortality can occur due to the loss of traffic control, emergency notifications regarding unsafe conditions around the community, and communication with emergency first responders.

Coastal communities in Oregon face special vulnerability because they are dependent on outside sources of electricity generation, predominantly hydroelectric power from the Bonneville Power Administration dams on the Columbia River, (ODOE, Pers comm.) and remote from those sources. The entire Oregon coast is connected to the rest of the US power grid via six power lines that cross the coast range (Figure 1). If enough of these lines fail, as occurred in a winter storm in 2007, the coast lacks the ability to provide power for itself even if the local distribution grid is intact.

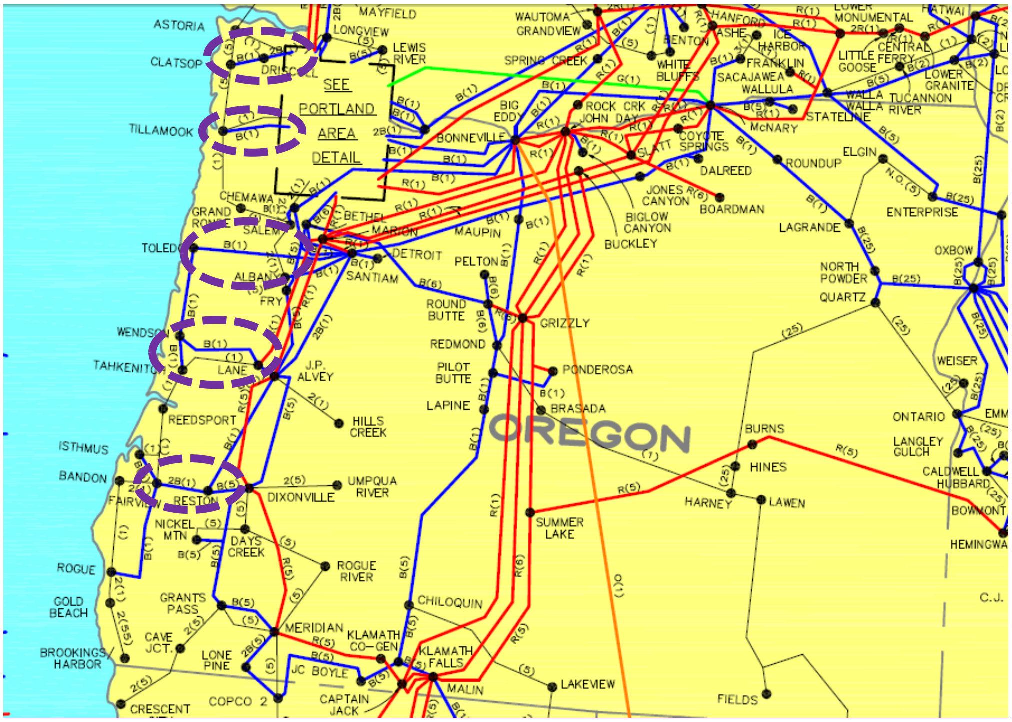

Figure 1. Electrical Transmission Lines to the Oregon Coast circled in purple.
Red lines represent 500kV transmission lines. Blue represents 230kV lines. (Source: WECC)

According to the Lincoln County, Oregon, Natural Hazards Mitigation Plan, "The windstorm and winter storm hazard risk assessment rates Newport as having a high vulnerability to windstorm and high probability of a future windstorm or winter storm," which are the leading causes of power outages. Additionally, Oregon faces the risk of a future Cascadia Subduction Zone earthquake and tsunami, which threatens to leave the entire coast without power for an estimated three to six months (OSSPAC, 2013). Another report states that, "storms with hurricane force winds occur somewhere in Oregon nearly every year, and storms with sustained hurricane force winds have an approximate 25-year recurrence interval (4% chance in any year) on the Oregon Coast (State of Oregon, 2012).

Faced with these risks, this transdisciplinary report assesses the specific vulnerabilities of a community on the Oregon Coast – Newport, Oregon – and evaluates the potential for coastal communities to harness an abundant offshore renewable energy resource and increase their resiliency to regional electrical grid disruption.

1.1.1 Regional Loss, Local Opportunity via Islanded Microgrids

> *Energy resiliency is the ability of an energy system to endure and maintain or retain sufficient operational activity during and after a major disruptive event such as a hurricane, a hacking event, or a disruption in fuel supply. It is sometimes described as dealing with "high consequence, low-probability" events (Watson et al. 2014).*

In the event that the Oregon coast becomes isolated from the high voltage transmission grid infrastructure (Figure 1), the local distribution grids may still be intact or capable of being repaired relatively quickly. The report from the 2007 Great Gale noted that "In general, local distribution networks performed better than the transmission systems . . . Many tall evergreen trees encroaching on transmission right-of-ways fell across the power lines causing further damage," (Elliott and Tang, 2012). This situation presents isolated communities with the opportunity to convert their electrical systems to an "islanded microgrid" configuration, which would allow them to produce and consume electricity at the local level.

The term "islanded microgrid" can be described as two individual terms. Islanding an electrical system describes the process of a physical disconnect, either intentionally or unintentionally, from one other part of the system. This is typically done as a last minute decision to prevent large cascading blackouts. A microgrid is a network that has the ability to operate without outside energy sources. Therefore, when we combine these two terms, we describe a scenario where an emergency action needs to take place and the system can still sustain itself.

Generally, it is not desirable to be islanded except to save the larger system. For example, in Europe in 2006, a high-voltage line tripped, resulting in three distinct islands which each operated at different frequencies (ENTSOE, 2007). Had operators not islanded three separate systems, the issue would have propagated across Europe's electrical system, likely resulting in cascading faults and a large blackout.

Islanded microgrids usually refer to small electrical networks (<115 kV), in which the normal chain of electricity supply has been interrupted. In this situation, the islanded microgrid has the ability to meet at least some of electricity needs through the use of traditional diesel generators or renewable energy sources. While this might not sound complicated, the seconds immediately following a disconnect can be extremely rigorous on the control system in place. Furthermore, reconnecting to the main system can be very difficult; in the case of the European blackout, it took 9 attempts and nearly 40 minutes to successfully reconnect each island.

Despite the technical challenges of reconnection post-disruption, the rise of distributed sources of renewable energy (ex: solar panels on one's house) has increased recognition of islanded microgrids as a potential mitigation technique for local effects of regional grid failures. As one report described:

> Amid the devastating news that emerged during and after 2012's catastrophic Superstorm Sandy, one bright spot shone light on a highly resilient aspect of America's infrastructure. Scattered up and down the East Coast were facilities that were able to continue providing power, heating, cooling, and hot water to residents, students, patients, and workers as the grid around them failed. These facilities were those served by onsite combined heat and power (CHP) systems. (Chittum 2016)

1.1.2 Oregon's Wave Resource

The US wave energy resource is estimated to be 1594-2640 TWh/yr. On the west coast of the US alone, the resource is estimated to be 590 TWh/yr. For Oregon specifically, the available resource is estimated to be between 143 and 179 TWh/yr (P. Jacobson, 2011 and M. Lehmann, 2017). As a location with one of the highest resources in the US and the need to provide local power generation to communities vulnerable to electrical isolation, there is an opportunity for government and planners in Oregon to use the energy readily found off its shores for both nominal and emergency generation.

The available resource can be directly measured using the extensive international network of wave buoys that the National Oceanic and Atmospheric Administration (NOAA) supports. Figure 2 shows the location of these buoys within the Pacific Northwest (P. Lenee-Bluhm, 2011).

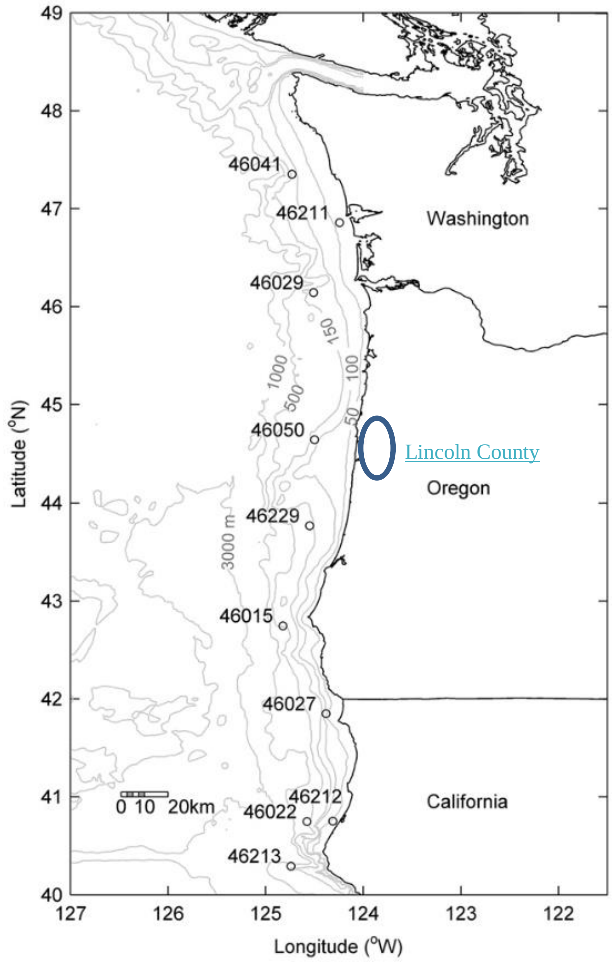

Figure 2. Location of NOAA buoys in the Pacific Northwest, with Lincoln County and Newport highlighted by the blue circle (M. Lehmann, 2017)

When considering the potential use of wave energy after a community loses access to its primary power sources, a better understanding of resource variation over space and time is required. The energy that can be extracted from an ocean wave is dependent on local sea state conditions (wave height and period) and these are, in turn, dependent on parameters such as bathymetry and season. For example, in Oregon the ocean is more energetic in the winter than in the summer. Also, coastal and ocean floor features alter the oncoming incident waves (P. Lenee-Bluhm, 2011).

Although buoy data is useful for the specific areas where they are located, we need to better understand the variability of the Oregon coast's ocean energy resource with increased resolution. This can be achieved by using data from hindcast models of the Oregon coast generated by WaveWatch III and SWAN (G. García-Medina, 2013). García-Medina compared data from these numerical models with the historical results of the NOAA buoys at the location of several of the buoys and found the results to be consistent– providing reliability to, and validating the data.

In this report, we will evaluate the potential available wave power along the entire Oregon coast, as well as off the coast of Lincoln County. WaveWatch III provided information for discrete latitudes and longitudes deep into the Pacific Ocean. Given our specific considerations of emergency generation and deployment, we only considered the data points up to approximately 10 miles offshore from the furthest western point within each geographical area (i.e., Oregon and Lincoln County). Additionally, we also had access to several years' worth of meteorological data (e.g., significant wave height, period, direction, wind speed, etc) – from 2011 to the beginning of 2016. We chose to limit the year 2012 since that year had a storm in March with winds classified as hurricane force, similar to those of the Great Gale of 2007 (Oregon Live, 2012). Furthermore, this time period will allow us to compare the available power after the storm with the available power for the year.

1.1.3 Incorporating Risk into Emergency Power Investment Decisions

> *A major obstacle to reform is the prevailing view that outages are a fact of life — a force of nature, and thus uncontrollable. (Rouse and Kelley 2011)*

One of the challenges of implementing risk management strategies to address energy resiliency vulnerabilities is a reluctance to commit large amounts of electrical utility funding toward projects whose greatest value would only be realized in the event of a major outage with an uncertain likelihood of occurrence during the usable life of the capital investment. The US Department of Energy noted that:

> Many of the threats to electricity system resilience can be countered or mitigated by investments from electric power companies and distribution utilities. But these organizations and their regulators have struggled with the question of whether the benefits of such investments justify the increases to utility rate bases necessary to fund them. (DOE 2013)

If energy resilience projects are to find financial support, it is important to study the risk of major long-duration power outages from multiple perspectives. Decision makers must understand, in quantitative terms, the likelihood of an event occurring within a given period of time, the vulnerability of the people who would be affected, the severity of the effect, and the cost of alternative solutions to mitigate or prevent the risk. With all of this information available, and a clear understanding of the remaining uncertainties, a decision maker may be able to compare the costs and potential risk reduction benefits associated with mitigation alternatives and better justify energy investment decisions to stakeholders.

1.2 Scope of the Transdisciplinary Report

1.2.1 Research Question:

What is the validity and value of Wave Energy Converters (WECs) as an emergency power source to mitigate the risk of coastal transmission line loss, and what are the key integration considerations for existing infrastructure to support such a system?

1.2.2 Report Format

The report follows a feasibility analysis format to address the research question for the example community of Newport, Oregon in a potential future sustained power outage scenario. This report discusses the *technical*, *natural system*, *socio-economic*, and *regulatory* dimensions of the research question, and builds on transdisciplinary efforts by the members of the NRT team.

1.2.3 Transdisciplinary Research Approach

This report is the product of a transdisciplinary and interdisciplinary research effort performed by a collaborative team of graduate researchers as part of the National Science Foundation National Research Traineeship in Risk and Uncertainty Quantification and Communication in Marine Sciences at Oregon State University. The team was composed of two Mechanical Engineering students, one Electrical Engineering student, and one student in Marine Resource Management.

Transdisciplinary research is described as a process wherein, "individuals work jointly to address a problem they define under a shared conceptual framework. More recently, transdisciplinary research and education approaches are also aligned with problem-oriented research," (NRC, 2014). In its ideal form, transdisciplinarity transcends disciplinary worldviews by incorporating more comprehensive frameworks and pursuing "problem-oriented research that crosses boundaries of academic disciplines and the public and private spheres," (NRC, 2014). This process creates a synthesis of multiple disciplines to address research questions with applied social relevance.

The diagram in Figure 3 is a concept map that represents the different elements of analysis that are being combined in this transdisciplinary report to support the central research question. The map includes not only research outcomes that will contribute to the whole, but also analysis activities performed by members of the collaborative group and the sources of data that feed the analysis.

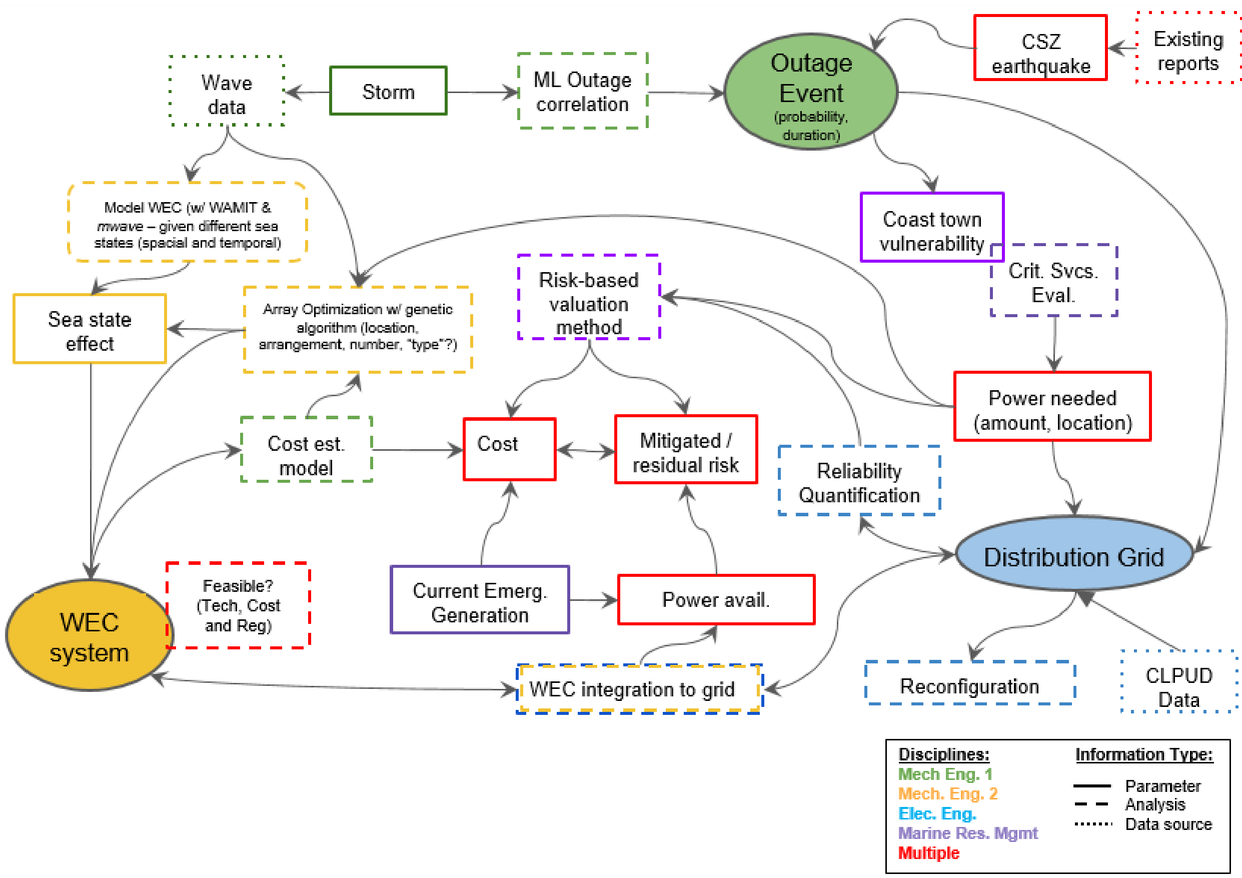

Figure 3. Interdisciplinary Research Linkages

For the purposes of this project, risk is defined as a combination of the likelihood and impact of an unwanted event (e.g., a blackout), enacted upon a population of interest. Our research approach attempts to quantify each aspect of the risk of long-duration blackouts on a coastal community of interest. Once each piece has been defined and quantified, an attempt to evaluate them collectively them may be performed, the purpose of which is to describe the validity and value of a MRE system as a risk mitigation alternative.

The concept map contains three central nodes: an *outage event*, a *community-scale electrical distribution grid*, and a *wave energy generation system*. The outage event is the initiating event for the long-duration blackout scenario and is related to large storm events on the Oregon Coast. While the focus of this outage event is on storm-related transmission outages, results from this report could be extrapolated to the results of a larger initiating event, such as a Cascadia Subduction Zone earthquake and resulting tsunami.

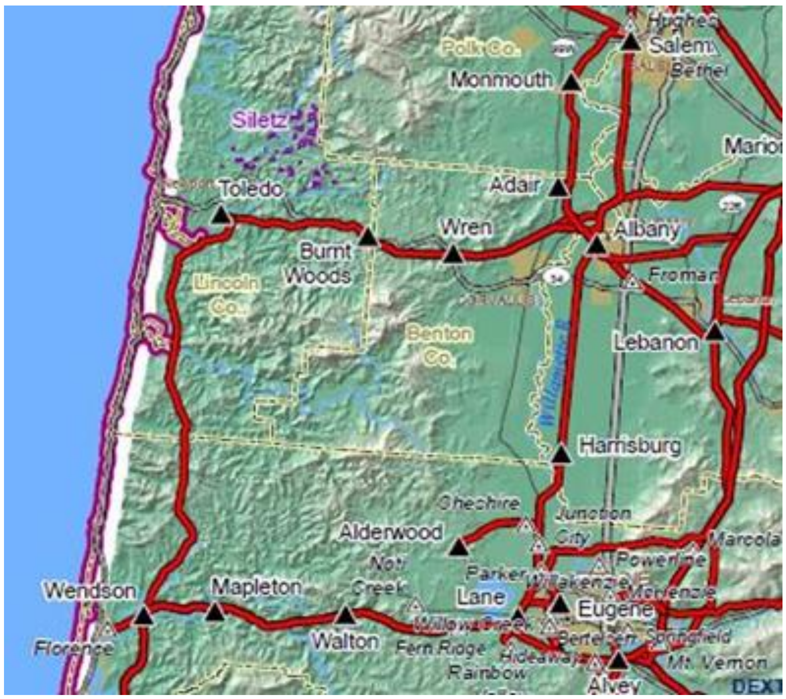

Figure 4. Transmission lines serving Central Lincoln PUD

Once an outage event of an unknown duration begins, the local community will suffer impacts. These impacts will vary depending on the community's reliance on electricity for critical services and economic functions. To quantify the impacts of the given outage on the community, we identify critical services in the coastal community of interest, as well as the electricity need, or load of those critical services. Quantifying the electricity load required then enables us to compare the losses associated with no energy generation against the value and costs of an emergency wave energy generation system.

The Distribution Grid node represents the local electrical infrastructure of the community of interest. Without a connection to the regional grid, the distribution grid may be transformed into an "islanded microgrid" that connects an emergency generation source to the critical load centers within the community. With help from Central Lincoln Public Utility District (CLPUD), steps were taken to create a model of the distribution network. This enables us to perform baseline simulations that will show whether or not wave energy will cause any major problems at the point of interconnection. Additionally, it allows us explore the idea of specifically routing power to critical infrastructure using renewable energy.

The grid model will consider how an emergency WEC system can be optimally integrated into the islanded microgrid to ensure power transmission from where the electricity is generated to where it is needed. While grid policy and regulation is beginning to adopt some advanced technologies, utilities are still wary of using variable renewable energy sources to enhance resiliency during an outage. Our solution, while not complete, will start considering how to integrate the energy into the existing grid system and specifically route the power to infrastructure that is deemed to have high social value in an emergency.

The WEC System node represents a hypothetical WEC array located off the coast of the community of interest. The optimal design of this system depends on the expected wave climate following an outage event (e.g., post-storm wave height and period over time), the power load needed for critical services, regulatory considerations for an emergency WEC system, and the integration requirements of the local distribution grid. This component will involve determining what location near a community will yield the most power, how many devices would be necessary to provide the required power, and how these devices might be arranged to best capture the power. Given sea state conditions, WEC array motions and power production are modeled by a boundary element model and an analytical model. By combining this numerical modeling with a custom WEC array optimization scheme, optimal WEC array arrangements are achieved. This optimization method is designed to maximize the power generated from an array by placing devices so that the device-to-device interactions are positively used. Combined with grid integration analysis will describe the amount of power available to the community of interest to mitigate the losses of a long-duration blackout.

With an optimal emergency WEC system, a cost estimate can be performed. In this report, an analytical cost model is developed for emergency wave energy generation, and tested given a two-week outage in the coastal community of interest. Cost is quantified in present value over the 20-year operational lifespan of the device for the purpose of being directly compared against the potential losses to the community of interest over that same period of time as a result of a long-duration outage event.

1.2.4 Collaborative Working Structure

Figure 3 is color-coded to demonstrate the collaborative working structure of the research team within this project. The development of the research goal and shared methodologies represented in the research approach was a transdisciplinary product of weekly team meetings over the course of several months. Each team member shared individual responsibility for many components within this schematic, but there are some pieces of information – and shared understanding – that are informed by multiple team members' expertise. These primary shared elements are highlighted in red. Cost is an example of one such shared topic. While directly addressed by the cost model and value of lost load estimations, these calculations depend on critical infrastructure load data developed collaboratively within the team. These shared elements were addressed by multiple people, and were often dependent on a chain of information or iterative in nature. Further details on the collaborative working process will be discussed in Section 8.

2 Background

2.1 The Great Gale of 2007

To understand some of the potential effects of a long-duration power outage on a coastal community, it is useful to consider the most recent major outage event that grew from the Pacific Great Gale of 2007. In December 2007, The National Weather Service issued its first ever "hurricane-like force" wind warning for the Northern California, Oregon, and Washington. As the storm pushed ashore it affected more than a 1,000 miles of the Pacific Coast. Winds in Oregon gusted up to 129 mph, storm wave heights reached 47 feet, and precipitation reached a total of 14.5 inches. Together, these forces caused widespread flooding, landslides, and wind damage to both public and private property.

The hurricane-force winds caused extensive damage to the transmission and distribution power systems in the northern coastal communities of Oregon and the coastal communities of Washington. Wooden poles were snapped in two, and power lines were pulled down when trees fell across the lines. In some communities, the power outage lasted as long as three weeks and, "caused collateral damages to other lifelines affecting wireless communications, weather stations, gas stations, emergency responders, pump stations, hospitals, medical clinics, and the 911 system" (Elliott and Tang, 2012). Five fatalities occurred in Oregon as a result of the storm, and the total direct costs from the storm were estimated to have been over $300 million for all three coastal states, with the estimated indirect costs likely as much as five to ten times higher (Elliott and Tang, 2012).

The President declared a major disaster for the State of Oregon in February 2007, and the Federal Emergency Management Agency (FEMA) established a command post to coordinate emergency response efforts. The Oregon National Guard also provided emergency response support during the storm and for many days after. The Camp Rilea Training Site was setup as an emergency shelter and staging area for emergency responders, and the Guard also provided emergency generators, fuel, food, and bottled water and provided emergency transport vehicles to affected communities.

Among the many effects of the storm, the emergency management response was hindered by a lack of critical services and infrastructure in a number of ways. Some notable findings from the post-storm report (Elliott and Tang, 2012) include the following:

- Many small communities in the affected area were isolated for a few days due to loss of lifeline services. The community of Jewell lost power for a total of six days. After two weeks, the community of Grays Harbor, Washington had reached 90% power restoration. More than 60,000 people lost power in the area between Astoria and Tillamook.
- Smaller communities in Oregon and Washington rely on wells and pumps to provide water. In Oregon nine water systems, including small water agencies in Tillamook and Jewell, were inoperable while the power was out. Larger systems with emergency power, such as Astoria and Cannon Beach, continued to function.

Figure 5. Downed power lines on Highway 202. (Source: NorthCoastOregon.com)

- Communications were limited to line of sight or local carriers only. Long distance telecommunications and cell phone services were disrupted and out of service for several days.
- Some satellite communication services were ineffective due to the dense fog and cloud cover.
- Additional disruptions in coastal communities included an inability to maintain a food supply in store, inability to provide fuel to citizens, loss of transportation capabilities in Clatsop County that cut it off from outside resources for three days, and debris removal and management issues affecting the county in in a number of ways.
- In Tillamook County, Hospital generators were insufficient. X-ray, oxygen systems, and imagery were down because the generators could not handle the equipment's demand. Medical patients were evacuated to the fairgrounds where the shelters had sufficient generator power. Home Depot came in with a truck filled with generators, which sold out in 3 hours. Tillamook set up emergency Shell gasoline fueling locations in northern, central, and southern parts of town for emergency services and the general public. The City of Tillamook's wastewater treatment plant and distributed wastewater lift stations lost power, causing flooding into the streets.

Figure 6. Aerial oblique view of landslide at MP 27 (Source: Elliott and Tang, 2012)

- In Cannon Beach, power was out for 5 days. The town had a backup generator for emergency power and shared its generators with the local restaurants, businesses, and others for a couple hours per day to help keep frozen food from spoiling. Pacificorp staff brought in a generator and hooked it into their substation, which is located at the end of their transmission line, two days after the storm hit. The wastewater treatment plant continued to operate on emergency backup power.
- The city of Astoria had no power and no long distance phone service. Additionally, a dialysis clinic lacked emergency power, so the National Guard had to provide backup generators. The local hospital did have emergency power. Fuel supply (diesel, gasoline, and propane) was identified as a critical limitation. The closure of Highway 30 due to downed trees and power lines cut off the main supply line from the fuel distribution center in Portland to the coast, preventing refueling of gas stations. Additionally, fuel stations lacked backup generators and were not able to pump gas even if they had an available supply. The city had a separate fuel supply supported by generators and was able to provide fuel to county, police, fire, ODOT, and ambulances. The wastewater treatment plant continued to function due to recent installation of emergency backup generators.
- In Oregon, the fatalities were caused by the flooding (one person drove a vehicle into the flooded waters of the Nehalem River, another was found in Hedges Creek), one from a vehicle accident at home while clearing debris, and two elderly persons who died of heart attacks during evacuation procedures. The report noted that other fatalities were incurred after the storm and were, "related to storm recovery activities, such as road reconstruction."

2.2 Oregon Coast Vulnerability to Power Outage

As previously shown in Figure 1, the entire Oregon coast receives its power from generation sources east of the coast range via six high voltage transmission lines. Because the coast is historically prone to Pacific winter storms that bring high winds and heavy precipitation, this long-distance electricity transmission infrastructure is vulnerable to disruption and damage from fallen trees, landslides, and flooding, as occurred in the 2007 Great Gale. Beyond the risks to the high voltage transmission grid, local level distribution grids are also vulnerable to damage from extreme events. These smaller scale grids are essential for transporting power from the larger transmission grid to homes, businesses, and critical infrastructure services.

In addition to storms, the anticipated Cascadia Subduction Zone earthquake is expected to cripple the transmission infrastructure for a period of three to six months. Such events threaten to leave coastal communities without power for an extended period of time, though the likelihood of occurrence within a given timeframe is uncertain.

When the power goes out for an extended period of time, the coastal communities that rely on that power begin to suffer losses immediately. These losses span a number of economic sectors as well as threaten the livelihood, safety, and wellbeing of visitors and residents. For the community of interest in this report – Newport Oregon – some of the specific vulnerabilities are described below.

<u>Fishing Industry</u>

The fishing industry is reliant on the availability of electricity in a number of ways. Without electricity, diesel fuel cannot be pumped at the dock (or in a hardship scenario ferried from a pump on land), ice factories cannot produce the ice many boats need to ensure freshness of their catch, fish processing facilities cannot operate, delivery vehicles may not have adequate fuel to ship product to other markets, and the loss of land-based communication networks would have multiple effects on business and marketing.

The severity of these effects on the loss of economic output of the fishery is variable by season. Depending on the time of year and the health of the fishery in the given year, fishermen are harvesting different species with different market values, and at variable quantities. According to ODFW commercial fishery landing statistics (ODFW, 2016), the value of all landings from Newport in December, January, and February of 2016 totaled $7.5M, $31.8M, and $15.3M, respectively. If a long-duration blackout event such as a winter storm were to occur during this time period, potentially millions of dollars of loss would occur.

<u>Businesses and Lodging</u>

Tourism is another large contributor to the coastal economy, generating $135M in wages in 2012, and it would also be adversely affected by a long-duration outage. The accommodations and food service sectors are the largest employers in Newport (City of Newport, 2015), and they rely on continued business from tourists and residents. During a long-duration blackout, businesses and hotels would likely be closed, resulting in wage and revenue losses.

<u>Timber Production</u>

Another major economic contributor to the Lincoln County economy is the timber industry, which includes a Georgia Pacific lumber processing plant east of Newport near Toledo. According to a study of the Lincoln County Economy in 2014 (Lincoln County, 2014), the timber industry generated a total of $104.9M in wages in 2012. Without electricity, this industry would also likely halt production due to an inability to transport and process harvested timber.

The Georgia Pacific plant does maintain a 31.8 MW thermal electricity plant, which may keep the processing facility in operation for as long as fuel lasts. From conversations with Central Lincoln PUD staff, it is assumed that this plant is capable of burning wood chips and other organic matter rather than be reliant on a hydrocarbon fuel source. However, it is uncertain whether the fuel reserves at the GP plant are similarly resilient to a long-duration disruption, so product transport may be disrupted.

Marine Science

The marine science sector contributes $62M in wages resulting from both short-term and long-term fixed research grants, state funding, and University tuition. These funding sources would not be directly affected by a long-duration outage, but the associated work performed at the Hatfield Marine Science Center and the NOAA research fleet would halt. Additionally, marine species and samples housed at these facilities may perish without electricity to sustain operations. The consequent disruptions or failures of the funded research could have uncertain negative impacts on future funding or lost benefits to society.

Banking

Many residents of Newport are of retirement age and may be dependent on a flow of outside capital from retirement savings, pensions, Social Security, or Medicaid. Without functional banks with electricity and communication capabilities, residents may be unable to withdraw money for their basic needs. This would also have widespread effects within the business community.

Critical Infrastructure and Services

Perhaps most important and most undervalued, the critical infrastructure and services of coastal communities such as Newport provide safety, stability, and emergency management capacity. These services include provision of water, fuel, wastewater sanitation, heating and cooling, food preservation, communication capabilities, and emergency services such as medical care, police, and fire protection. In the absence of these services, coastal residents face risks such as injury, sickness, and death.

Critical services and infrastructure are further discussed in Section 2.4.

Fuel and Transportation Lifeline Vulnerabilities

We assume for the purposes of this analysis that in the event of a storm-related sustained outage, major highways connecting the coast to the remainder of the state are not passable for the delivery of fuel, food, and other consumables not produced locally. The implication of this is that current emergency generators that run on diesel or propane would have an interruption of supply and could not be able to operate for the duration of the outage event. This assumption considers the propensity for coast range roads to experience landslides during large storms, but we recognize that the condition of roads following a storm event is uncertain and difficult to predict, therefore this assumption is conservative.

Coastal lifeline vulnerability assumptions change significantly if we instead consider a Cascadia Subduction Zone earthquake scenario. According to the Oregon Resilience Plan it is expected to take three to six months to restore electric service, one to three years to restore drinking water and sewer service, and up to three years to restore healthcare facilities following a Cascadia Subduction Zone earthquake event. It is likely that landslides and seismic land deformation will compromise highways to the coast. Further, the earthquake will incapacitate or destroy critical fuel infrastructure along the Willamette River in Portland, altering the availability and accessibility of fuel to coastal communities. It is expected that the coast will depend on shipments by either air or sea, and will be one among many users vying for a reduced fuel supply. The natural gas pipelines that supply the coast would likely experience ruptures and be out of commission. In the wake of a large tsunami wave, the port facilities in Newport would likely also suffer damage or complete destruction, complicating sea-based relief efforts.

Together, these anticipated effects paint a sobering picture of the energy system for the Oregon coast. The loss of the transmission grid, fuel infrastructure and supplies, and transportation routes would mean that even emergency generators would quickly run out of fuel without a external resupply efforts. A ship-based generator on a Navy ship may have the ability to provide local grid-level power, but the uncertain condition of the port could prevent entry or anchoring of a large vessel. Technology exists to airlift fuel in large bladders, but the costs and logistics of such an effort are beyond the scope of this report. Access to any available fuel supplies would be highly competitive between emergency responders, evacuation services, and infrastructure restoration crews in addition to a continued supply for emergency power generators. Given these projected constraints, a risk mitigation strategy that does not rely on fuel, such as a renewable energy generation facility, would appear to have significant benefits over a fuel-dependent alternative.

2.3 Newport's Energy Infrastructure

Before detailing the technically feasibility of supplying Newport's critical infrastructure with wave energy, we will cover how power is distributed to Lincoln County Public Utility District's customers, and why CLPUD, and Newport in particular, is uniquely organized to realize this opportunity.

Figure 2. Service area for Central Lincoln PUD in central coastal Oregon

Central Lincoln Public Utility District (CLPUD) supplies all of Newport's energy needs. CLPUD is a publicly owned utility, meaning that it is owned by its customers and makes decisions through a board of local community members, rather than a board of investors. CLPUD provides power to approximately 38,600 customers over a 700-square-mile service area. The peak demand of the system is 270 MW. CLPUD has no energy generation capabilities, thus it has contract agreements with the Bonneville Power Administration (BPA) to buy BPA-generated electricity. The main connection between CLPUD-owned distribution lines and the BPA transmission system is located in Toledo, OR (see figure below).

This single connection to BPA-generated electricity situates Newport and Lincoln County as more vulnerable to electrical outages compared to community with local energy generation and redundant connections to external energy generation sources. However, there are two characteristics of Newport that enable it to integrate emergency wave energy generation.

Figure 3. Overhead view of the connection between the Bonneville Power Administration's transmission system (top right) and Central Lincoln PUD's system (bottom left).

First, Newport will install wave energy infrastructure that will enable it to use an emergency wave energy generation system. In late 2016, the Department of Energy awarded Oregon State University a grant of up to $40 million to develop a grid-connected national wave energy testing facility (Department of Energy, 2016). This facility will be located south of Newport in the Seal Rock area. Currently, there is no direct connection from South Beach to downtown Newport; power is first transported to Toledo, OR and then to Newport. Therefore, if emergency wave energy generation is implemented, it is vital to maintain the Toledo-Newport connection.

Secondly, CLPUD has already begun implementing smart grid technology that will make wave energy integration technically feasible. CLPUD has implemented Advanced Metering Infrastructure (AMI) through the American Recovery and Reinvestment Act of 2009 (OpenEI, 2012). The project, titled Smart Grid 2020, consists of installing smart meters at customer locations. With this technology, CLPUD is able to remotely collect and monitor, in near real-time, the quality and quantity of power at each customer's location and detect outages as they occur (Figure 9). Moreover, CLPUD can leverage this technology to control and manage grid operations through distributed automation schemes, increasing the reliability and resiliency of a system. This capability has allowed us to explore the idea of an islanded microgrid during an emergency scenario.

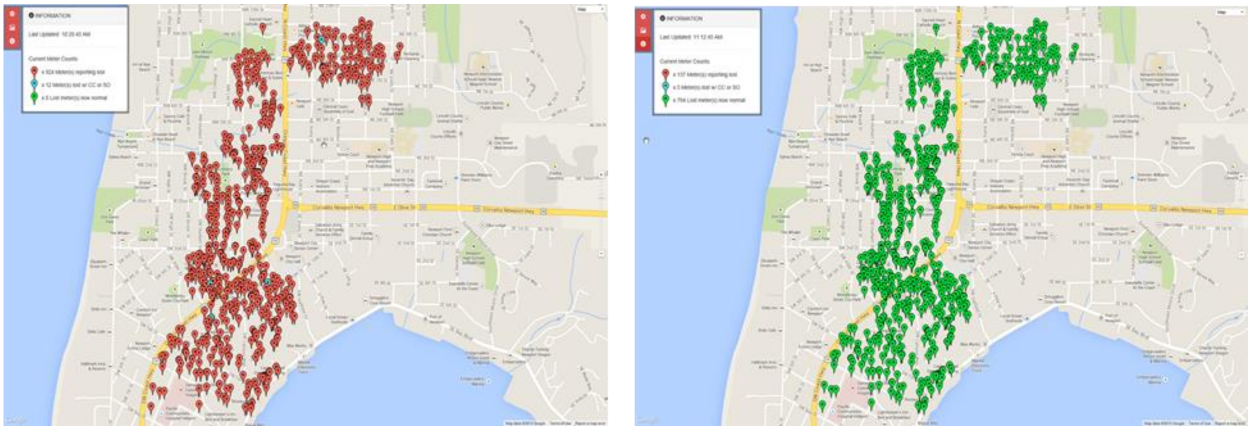

Figure 9.4. Central Lincoln PUD's in-house outage tracker. Image on the left shows the smart meters reporting customer are disconnected. The right shows the same outage but an hour later where all customers are receiving power.

With its progressive attitude towards incorporating renewable energy, existing smart grid infrastructure, and experience with wave energy, CLPUD is uniquely positioned to implement wave energy as emergency generation.

2.4 Identifying Critical Infrastructure and Services

To appropriately size and scale a WEC array, it is necessary to identify the local critical infrastructures necessary to sustain the community and their associated required electrical loads.

The US Department of Homeland Security has identified 16 critical infrastructure sectors, "that compose the assets, systems, and networks, whether physical or virtual, so vital to the United States that their incapacitation or destruction would have a debilitating effect on security, national economic security, national public health or safety, or any combination thereof."

The list of Department of Homeland Security Critical Service Sectors was compared against the services and infrastructure in Newport and corroborated by a review of the Lincoln County Multi-Jurisdictional Natural Hazards Mitigation Plan (Oregon Partnership for Disaster Resilience, 2015) to produce a proposed list of critical electricity-dependent services and infrastructure. This list is included here in Table 1.

This list represents an ideal suite of available critical services in the event of a long-duration power outage; however, this list may be further prioritized toward emergency, water, and health services if insufficient emergency power is available. Some services such as traffic lights or Internet, while important, have been omitted from the list because alternative methods of traffic control and communication would be available.

We provided the list of critical service infrastructure to CLPUD personnel, from which typical energy demand profiles were generated and shared with us. Where load data was unavailable, loads were estimated based on the Department of Energy's OpenEI database. Loads detailed in Table 1 represent the maximum load required. The power demand for all identified Newport critical service infrastructure would equal 4,511 KW of instantaneous power generation demand.

Table 1. Proposed List of Critical Service Infrastructure for Newport, Oregon

Critical Service Sector	**Associated Newport Infrastructure**	**Electricity Demand (OpenEI Reference) (Maximum Monthly) [kW]**	**Electricity Demand (CLPUD)** *(normal operations)* **[kW]**
Chemical	N/A	N/A	N/A
Communications	Cell towers (8 registered towers, 10 unregistered, 114 antennas)	N/A	N/A
Commercial Facilities	N/A	N/A	N/A
Communications	KPPT Radio Broadcaster	14.1[a]	5.9[†]
	KYTE 102.7 Radio Broadcaster	14.1[a]	18.0[†]
Critical Manufacturing	N/A	N/A	N/A
Dams	N/A	N/A	N/A
Defense Industrial Base	N/A	N/A	N/A
Emergency Services	Lincoln County Jail	N/A	208.5[†]
	Lincoln County Sheriff's Office	253.4[b]	124.3[†]
	Newport Fire Station	14.1[a]	34.7[†]
Emergency Services – Shelter Locations**	Oregon National Guard Armory	253.4[b]	16.7[†]
	Newport Recreation Center	14.1[a]	N/A
	Newport High School – East & West	819.4[c]	N/A
	Sam Case Early Childhood Center	237.4[d]	N/A
	Newport Intermediate School/Isaac Newton Magnet School	237.4[d]	N/A
	Yaquina View Elementary School	237.4[d]	N/A
Energy	Lincoln Co PUD Main Office	253.4[b]	N/A
Financial Services	One bank of the community's choosing	253.4[b]	N/A
Food/Agriculture	JC Market Thriftway?	305.1[e]	N/A
Government Facilities	Newport City Hall (Police Department located in City Hall)	253.4[b]	100.3[†]
Healthcare and Public Health	Newport Hospital	1367.3[f]	N/A
	Oceanview Senior Living	N/A	N/A
	Newport Rehab and Specialty Care	N/A	N/A
Information Tech.	N/A***	N/A	N/A
Nuclear Reactors, Materials, and Waste	N/A	N/A	N/A
Transportation Systems	Lincoln Co Fleet Services	14.1[a]	5(Narayan)
	Private fuel pumps/supplies (8)	N/A	40 (Narayan)
Water and Wastewater Systems	Newport Water Treatment Plant	2552	233
	Municipal water pumps (2 locations?)	N/A	N/A
	Wastewater pumps (12 locations)	N/A	N/A
Total Critical Infrastructure Load		4,511.3 KW	

* County emergency communications also rely on radio transmitters and repeaters, some of which may be remote.
** Shelter areas are not included in the DHS list of critical services, but are included here to provide shelter and heat to affected residents.
*** County emergency managers may choose to include Internet services as critical infrastructure, but they have been omitted in this analysis.
[†] Data provided by CLPUD's smart meter data readings
[a] Numbers based off of DOE reference building codes for a Small Office
[b] Numbers based off of DOE reference building codes for a Medium Office
[c] Numbers based off of DOE reference building codes for a Secondary School
[d] Numbers based off of DOE reference building codes for a Primary School
[e] Numbers based off of DOE reference building codes for a Super Market

[f] Numbers based off of DOE reference building codes for a Hospital

2.5 Current Emergency Blackout Response Measures

Some facilities in Newport have diesel-powered emergency generators of sufficient capacity to maintain operations for a period of hours or days. CLPUD does not possess enough backup generators to support critical services, but onsite fuel supplies are expected to provide from 24 to 72 hours of operation before refueling will be required (Kuhns & Co., 2016). Gas pumps in town also require electricity to operate, and during the Great Gale of 2007, generators had to be delivered from elsewhere in the state for both personal and public use (Elliott and Tang, 2012).

Based on a report from EPRI (2003), the estimated cost per kilowatt (kW) for a diesel generator is $15.34 for 200 hours of operation per year with fuel costing $1.00 per gallon. Extrapolating these figures into a cost per kilowatt-hour of generation yields a result of $0.19/kWh in 2003 dollars ($0.25 in 2017 dollars). By comparison, the residential electricity rate in Newport, Oregon is $0.0785/kWh. This does not account for potential increase in fuel prices during an emergency scenario.

According to an analysis in Zarakas (2014), “A 20-kW portable generator (powered by diesel or gasoline) costs about $25,000 . . . we assume an average cost for portable generators of about $1,250 per kW.” To achieve the 4.5 MW estimated requirement of critical services, the cost of generators would total nearly $5.5 billion.

Emergency generation also requires integration activities, including installation of wiring, switches, and safeguards to protect against inadvertent damage to the grid. Zarakas (2014) notes that, “The cost of connecting the portable generator to the load can be significant and could match the cost of the equipment itself.” (Zarakas, 2014)

The reliance on emergency diesel generators poses an additional reliability risk. As one report noted,

> These backup generators are not completely reliable; they are often diesel-based generators with limited capacity and run time, and they require regular deliveries of fuel that might not be available during disasters. During Superstorm Sandy backup generators failed for hospitals in some instances, leaving some with no option other than full evacuation. Multiple facilities reported that their backup generators failed during the storm. (Chittum 2016)

During a storm-related, long-duration outage scenario, it may be expected that the fuel supply for emergency diesel generators can be replenished indefinitely. In the event of a Cascadia Subduction Zone earthquake and tsunami, however, the expectation is that roads across the coast mountain range will be impassable and the fuel supply in coastal communities will be limited for an unknown period of time.

2.6 Wave Energy Generation Potential

Given the large amount of potential energy in ocean waves, an industry is growing that hopes to capture some of this energy to provide electricity in a manner that is environmentally conscientious and economically comparable with existing renewable energy sources (Quadrennial, 2015). In the last couple decades, many variations of device designs have arisen; however, the industry has yet to settle on a single design or set of designs. This is likely due to the complexity of the ocean space and the importance of designing the device to the specific sea states that will be experienced.

Currently, the implementation of wave energy converters for large scale power production is facing several hurdles – primarily achieving cost competitiveness, understanding environmental impacts, and overcoming regulatory requirements. Since the initial rush towards commercial implementation of WECs, some in the industry have shifted their development focus towards smaller scale energy production that can be used for emergency generation. M3 Wave, a local Oregon company, has been pursuing a device design and business model that works best for such scenarios (M. Morrow, 2016).

The use of WECs for emergency generation could potentially circumvent some of the current regulatory and environmental concerns due to temporary deployment and exigent circumstances. However, for wave energy use as emergency generation to be realized, the return on investment needs to be carefully understood and quantified. WEC developers will need to consider that the devices might spend most of their lifetime in storage to then be transported and deployed when needed. This report will discuss the quantification of an emergency generation device and the potential value that would be provided by its implementation.

2.7 Regulatory/Social Considerations

The traditional permitting process for marine hydrokinetic devices under the Federal Energy Regulatory Commission (FERC) can span up to seven years and entail extensive consultation and environmental studies to satisfy regulatory agencies with authority over the ocean and coastal zone. In addition to the FERC license, a WEC developer must also obtain permission to lease the seafloor and install transmission cable landing infrastructure on shore, which involves additional technical and public process requirements. However, the presence of an emergency situation may present an opportunity to change the rules of the regulatory landscape and allow emergency approval of a temporary WEC array. Furthermore, a wave energy device is required to abide by both the ANSI and IEEE standards for electrical equipment where strict monitoring and electrical characteristics need to be met. Both of these concepts are further explored in Section 5.

2.8 Coastal Resilience Zones

In the event that the coast or a portion of the coast loses power for an extended period of time, it is necessary to have prepared a response suitable for the intensity of the event. This response should consider aspects such as power, communications, food, clean water, etc. The intensity of an event could range from a cascading blackout from weather-related transmission outages to a Cascadia Subduction Zone event. Current emergency power response relies primarily on diesel generators that last about two days before refueling. The location and extent of an event and its consequences also affect the intensity of the event, are highly uncertain.

In response to this uncertainty, there is the potential to create discrete, permanent resilience zones that can support regions of the coast in case of emergency. The resilience zones would be a location within a region designed to be robust towards crisis that may result in a power outage. In this way, communities would not be individually burdened with preparing for emergencies, but could share the financial commitment. Renewable energy generation in conjunction with smart grid technology could be used to provide the power required for emergency services, forgoing the high cost, logistical difficulty, and harmful health and environmental effects of diesel generation. With wave energy as a local, plentiful, and available resource, it has the potential to be an advantageous energy generation solution.

Wave energy could be used within resilience zones either as a deployable resource or as with an existing offshore structure that is already in place and grid connected. The Pacific Marine Energy Center's (PMEC) South Energy Test Site (SETS) could provide the permanent infrastructure to enable emergency wave energy generation in Lincoln County, Oregon (S. Armstrong, 2015 and B. Goodwin, 2016). SETS will be a grid-connected WEC test facility located about 6 miles off the coast of Newport, Oregon that could be utilized for hosting WECs after an emergency and would eliminate the need to deploy necessary WEC system infrastructure (such as cables and other electrical equipment) post-emergency. One potential drawback of the proposed SETS location is that the power will be cabled to shore south of Newport and would have to be routed through Toledo before arriving in Newport itself. Despite the increased potential for more lines requiring repair post-emergency, this could still provide power relatively quickly and for longer than existing diesel generators.

3 Technical Feasibility

When considering using wave energy as an emergency generation source, we consider the total available resource, how much of this resource is converted to electricity, and how the electricity is able to integrate into the existing grid and reach critical infrastructure. This section will include 1) the determination of optimal locations for emergency wave energy generation based on available resource and WEC array efficiency, as well as 2) the modeling of Newport's distribution network to determine the feasibility of integrating wave energy.

3.1 Resource Assessment and Conversion

3.1.1 Optimal Wave Power Locations for Lincoln County and Oregon State

Once a storm has occurred which necessitates emergency power generation, WECs would be deployed as soon as waves are safely passable for a boat and crew, and would be placed in a location that provides the most available power. By optimally locating the emergency WEC array, we are able to provide critical infrastructure energy needs with the least equipment (and cost) required.

To determine where the best location might be, sea state data off the coast of Lincoln County is evaluated over a two week period (which corresponds to the theoretical sustained outage being modeled in this report). The data acquired from WaveWatch III yields 3720 data points corresponding to unique latitude and longitude pairs of Lincoln county and 1634 data points for the entire Oregon coast. Each of these locations has a corresponding water depth, significant wave height (Hs) and modal period (Tm). The Hs and Tm are based on hourly samples.

To determine which two-week period to evaluate, sea state data from 2011 to 2016 was examined to find the largest storm. On March 12th of 2012, a storm occurred on the coast with hurricane force wind warnings and wave heights up to 11 meters (as recorded by the NOAA buoy 46050). Consequently, we decided to measure the available power in the two weeks following this storm – March 14-27, 2012. The latitudes and longitudes of the spaces examined are shown in Table 2.

Table 2. Boundary corners for the selected search spaces.

	Lincoln County	Entire Oregon Coast
Southern Boundary	44.28º	42º
Northern Boundary	45.04º	46.25º
Western Boundary	-124º	-123.85º
Eastern Boundary	-124.33º	-124.75º

The upper and lower bounds correspond to the southern and northern boundaries of Lincoln County and Oregon State respectively. The left boundaries was chosen to be 10 miles from the furthest western points of land within Lincoln County and the entire state. The right boundaries were made to be just inland from the furthest eastern point of the ocean. Figure 10 shows the chosen spaces and the corresponding water depths.

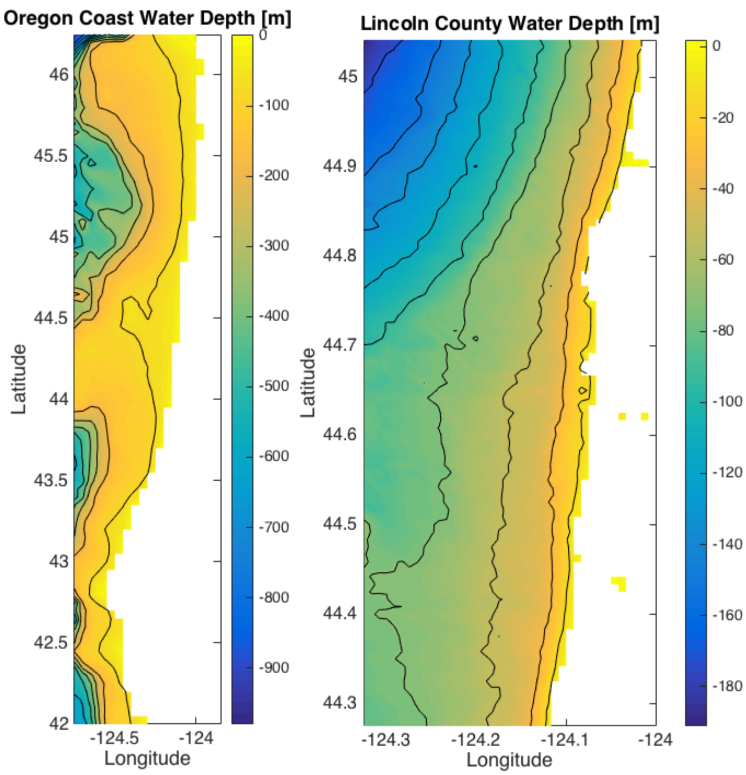

Figure 10. Water depth variability for a minimum of 10 miles off the Oregon Coast (left) and Lincoln County (right)

The device chosen for evaluation is a truncated cylinder with a diameter of 10m, a draft of 10m and overall height of 15m. Two pieces of software are required to determine the power of a device. The WEC motion is initially modeled in the boundary element method software, WAMIT, at representative water depths across the ocean space (Figure 10). The device motion is modeled with 6 degrees of freedom. Once the WEC motion is modeled in WAMIT, an exhaustive search is used to determine the best location to place the WECs. At each ocean location tried by the exhaustive search, the analytical modeling software, *mwave*, calculates the electricity generated by the WEC.

Since *mwave* operates in the frequency domain, the time series data from WaveWatch III must be represented in frequency form. Rather than using a single sea state averaged over the two-week period and losing the variability in ocean conditions, every time a device is evaluated at a location, the time series from WaveWatch III is represented by several frequency domain sea states (Bretschneider spectrum). For each of these sea states, an optimal damping (a WEC control method) was found for the device using the Golden Search optimization method.

Figure 11 represents the total available power determined for each location. Also, Figure 11 shows the regions with the best available power (represented with black circles). The resource improves as the distance from shore increases, but the search space was restricted to about 10 miles off the coast.

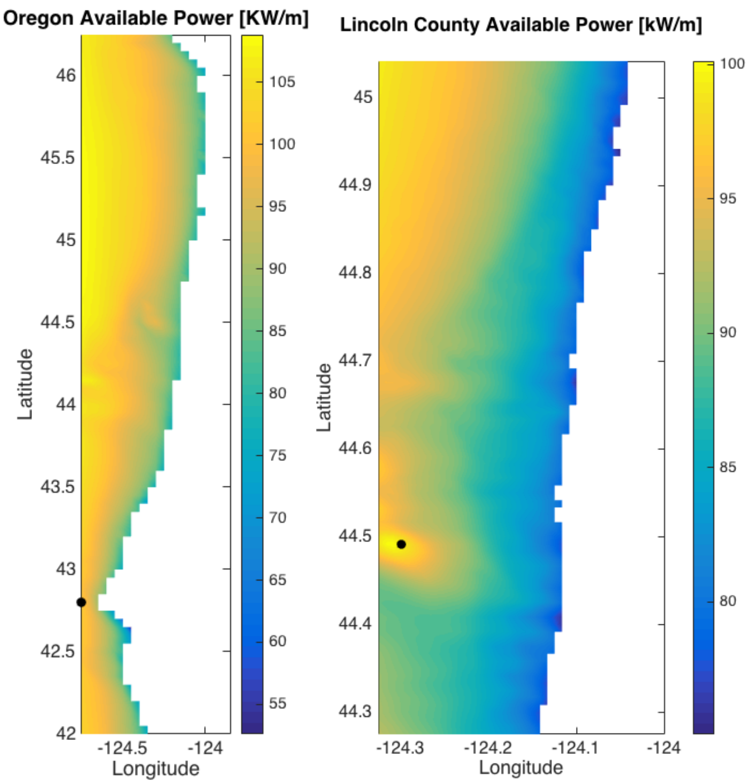

Figure 11. Total available power off the Oregon Coast (left) and Lincoln County (right).

The optimal locations for all of Oregon and locally for Lincoln County were found to be at 42.8º, -124.75º (left) and 44.49º, -124.30º (right), respectively (shown in Figure 12).

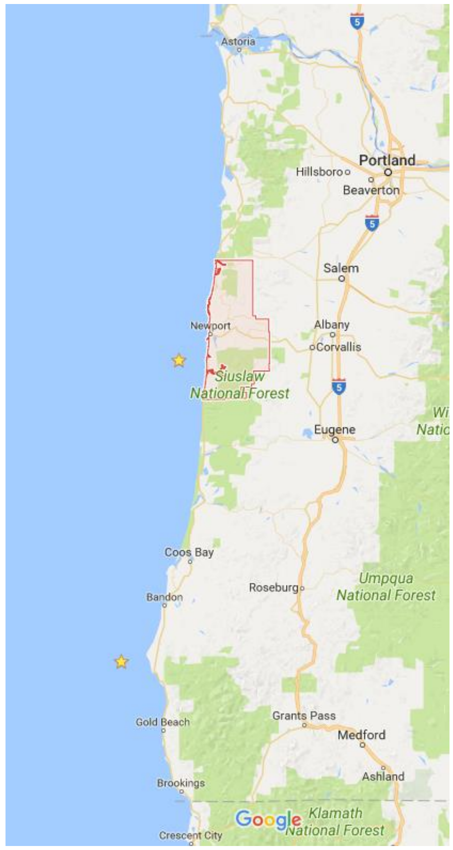

Figure 12. Locations of best available power along the entire Oregon Coast, as well as Lincoln County (highlighted in red).

The available power density at these locations is 149.67 kW/m (Oregon Coast) and 143.08 kW/m (Lincoln County). With an assumed capacity factor of 40%, the power that could be extracted by our modeled device over two weeks following the storm in March 2012 is 41.42 MWh (Oregon Coast) and 40.34 MWh (Lincoln County). This equates to 127.43 kW (Oregon Coast) or 124.11 kW (Lincoln County) average instantaneous power generation capacity for a single device. Consequently, the emergency WEC system would require 37 devices at the Lincoln County location based on the device modeled in this section of the report. If a more efficient device type was used and if the devices were strategically placed in an array, the required number of devices would likely be less 37.

3.1.2 Post-storm Power vs Full Year Power

Once the power has been determined for a two-week period, we then evaluate the power output at a single location for a single year. This comparison will provide results regarding the potential for a power increase immediately following a storm when compared to the generation of power for an extended period of time. The same methodology performed across multiple locations in the previous section is used here, except that WaveWatch III data is extended to include the entire year of 2012, rather than just the 2-week period in March, and it is limited to the optimal location of interest (44.49º, -124.30º). Table 3 shows the compiled results.

Table 3: Compiled results for the Oregon Coast and Lincoln County comparing a 2-week, post-storm period and an entire year.

	March 14-27, 2012	**2012**
	Available Power [kW/m]	
Oregon	149.67	101.26
Lincoln County	143.08	99.54
	Captured Power [kW]	
Oregon	127.43	70.47
Lincoln County	124.11	74.67
	Lifetime Power [MWh]	
Oregon	41.42	587.07
Lincoln County	40.34	622.31

We observe that the annual power produced is less than that of the two-week period. This is primarily due to the decrease in wave energy potential during the summer months. Further studies are required to better understand the wave resource behavior immediately following a storm and the potential for increased power production within that window.

3.1.3 Power Fluctuation (March 14-27, 2012)

Using wave energy as emergency generation must *consistently* provide enough power to sustain emergency services in the aftermath of an emergency. Thus far, we have quantified the *average* power produced over a selected time span. While this is useful information for estimating the size of the WEC system required to power critical infrastructure post-emergency, we also need to know how well the *instantaneous* power satisfies the required load. To determine this, we evaluated the power at discrete points throughout the two-week period in March. We chose to evaluate twice a day (at 12pm and 12am) to account for any potential variability caused by the time of day. Figure 13 shows the instantaneous available power for the two-week period at the selected points in time.

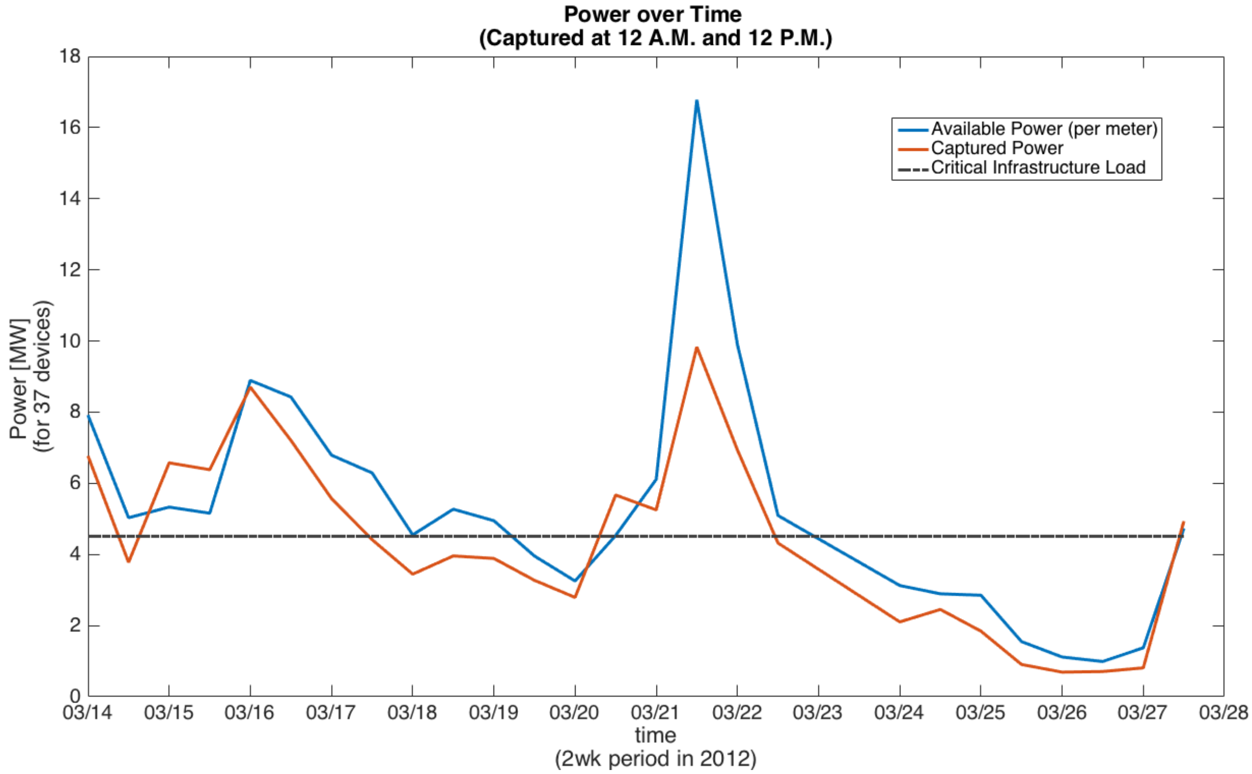

Figure 13. Power for 37 devices over a two-week period at the optimal location off Lincoln County's coast.

Observing the resulting power of 37 devices, we note that there are moments in which the necessary power of ~4 MW would not be produced. This indicates either 1) the need for more than 37 devices to ensure the minimum required power is always met or 2) to supplement the WEC system with a bank of batteries or with backup diesel generators to provide additional power. There does not seem to be much of a difference in power generation between the day and the night.

3.2 Modeling and Analysis of CLPUD's Distribution Network

3.2.1 Leveraging Existing Tools and Technology

Our proposed emergency WEC system relies on the advancement of smart grid technology. A deployable WEC system alone cannot feasibly power Newport's total electricity load (both critical infrastructure and all other customers). Therefore, this solution requires remotely disconnecting customers that do not supply critical infrastructure services, which is only possible through the use of AMI. With AMI, utilities like it, can limit power distribution to customers that critical infrastructure services.

3.2.2 Methods to Model Distribution Network

To accurately model Newport's distribution system, we first identified the location of the main feeders and their routes (Figure 14). In addition to the routes, Figure 14 shows the locations of main substations and protective devices (e.g.: manual/digital switches, vacuum fault interrupters, and reclosers) and how they interface with each feeder. There are two substations (with an additional substation located farther north) that supply most of Newport's power.

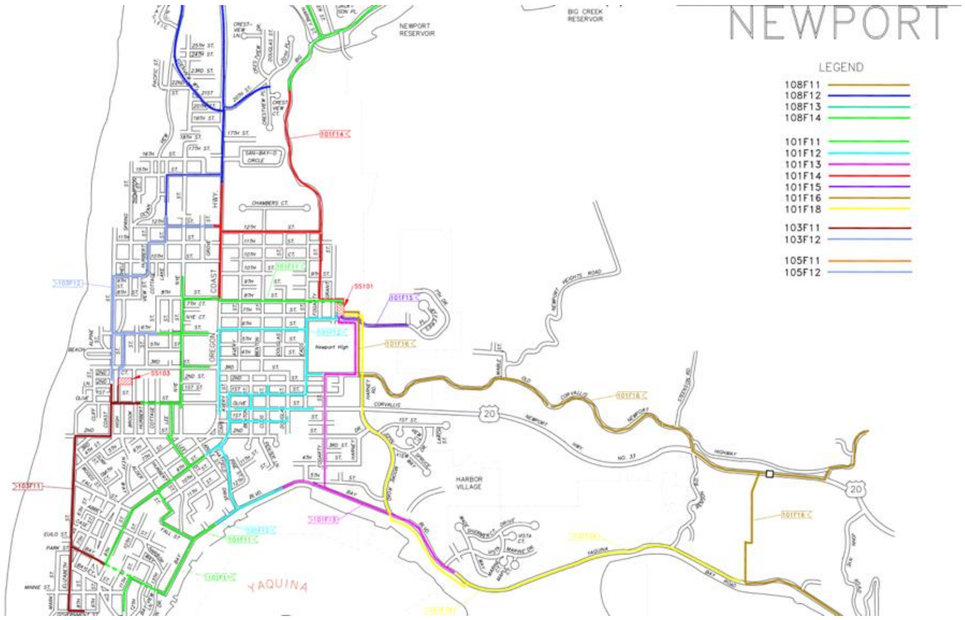

Figure 14. Map of distribution feeders in downtown Newport, OR. Locations of protective equipment have been removed at the will of Central Lincoln PUD for security reasons.

The next step in modeling the distribution network is identifying locations of main connection points. Figure 15 shows each critical load connection to each feeder. Table 1 details the maximum load demand.

Distance, ampacity, and per-unit impedance for each electrical connection between critical infrastructure facilities is included in Appendix A. The rated voltage for each line is 12.47 kV. In reality, line types (or the conductor they use) vary across the network as lines are added and replaced over time to meet local load variation. However, for the sake of this study, we assume line type is uniform across the network.

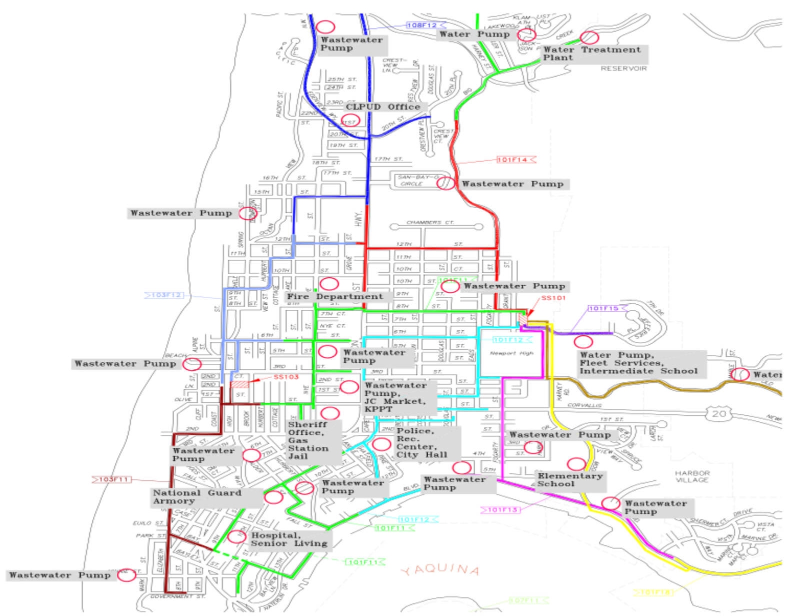

Figure 15. Map of distribution feeders with the added layer of Newport critical infrastructure

Figure 16 shows the one-line diagram of Newport's distribution system. The resulting model is a combination of a radial and a networked system (Sallam, 2011), leveraging the higher reliability of a networked system and the maintainability of a radial network.

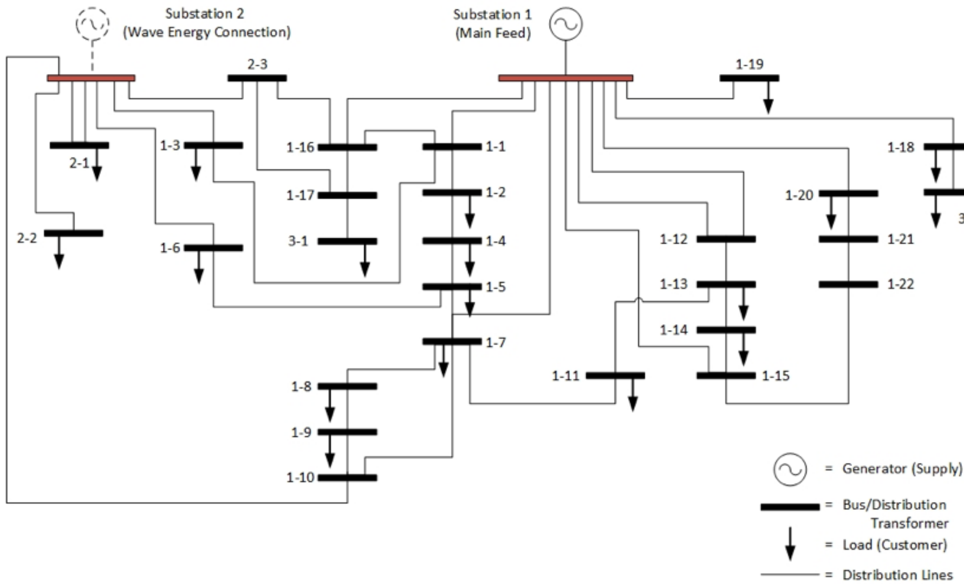

Figure 16. One-line diagram of Central Lincoln PUD's distribution network for the downtown Newport area. Specific labeling of the buses has been anonymized to hide the location of protective equipment.

The generator at Substation 1 represents the main supply of power from BPA. Substation 2 will connect the emergency wave energy system to the distribution system.

3.2.3 Analysis and Simulation of Central Lincoln's Distribution Network

In this section, we complete a basic assessment of the power system to see if there are any major issues with the integration of wave energy at a substation (which does not usually intake a major source of generation). The simulations that follow were performed in Matlab making using of the open-source power system optimization toolbox MATPOWER (Zimmerman, 2011).

Table 3 in Appendix A shows the results of running a power flow algorithm, which determines how electricity will flow through our modeled network and check for any major faults caused by wave energy integration at Substation 2 (SS 103 on Figure 14 and 15). The power production of the WEC system is assumed to fulfill critical infrastructure.

We need to check is to see if any of the line limitations have been violated. The most power being delivered through any one section of conductor is 1.69 MW and is from Substation 2 to bus 1-6. Dividing that number by the operational line voltage (12.47 kV), the line operates at we find that there is 135.5 A of current, less than which is well below the rated ampacity of 310 A.

While line limits are not violated by the electricity produced by the WEC system, there are other system requirements to consider. Since the wave farm were designed just to supply the critical infrastructure exactly, then the losses, inherent to energy transportation, are not being considered. While the losses of the system are minimal, the slack generator located at Substation 1 outputs a non-zero active and reactive power. If this study points out that if the WEC system is unable to provide reactive power to the system, then this solution would not be feasible. Further, we assume that all customers require only real power is required, but realistically, several customers will require some reactive power as well. This is because several of the loads (water pumps, hospitals, fleet services, etc.), which require reactive power supply.

3.2.4 Summary of Network Analysis

The simulation performed above, while simplified, points out some key issues that need to be addressed if wave energy is to be used as an emergency generation source. While the system can handle this new generation, there are concerns about reactive power support. Another issue not addressed in this analysis is the impact of seasonal variations on power reliability. In Section 3.1, we observed that wave energy produced could range from 15 MW during winter to 0.4 MW in summer. Without technical advancements such as energy storage, wave energy may not be the solution to emergency response. Lastly, it is important to know that these results are only as good as the model itself. There are several key components (e.g. shunt capacitors) that are excluded from this model because of either a lack of data or the additional complexity that those components bring with them.

4 Economic Feasibility

4.1 Valuing Losses from a Long-Duration Blackout in Newport, Oregon

4.1.1 Introduction

An essential aspect of the quantification of risk from long-duration power outages is the magnitude of the potential impact to the affected community. If the impact can be combined with the expected likelihood of a negative event occurring in a given period of time, then an expected value analysis can be performed to compare the potential losses over a given period of time against the cost of a mitigation or prevention measure such as a new emergency power generation source.

The purpose of this section is to identify a range of potential values for a long-duration power outage in the community of interest – Newport, Oregon – under a storm-related outage scenario. To accomplish this estimation, we present a survey of outage valuation methods from the available literature, then apply a range of methods to the community of interest based on available information about the community's demographics, economy, critical social and infrastructure services, existing emergency generation capabilities, and energy demand.

4.1.2 Methods

The valuation of a long-duration blackout cost for Newport, Oregon was performed by first reviewing the literature surrounding value of lost load (VOLL) estimation methods and results from around the world, their strengths and weaknesses, and their applicability to the community of interest. These methods and metrics are then applied to Newport's specific demographics and economic statistics to approximate a range of potential outage costs associated with a hypothetical power outage of a two-week duration. Following the lost value estimates is a discussion of uncertainties and gaps with the analysis and their potential effect on the veracity of the estimates.

Given that during the Great Gale of 2007, some communities in Oregon and Washington experienced outages ranging from a few days to a maximum of 3 weeks (OSSPAC, 2013), the two-week scenario was chosen as a reasonable event duration for a low-likelihood, high-impact event isolating the Oregon mid-coast from the larger BPA transmission grid. However, the likelihood of such an event occurring within a given timeframe (e.g., 20 years) is uncertain, complex, and dynamic, relating to many factors such as the prevalence of large storms, the condition of the BPA transmission grid across the coast range at the time of a storm, and the presence of risk amplifying factors such as large trees in the vicinity of high voltage lines or the geographical vulnerability of electrical infrastructure to landslides and flooding. Therefore, a quantitative measurement of the scale of the impact of a long-duration blackout is only one factor in the quantification of total risk.

A second outage scenario of 6 months duration was also included to show the potential "worst case" outage in the event of a Cascadia Subduction Zone (CSZ) earthquake (OSSPAC 2013). This estimate is included to illustrate an outer bound of potential negative impacts and is not the main focus of the overall report's analysis.

4.1.3 Common Methods of Outage Valuation

The science of blackout valuation is constantly refining. As has been noted in the literature (Castro et al., 2016; Schroder and Kuckshinrichs, 2015), it is necessary to find a common basis for measurement of loss to individuals and economic producers when an outage occurs. While many types of loss occur when a community lacks electricity, most estimates attempt to convert these losses to dollars to facilitate comparison, quantification, and cost benefit analyses of potential investments that may reduce the loss. Based on a survey of blackout valuation analyses in the available literature, most focus on one of two general methods of valuation: willingness-to-pay surveys of customers and macroeconomic models.

<u>Macroeconomic Analysis</u>
Macroeconomic analyses use available data about a community's economy to develop a production-function analysis, "in which electricity is treated as an input necessary to produce a valuable output; when the input fails, the output good is not produced, therefore enabling a cost of electricity outage to be derived. Thus, the consequences of a power interruption are estimated through the computation of lost production for firms or lost time for households." (Castro 2016)

The economic models can be theoretically based on GDP statistics or ex post facto costs of actual outage cases. Many of these analyses occur on the scale of major cities or entire countries, however, so there may be system or parameter uncertainties associated with an effort to apply those findings to a smaller coastal community with seasonal variability in its economic activity.

Macroeconomic outputs are classified into three main categories, each of which is further subdivided under the following framework (Manson and Targosz, 2008):

- Direct economic impacts
  - Loss of production
  - Costs to resume production
  - Damage to equipment
  - Loss of materials
- Indirect economic impacts
  - Delayed receipt of rents
  - Financial cost of losing market share
- Social impacts
  - Uncomfortable temperatures at work or at home
  - Loss of leisure time

- Risks to health and safety

Macroeconomic analyses are sometimes favored over survey-based VOLL estimates because they utilize real data and they do not require expenditure of additional resources to develop and execute surveys among community members. However, some of the difficulties of applying this approach to a long-duration blackout scenario include the widespread indirect economic effects of an outage, an inability to capture the specific value of critical services to community members, and difficulties in measuring the value of non-economic lost value such as leisure or community wellbeing (Schroder and Kuckshinrichs, 2015).

<u>Contingent Valuation and Willingness-to-Pay Surveys</u>
Surveys are commonly used in VOLL estimation as a means to determine a utility customer's willingness to pay for a good – in this case, uninterrupted electrical service. From these customer preferences, the value of the good may be estimated. The resulting VOLL is then calculated based on the duration of the electricity disruption. (Schroder and Kuckshinrichs, 2015)

Under a discrete-choice contingent experiment format, "Households are either told that, for additional payments, front-door delivery of power will remain uninterrupted (Layton and Moeltner, 2005; Carlsson and Martinsson, 2007), or asked to choose from a set of outage bundles that vary in timing, length and/or frequency, and are each linked to a specific fee added to the electricity bill (Beenstock et al., 1998; Carlsson and Martinsson, 2008; Baarsma and Hop, 2009; Blass et al., 2010)."

A commonly cited VOLL estimate is based on a meta-analysis conducted by Lawrence Berkeley National Laboratory (LBNL) of 28 interruption-cost surveys that polled residential, commercial, and industrial power customers regarding their willingness to pay to avoid power disruptions (Sullivan et al., 2009). Based on the results of the interruption cost surveys, LBNL developed the Interruption Cost Estimation (ICE) calculator, which, "assesses the average frequency and duration of outages in a given area and estimates potential losses based on the number and type of customers affected." (Chittum 2016; Sullivan 2009, Sullivan et al., 2017)

The primary drawback of the survey-based VOLL methodology is that none to date have asked customers to assign value to outages lasting longer than 24 hours. Thus, application of this method to a long-duration outage scenario suffers an incompatibility with uncertain significance to the veracity of the resulting VOLLs.

4.1.4 Valuation of Critical Services

Of the many VOLL estimates in existence, very few have recognized the distinct value of critical services. The literature regarding the value of critical infrastructure services has been described as "sparse" and "taken for granted due to institutional or policy reasons (Cohen 2016)." In past attempts to survey customer willingness to pay to prevent loss of these services for a significant period of time, it was noted that,

"Given the critical nature of some of these services to cover basic human needs, and a lack of historic problems with service provision, respondents may question the realism of stipulated interruption scenarios. Furthermore, any suggestions of taking away services traditionally provided by local governments will undoubtedly trigger protest responses, and may introduce sample selection problems into the empirical analysis (Hensher et al., 2005; Willis et al., 2005; Cohen 2016)."

Zarakas et al. (2014) further noted that, “Customers would probably not place any value on losing access to critical services during short lived outages. Instead, they would begin to be realized as the duration of outages . . . exceeded 48 or more hours or more.”

Cohen (2016) utilized an essential input approach to generate estimates of the value of critical services. The study found that, “customers are especially sensitive to losing medical, communication, transportation, and sanitation services,” and therefore the traditional method of assigning a value to a person’s willingness to pay per kilowatt hour (kWh) unserved may fail to acknowledge the, “much broader set of impacts and thus a much larger volume of lost electric load.” (Cohen 2016).

Cohen (2016) developed a valuation model that combines household production theory (Becker 1975) with a Random Utility framework (Ben-Akiva and Bierlaire 1999) to derive European households' willingness-to-pay to avoid disruption of electricity provision to the “front door," as well as the loss of important public services. The study found that 20-80% of residents’ total willingness-to-pay relates to the publicly provided critical infrastructure services. The study concluded that, “the WTP to secure infrastructure services ranges from <u>close to 40% to over double the amount associated with front-door losses alone</u>.”

Narayan (2012) noted that determining a residential customer’s WTP to prevent loss of critical services during a long-duration outage is difficult because, “without experiencing an extended outage there is little reason to believe that residential customers could provide an informed, quantitative answer to such a question, even if they generally understand some of the consequences of an extended blackout.” Instead, they reasoned that an expenditure of 1-4% of household income would be a reasonable range of cost as “social insurance” to sustain critical services in the wake of a major outage.

Dobes (2015) conducted a choice modelling survey (Bennett and Blamey 2001; Bateman et al. 2002) of residents in Cairns, Australia, which found that households would be willing to pay $357AUD ($282 USD) per year to reduce the time it took after a tropical cyclone to restore utilities (water, sewage, electricity, gas) from 5-8 days down to 3-4 days. This analysis captured both critical service value and the concept of an outage duration greater than 24 hours.

In their analysis of the value of distributed emergency generators, Zarakas et al. (2014) also used the “insurance” concept as reason to support an $8 annual cost per person for a system providing 2.7MW of gasoline generator power[1] to sustain critical services for a hypothetical city of 100,000 people. Considered together, these studies of critical service value offer potential avenues of VOLL estimation, but each carries uncertainty and may not translate perfectly to a new community or scenario.

4.1.5 Value of Mortalities Prevented

During a long-duration outage, mortalities could be directly attributed to a number of outage-related events such as inoperable traffic signals, lack of water, poisoning from consumption of spoiled food, hypothermia or heat stroke, illness due to unsanitary conditions, lack of power to medical facilities, or inoperability of life support devices such as kidney dialysis machines. Mortalities may also be associated with the loss of cellular communications and emergency dispatch networks preventing live-saving help from arriving in time.

[1] The roughly $6.8 million total cost of the proposed system was amortized at a carrying charge of 12 percent, yielding an annual cost of roughly $816,000.

Various federal entities have estimated the cost of a premature mortality. The value estimates range from $250,000 to $7M per mortality; however, the likelihood of such events occurring over the course of an outage is uncertain, and no attempts to estimate a mortality rate resulting from power outages have been developed in the literature. Therefore, while it is difficult to incorporate these values into a cost benefit analysis for grid resiliency improvements, neither should the value of a saved life be discounted entirely.

One way to extrapolate the potential lives lost as a result of a future long-duration power outage would be to find a statistical relationship between the rate of mortality of medical facilities and emergency call situations during an outage vs. during normal operation. The outage in question would have to be of sufficient duration, however, as to surpass the hospital's emergency generator fuel reserves. These events are rare and usually the result of a natural disaster or major accident. Data on hospital mortality rates are not readily available and consequently difficult to analyze within the scope of this NRT program. Without this term, the equation for calculating lost value from blackout-related deaths suffers significant uncertainty.

Applying the government-estimated mortality value metrics to the 2007 Great Gale scenario, the cost of mortalities alone would have resulted in $1.25-$35M cost if the five recorded mortalities in Oregon could be attributed to the loss of power[2]. These costs are borne by family members, employers, co-workers, and on a macro scale the insurance industry that may be responsible for paying compensation. This presents an additional difficulty from a policy perspective, because any investments to prevent these mortalities would be akin to a public insurance program where all people may but each has an individual probability that it will benefit them directly.

4.2 Application of Valuation Methods to Newport Oregon

The following statistics may be used to develop a macroeconomic estimate of the value of lost load for Newport, Oregon:

- Population: 10,116
- Total number of households: 4,537
- Per capita median personal income (Newport): $47,270
- Typical average load for period 2/1/17 – 2/28/17: 11,025 kW (16,380 kW max)
- Average load extrapolated to two-week period: 3,704,400 kWh
- Critical Infrastructure load (imported from Section 2.4): 4,511511 kW
- Critical Infrastructure load extrapolated to two-week period: 1,515,797797 kWh
- Proportion of electrical customer types (estimated based on 2016 CLPUD electricity sales information)(CLPUD, 2016): 43% residential, 18% commercial; 37.5% industrial[3].

In order to determine a typical wintertime power load for Newport, load data from a CLPUD substation in February 2016 were obtained, and the average load for the entire month was calculated.

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[2] In reality, the recorded mortalities were attributed to traffic accident, drowning, heart attack, suicide, and accidents during debris clearing. Of these, only one or two might be attributable to the loss of power and associated critical services. This underscores the difficulty of attaining reliable impact estimates from historical outage scenarios.

[3] Note: Because these percentages are based on sales, they are not reflective of actual consumption as different customer types are charged slightly different rates.

The macroeconomic and power load statistics for Newport were applied to the VOLL valuation methodologies described in Section 4.1.3 and are shown in Table 3. Note that these values do not discriminate between the value of critical services and whole economy value lost.

The Newport-specific macroeconomic analysis was performed by multiplying the median personal income by the city population, then divided the result by 8,760 to arrive at a per-hour VOLL.

Table 3. Value of Lost Load (VOLL) for a Hypothetical Long-Duration Blackout in Newport, Oregon

VOLL Method	Basis	VOLL metric ($/kWh not served)	VOLL of two-week outage (Feb 2017), Newport OR (3,704,400 kWh)	VOLL of two-week outage Newport OR CI load only (1,515,797 kWh)	VOLL of CSZ worst-case scenario (6-mo. outage)***
Macroeconomic Analysis	Calculation based on Newport, Oregon GDP and February 2017 power demand profile***	$9.56 (calculated)	$18,341,278	N/A	$239M (based on Feb demand)
Macroeconomic analysis	US GDP per capita per day	$112.84/day	$15,980,852	N/A	$208M
Willingness to Pay Survey	Application of LBNL ICE Calculator, using CLPUD SAIDI/SAIFI 4-yr average for February as of 2016; Newport median income	Residential (43%): $1.8 Small C&I (55%): $186.7 M/L C&I (55%): $40.4	Residential: $2.87M Small C&I: $297M M/L C&I: $64.3M	Residential: $1.17M (*0.4) = $469K (*2) = $2.34M	Res: $37.3M S. C/I: $3.8B M/L C/I: $836M
Willingness to Pay Survey	Range of estimated VoLL from 18 studies in 13 high-income countries (Cheng, Vankatesh 2014)	$4-40/kWh	$14.8M – $148M	$6M – $60M	$192M - $1.9B
Willingness to Pay Survey	Sullivan et al (2015) (16-hour outage, direct cost, based on meta-analysis of 34 studies)	Res(43%): $1.3 S C&I(55%): $258 M/Lg C&I(55%): $12.7	Res: $ 2.70M Sm C&I: $ 411M M/Lg C&I: $ 20.2M	Res: $847K (*0.4) = $339K (*2) = $1.69M	Res: $35.1M S. C/I: $5.3B M/L C/I: $262M
Willingness to Pay Survey	Sullivan et al (2015) (direct cost plus multiplier of 1.5-3x for indirect costs for 16-hour outage)	Res(43%): $1.95-3.90 S C&I(55%): $387-774 M/L C&I(55%): $19.05-38.10	Res: 3.1-6.2M Sm C&I: $788M-1.5B M/Lg C&I: 39-78M	Res: $1.2-2.5M (*0.4) = $0.48-1M (*2) = $2.5-5M	Res: $40-81M S. C/I: $10.2-19.5B M/L C/I: $507M-1B
Choice Modelling	Households WTP to have utilities function 1-5d faster after a cyclone in Cairnes (Dobes 2015)	$271/yr per household (converted from AUD)	4,537 x $271= $1.2M* / year	4,537 x $271= $1.2M* / year	N/A
% Community Income	Adapted from Narayan 2015 - 1-4% of annual income as "social insurance"		$4.7-19M/year	$4.7-19M/year	$4.7-19M/year
Discrete Event	Value of premature death** (EPA, 1997)	$4.8M/death ($7.3M in 2017 dollars)	Uncertain	Uncertain	Uncertain
Discrete Event	Value of premature death** (US DOJ)	$250,000 to $7M/death	Uncertain	Uncertain	Uncertain
Discrete Event	Value of premature death** (RAND) based on payouts to civilians following 9/11/2001 attacks	$3.1M/death	Uncertain	Uncertain	Uncertain

* Estimate likely low due to differing assumed timeframes of reconnection under the Newport scenario.
**Source: FEMA 2005 (viewcontent.pdf)
Highlight: CL PUD stats don't differentiate small vs. med/lg commercial & industrial customers. Both dollar amounts based on full 55% C&I proportion of CL PUD demand based on 2016 revenue. The actual costs will therefore lie somewhere between the two highlighted values.
*** The CSZ estimate is based on an extension of the February 2016 power demand for Newport's total electricity demand. Actual demand varies seasonally and typically is approximately 10% lower in the summer months (PEV, 2014).

Macroeconomic Method:
The macroeconomic valuation approach, applied to Newport, would suggest an outage cost of $15.9M – 18.3M for a two-week outage event, with a significant degree of imprecision due to seasonal economic variability and other factors such as fuel supply and willingness and ability of tourists to visit during the aftermath of a major outage-causing event. Indirect economic effects, the value of social wellbeing, and the discrete value of critical service loss are also not incorporated in this type of estimate.

Survey Method
The survey-based VOLL estimates for the entirety of Newport's electricity demand over a two-week outage (both critical and non-critical services) range from approximately $67M - $300M using the ICE calculator. Using the Sullivan et al VOLL multipliers, the estimate ranges from $23M - $414M, and if indirect costs are incorporated the estimate balloons to as high as $1.5B. The wide range in estimates is due to uncertainty regarding what proportion of Newport's commercial and industrial may be classified as "small" versus "medium/large".

Typically, VOLLs from the survey method are much higher than the macroeconomic VOLL results. The bulk of the VOLL comes from commercial and industrial business customers' willingness to pay to prevent the outage. The VOLLs for residential customers, while higher than the normal price of electricity, are significantly lower than the value of a single mortality. These results highlight the notion that critical social services may be undervalued. They also show that an emergency generation alternative such as MRE, absent a more comprehensive estimate of the value of critical services, would have limited value without the ability to provide enough power to support business continuity.

4.3 Valuation of Critical Infrastructure and Services

Due to technical and cost considerations, it may not be feasible for an emergency power generation system to fulfill all electricity needs for Newport, much less the full Central Lincoln PUD service area, in the event of a transmission disruption event. Instead, a coastal community or wave energy developer may choose to install a smaller array of devices with sufficient capacity to provide for only the most critical infrastructure and services during a long-duration blackout.

In the power scenario we have described, a renewable energy generation supply is assumed to be able to keep critical infrastructure and services operable at a minimum, with the potential to electrify other areas of the grid when additional power is available. Thus we expect that the losses associated with safety, stability, and emergency management would be avoided; however, the primary economic forces of the community would have inconsistent or absent electricity to operate. A WEC array focused only on emergency generation in this manner would not prevent the type of loss commonly evaluated under the macroeconomic and contingent valuation methodologies described previously. Economic losses associated with business and industry would still be incurred, as would likely the types of loss associated with normal household activities and leisure.

Critical Services VOLL
If the 0.4-2X multiplier from Cohen (2016) were applied to the Newport-specific GDP-based VOLL in Table 3 (Row 1), then the value of critical services over a two-week outage scenario would range between $7.3M - $36.7M. These values may be incompatible however due to the fact that the macroeconomic VOLL method does not differentiate between critical and non-critical services.

Under the survey-based VOLL estimation methodology, where residential VOLL is differentiated from commercial and industrial VOLL in Table 3, it is assumed that the critical services multiplier would not be reasonable to apply to electrical loads from commercial or industrial customers because the presence of critical service alone would not allow them to resume economic production. Therefore, if the Cohen (2016) multiplier of 40-200% is applied to the ICE calculator results (row 3), **the value of critical services would range from $469K to $2.34M in losses**.

If we apply some of the other critical service valuation rubrics described in Section 4.1.3 (e.g., the per-household payment or percent of annual income as social insurance concepts), the value to a community of Newport's size ranges from $1.2M per year (Dobes 2015), to a maximum of $4.8M.- 19.1M per year (Narayan 2015). If these payments were made over a 20-year assumed project lifespan, the totals would range from $24M (Dobes) to $95M - $382M (Narayan).

As should be apparent, there is still uncertainty regarding how critical services may be assigned a dollar value, with a wide range of potential costs in the event of a long-duration blackout.

4.4 Uncertainties in the Valuation Analysis

1. The VOLL for outages longer than 24 hours have not been adequately studied, therefore all survey-based VOLLs in Table 3 carry systemic uncertainty.
2. The VOLL for critical services has not been extensively studied, and direct application of cited methods may be incompatible with the community of interest.
3. VOLLs based on surveys rely on the perceptions of the survey participants regarding the likelihood of a severe outage occurring and the anticipated impact on the respondent's life and livelihood. Studies have noted that in communities where a long-duration blackout is not expected to occur or where there is no prior experience to inform potential impacts, survey responses may be biased to undervalue electricity-dependent services.
4. Seasonality in high-value industries such as tourism and fishing may affect actual VOLLs depending on when an outage event occurs.
5. The link between long-duration outages and loss of life has not been established with enough certainty to be quantified for cost estimation.

4.5 Cost Estimate for an Emergency WEC System

4.5.1 Introduction

This study provides an analytical cost model for the cost of emergency wave energy generation using a present value metric, and quantifies the cost of the proposed emergency WEC system in Newport, Oregon for a two-week outage. This cost is compared to the value of loss load for Newport under a two-week outage (for direct comparison with emergency wave energy costs) as well as an outage in the event a Cascadia Subduction Zone event occurs. This information can enable coastal stakeholders to make informed decisions about improving resilience in coastal areas by providing a tool with which to gauge the economic value of emergency wave energy generation.

Using conclusions drawn from a literature review of cost models for of wave energy converters, we describe an analytical cost model. We then apply this cost model to the proposed WEC system in Newport for a two-week sustained outage event. We compare the cost of this WEC system to those for expected loss estimates and conventional emergency generation in both the storm and CSZ event. Lastly, we discuss the impact of those comparison results in the context of emergency electricity generation and coastal community resilience.

4.5.2 Literature Review

Wave energy technology is a new type of renewable energy generation, which uses movement of ocean waves to produce electricity through a device, commonly called a wave energy converter (WEC). Due to the relatively nascent stage of this industry, wave energy requires substantial subsidies and support to advance technology from research and development to commercialization (A.E. & Environmental, 2006). While developers have invented devices to harness wave energy, they are not yet efficient or cheap enough to be market-competitive. Further, businesses and investors retain high investment risk premiums for this unproven technology. Being able to accurately forecast the cost of commercial installations enables wave energy stakeholders to make more informed decisions about financing wave energy development. Regularly, because the power purchase price of electricity produced by commercial wave energy arrays is unknown, the most sophisticated metric that can be used is the Levelized Cost of Energy, or LCOE. Thus, most studies reviewed in this chapter are based on LCOE. The LCOE takes into account the time value of money by dividing the present value of the total lifetime costs over the energy produced over the development's lifetime. It does not account for the energy product's market value (Pecher, 2017).

The use phase of an emergency WEC device is fundamentally different from one used to produce energy nominally, which consequently affects the costs included in the economic analysis. For instance, commercial devices are built to withstand repetitive and extreme wave loads over a 20-year life to produce as much energy as possible for profit. Emergency WECs would be built for intermittent, sparse use, experiencing reduced loading. This would affect both the design, build, and maintenance costs. Further, emergency devices would not incur costs associated with long-term operations and maintenance, but rather scaled-down installation and decommissioning costs. These emergency devices would be designed for easy deployment, operation, and decommissioning, with all maintenance being completed onshore. Extra costs would include storage costs for the device and other equipment.

Based on these variations in cost inclusions for the LCOE metric, literature reviewed here will include those calculations that have relevance for small-scale deployments, not accounting for any future reduced WEC costs through inclusion of aspects like learning rates, large array economics, etc.

Some of the first relevant cost models for WECs were created by EPRI, in effort to spur development in the U.S. (Previsic et al., 2004; Bedard et al., 2004; Bedard et al., 2004; Bedard et al., 2005). In each economic analysis, EPRI calculated LCOE for a particular region in each state (California, Oregon, Massachusetts, and Hawaii) considering resource potential and state-based tax incentives. The analyses included the use of the Ocean Power Delivery Pelamis WEC for a pilot plant of about 1000 MWh/year and a commercial plant of 300,000 MWh/year for a utility and non-utility generator. EPRI calculated LCOE by accounting for Capex, Opex, and decommissioning costs over annual energy produced (AEP), assuming various profit structures for a hypothetical utility and non-utility generator. Although consider these four analyses were consdiered for their general methods, of particular interest is EPRI's estimation of the cost of the pilot plant, which is closer in scale and purpose than the commercial scale to the proposed emergency WEC deployment.

The cost model for the pilot plant in Oregon included the capital costs to purchase the WEC and necessary equipment, the construction costs to build the plant, and the grid interconnection costs. It did not include detailed design, permitting, and construction financing, yearly O&M costs, or testing and evaluation costs. Based on this model, a single Pelamis WEC could be installed in Oregon for $4.7 million ($USD 2004), or $3.1 million after tax credits while producing 1001 MWh/yr (Bedard et al., 2004). The project lifespan for this pilot plant was a year. When performing the cost analysis, EPRI quantified cost uncertainty by a Monte Carlo simulation resulting in -20% - +23% cost variation range.

EPRI added to these state-specific analyses by publishing two following papers that estimated the feasibility of eight devices for a pilot project (1500 MWh/year) and a commercial project (300,000 MWh/year) (Previsic et al., 2004; Bedard et al., 2007). The 1500 MWh/yr plan is equal to about 500 kW, or the size needed for an emergency generation source. Performance was compared for four different regions: Washington, Oregon, Maine, and Hawaii. Cost of the plant was then estimated for each device considering site-specific conditions, with consideration as to how that cost would change given performance variations (average annual wave power density, estimated AEP, and capacity factor) in different states. Each device was qualitatively described based on its design, survivability, manufacturability, licensing, grid integration ability, tuneability, operations and maintenance, deployment and recovery, and company viability. These same concepts are considered when forming this study's cost model for the emergency WEC.

SI Ocean and Carbon Trust also created cost estimate methodologies, both based on LCOE. SI Ocean calculated the cost of energy of early arrays, predicting how cost was likely to decrease over time (SI Ocean, 2013). When calculating the LCOE of these arrays, they included capital expenditures (C_{Capex}), annualized operational expenditures ($C_{O\&M}$), and specific levelized decommissioning costs ($C_{Decommissioning}$) to represent development costs.

$$LCOE = \frac{C_{Capex} + C_{Decommissioning}}{87.6 * Load\ Factor} * \frac{r * (1+r)^n}{(1+r)^n - 1} + \frac{C_{O\&M}}{87.6 * Load\ Factor}$$

Here, *r* represents the discount rate, *and n* represents the lifetime of the development. Annual energy production (AEP) is represented through a load factor:

$$Load\ Factor = \frac{AEP}{87.6 * r}$$

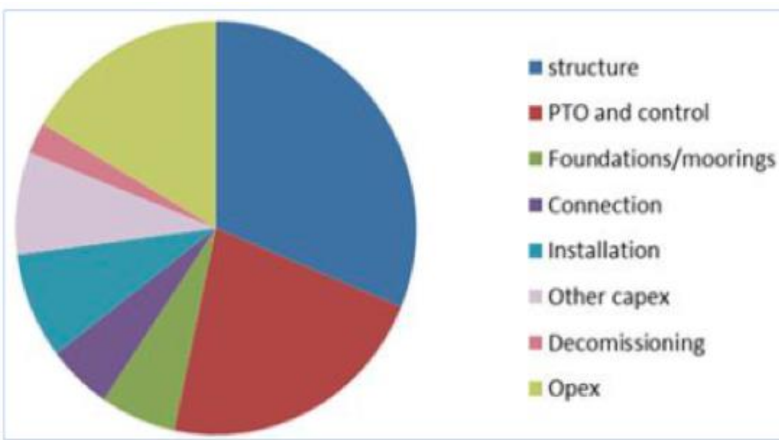

Figure 17. Proportion of WEC system costs by type

The lifetime of the development is assumed to be 20 years, while the discount rate is set to 12%. Based on their cost model, base capital cost for a medium resource site was ~52¢/kWh, and for a high resource site was ~41¢/kWh. Cost per cost category is shown in Figure 17. This cost, however, varied significantly (as much as 30 ¢/kWh) based on uncertainties about operating costs, standard insurance rates, foundation cost, resource information, and learning rates. The model was especially sensitive to annual energy production and discount rate. Discount rates used by developers when assessing project were sensitive to perceptions of risk, and accounting for how that perception of risk would change over time through learning rates was a major source of uncertainty in this method. These cost categories are referenced for the building of the presented cost model, and although uncertainty or sensitivity are not quantified with cost categories, they will be important to keep in mind for future work in validating the presented cost model.

As part of the Marine Energy Challenge, Carbon Trust then developed a cost estimation methodology (Carbon Trust and Entec UK, 2006) that could be applied to all WEC technologies, so that a standard LCOE approach could be used to compare devices. LCOE was calculated by the sum of the present values of all capital, O&M, and decommissioning costs over the present value of energy production. Although simplified, Carbon Trust described each main cost category within the LCOE calculation, citing specific cost drivers for each category.

Carbon Trust followed with a report detailing future cost reduction pathways for the offhsore renewable energy sector. Although future cost reduction does not apply to an emergency WEC, capital and O&M cost breakdowns are described, summarized in Figure 18.

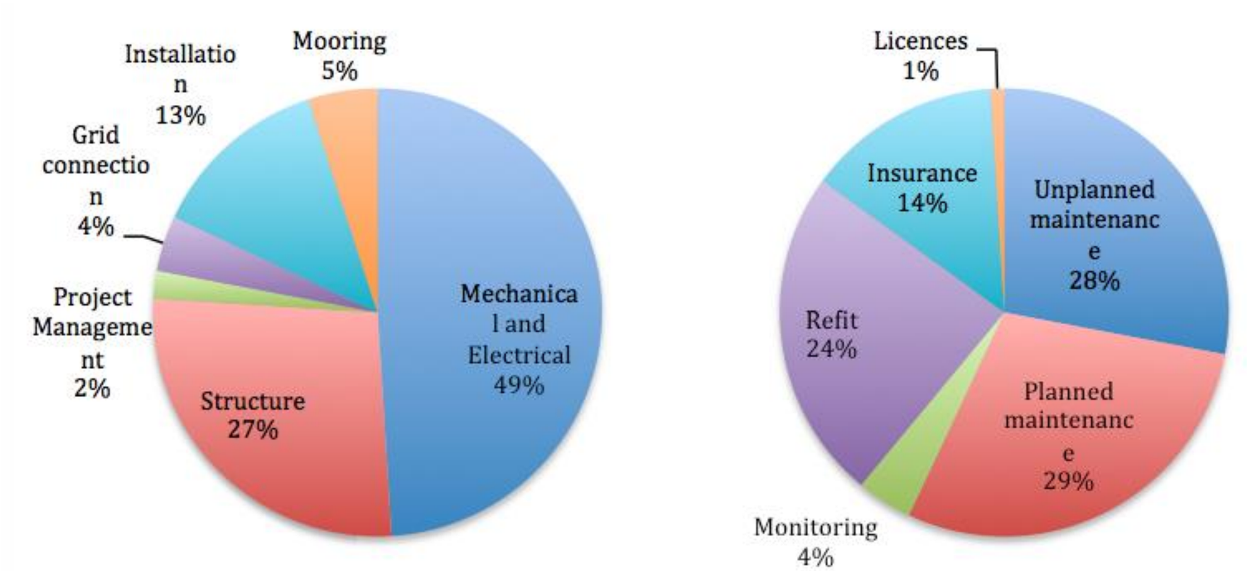

Figure 18. Cost category breakdown for capital costs (left) and operational costs (right) (Carbon Trust and Entec UK, 2013)

Alternatively to Carbon Trust and SI Ocean, a number of economic analyses using LCOE have been presented in published literature (Kofoed et al., 2014; Stallard et al., 2009); Jeffrey, 2014; Rhinefrank et al., 2006); Black & Veatch, 2012; Neary et al., 2014; Jenne et al., 2015; Previsic et al, 2012; Ocean Energy Systems, 2015). Ocean Energy Systems (2015) published their LCOE methodology:

$$LCOE = \frac{CAPEX + \sum_{t=1}^{n} \frac{OPEX_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{AEP_t}{(1+r)^t}}$$

In which AEP is calculated by:

$$AEP = Project\ Capacity * CF * Av * 8760$$

where *CF* is the capacity factor, and *Av* is the availability factor. Using this methodology, they calculated the LCOE for three stages of project maturity (a first array or demonstration project, a second array or larger demonstration project, and a first commercial plant) based on industry survey responses. These results are the scale and maturity level an emergency WEC array would need to be to power a coastal community's critical services.

Regarding local factors related to cost of energy, Oregon Wave Energy Trust has investigated wave energy generation costs in the specific region of the present case study (OWET, 2009). While the scale of the development is larger than the emergency generation case, some cost categories and assumptions made are relevant and can be used directly in the emergency WEC cost model. Particularly, Oregon Wave Energy Trust provides a reliability metric for outages: 10 days of planned outage are scheduled, while a forced outage rate of 7% is assumed for winter months. Further, all integration and transmission rates are based on Bonneville Power Administration practices and rate schedules.

In 2009, Stallard et al. used information from the EU FP7 Equimar project to compare alternative approaches to evaluating the economic viability of a marine energy development. They identified high-risk cost categories, and found that discount rates and profiles are dependent on risk, which varies significantly by location, the type of technology used, etc. Therefore, they suggest that discount rates be applied differently across varying revenue streams. This has implications for this study, given that risk is very different for emergency wave energy generation it would be for commercial purposes.

In 2010, Dalton et al. completed a feasibility study of the Pelamis WEC in Ireland, Portugal, and the U.S using a novel, Excel-based, techno-economic model, NAVITAS (Dalton et al., 2010). The output of NAVITAS includes cost of energy, net present value, and investment return rate based on a 20-year life, and all three are used to model the effects of a varying tariff rate.

Table 4. Cost of WEC comparison

Study	Location	Number of Pelamis	COE (€/kWh)	Subsidy
Previsic et al., 2004	California	213	0.08	0.06
ESBI, 2005	Ireland	209	0.105	-
St. Germain, 2003	Canada	15	0.10-0.15	-
Bedard, 2006	California	44	0.05-0.12	-
Carbon Trust, 2006	UK	13000	0.08-0.30	-
		13	0.10	-
Allan et al., 2008	Scotland	4000		
Dunnett & Wallace, 2009	Canada	15-27	0.18-0.30	-
Ocean Power Development, 2008	UK	1	0.08-0.16	-

All costs used in NAVITAS were based on the study by Previsic et al. except cable cost, which was sourced from the ESBI study. O&M costs were treated as capital costs, and were found to be within 1-3% of the 40% total cost as reported by (Previsic et al., 2004; Dunnett and Wallace, 2009; St. Germain, 2003; Allan, 2011). Salvage Value and Remaining Life for selling and recouping cost was expressed as:

$$S = \frac{RC * RL}{Lt}$$

where *RC* is the replacement cost of a component, *RL* is the years remaining and *Lt* is the component's lifetime. Any decommissioning costs were subtracted from the final salvage value. An inflation rate of 5%, a borrowing rate of 10%, and a discount rate of 4.76%-12% was assumed, and the electricity tariff was assessed at 0, 5, 10, 20, 30, and 40 ¢/kWh. Results showed that previous studies underestimate cost of energy based on the tariff used.

In 2011, Allan et al. calculates LCOE of WECs as well as tidal energy devices, comparing these costs to conventional energy generation (Allan et al., 2011). They then conduct a sensitivity analysis, finding that the LCOE of wave and tidal energy (£190 and £81/MWh, respectively) is most sensitive to capital costs, fuel costs, and the discount rate used. They also bring attention to those previous studies that use an annuitizing method, arguing that because annuity methods convert costs to a constant flow over time and thus require constant output, the variability of wave energy renders annuitizing methods irrelevant. Of interest to the proposed study of emergency wave energy generation are the component costs used for 1MW wave generation, which are summarized in Table 5.

Table 5. WEC cost breakdown

	(000£)	%
Onshore transmission and grid upgrade	36.22	1
Undersea cables	181.12	5
Spread mooring	362.24	11
Power conversion module	1847.44	51
Concrete structures	724.88	20
Construction facilities	144.88	4
Installation	144.88	4
Construction management	181.12	5
Total	3622.44	100

Dalton et al. (2012) assess the viability of Irish feed-in-tariffs and the impact of learning curve, supply/demand curves, and future cost of cash on phased-project installations. Based on a 500 MW Pelamis array in Ireland, they calculate net present value using NAVITAS, assuming a borrowing interest rate of 7.5%. Inflation is factored out by discount rate definition. Insurance and O&M rates vary between 3-5% of Capex. Other component costs that are relevant to the proposed cost model are listed in Table 6 and Table 7.

Table 6. WEC component costs

WEC Parameter	% of IC of WEC
Mooring	10
Cabling	10
Installation costs	33
Spare Parts	2
Sites and permits	2
GHG investigations	0.05
Management fees	10
Decommissioning fees	10
Grid connection	5

Farm Size	Discount Rate
0-5 MW	14
6-10 MW	12
11-20 MW	10
21-50 MW	8
50 MW	6
> 50 MW	6

Each of these studies provides a piece of knowledge regarding construction of an LCOE-based cost model, whether it be a value used for inflation rate, the costs included in Opex, or whether a discounting or annuitized method should be used. In the next section, lessons from previous literature are applied to emergency WEC analytical cost model development.

4.5.3 Methodology

The methodology proposed to calculate the cost of emergency wave energy generation is based on the assumption that the emergency WEC is a deployable system. Due to this assumption, the analytical cost model is based on a generic WEC structure breakdown (as proposed by Hamedni et al. (2014), so that it can be adapted for any WEC type. Additionally, the cost model is based on an abbreviated version of generic WEC project phases (as described by Pecher and Kofoed), which include pre-installation, implementation, operation, and decommission phase costs. The methodology uses a life cycle cost approach and covers the full life cycle costs of an emergency deployable WEC system.

This model uses Net Present Value (NPV), measured in 2017 USD, to value the WEC system, for two reasons. First, the cost of the emergency WEC is viewed as an investment by local governments in electrical security. The need of these entities is to know the present total cost of the investment, rather than a levelized cost or the future value of the investment. Second, the total cost of the emergency WEC system will be compared with the value of lost load (VOLL, or the estimated amount that customers are willing to pay to avoid electricity outages) in Section 4.1 of this report, which is measured in NPV, 2017 USD.

The NPV metric is equal to the sum of the cash inflows and outflows (R_t), discounted to their present value:

$$NPV(i,N) = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t}$$

where (t) is the time of the cash flow, (N) is the design life of the emergency WEC, and (i) is the discount rate. The discount rate converts one-time costs to annual costs, and factors out inflation rate (meaning all costs are constant USD) (Dalton et al., 2010):

$$r_{discount} = \frac{r_{borrowing} + r_{inflation}}{1 - r_{inflation}}$$

Here, $r_{borrowing}$ is the borrowing rate for a loan and $r_{inflation}$ is the inflation rate. In previous literature, a 12% discount rate was used (Dalton et al., 2010), while others calculated discount rate given a 10% borrowing rate (Myhr et al., 2014), (Dalton et al., 2010), 5% (Dalton et al., 2010), or 2.5% (Myhr et al., 2014) inflation rate, but many of these studies are based on inflation rates in Europe. The average inflation rate in the U.S. in the last 20 years has been just over 2% (Inflation,EU, 2017). In this study, a 10% borrowing rate and a 2% inflation rate are used. Interest is assumed to be compounded annually.

The costs incurred over the lifecycle of the co-located array include the cost of pre-installation ($C_{Pre\text{-}installation}$), implementation ($C_{Implementation}$), Opex ($C_{Opex}$), and decommissioning ($C_{Decommissioning}$) phases of the project:

$$C_t = C_{Pre-installation} + C_{Implementation} + C_{Opex} + C_{Decommissioning}$$

These cost categories will be further described in the following sections.

4.5.4 Pre-Installation

For a permanent WEC array installation designed for a given lifespan, pre-installation costs include costs associated with feasibility studies; site selection, characterization, and monitoring; permitting; stakeholder engagement efforts; and array design.

$$C_{Pre-installation} = C_{Feasibility} + C_{Site} + C_{Permit} + C_{Engagement} + C_{Design}$$

In the case of emergency wave energy generation, however, the included cost components change. Site selection, feasibility, and design cost components are assumed here to remain relatively unchanged compared to a pilot-scale plant, but will be less than a commercial plant.

Permitting costs remain part of the pre-installation costs, but are reduced to be more consistent with temporary permitting in emergency scenarios. This use case is premeditated, but not planned; while the WEC system is bought in advance, and therefore is planned to be used at sometime, the moment it is deployed and the length of time for which it is deployed is uncertain. The WEC system could be used many times, or not at all in its lifespan. Therefore, the permitting is more akin to an emergency ocean permit, rather than a permanent WEC installation. In the case of emergency ocean permits in the oil and gas industry, permits and environmental impact assessments are customarily paid for post-event. In the case of emergency ocean dumping permits, no permit must be obtained if the dumping is done to avoid death at sea (EPA, 2016). Currently, there is no permitting scheme for emergency WEC systems.

The cost of engagement is another cost component that was altered for the emergency WEC system use case. Engagement costs are context-specific, but should be included given their potential economic impacts. For instance, in the case of a community that has already engaged with wave energy developers, the engagement costs may be low. However, a community with little exposure to wave energy might not support an emergency WEC system. Another factor that will significantly change the cost of engagement will be the culture of the electric utility. For a publicly owned utility that requires a vote of a member board to make a purchase such as an emergency WEC system, engagement costs may be substantial. However, if the utility makes investment decisions based on the decision of a board of investors, the engagement costs might change.

Most economic analyses either do not include pre-installation costs (OWET, 2009; A.R. Characterization, 2013; Previsic et al., 2004; Dunnet and Wallace, 2009; Callaghan and Boud, 2006) include a conservative estimate for these costs in capital expenditure (Capex), or include these costs but do not fully describe how they are calculated. Pre-installation costs from previous literature for WEC and other offshore renewable energy systems are listed in Table 7.

Table 7. WEC system pre-installation costs

Reference	Description	Cost
Bedard et al., 2004	Siting and Permits Greenhouse gas Investigation (**wave array**)	2% of IC 0.5% of IC
Previsic et al., 2012a	Permitting and Environmental Studies (5 MW of **wave array**)	14% Capex
Dalton et al., 2010	Pre-operating costs (**wave array**) Design, siting, and permitting (106.5 MW **wave array**)	10% Capex 2% WEC cost
Allan et al., 2011	Pre-development costs: site selection, EIA, public enquiry of an offshore wind and **wave array** (100 MW)	1.9 mil pounds
Li et al., 2011	Permitting, licensing, certification, and siting for **tidal array**	0.037 per W installed power
Chiang et al., 2016	Viewshed costs of offshore **wind array**	3%
Castro-Santos & Diaz-Casas, 2014	Feasibility study, legislative factors, and farm design for a **floating wind turbine**	6.79M €
Myhr et al., 2014	Environmental, met station, and sea bed surveys, front-end engineering and design, project management and development services of 500MW **floating wind turbine**	€104,106k
Astariz et al., 2015	"Engineering tasks and licenses" in a **co-located wind-wave array**	570,000 €
Castro-Santos et al., 2016	Feasibility study Legislative factors Farm Design for a **hybrid wind-wave platform**	100,000 € 474,951 € 5,141,382 €

Few researchers scale their pre-installation costs based on the size of the array (in W), and others differentiate between pilot and commercial scale arrays. To add to understanding of pilot-scale array costs, a current construction project, Pacific Marine Energy Center's South Energy Test Site (PMEC SETS) is investing $5 million in design and permitting in the second phase of the project. This does not include money spent on pre-installation costs during the first phase of the project (S. Quinn, Pers. Comm). This cost is inflated due to the uncertainty of the type or number of devices varying over the lifespan of the facility, but the project is also smaller than most proposed commercial installations. During early phases of development in the US, these pre-installation costs are significant to total project cost, but will most likely be highly influenced by learning rates and public perception.

In this study, we base pre-installation costs on a 5 MW WEC pilot array (Dalton et al., 2010; Previsic et al., 2012), which is similar to the same rated capacity of the proposed emergency wave energy array. This number is based on permitting and environmental studies. This number is considered to account for $C_{Feasibility}$, C_{Site}, and C_{Permit}. $C_{Engagement}$ is considered negligible relative to all other site costs, especially since most U.S. utilities are investor-owned. Finally, because the value being used is based on a study that bundles design costs into development costs, C_{Design} is not addressed in the value we are using from (Previsic et al., 2012). Therefore, design costs were calculated to be equal to the salary of two, full-time engineers over a two-year period to be sufficient. This assumes design work includes the electrical design of the onshore powerhouse, the mooring and anchoring, and the connector design between the WEC, cabling, and powerhouse. This cost also includes the act of contracting individuals to complete the installation work, should the emergency wave energy system need to be deployed.

4.5.5 Implementation

Implementation costs are more studied than pre-installation costs, and are included in all economic analyses. Cost categories used varies, and are detailed in Table 8.

Table 8. WEC system installation costs

Reference	Description	Cost
Previsic et al., 2004b (USD 2004)	Onshore Transmission and Grid Interconnection	$162,000
	Subsea Cables	$1,438,000
	Pelamis Power Conversion Modules	$1,565,000
	Pelamis Manufactured Steel Sections	$850,000
	Pelamis Mooring	$243,000
	Installation	$841,000
	Construction Mgmt and Commissioning (10% cost)	$509,000
Bedard et al., 2004 (USD 2004)	Onshore Transmission and Grid Interconnection	$580,000
	Subsea Cables (14km)	$300,000
	Pelamis Power Conversion Modules	$1,535,000
	Pelamis Manufactured Steel Sections	$850,000
	Pelamis Mooring	$243,000
	Installation	$699,000
	Construction management and Commissioning (10% cost)	$420,000
Callaghan & Boud, 2006 (2006 £)	Materials, components and labor in manufacturing and fabrication; deployment; foundations and moorings; electrical cables and switchgear	£1700-4300 /kW
Dalton et al., 2010; Commission for Energy Regulation, 2005 (% of initial costs of WEC)	Mooring	10% IC
	Cabling	50%
	Replacement costs (full replacement of WECs after 10 years)	90%
	Spare parts	2%
	Management fees	10%
	Grid connections	5% of AEP
Dunnett & Wallace, 2006 (2006 CDN)	AquaBuOY Capital Cost	$935/kW
	Underwater cable	$130,000/km
	Overland transmission[158]	$9.125 million / km (1999 USD)
	Mooring	$20/m
Allan et al., 2011 (2006 £)	Onshore transmission and upgrade, undersea cables, spread mooring, power conversion system; concrete structures; construction facilities, installation, and construction management of a 100-MW wave array	£362.2 million /kW

The cost categories being considered in this study include the costs of building, transporting, storing, installing, and commissioning all subsystems of the array. The subsystems include the WECs, mooring, and anchors, and an electrical system.

$$C_{Implementation} = C_{Build} + C_{Transport} + C_{Storage} + C_{Install} + C_{Commissioning}$$

Due to the context-specific detailing and the prevalent use of the methods in Previsic et al., 2004 and Bedard et al. (2004) in other literature, $C_{Transport}$, $C_{Storage}$, $C_{Install}$, and $C_{Commissioning}$ are based on Bedard et al., 2004. The cost of C_{Build} is based on costs reported for a point absorber in Previsic et al., 2004. To note, costs in Bedard et al. (2004) are based on a single WEC system. To supplement this information, Previsic (2004) scales the implementation costs of a single WEC to two-, four-, and eight-WEC system. The scaling approach used in that study will be applied to that of the proposed emergency WEC array. For cabling and electrical costs, those in Previsic (2004) are supplemented and validated by information provided in Dalton et al. (2010) and Sullivan and Dalton (2009).

The method for calculating each cost components is described. C_{Build} is calculated by

$$C_{Build} = (C_{WEC} * n_{WEC}) + (C_{Mooring} * l_{Mooring}) + \left(C_{Cable_{Inter-array}} * l_{Inter-array}\right) + (C_{Cable_{Export}} * l_{Export}) + C_{Powerhouse}$$

Where C_WEC represents the cost per WEC, and n_{WEC} represents the number of WECs. $C_{Mooring}$, $(C_{Cable})_{Inter\text{-}array}$, and $(C_{Cable})_{Export}$ are the per-length cost of the mooring and cabling, and $l_{Mooring}$, $l_{Inter\text{-}array}$, and l_{Export} represent the length of the mooring and cabling. $C_{Substation}$ represents the cost of building the onshore powerhouse. Even though the WEC will not see the wave loading a permanent WEC experiences over its lifetime, it is assumed that the structure of the WEC will remain unchanged for lower reliability standards, and therefore that the cost will not reflect decreased reliability standards. However, if WEC developers were to design specifically for this special use case, the cost of the WEC could be decreased. Installation costs are represented via the equation:

$$C_{Install} = n_{Deployment} * (C_{Installation\_Cable} + (C_{Installation\_WEC} * n_{WEC}))$$

Where $C_{Installation\_Cable}$ and $C_{Installation\_WEC}$ represent the cost of the cable installation and the incremental cost of installing each WEC, respectively. Transportation costs are comprised of the time it takes to transport the WECs $t_{Transport}$, as well as the cost rate of the vessel used to transport the WECs ($r_{transport}$) and the number of times the WECs are deployed ($n_{Deployment}$).

$$C_{Transport} = t_{Transport} * r_{transport} * n_{Deployment}$$

The cost of storing the emergency WEC system depends on the specific project. The WEC can be stored at a local or nearby port, in which case the cost of storage ($C_{Storage}$) would be equal to the rental rate (r_{Rental}) over the entire lifespan of the system (t).

$$C_{Storage} = r_{Rental} + t$$

If the municipality has resources for land purchasing, the utility can purchase property or use available, already-owned property. The cost of owned land would be equal to the cost of the land and any affiliated property taxes.

4.5.6 Operation

Operational costs include O&M, but also insurance costs, and costs associated with ongoing business, administration, and legal services and resources.

$$C_{Operation} = C_{O\&M} + tC_{Insurance} + tC_{Administration}$$

Administrative and insurance costs are calculated by multiplying the sum of yearly administration, business, and legal fees ($C_{Administration}$) and insurance rates ($C_{Insurance}$) by the lifespan (t) of the co-located array. In the specific use case of an emergency wave energy system, these costs are expected to be minor compared to the other costs of the system, and are estimated through comparisons of pilot or demonstration plant rates. Rates used in previous literature are highlighted in Table 9.

Table 9. Administrative and insurance costs

Reference	Cost
Astariz et al., 2015	2%
Castro-Santos et al., 2016	13-14% Opex
Castro-Santos & Diaz-Casas, 2014	15000 €/MW
Myhr et al., 2014	37 €/MWh
Bedard et al., 2004	2% Total O&M Cost

The cost of O&M, while usually a significant portion of WEC system costs, is a minor cost in this emergency WEC system. The WEC system components will be stored onshore during most of their lifetime, and thus will experience less wear and corrosion, and can be inspected periodically with little cost. When the WEC system is deployed, it is expected to be deployed only for a short period, so offshore O&M will not be necessary. Instead, when the WEC system is retrieved after an outage, it can be inspected and serviced onshore. Therefore, the maintenance of the WEC system is more similar to onshore electrical and structural equipment located in coastal environments or a pilot WEC system, rather than a commercial WEC system. When looking to previous literature for O&M cost estimates, O&M was often not included for pilot projects. However, for commercial projects, operations (which included O&M, insurance, and spare parts) accounted for ~4% of total project costs. Based on this estimate, it is assumed that O&M costs are negligible.

Although insurance, administration, and O&M rates vary by phase of the project, a single operations cost rate (2% of capital costs) is applied over the lifetime of the device.

4.5.7 Decommission

After the emergency wave energy system reaches the end of its useful life, the WEC system can be decommissioned. Decommissioning costs include the cost of removal or replacement of the electrical system after the project lifespan. Then, each subsystem (the WECs, mooring, cabling, and onshore electrical components) will need to be dismantled, transported, and processed. After processing, the materials must be disposed of or sold as scrap.

$$C_{Decommissioning} = C_{Dismantling} + C_{Disposal}$$

Decommissioning costs in existing literature are included in Table 10. There is currently no literature which describes the cost of dissembling the demonstration WEC systems, however, there is literature which chronicles the cost of decommissioning for a commercial WEC system. These costs for commercial sites are inflated compared to the proposed emergency WEC use case, as the commercial case includes removal of embedded equipment from and cleaning of the site. These costs are also the most expensive portion of the decommissioning phase (see Table 10).

Table 10. WEC system decommissioning costs

Reference	Category	Cost
Astariz et al., 2015	0.75% IC	4,080,690 €
Castro-Santos et al., 2016	Device	255,000 €
	Platform	59,092,054 €
	Mooring, Anchors	496,096 €
	Electrical System	2,747,353 €
	Cleaning	1,730,914 €
	Processing (dump/scrap)	-424,26,738 €
Castro-Santos & Diaz-Casas, 2014	Dismantling and eliminating of material, cleaning of site	5900 €/MW
Myhr et al., 2014	Removal, transport, and recycle	160% of IC

For this study, decommissioning costs are based on dismantling, transportation, and processing costs. Dismantling costs are based on the cost rate of labor for dismantling and the time it takes to dismantle the equipment. Disposal costs are context dependent; either a cost is incurred for vehicle rental and disposal, or the disposal company bands both fees together.

4.5.8 Results

The analytical cost model described previously calculates the cost of a small emergency wave energy array off the coast of Newport, Oregon.

4.5.9 Study Area

The selected case study area is about 3 geographic miles off the coast of Nye Beach in Newport, Oregon (Figure 19) just past Oregon's territorial sea. Depths here range from 45 to 55 meters. To give a sense of of the wave climate, a nearby study site has significant wave heights of 1-2.5 meters during the summer months at 6-9 second energy periods, and 2-5 meters during the winter months at 8-12 second energy periods, with maximum wave heights of 7-14 meters (NNMREC, 2017).

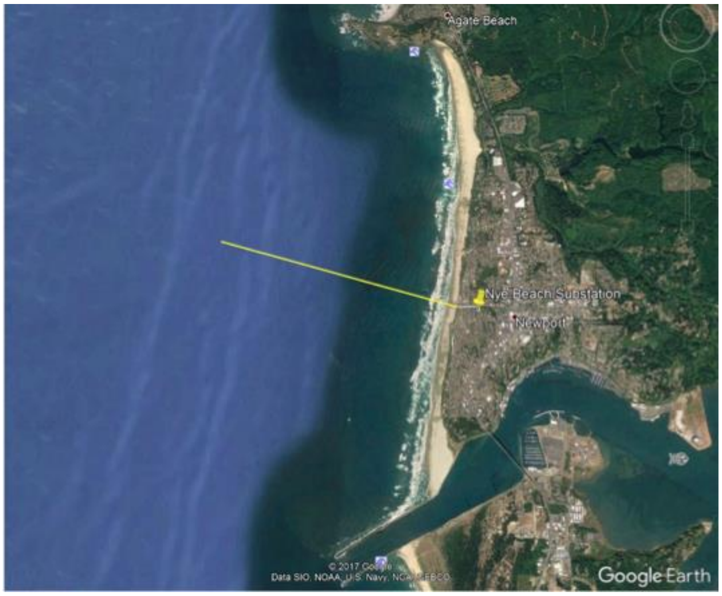

Figure 19. Proposed location of an emergency WEC offshore from the Nye Beach Substation

This specific area was chosen as the case study for a variety of technical and non-technical reasons. First, data and other necessary information were made available for use through collaboration with Central Lincoln Public Utility District (CLPUD), who services the area. Second, through engagement between Oregon State University, Oregon Sea Grant, the Northwest National Marine Renewable Energy Center, state and federal agencies located in Newport, and the Newport community, Newport has a populace who has been exposed to wave energy technology and is generally in support of limited, responsible wave energy development. Lastly, Newport is one of the largest towns on the Oregon Coast, and is an economic hub for the central Oregon coast. While southern coastal cities are larger (such as Coos Bay-North Bend or Brookings-Harbor), these southern coastal towns experience fewer low-probability, high-risk storm events and will experience a lessened impact from a Cascadia Subduction Zone earthquake and resulting tsunami as compared to Newport. Newport has the highest population and resources of the central coast, while also being vulnerable to large outages caused by storms and natural disasters.

4.5.10 Electricity Load

The design of the emergency WEC array is based on the requirements of providing electricity to power critical infrastructure services in Newport, Oregon, as detailed in Section 2.4 and Table 1.

4.5.11 Array Design

The proposed emergency WEC array was designed to meet the need of the calculated load of critical infrastructures in Newport. The array is comprised of point absorber WECs, based on the Wave Swing (Figure 20).

This device was chosen based on its rated power production characteristics meeting the demand for the load of critical services in Newport, Oregon, as well as the device maturity (it was deployed and grid-connected in Portugal in 2004). There is also power production and cost data for this device available through EPRI. The proposed point absorber has a rated power production of 4 MW, depending on the wave climate, and was tested in Reedsport, Oregon for power production given the local wave climate (based on Coquille River Reference Station wave data) (Previsic et al., 2004). Given this wave climate, one WEC was able to produce 3078 MWh annually, or 109.9 MWh over a two-week period. To power critical infrastructure services in Newport, 14 WECs would be required. The scale of the Wave Swing when it was tested was 9.5 m in diameter, and performs optimally in ~45 m water depths.

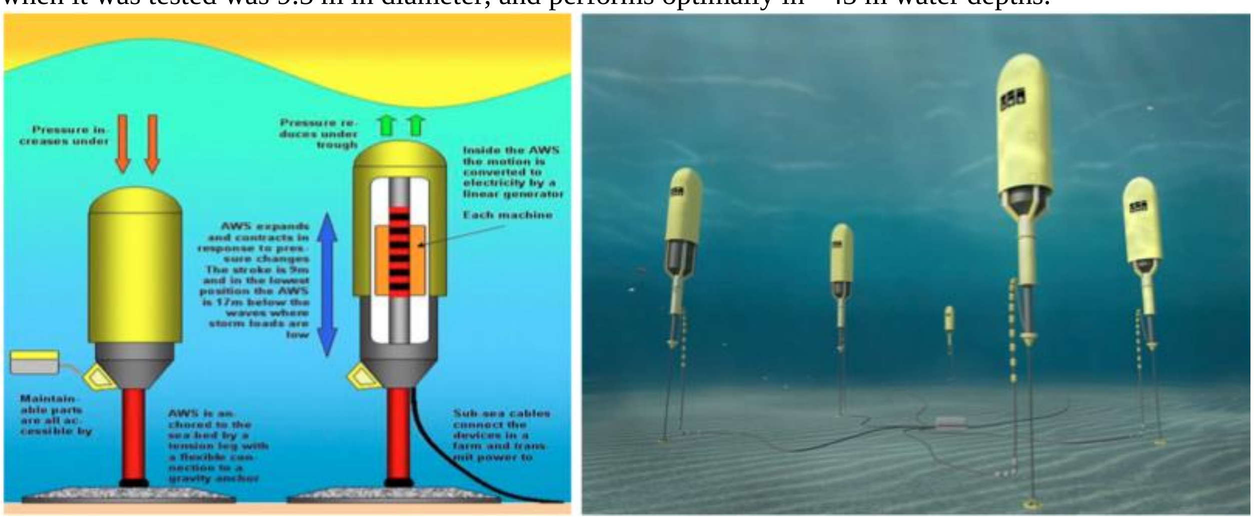

Figure 20. Archimedes Wave Swing

4.5.12 System Design

The WEC system is connected to the Nye Beach substation via about 3 geographical mile of subsea cable to an electrical junction. The onshore transmission system then follows roads to the power station along a 0.25-mile path, and subsequently to the newly converted digital Nye Beach substation. Most substations in the U.S. have not been converted, which should be considered when estimating costs for onshore transmission systems in other areas.

Interarray cabling consists of a riser cable connecting each of the 14 WECs to a bottom-mounted junction box. The junction box then connects to the subsea transmission cable, which transmits the electricity to the onshore electrical junction. The interarray cabling cost is dependent on the length of the cable. This length is determined by the length of cable required to span the distance between the WEC connection and the sea floor, and the distance from the WEC foundation to the subsea junction box. Because the device is bottom-mounted, the length from the WEC connection to the sea floor is assumed negligible. In this study, we assume a minimum spacing distance between each WEC of 150 m (Previsic, 2004), configured in a single line parallel to the shoreline and incoming wave direction. This amounts to 1.8 km of interarray cabling. The cost of interarray cabling comes from a study by Myhr et al. [89], in which interarray cabling costs were determined for a 5 MW floating offshore wind array.

The WEC is bottom mounted and has a gravity foundation. The cabling, which is a 10kV cable and 7-10 cm in diameter, is moored and anchored through a system similar to that used with the Ocean Observing Initiative (OOI) at University of Washington (Howe et al., 2010; Port of Newport, 2017), every 0.25-mile from the WEC, with the last 0.25-mile floated by buoys. Instead of a mid-water column, floating platform of sensing equipment attached to this mooring and anchoring system like with OOI, the line extends to the surface, where a buoy is attached for easy retrieval.

4.5.13 Cost of System

The basis for cost calculations are listed in the Methodology section of this report, and further detailed in Table 11. Costs are adjusted to 2017 USD.

Table 11. WEC system estimated costs

Basis	Project Phase	Cost Category	Cost Sub-Category	
Castro-Santos et al., 2016	*Pre-installation*	Feasibility Study		$118,000
Bureau of Labor Statistics, 2017		Design		$66,500/person/year
		Permitting		14% capital cost*
Previsic et al., 2012	*Implementation*	Installation		$639/kW
Previsic et al., 2004		Build	C_{WEC}	$5.2-7.8 mil/WEC
			n_{WEC}	14
Bedard et al., 2004			$C_{Mooring}$	$243,000/WEC
Myhr et al., 2014			$C_{Cable\_Interarray}$	$307,000/km
			$l_{Cable\_Interarray}$	1.8 km
Dalton et al., 2010			C_{Cable_Export}	$432,200/mile
			l_{Cable_Export}	3 miles
Bedard et al., 2004			$C_{Powerhouse}$	$750,000
Port of Newport, 2017		Storage		$32,706/year
Port of Newport, 2017		Transport	Work Barge	$17,664-26,496/ deployment
			Hoist crane	$2280/deployment
			Hoist dock	$1080/deployment
Bedard et al., 2004		Commissioning		$543,675
Bedard et al., 2004	*Operations*			2% capital cost*
Astariz et al., 2015	*Decommissioning*			0.75% capital costs*

**Capital costs include installation, build, and commissioning costs.*

Pre-installation costs for the emergency wave energy generation include feasibility study costs, as well as the cost of personnel who would be compensated over the course of designing the emergency WEC system. While feasibility study costs are based on work by Castro-Santos et al. (Castro-Santos et al., 2016), design costs are based on the national median for annual engineering salaries (considering civil, electrical, environmental, and mechanical disciplines, which could all be involved in a project such as this) (Howe et al., 2010). Based on the maximum national median among these disciplines, the highest salary was selected for use. This study assumes two employees would work full time on this design over 5 years, and assumes these employees would also oversee construction to prepare the system.

Installation costs are based on work by Previsic et al. (2012), which considers a 5 MW wave energy development 5 km from shore. In this study, installation costs are on a per unit energy basis, which was used to scale the installation costs to the required energy demand.

Build costs are based on WEC building costs from the WaveSwing developers, referenced by Previsic et al. [103]. Cabling costs were based on values from Bedard et al. (2004) and Myhr et al. (2014). The length of the interarray cabling assumes that there is a cable separately connecting each WEC to the junction box where the transmission cable begins. This interarray cabling length can be reduced if adjacent WECs could share the same interarray cable.

Storage and transport costs are calculated under the assumption that the WEC would be stored locally in the South Beach Marina (Figure 21), where there are port facilities to store, load, and transport the WECs. Storage costs are based on the rental of 15,100 square feet of storage space, and it is assumed that the WECs can be stored upright to that each device takes up a 10 m by 10 m footprint, and that the marina permits the rental of that size of storage space. It is also assumed that the rent rate is not raised each year.

Although the rent rate will change over time, it is impossible to predict future rent rates set by the Port of Newport.

Figure 21. Yaquina Bay (South Beach Marina pictured on right)

Transport costs include the cost of the hoist crane and dock, as well as cost of a work barge and crew for the length of 2-3 days, but do not include the cost of a licensed captain, which will have to be accounted for and contracted prior to the investment in this system. It is assumed that the hoist crane and dock will be used for 12 hours over the course of the installation period, and then again during retrieval (24 hours total). In reality, both storage and transport costs could be reduced through contracting with the Marina for long-term storage reduced rental rates.

Commissioning costs are based on work by Bedard et al. (2004). Due to the fact that documentation of decommissioning costs are unavailable, and the cost of industrial recycling and scrap is either not readily available from service providers, or it is market-dependent when the material is sold, decommissioning costs were estimated from previous literature. Most decommissioning costs summarized in Table 10 were estimated for site cleaning and embedded equipment removal of commercial-scale sites. Therefore, the most reasonable estimate was chosen for the given single-WEC site. For site-specific cost estimates, these decommissioning costs can be estimated through a professional quote from contracted dump and recycling services.

4.5.14 Discussion

Assuming 3 days for installation and retrieval, and a cost of $6.5 million/WEC, the cost is calculated by the following equation, given the ability to vary the number of deployments and the lifetime of the device.

$$C_{Total} = 116{,}383{,}096 + 32{,}706t + 29{,}856n_{Deployment}$$

Where t is the lifespan of the device, and $n_{Deployment}$ is the number of times the emergency WEC system is deployed. The Net Present Value then becomes

$$NPV(i,N) = 116{,}383{,}096 + \sum_{t=0}^{N} \frac{32{,}706}{(1+0.015)^t} + \sum_{n=0}^{M} \frac{29{,}856}{(1+0.015)^t}$$

Where t is the year of the system's lifetime, and N is the full lifetime of the system in years, so that the cost of the yearly rental is summed over the lifetime of the device in present value. Deployment costs are summed over the number of deployments in a given lifetime in present value. The total cost of the system is calculated for 20-, 30-, 40-, and 50-year lifespans, as well as 1, 2, 3, 4, and 5 deployments, in Table 12. It is assumed that deployments are evenly spaced within the lifespan of the device (for example: one deployment occurs in year 10 of a 20-year lifespan, or 3 deployments occur every ~6.7 years of a 20 year lifespan).

Table 12. Cost comparison – two-week outage scenario

Number of Deployments	**Lifespan (years)**			
	20	30	40	50
1	116,970,339	117,192,438	117,383,691	117,548,373
2	116,992,507	117,211,539	117,400,149	117,562,554
3	117,021,934	117,235,552	117,423,104	117,584,474
4	117,044,101	117,260,224	117,444,976	117,604,736
5	117,069,913	117,283,657	117,504,586	117,625,430

The total project costs are most dictated by capital costs, which make up ~85% of the total cost. When comparing our estimates to Value of Loss Loads (VOLL, or the socioeconomic value of electricity loss) (Table 3), the cost of the emergency WEC system is consistently more than the critical infrastructure VOLL of an outage lasting two weeks.

These VOLLs do not include valuations of premature deaths, nor do they account for inflated valuing of critical infrastructure (for instance, a person may be willing to sacrifice more energy at home than at the hospital, thereby attributing a greater Willingness to Pay value to the hospital to maintain nominal electricity supply and a lesser Willingness to Pay value to a residential home). If VOLLs reflected this additional value, and the WEC were to be used more than once in its lifetime, the cost of the wave energy system would become more comparable to the VOLL of critical infrastructure services over a two-week outage.

Table 13. Cost comparison -six-month outage scenario

Number of Deployments	**Lifespan (years)**			
	20	30	40	50
1	116,970,339	117,192,438	117,383,691	117,548,373
2	58,496,253	58,605,770	58,700,075	58,781,277
3	39,007,311	39,078,517	39,141,035	39,194,825
4	29,261,025	29,315,061	29,361,244	29,401,184
5	23,413,983	23,456,731	23,500,917	23,525,086

An interesting case is also highlighted in Table 13, in which a two-week outage is extended to a six-month outage caused by a Cascadia-Subduction Zone Event. Under these conditions, this emergency WEC system could provide high value to Oregon's central coast community by acting as an area of increased resources. During such a CSZ aftermath, it has been proposed that many fuel resources across the western part of Oregon will be lost or compromised. With the condition of roadways and other infrastructure in potential impassibility, the limited fuel that is available may not have a route by which to be transported to those who need it.

4.5.15 Conclusions

In this study, we developed an analytical cost model to estimate emergency wave energy generation costs and used this model to calculate the cost of a single-WEC system off the coast of Newport, Oregon. The total cost of the system was approximately $117 million, using net present value in 2017 USD. Capital costs comprised ~85% of total costs, and operational costs were minimal, given the sparse usage of the device and ability to service the equipment onshore. Uncertain cost categories include pre-installation and decommissioning costs, mostly due to lack of research into small-scale, temporary WEC systems, as well as the dependence on context with these costs (permits required for this system, for instance, will be differ between governments, locations, cultures, and more). Further research into the costs associated with these cost categories would allow this cost model to gain more accuracy.

Other uncertainties related to this model relate to the storage, transportation, installation, and maintenance of the emergency WEC system. Although we state assumptions we made for how the system is to be stored, transported, and installed, the marine industry infrastructure in Newport, Oregon, as it currently exists, is not prepared to support this emergency WEC system. A larger, potentially covered, local storage space would aid in storage of the devices. However, this dedicated storage would also need to be located near or in port, marina, or harbor facilities to enable the maintenance of the system, as well as the transportation and installation of the system. Another potential solution is to, rather than build additional storage and marine operations facilities, store and transport the emergency wave energy system from a nearby port, so that the WECs could be towed into the emergency relief area. This tradeoff between increasing transportation distances and increased marine operations infrastructure must be decided on a context-specific basis.

Related to this issue of marine operations infrastructure, is the issue of installation. The conventional way of laying cable requires specialized vessels and personnel, which often must be ordered from ports located far away. This results in high costs and a high waiting time for the boat to arrive. In this study, I proposed a different way to fix cables temporarily, although this method needs to be tested to determine if it is effective. Alternatively, there are other means of laying cable, such as cable-laying remote operating vehicles. This method of cable laying needs to be further explored. Mooring and anchoring, likewise, must also be reviewed from a logistics perspective. Through specialized design of the device and the anchoring and mooring components, logistics can be simplified, to a point. Expertise from marine operations professionals must be solicited to better plan these logistic components.

Future work could also include integrating a model to predict numbers of sustained outages over a 20-, 30-, 40-, and 50-year period to the value of the emergency WEC system. This model could also be expanded to calculate the probability of sustained outages, which would aid in determining the probability of emergency WEC use. Rather than fixing the time and number of durations for cost estimates, a Monte Carlo simulation could be used to simulate how many outages would occur in a given lifespan for the emergency WEC system, and the probable length of the outages.

To further contextualize the value of an emergency WEC system, an independent study to estimate VOLL in Newport, Oregon to verify methods used in previous literature should be completed. Moreover, there is a marked gap in research concerning the quantification of VOLL of critical infrastructure services. While VOLLs used here show the value of an outage, they may be an underestimate since they do not focus on critical infrastructure services, which may be more highly valued by the general populace.

Additionally, the value of this system is highly dependent on the context of where it is being used. An island community that is electrically isolated but has a small electricity load to provide may also not have the port resources or ability to deploy and retrieve such a system. Similarly, a large coastal city like Miami, Florida may not have the wave resource to make this solution viable. A question to consider in future analyses might include how the economic feasibility of this system changes with varying loads of electricity. Since electricity loads often correspond to seasonal climate variations, a single-WEC deployment may be sufficient for the summer in winter-peaking areas (like coastal Oregon), but not summer-peaking areas (like coastal southern California).

Another factor to consider is that while wave energy systems are traditionally designed to survive wave loads associated with a 20-year lifespan, this emergency case may have different engineering requirements. This change in use may prompt developers to consider alternate device designs to reduce costs or better meet wave load specifications. There is a potential market gap in which a business can provide emergency WEC systems when needed, rather than each municipality taking full responsibility for design, build, implement, and decommission of the system. A developer or company would need to consider WEC system design and its associated costs under this specific business model.

Lastly, this use case of emergency wave energy conversion brings to question the advantage a temporary wave energy system has when compared to a permanent wave energy system. The largest obstacle to full-scale wave energy installation is the high cost associated with such a system. By reframing the use case of a wave energy system to emergency relief, this obstacle is, somewhat, overcome (the motivation is not profit driven, but instead motivated by preserving life, property, and quality of life). If the value of wave energy is higher from emergency relief and coastal community resiliency perspectives, why not have the system permanently deployed?

While it is reasonable to argue for the establishment of "resiliency zones" along the Oregon coast, in which there is permanent wave energy generation that can support communities through a sustained power outage, there are barriers that might impede this argument, at least in Oregon. First, persuading communities to invest in a permanent system to retain resilience during uncertain future events is no small task, especially when the system is expensive and includes a relatively unproven technology. Second, there are other social, environmental and regulatory barriers that might impede a permanent installment. A permanent installment, despite its benefit to a local community, still has environmental implications that differ from a temporary installment. Likewise, the regulation associated with that permanent installment varies significantly to one that is associated with a temporary installment. Ultimately, the success of a resilience zone or emergency wave energy deployment depends on the needs of the community and their willingness to support it.

This cost model is offered as the first method to economically analyze this system, and is motivated by the desire to help coastal communities increase resilience in regards to accessibility to electricity. While such a solution may not be economically or technically feasible in certain contexts, it has the potential to provide critical infrastructures with the electricity required to reduce outage impacts, including preventing human loss of life and injury, promoting economic stability, and reducing damages to property.

5 Regulatory Evaluation

5.1 Emergencies and the WEC Permitting Process

The Federal Energy Regulatory Commission (FERC) is the Federal agency with lead authority over the licensing of marine hydrokinetic (MHK) projects in the US, and it currently offers two types of license: a pilot license and a traditional license. Pilot project licenses are intended for testing new device technologies no greater than 5 MW in size and have a 5-year duration. The traditional license has a duration of 30-50 years. Both of these processes can take 3-7 years to complete and involve consultation with several federal, state, and local agencies with specific regulatory authorities over some aspect of the ocean or coastal zone. Authorized projects in the US have so far required extensive environmental investigation and monitoring regimes to support the licensing decision. Additionally, an MRE developer must obtain separate permits for use of the seafloor and construction of land-based cable interconnection facilities, each with its own public and technical process.

MRE project developers have noted that the permitting process is arduous and expensive, representing a barrier to the growth of the industry (Dubbs, 2013). Because losses associated with a blackout begin immediately, hours count. If a traditional permitting process under FERC may be expected to take 3-7 years, the traditional permitting process also presents a significant risk to the validity of MRE to be an effective emergency power source in the aftermath of a disaster.

Because the MRE industry is still nascent in the US, there is a high degree of uncertainty regarding the potential environmental effects of development. As a result, the licensing and permitting process for MRE has become the primary venue for characterizing and mitigating uncertainties and perceived risks, using the best available science, to ensure compliance with marine protection regulations. In Oregon, permitting process participants have identified the following high-priority risks: potentially harmful or harassing acoustic levels, electromagnetic frequency effects on sensitive species from devices and cabling, pinniped haulout on devices, fish aggregation and artificial reef effects to the environment from structures in the water, and entanglement of fishing gear which increases marine mammal entanglement risk.

One interview respondent stressed that in consideration of the many technical and regulatory uncertainties associated with MRE, the most prudent course of action to mitigate risks from long-duration blackouts should be to invest in the traditional type of WEC permitting process and installation before it is needed. Such a path would provide the proponent of the project to have greater regulatory certainty, greater forethought in designing the optimal system for the specific ocean environment, and a greater return on investment because the WEC will be able to produce power with or without an emergency.

Alternatively, if a community or private MRE developer were to propose a temporary WEC project specifically intended for emergency deployment, they would need the ability to secure some form of anticipatory pre-approval of a WEC deployment if it is to be effective at mitigating risk during an emergency. Such a permitting process might include conditions under which an emergency deployment is allowed, limits on the duration of deployment, monitoring regimes as practicable during the emergency, and technical standards for interconnecting a WEC to a grid, which may or may not require local grid modifications prior to a disaster occurring. To facilitate this option, policymakers could petition the FERC to develop a new class of MHK permit that allows rapid deployment of temporary solutions immediately after a disaster provided that qualifying conditions are met.

While no legal path to allow the emergency temporary use of a WEC system currently exists, legal and historical precedents suggest that such a system may be able to obtain rapid approval in an emergency.

Following Hurricane Katrina in 2005, many emergency response actions were exempted from federal and state environmental protection laws. Flood waters were pumped into Lake Pontchartrain without the normal requirement for a National Pollutant Discharge Elimination System permit under the Clean Water Act. Materials were deposited in wetlands, without a permit under Section 404 of the Clean Water Act, based on the authority of executive procedures from the US Army Corps of Engineers. EPA granted "four kinds of waivers from Clean Air Act requirements," to allow refineries to increase fuel production to stabilize Gulf Coast industries. At the state level, "The Louisiana Department of Environmental Quality granted relief from the rules applicable to wastewater discharges; air emissions relating to repair activities and temporary power sources; on-site solid and hazardous waste management; inspection and rehabilitation of underground storage tanks; and numerous inspection, monitoring, and discharge reporting requirements." Several other instances like these led one scholar to conclude that "the emergency response to Hurricanes Katrina and Rita . . . was not inhibited by the environmental laws. Exemptions or waivers were granted, or the authorities simply looked the other way." (Gerrard, 2006)

Following the Deepwater Horizon oil spill, an Incident Command System under USCG leadership[4] came to a decision to employ formulations of the dispersant Corexit to oil at the ocean surface and in the subsurface at the location of the Macondo well. While it later came to light that this decision carried environmental consequences of its own, it shows a utilization of the Precautionary Principle (UNCBD, 1992). The precautionary approach to natural resource management, which first emerged in Germany in the 1970s and was codified in Principle 15 of the Declaration of the United Nations Conference on Environment and Development, states:

> *In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation.*

In emergency instances such as the Deepwater Horizon spill, this language could be used to support a risky decision, such as the use of a treatment with uncertain system effects, when there is a perceived threat of a greater irreversible harm (e.g., a massive oil spill). In this case, the uncertain effects of the remedial alternative were judged to be a lesser risk than the imminent threat to irreplaceable human and natural resources. This example begs the question whether a similar justification might apply to a long-duration power outage scenario wherein some degree of ocean risk may be weighed against imminent threats to human life and property.

The existing precedent in law suggests that in the event of a natural disaster, legal and political will favors actions to preserve human life and property over environmental protection regulations. If one considers the relative risk posed by a temporary moving structure in the ocean that could alleviate human suffering, such a regulatory path may be considered reasonable to pursue on a policy level.

The environmental protection laws that most directly affect the permitting process for MRE are the National Environmental Policy Act (NEPA), the Coastal Zone Management Act, the Endangered Species Act, the Marine Mammal Protection Act, the Magnusson Stevens Act, the Rivers and Harbors Act, and

[4] Per the National Contingency Plan (40 CFR 300), The USCG is the On-Scene Coordinator (OSC) for maritime spills and is charged with ensuring that the responsible party takes appropriate action. NOAA is designated by Congress to be the scientific advisor to the OSC and act as the Scientific Support Coordinator for scientific issues that include "expertise in environmental chemistry, oil slick tracking, pollutant transport modeling, natural resources at risk, environmental tradeoffs of countermeasures and cleanup, and information management." (Lubchenco et al., 2012)

the Federal Power Act. Of these, NEPA[5], CZMA, and the ESA all have exemption provisions in federal disaster areas or when it is "in the paramount interest of the country"[6] (Gerrard, 2006). The MMPA does not contain emergency provisions, but a process exists to obtain preemptive permission for incidental take of a protected species resulting from a proposed action. Under the Magnusson Stevens Act, NOAA-NMFS requires consultation for emergency Federal actions that may adversely affect essential fish habitat, but guidance states that agencies, "may consult after-the-fact if consultation on an expedited basis is not practicable before taking the actions" (NOAA 2004). For the Rivers and Harbors Act, the US Army Corps of Engineers has the authority to provide emergency authorizations for projects in navigable waters (USACE, 2015). Additionally, the USCG has broad authority to govern maritime navigation and the anchorage and movement of vessels in navigable waters of the United States, so it is reasonable to assume that exemptions from maritime regulations are also within the USCG authority.

If a community or developer had not previously obtained a conditional WEC permit before a disaster strikes, but a Federal Disaster is declared, then the leader of the Federal Incident Command System (normally FEMA) may be able to order the deployment of an emergency WEC system under current authorities. Any concerns related to safe ocean navigation would fall under the purview of the ICS, as the USCG is the designated ICS commander for ocean-related emergency response. However, because an emergency WEC is an untraditional disaster mitigation application, it does not appear that FERC has been historically included under the Incident Command umbrella authorized by the Stafford Act. Therefore, it is uncertain whether the Incident Commander would be able to override FERC's permitting authority. An Incident Commander may also lack the ability to override seafloor leasing authorities (BOEM in federal waters and the Department of State Lands in state waters), the renewable energy development area designations defined in the Oregon Territorial Sea Plan, any rights of way required to run the electrical cable from shore to a grid substation, or a myriad of state and local plans and ordinances. Again, the temporary nature of the mitigation solution, combined with the severity of the emergency, may lead State and Federal executives (e.g., the Governor or President) to direct that these regulations not impede deployment.

To better understand how regulatory perceptions of risk associated with MRE are affected by the presence of an emergency, a series of semi-structured qualitative interviews (Creswell, 2014; Ingles, 2007) was conducted with participants in current FERC permitting processes for a marine renewable energy project off the coast of Newport and a tidal energy project in Maine. Respondents were asked to describe their perceptions of risk associated with MRE from their individual perspectives as participants in the process (generally categorized as agency regulators or MRE development staff). Respondents were further asked to speculate on how their perceptions of risk might be different in the event of an emergency that threatened life and property, as well as what legal avenues may exist to accelerate the approval of an MRE project were an emergency to occur.

The quotes below reflect perspectives from MRE permitting process participants regarding how emergencies change perceived risk within a permitting context. Interview participants were not asked directly whether the consideration of emergency scenarios changed how they thought about the risks being managed under their current FERC permitting processes, but rather how the presence of an emergency might affect a proposal to deploy MRE as a response measure. This formulation may have introduced bias toward a temporary deployable MRE use case. However, because the bulk of the interviews were conducted in support of a separate research effort to characterize risk perception within

[5] While the text of NEPA itself contains no emergency exemptions, the implementing regulations of the Council on Environmental Quality authorize lead agencies to make "alternative arrangements" in emergency situations." 40 C.F.R. § 1506.11

[6] 16 U.S.C. § 1456(c)

their existing processes, some insights may be gleaned with relevance to the research question of this NRT report.

Generally, respondents from resource agencies appeared to be primarily concerned with ensuring protection of the specific resources and issues for which they have regulatory authority and responsibility. Some talked about the perceived benefit of renewable energy sources to help mitigate the onset of climate change and ocean acidification, but it was explained that in collaborative permitting process discussions, those benefits were not weighed relative to risks in a way that affected regulatory requirements for environmental studies to determine the direct effects of project approval. None of the respondents specifically mentioned the potential outage disaster mitigation benefits of their MRE projects, nor mentioned that they had been discussed within the permitting discussions. Several respondents described a proportionality aspect to the intensity of environmental study required for a project depending on its size, scale, and duration of deployment in the water. Projects with shorter durations and with a perceived smaller physical footprint of potential environmental effect were described as having less stringent characterization and monitoring measures.

When prompted to consider the potential for a long-duration blackout and the possibility of employing a MRE technology to mitigate detrimental effects, responses were generally consistent with the concept that an emergency situation does affect the perception of relative risk to the ocean. Respondents' conceptualizations of the permitting process for such a solution varied between the three potential regulatory pathways described in this section. Selected quotes from these interview responses included the following:

> *"It would seem reasonable to have some sort of temporary permit while you're working on something bigger, but see the problem is: Cascadia Subduction Zone happens. Where are you going to find the vessels to get those things out there? It's not the permits keeping you from getting out there, but you don't have the vessel infrastructure to get them out there, and then if you get them out there where's the cable going to get the electricity back to shore? So there's a lot of . . . it's a great idea but I've been arguing that if you want wave energy to be there for the Cascadia Subduction Zone you need to lay the infrastructure ahead of time."*
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> ----------
>
> *"Oh yeah I imagine you could have a floating [electrical] line under an emergency condition. When you're talking about the big one or something like that and suddenly all bets are off. It is an emergency situation. You can have things in an emergency situation that wouldn't, you bypass all permitting. It's an emergency situation."*
>
> ----------
>
> *"This would be a national emergency. You're talking about the Cascadia fault line, you're talking thousands and thousands of dead, tens of thousands of injured, no communication whatsoever, no bridges, no roads, no water, no power, people living in tents, running out of food, and the only way in or out are helicopters, and you can get power to a community by floating a line? You gonna start counting fish? I think not. I think the Governor says, President says, 'Put that that freaking thing in, yes, absolutely.' Yeah under situations like that, but you can't play that card for anything short of national disaster, imminent real risk to the population, and a need to rescue people."*
>
> ----------
>
> *"So, in that scenario, it is clear that this deployment is to address this human issue as opposed to like, 'Oh well we're mitigating for climate change and trying to transition from fossil fuels,' which doesn't get put in the equation. But if you're saying, 'I'm asking to do this to solve this immediate local problem," then I think it absolutely would go into the equation.' . . . I would imagine it's a state or federal agency like FEMA or something*

that's saying "We'd like to have this in our suite of options" and so then it's one agency asking another agency as opposed to like a private applicant."

"I mean I think that's an excellent question . . . that you should raise it at the state level because if we're talking about all this emergency preparedness, it'd be really great to at least have had someone thought about a roadmap of what that would look like. You know, before we get to the point of a tsunami and an earthquake and a wave energy buoy sitting in Toledo and everybody's like, "It'd be sure great if we could put that out there but . . . ' Yeah, I think there needs to be some sort of emergency contingency permit kind of thing."

"[With] the Endangered Species Act, there are provisions for emergency consultations. What the ESA provides is that if there's an action that could threaten life, property those types of things then there's a very short consultation process. I think most of these rules are from some of the wildfires [in the past]. . . so what happened is there would be a wildfire, and the BLM would put pumps in the rivers to pump water to put the fires out, and some of those pumps would suck up small salmonids. Clearly and rationally, you know, folks realized, you have to protect houses, you have to protect life, there has to be a better way than saying, 'Okay let's do a Biological Opinion and we'll produce that in 145 days. It's just not practical. . . We are not going to stand in the way. In fact we're absolutely obligated to stand aside because if there's a chance people could get hurt or property could get lost we don't want to get in the way of saving lives or protecting property . . . But we step aside and what we do is we do an after the fact consultation, so after they're done dealing with this emergency situation we issue a biological opinion and any take that would have occurred then is considered. So if you had a storm that wiped out the entire grid and there was some power available for hospitals and this thing was on the shore and all I had to do was put it in, you know, we wouldn't stand in the way."

The practical application of a temporary deployable WEC presents new technical challenges whose solutions may introduce new types of ocean-related risks compared to the traditional WEC installation method. The transmission cable would need to be temporary in nature, meaning that it would not be possible to bury the cable in the seabed to reduce the potential risk of EMF effects on species or interference with fishing gear that touches the seafloor. If a floating cable were deployed with sequential floats, it may represent a hazard to navigation per USCG authority. One potential path to USCG approval given the emergency nature of the deployment would be to ensure that a floating transmission line is clearly marked and its presence advertised on marine radio channels.

Even a temporary WEC solution will require some kind of anchoring system to keep it stationary, but the current state of the art of using three multi-ton concrete anchors presents issues related to supply chain, specialty vessel availability post-disaster, and benthic disturbance. As a potential solution, one company is developing Anchoring Remotely Operated Vehicles (AROVs) (Sustainable Marine Energy Ltd., 2017) that would allow an operator to lower an autonomous anchor installation machine from an overhead vessel, drill into a rocky seabed, and install a helical screw anchor that reportedly can hold 100 tons depending on the rock type. The screw anchor would be removable upon decommissioning. While one interview respondent reported that rocky environments are recognized as important habitat for valued marine species in Oregon, it is possible that a similar system could allow rapid deployment of a WEC in a soft bottom environment in the future.

Because the traditional commercial MRE permitting process lacks the flexibility that a deployable WEC model would have to deliver emergency power wherever and whenever it is needed (within the limits of portability), a temporary deployable MRE use case may be a viable alternative worth pursuing on the state and federal policy level. Furthermore, a temporary deployable system may be able to circumvent some of the extensive and expensive environmental investigation and monitoring requirements associated with the traditional permitting process. By limiting the situations in which a WEC is used to only those situations when risks to the ocean are perceived to be of less urgency than risks to humans and property, the deployable WEC use case may be able to benefit from an entirely different risk perception profile.

5.2 Regulations and Policy Affecting Utility Investment

While the risks associated with a potential long-duration loss of power on the Oregon coast are beginning to show increased visibility, it is uncertain how the potential losses from lower-likelihood, high impact events should be incorporated in the justification for investments in improvements to the energy grid or the construction of new generation capabilities.

The Oregon Public Utility Commission (PUC) represents the electricity ratepayers in Oregon and has a mission to, “Ensure Oregon utility customers have access to safe, reliable, and high-quality utility services at just and reasonable rates.” In implementing its mission, if the PUC determines that a proposed capital project by a utility cannot be proven to be “a prudent investment”, the PUC has the authority to prevent the utility from recuperating its project costs using ratepayer fees (Beecher, 2008; Noelb 2006). A determination of imprudence could cause failure of a large-scale investment such as the construction of a renewable energy facility and would make it nigh impossible to attract other outside investment. Such a situation occurred during the development stage for the Block Island offshore wind farm project in Rhode Island, the first of its kind in the US. The RI PUC judged the project too expensive with an uncertain final cost and value to investors. Resolution came when the State rewrote the PUC’s authority to prevent it from impeding the project. (Gibbons 2012)

The existing uncertainty regarding how to measure the likelihood and impact of a long-duration outage on the Oregon Coast makes it difficult to prove investment prudence with any great degree of certainty. Therefore, a PUC, depending on its uncertainty tolerance, may prohibit a technology that appears more expensive than more developed fossil fuel alternatives without taking its emergency value proposition into account.

While the PUC may prevent investments in emergency generation facilities such as MRE, publicly-owned utilities such as the Central Lincoln PUD are not governed by the PUC. The PUD’s board of directors could therefore potentially have greater flexibility to structure their rates to support more economically risky investments. (ODOE, Pers. Comm.)

5.3 Grid Interconnection Standards

The most relevant standard to the connection of ocean wave energy is IEEE Standard 1547 which designed specifically to help accommodate energy sources at a distribution level. In addition to ANSI C84.1 standards, IEEE Standard 1547 dictates what the accompanying power system technology needs to accomplish to reduce the impact DER’s have on the grid. Of the many requirements, the ones that are inherently important to this project are as follows:

- Each unit of 250 kVA or greater must monitor its connection status, real power output, reactive power output, and voltage at the point of connection
- The DER unit shall cease to energize the area’s power system for faults on the area’s power system to which it is connected,
- the DR shall cease to energize the area’s power system within the clearing time as indicated,

- No DER reconnection can take place until the frequency has stabilized to the range of of 59.3 Hz to 60.5 Hz,
- For an *unintentional* island in which the DER energizes a portion of the area's power system through the interconnection point, the DER interconnection system shall detect the island and cease to energize the area's power system within two seconds of the formation of an island

While the first key standard listed above is very straightforward, the follow standards have big implications to the technical feasibility to our project. If for any instance that there is an outage on the electric system, ocean wave energy has to immediately disconnect from the grid. Additionally, if there is any instance of *unintentional* islanding ocean wave energy has to disconnect from the the grid as well. Unfortunately, in the case of *intentional* islanding, there have been no standards set. What these three things imply is that for our strategy of an islanded microgrid, ocean wave energy, or any renewable energy for that matter, cannot help with the effort to power critical infrastructure.

Fortunately, the limiting factor here is not technology but that there have not been enough studies and experiments to fully understand what role does renewable energy play during an outage. Smart inverter technology can already do the things we need it to, but because of the standards and lack of understanding we are left with this problem.

6 Results and Discussion

The objective of this report is to measure the validity and value of an emergency WEC system to be used during sustained, storm-related outages in Newport, Oregon. To that end, we measured the feasibility of such a system by considering societal and energy-supply aspects of the risk of an outage, the wave energy array's technical and economic feasibility, the technical feasibility of inputting wave energy into the grid, and the regulatory feasibility of emergency deployment. The goal of our work is to provide local and regional stakeholders with information that will enable them to consider emergency WEC systems as a potential solution to outage risk. In this section, we collate results from each of these perspectives to form collective conclusions about the value and validity of an emergency response WEC system in Newport, Oregon.

In Section 6.1, we characterize the risk of an outage. Then, sections 6.2 and 6.3 contain concluding remarks regarding the value and validity of the proposed WEC system. Lastly, we recognize that while this report makes progress towards describing an emergency deployable WEC system, there are still many questions to be answered for accurately determining whether this system is viable, and if so, how.

6.1 Clarifying Risk of Long-Duration Blackouts

Electrical power systems have traditionally been designed for reliability – to withstand high frequency off-nominal operating conditions. Low probability, high risk events are often overlooked in design, which results in a higher likelihood of power outages due to these events. In more coastal or islanded communities, the effects of electrical vulnerability are magnified by increasing coastal populations, relative electrical isolation from the larger electrical infrastructure, low-levels of local energy generation, aging electrical infrastructure, and climate change effects.

6.1.1 Severity of Impact (Value of Load Lost to the Community of Interest)

When an extended outage occurs, the value of lost load is highly variable depending on the method of evaluation. Also, most methods don't currently consider beyond 24hrs, and often don't consider added value from loss of critical services (e.g. losing some amount of electricity to a private home will have a different valuation of loss of load when compared to losing electricity to a hospital due to the potential repercussions.)

The specific value of critical services is still a matter of debate among the research community, but the best available methodologies suggest that the VOLL of critical services alone for a community of Newport's size might range from $469,000 to $2.34 million for a two-week outage. The most extreme valuation proposes a social insurance scheme totaling up to 4% of annual community income, valued at $19M per year.

Alternatively, a WEC array sized to provide for the total needs of the community, including continued economic production (approximately 11-16 MW of generation capacity), could include avoided economic losses and increase the value of a WEC solution to anywhere between $16 million to $1.5 billion for a two-week outage. This wide range of estimates emphasizes the uncertainty associated with valuing the losses from long-duration power outages.

The survey-based method of VOLL estimation has not traditionally focused on outages lasting longer than 24 hours, nor on the specific value of critical services to residents of a coastal community in this region of the world. Advancements in this field may reveal a greater perceived value of these services, affecting the total value proposition. Furthermore, while it is difficult to predict the likelihood of a prevented mortality and incorporate the associated value into a cost benefit analysis, neither should the value of a saved life be discounted entirely.

As part of the National Governor's Alliance Policy Academy on Oregon Coast energy resiliency, it was revealed to our team that researchers at LBNL are currently pursuing a VOLL analysis tailored to address coastal perspectives of critical services in a long-duration outage (ODOE, Pers. Comm.). The lack of research about outages longer than a single day and the variability of value of loss load indicates a need for further work regarding preparation for such events. The following sections discuss the potential implementation of marine renewable energy in the aftermath of events causing extended outages.

6.2 Value of Emergency MRE as Blackout Risk Mitigation

The question of value relates in one sense to the economic prudence of an investment in an MRE project compared to the potential benefits it would provide to a host community in the aftermath of a long-duration outage situation. For emergency wave energy generation to be economically feasible, the community must have 1) the wave energy resource to meet community critical infrastructure demand, and 2) the ability to access and implement that resource. Oregon is considered to have a good wave energy resource, yet accessing that energy has challenges to overcome and consequently may be too expensive for only a short deployment.

The MRE technology analyzed in Section 4.1 of this report is based on a point absorber technology capable harnessing, with an estimated capacity factor of 40%, 124.11 kW generation capacity per device in a post-storm sea state. To satisfy the estimated critical infrastructure energy demand for Newport, a total of 37 devices would be required.

In contrast, the technology assessed for development of the cost model claims potential power production of up to 4 MW per device, based on a report from 2004 that simulated power production given wave data from Coos County, Oregon, just south of Lincoln County. These figures have not yet been proven at scale, but if accurate indicate that 14 WECs would power Newport under normal wave conditions, not 37. This reveals that the cost of the WEC system to the community varies significantly on the wave modeling assumptions used, as well as the chosen device technology's power production. If an emergency wave energy generation system were designed and optimized – through changing the type of device, the control scheme, and the array layout to maximize power production – the emergency wave energy system could increase cost competitiveness. As these technologies mature and are verified via real-world testing, the total number of devices required to support critical services may decrease. These advancements would strengthen the value proposition for an emergency WEC concept.

The energy requirement of our selected critical services, estimated to be approximately 4.5 MW of instantaneous demand, would require a wave energy array containing between 10-40 devices (given current technology maturity levels and the estimated wave climate following a severe storm). The expected costs of such an array significantly outweigh the value of critical service continuation as currently understood, suggesting that benefits would not outweigh costs. The critical service VOLL of a two-week outage pales in comparison to the cost of an $80 million WEC system – a system that we are unsure how to install after a storm when conditions could still be too rough for boats to go out. However, if more than one long-duration outage may be expected during the operational life of an emergency WEC system, the value proposition improves dramatically.

There are several other avenues that could also improve the potential value of an emergency WEC system.

First, if the critical service infrastructure is run at less than full demand, as envisioned in Narayan (2012), then the total amount of power required from an MRE system could be reduced significantly. This in turn could reduce the number of required devices and bring overall costs down, while still providing much of the value that critical services provide. Emergency power management schemes for critical infrastructure are outside the scope of this report, but they could be a beneficial avenue of future research.

Secondly, because no probabilistic correlations are found in the literature between long-duration blackouts and increased risk of mortality, the value of prevented mortalities was deemed too uncertain to include in the quantitative analysis. If this avenue of research matures, the value proposition of an emergency MRE solution may improve; however, proponents of emergency MRE should be cautious of using fear-based messaging to promote technological development.

Next, as the length of a power outage increases, so too does the value of a mitigation solution. If we consider the expected effects of a Cascadia Subduction Zone earthquake (an outage lasting up to 6 months), the VOLL for critical services based on current methods could increase to a range between $6-30 million. The VOLL for total energy demand (including business losses) ranges into the billions. The value of avoiding such an extreme long-duration outage is highly uncertain and likely undervalued because there would be significant additional benefits related to lives saved, reduced need for costly alternatives such as sea- or air-based fuel delivery, and a general improvement in the ability of the community to "bounce back" from the disaster. While an analysis of the full benefits would be speculative and highly uncertain, current estimates show a 17% probability of a full-rupture CSZ earthquake in the next 50 years (Goldfinger et al., 2016). Consequently, further research on the value of electrical system resiliency following this quantitatively probable event should be further explored.

Another consideration for altering potential value involves increasing the size of an array to provide for the total needs of a community including continued economic production (approximately 11-16 MW of generation capacity). The VOLL estimates would then include avoided business losses and increase to a value ranging anywhere from $16 million to as high as $1.5 billion for a two-week outage. The larger economy of scale may tip the value of risk mitigation in favor of an MRE solution. However, increasing the amount of power required to meet load would increase the number of WECs required. This increase in the total number of required WECs not only changes the cost of the WECs and cabling, but the storage, transportation, installation, and decommissioning costs. Together, this could make an emergency WEC solution infeasible for this use case, from a cost of logistics standpoint. It is of interest to consider where that tipping point occurs: how many WECs are feasible, and when do they become infeasible? Ultimately, this question hinges on the ability and quickness of installing the array.

A last consideration which could improve the value of emergency WEC generation is that in comparison with diesel emergency generators, it appears that an MRE solution might surpass a diesel-powered solution on both a cost basis and arguably on a resiliency basis as well. Our calculations estimate the cost of providing for the full suite of critical infrastructure in Newport to cost $5.5 Billion, and the amount of fuel delivery and management to support this infrastructure would be staggering. Diesel generators may make sense for individual buildings for limited periods of time, but they appear to be a poor solution for larger energy system support or for long durations given their fuel reliance and propensity for mechanical failure. As such, there is the potential for value added through a major offset of the cost compared to existing diesel generation, through the implementation of an emergency generation source that is less harmful to the environment than diesel, through the ability to extend the lives of existing generators, through the ability to reduce life lost. The importance of the LCOE compared to the potential to minimize loss of life quality is a driving question.

6.3 Validity of an Emergency WEC System

6.3.1 Resource Availability/Production

Given the vast amount of available energy in the waves and tides, ocean energy is currently being pursued as a primary energy source around the world. With the potential available resource off the Oregon coast, we are suggesting that marine renewable energy could be utilized in emergency scenarios to provide power when extended blackouts occur. For this to be feasible, there are three main aspects to consider – is the wave energy resource available, what are the capabilities of an MRE device to capture that energy, and once captured, is the grid capable of utilizing the provided electricity.

The amount of energy contained off the Oregon coast varies greatly based on the time of year and it has been found that at a location of 40m water depth the mean wave energy is 31kW/m with 40% of that being 10kW/m or less and 1% being 200kW/m or more. Sea states in the summer are less energetic; however, instances of extended blackouts are also less likely to occur in summer months. For the two weeks following a storm occurring on March 12th, 2012, the amount of available energy in the waves was found to be 149.67 kW/m at a water depth of 140m.

Having modeled a simplistic point absorber operating with 6-degrees of freedom (a simple cylinder with a 10m diameter and a 10m draft), we have determined that 37 such devices (with a rated power of 310.28 kW) would be necessary to supply the 4MW of power required for the critical infrastructure. This number seems high which is likely due to the lack of device optimization – both in the shape and the power take off system.

We have concluded that while the resource is available in Oregon, the ability to efficiently capture the necessary energy is suspect. At this stage, the challenge of deploying and retrieving 37 MRE devices in a timely manner may not provide the necessary value. In an emergency scenario, the purpose of implementing MRE would be to limit loss of essential services and to do so requires implementation rapidly after power is lost. The infrastructure required to deploy, connect and manage 37 devices will not likely be available. However, it is reassuring that the wave energy industry is reporting devices with the ability to more efficiently capture energy. Additionally, the apparent number of devices required points towards considering permanently installed generation sources rather than deployable.

6.3.2 Technical Feasibility of Emergency MRE

In a post-storm environment based on data from NOAA buoys in March 2017, the amount of energy in the waves is approximately 132 kW/m. The typical wave power at the Coquille River reference station is 21.2 kW/m. This order of magnitude difference means that not only would a WEC in these conditions face more extreme forces on its mooring system, but deployment operations in high waves (1.27 – 7.04 meters) could endanger the crews of the installation vessels. For reference, offshore wind turbine O&M crews are not allowed to approach a turbine unless wave heights are less than 1.5m. Installation of a permanent WEC array is normally planned for the summer months when seas are calmer, and an emergency WEC deployment would be logistically infeasible following a winter storm. Moreover, this finding tells us that the depth of the water and location distance from shore and surrounding wave climate is a significant factor to consider when determining which WECs to use and how to deploy them. It also means that location-specific wave data is required to accurately estimate the power production of a WEC.

The installation of multiple emergency WECs into an array introduces additional technical complications. The amount of time for installation of each device is uncertain, as is the time required to lay and interconnect the electrical transmission cables from the devices into junction boxes and to shore. Connection activities will likely require specialty services such as divers and/or specialty connection equipment to ensure that all connections stay dry. If the installation time for an adequately sized WEC array requires multiple days to effectively begin mitigating the effects of a blackout, then the value proposition of an emergency solution becomes suspect.

In addition to the installation complications of a multiple-device emergency WEC array, a challenge would be the requirements for storing up to 37 10-meter diameter devices until they are needed and transporting these devices to the water in the aftermath of an outage event.

Under a temporary emergency WEC use case, it is assumed that no transmission cable is already in existence for a deployable device to connect to. This means that a cable would have to be laid rapidly, likely towed from a large spool on the beach by a capable vessel. From there, the cable could be either submerged to the seafloor or allowed to float on the surface with the help of buoys. During deployment, the cable would present a navigation hazard requiring special dispensation from the USCG or, if on the seafloor, notices to bottom-trawling fishing vessels about its location so it could be avoided. Although in the event of an emergency where the deployment of the WEC(s) is required, normal ocean operations would likely be temporarily halted or would be more accommodating to a temporary adjustment of what is normal routine.

6.3.3 Grid Integration Feasibility for Emergency MRE

Assuming WEC technology will eventually support the ability to efficiently capture the resource, the grid is able to make use of the provided electricity. Micro-grids have been studied extensively with renewable energy sources such as solar and wind. With the current studies performed, there are no major issues with integrating WECs to the Nye Beach substation. While there are significantly more ways to explore what impact wave energy will have to CLPUD, in the extents of this project, wave energy can satisfy the energy needs of the critical infrastructure without causing any major violations. Doing a simple load-flow analysis, using the data gathered from the OpenEI database and the information from CLPUD, there are no major violations which would cause faults. Even at a maximum output of 4MW, there are no line limit violations and the N-1 security criteria is met. However, there are necessary upgrades to the surrounding infrastructure to give CLPUD better situational awareness. These upgrades would likely take the form of a higher rated transformer (or a new one to work in parallel), real and reactive power, voltage, and frequency sensing capabilities, and the communication infrastructure to support this.

However, there is a caveat in that these results are only as good as the model itself. One could contend that the conductor used to transport energy is not homogenous through the system because different portions of the grid have higher demand on a normal basis. Additionally, perhaps even more importantly, is the way in which we've modelled the connections throughout the system. Currently, we've aggregated many of the loads into points to show that they are roughly supplied by the same pole and transformer. A more accurate model would include the individual poles that are a part of the feeder.

One issue not mentioned thus far is that wave energy is a variable. In the best conditions, the same array spec'd to produce 4 MW of power in a two-week duration can sometimes produce upwards of 15 MW in the winter and as little and 500kW in the summer. This wide swing indicates that there needs to be some type of power smoothing either through the form of batteries or some other technology. In its current state, CLPUD's distribution network would likely not be able to fully utilize or perhaps even transport this power.

With respects to interconnection standards, wave energy may be permitted to participate in this disaster mitigation plan. Initially written in 2003, IEEE standard 1547 prohibited distributed energy resources from participating in grid disturbances by immediately de-energizing themselves as to not cause additional problems. Changes to this standard in 2014 now allow distributed energy resources to ride-through disturbances but in the case of islanding they still are required to be de-energized. This means that in our scenario where CLPUD loses power from BPA the wave array will have to be disconnected. However, IEEE 1547 is going through yet another revision/amendment process and, as such, we can only hope that our desires to use wave energy as a emergency generator will be reflected there.

6.3.4 Regulatory Feasibility

It appears to be possible that the presence of an emergency could lessen the traditional permitting requirements of a WEC project to allow a temporary deployment, either through emergency authorities and processes or via the development of a new type of anticipatory emergency permit process. The temporary nature of an emergency WEC, coupled with the severity of risk to human life and property, would appear to affect the perception of relative risk in favor of an emergency power solution.

Interconnection standards for distributed energy resources are still lagging behind to what's technically capable. In their current state, standards allow for distributed energy resources to be energized if there is a fault **BUT NOT** if there is an islanding event occurring. If for instance the BPA tie in Toledo were to be severed, wave energy cannot help with the effort of providing power to critical infrastructure (regulation-based). These standards are still changing but until there have been more studies showing distributed energy resources impact to the grid in these scenarios change will be a slow process.

Some challenges to the implementation might not come from the technological side, but from the regulatory side. PUDs must have systems in place to include a variable resource like wave energy in the case of a blackout. Currently there is not a permit type for emergency generation using the ocean as a resource. However, the creation of such permit could provide a new market for those in wave industry – providing an assurance that regulations will not impede the implementation of their device in an emergency setting. A permit could also reassure existing stakeholders that the device implementation will have a defined extraction time and will minimize potential conflict with existing ocean users.

6.4 Permanent vs. Temporary WEC

One goal of this analysis is to determine whether a potential business opportunity may exist for emergency response wave energy generation, in which portable WEC systems could be stored by a company and provided at any location when needed. A "portable resilience zone" would enable communities to share the cost of the emergency WEC system and potentially provide sustained income to a WEC developer. Based on the findings in the above section, it appears that the temporary deployable WEC use case would be economically infeasible given the power demand of critical services and the generation capabilities of currently available WEC devices.

There is an outstanding question for the emergency WEC use case regarding who would be the customer. There is potential that FEMA or the Navy may decide to add MRE devices to their suite of emergency response tools. By investing in this preventative measure, these entities could save money and social costs over time, rather than relying on emergency response measures. In this event, a single WEC may be reused in multiple emergency situations around the country or the world during its lifespan, increasing the total value of the investment.

If a WEC array already existed offshore the community of interest, as is expected to be the case in Newport once the NNMREC SETS project is installed, technical feasibility issues associated with emergency deployment would be avoided. A permanent array would be subject to all the normal environmental investigation and monitoring requirements as part of the permitting process.

An idea worth further exploration is the value of blackout risk mitigation for a pre-existing permanent MRE installation on the coast. If an array of sufficient size is already present and selling its power on the electricity market, might the value of this array during an emergency be factored into the lifecycle value of the project? For example, if an MRE array under normal circumstances must sell power at a higher than market rate to be economically viable, but it can be reasonably expected with some probability that a long-duration outage will occur during the lifetime of the project, can the developer take advantage of the project's increased value during an emergency and "boost" the Levelized Cost of Energy metric to be more competitive with cheaper but farther away energy alternatives? Uncertainties with this approach include the difficulty of predicting the recurrence interval of long-duration outages and policy-related questions regarding whether an MRE investor should be allowed to recover higher costs during an emergency.

The creation of resiliency zones along the coast could better provide an existing infrastructure for use as a nominal energy provider under normal circumstances and as a primary energy supplying in emergency situations when a coastal community might be secluded from the primary grid system. Since PMEC SETS will be grid connected, it has the potential to be utilized in Lincoln County as a source of emergency generation. However, the electricity generated from SETS will be integrated into the grid at Seal Rock, south of Newport Bay, and would require routing through Toledo in order to be used by Newport in the event of an emergency. Such an extended routing could prove challenging if the line(s) connecting Seal Rock to Toledo and Toledo to Newport are down in connection with the outage.

7 Conclusions

This transdisciplinary report evaluated the potential risk of long-duration blackouts on the central Oregon Coast and assessed the feasibility of harnessing the abundant wave energy resource offshore to mitigate those risks. Through consideration of the issue from multiple disciplinary lenses, our team assessed the specific vulnerabilities of a coastal town in Oregon and developed a proposed list of critical service infrastructure that could provide for the basic needs and safety of the community. This list of services and their power demands may be valuable to state and local planning authorities as they plan for coastal resiliency.

Our team also revealed that marine renewable energy may be a valid risk mitigation alternative from a technical and regulatory standpoint with the proper consideration of grid integration needs and support for emergency MRE permitting options on a policy level. The relative value of such an alternative is still uncertain given the current state of understanding of community impacts in the wake of an extended outage and uncertainty regarding the ability to predict the recurrence interval of an outage of sufficient scale to warrant investment.

Future work related to this topic should focus on refining our analysis and reducing uncertainty in the following components:

1. Develop VOLL estimates specific to a long-duration outage scenario (i.e., longer than 24 hours) for smaller communities, with special focus on the direct and indirect value of critical services, including the potential value of lives saved and overall acceleration of a community's ability to "bounce back" from a disaster.
2. Expand the analysis to a more comprehensive assessment of the impacts and probable response actions associated with a Cascadia Subduction Zone earthquake and tsunami, which may affect the value proposition of an emergency MRE solution.
3. Investigate electricity demand management strategies for critical services to reduce the total demand that an emergency solution would need to support.
4. Monitor the capabilities of emerging WEC devices, with a focus on reducing the total number of devices needed to satisfy critical service electricity demand and facilitate temporary deployments of a WEC system. This research should also include advancements in installation and decommissioning methods that may be more suited to a post-disaster rapid deployment using available oceangoing vessels.
5. Research alternative power purchase models for MRE that could potentially affect the levelized cost of energy for a permanent MRE installation if the value of emergency power provision were incorporated over the project's expected service life.
6. Refine the power output models for a WEC device in post-event ocean conditions to better characterize the variability of available power over time.
7. Develop decision rules and technical standards to facilitate intentional conversion of isolated distribution grids into "islanded microgrids"
8. Conduct research into community attitudes about the value of marine renewable energy as an emergency services provider.

8 Collaborative Working Structure

8.1 Individual Contributions

Jeff Burright conducted the regulatory permitting evaluation in Section 5.1, studied and reported the specific vulnerabilities of the community of interest in Section 2.2, and developed the estimates of the grid outage valuation in Section 4. He also engaged state and local personnel from Lincoln County, the Central Lincoln PUD, and the Oregon Department of Energy in information gathering conversations to fill factual gaps in the collaborative group's understanding of the social and electrical systems related to the research question.

Caitlyn Clark developed a cost model for emergency WEC deployment and applied it to the case of Newport, Oregon. She also compared machine learning methods to predict long-duration storm outages in Newport, Oregon, with details from that study outlined in her Master's thesis, which can be found in Oregon State University's Scholars Archive.

Chris Sharp evaluated the resource – determining which of the available sea state data was going to be useful. He used this information to characterize the potential power output of a modelled device for both two week time scale and a year time scale. Optimal locations were determined as well as an initial investigation into power variability over a set time period.

Brandon Johnson modelled and analyzed Central Lincoln PUD's distribution network as well as gathering load information for customers that Jeff Burright helped determine. Also, he helped look at the interconnection standards that would be required from an international viewpoint.

8.2 Collaborative Process

The process for developing this transdisciplinary collaborative project occurred in phases. First, our team engaged in brainstorming sessions during the NRT Intensive Field Camp to determine what aspects related to marine renewable energy were of interest to all of us, and of those, which topics might be most compatible with our combined disciplines. This free-form process of information sharing built our excitement to work together and helped us to understand each other's strengths. Eventually we gravitated toward the concept of coastal blackout risks because it melded aspects of WEC optimization, grid integration, and socioeconomic/regulatory concerns.

Next, we began to diagram the coupled natural human system associated with a large-scale blackout. We spent many hours over the course of several months in front of a whiteboard, sketching the essential pieces of the system and the connections between them. Our system model underwent many iterations as we refined our approach based on new information we were gathering in our early research, as well as a better understanding of what we could each feasibly contribute from our individual disciplines. These research design sessions were punctuated by meetings with our advisory cluster, who helped to nudge us toward an achievable focus of analysis. The cluster meetings also forced our group to develop informational materials that could explain our often complicated transdisciplinary system understanding into externally digestible communication products such as diagrams and outlines.

The research design phase was the most arduous and time-consuming part of the transdisciplinary project, taking nearly six months to result in an actionable outline for our transdisciplinary report. Ultimately we emerged with individual lists of work we could accomplish and a system diagram that would show us how our individual contributions could be interconnected to serve the central research question.

Once we had a research plan in place, the individual work began. We maintained contact via weekly meetings and the Slack communication tool. As initial interdisciplinary findings became available, we revisited our research outline and developed a team project schedule that included information interdependencies and incorporated our individual schedule priorities outside the NRT program.

Once each team member had conducted our individual interdisciplinary work products, we engaged in a collaboration workshop where we integrated our findings, drew conclusions related to our central research question, and identified the significant remaining uncertainties in the analysis. From these discussions, the team collaboratively wrote the discussion section of the transdisciplinary report.

Figure 22 shows a graphical representation of the collaborative transdisciplinary process undertaken to produce this report.

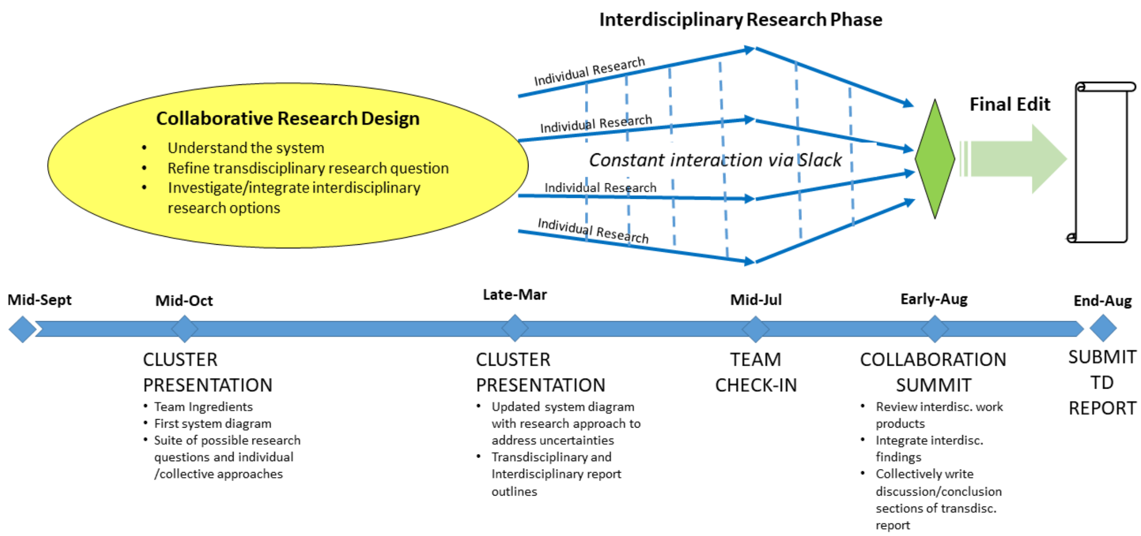

Figure 22. NRT Collaborative Transdisciplinary Process

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Appendix: Newport Critical Infrastructure Additional Information

Table 1 Critical infrastructure and their addresses used for power flow studies

Critical Service Sector	Associated Newport Infrastructure	Location (Newport, OR)
Communications Sector	KPPT Radio Broadcaster	145 Oregon Coast Hwy #D
	KYTE 102.7 Radio Broadcaster	906 SW Alder St
Emergency Services Sector	Lincoln County Sheriff Jail	251 W Olive St
	Lincoln County Sheriff's Office	225 West Olive Street
	Newport Fire Station	245 NW 10th St
	Newport Police Department	169 SW Coast Hwy
Emergency Services – Shelter Locations**	Oregon National Guard Armory	541 SW Coast Hwy
	Newport Recreation Center	225 SE Avery St
	Newport High School – East & West	322 NE Eads St
	Sam Case Early Childhood Center	459 NE 12th St
	Newport Intermediate School	825 NE 7th Street
	Yaquina View Elementary School	351 SE Harney St
Energy Sector	Lincoln Co PUD Main Office	2129 Oregon Coast Hwy
Food and Agriculture Sector	JC Market Thriftway	107 North Coast Highway
Government Facilities Sector	Newport City Hall	169 SW Coast Hwy
Healthcare and Public Health Sector	Newport Hospital	930 SW Abbey St
	Oceanview Senior Living	525 NE 71st St
	Newport Rehab and Specialty Care	835 SW 11th St
Transportation Systems Sector	Lincoln Co Fleet Services	880 NE 7th Street Newport
	Private fuel pumps/supplies (1)	22 N Coast Hwy
Water and Wastewater Systems Sector	Newport Water Treatment Plant	2810 NE Big Creek Rd
	Municipal water pumps (2 locations)	973 NE Lakewood Dr. and 833 NE 7th St
	Wastewater pumps (2 locations)	442 NE 10th St. and 755 NW Beach Dr.

Table 2 Feeder information used for power flow studies

From Bus	To Bus	Length (mi)	Cable Type	Ampacity (A)	Total Impedance (p.u)
Substation 1	1-1	0.41	1/0BC	310	0.09 + j0.13
	1-7	0.91			0.21 + j0.29
	1-12 (Feeder 13)	0.38			0.08 + j0.12
	1-12 (Feeder 12)	0.36			0.08 + j0.12
	1-15	1.1			0.25 + j0.35
	1-16	0.76			0.17 + j0.24
	1-18	0.26			0.06 + j0.08
	1-19	0.25			0.06 + j0.08
	1-20	0.85			0.20 + j0.27
Substation 2	2-1 (Feeder 12)	0.29			0.09 + j0.12
	2-1 (Feeder 11)	0.2			0.05 + j0.06
	2-2	1.04			0.24 + j0.33
	2-3	0.78			0.18 + j0.25
	1-6	0.88			0.03 + j0.04
1-1	1-2	0.19			0.04 + j0.06
	1-16	0.15			0.03 + j0.04
1-2	1-3	0.32			0.07 + j0.10
	1-4	0.27			0.06 + j0.09
1-4	1-5	0.23			0.05 + j0.07
1-5	1-6	0.2			0.05 + j0.06
	1-7	0.33			0.08 + j0.11
1-7	1-8	0.23			0.05 + j0.07
	1-10	0.37			0.09 + j0.12
	1-11	0.31			0.07 + j0.10
1-8	1-9	0.35			0.08 + j0.11
	1-10	0.4			0.09 + j0.13
1-9	1-10	0.55			0.13 + j0.18
1-12	1-13	0.38			0.09 + j0.12
1-13	1-11	0.22			0.05 + j0.07
	1-14	0.34			0.08 + j0.11
1-14	1-15	0.26			0.06 + j0.08
1-16	2-3	0.88			0.03 + j0.04
	1-17	0.91			0.21 + j0.29
1-17	3-1	0.38			0.08 + j0.12
1-18	3-2	0.57			0.13 + j0.18
1-20	1-21	1.2			0.28 + j0.39
1-21	1-22	0.7			0.16 + j0.22
1-22	1-15	1.2			0.28 + j0.39

Table 3 Power Flow Results for system in Section 4.2

```
MATPOWER Version 6.1-dev, 25-May-2017 -- AC Power Flow (Newton)

 it    max P & Q mismatch (p.u.)
----  ---------------------------
  0         6.000e-02
  1         1.778e-04
  2         1.187e-08
  3         5.234e-15
Newton's method power flow converged in 3 iterations.

Converged in 0.01 seconds
================================================================================
|     System Summary                                                           |
================================================================================

How many?                How much?              P (MW)            Q (MVAr)
---------------------    -------------------  -------------  -----------------
Buses             29     Total Gen Capacity      54.6        -100.0 to 100.0
Generators         2     On-line Capacity         4.6           0.0 to 0.0
Committed Gens     1     Generation (actual)      4.5               0.0
Loads             10     Load                     4.5               0.0
  Fixed           10       Fixed                  4.5               0.0
  Dispatchable     0       Dispatchable          -0.0 of -0.0      -0.0
Shunts             0     Shunt (inj)             -0.0               0.0
Branches          41     Losses (I^2 * Z)         0.01              0.01
Transformers      41     Branch Charging (inj)     -                0.0
Inter-ties         0     Total Inter-tie Flow     0.0               0.0
Areas              1

                          Minimum                      Maximum
                 -------------------------  --------------------------------
Voltage Magnitude   0.997 p.u. @ bus 1082       1.000 p.u. @ bus 103
Voltage Angle      -0.24 deg   @ bus 1082       0.35 deg   @ bus 103
P Losses (I^2*R)             -                  0.01 MW    @ line 103-1019
Q Losses (I^2*X)             -                  0.01 MVAr  @ line 103-1019


================================================================================
|     Bus Data                                                                 |
================================================================================
 Bus      Voltage          Generation             Load
  #   Mag(pu) Ang(deg)   P (MW)   Q (MVAr)   P (MW)   Q (MVAr)
----- ------- --------  --------  --------  --------  --------
Sub 1  0.997  -0.209*       -         -       1.06      0.00
Sub 2  1.000   0.000     4.52      0.01        -         -
 1-1   0.998  -0.144       -         -         -         -
 1-2   0.999  -0.113       -         -       0.03      0.00
 1-3   0.999  -0.054       -         -         -         -
 1-4   0.999  -0.118       -         -       0.31      0.00
 1-5   0.999  -0.109       -         -       0.37      0.00
 1-6   0.999  -0.046       -         -         -         -
 1-7   0.998  -0.175       -         -       0.37      0.00
 1-8   0.998  -0.182       -         -         -         -
 1-9   0.998  -0.192       -         -       1.40      0.00
 2-1   1.002   0.354       -         -         -         -
 2-2   1.002   0.354       -         -         -         -
 2-3   0.999  -0.098       -         -         -         -
 3-1   0.998  -0.140       -         -       0.25      0.00
 3-2   0.997  -0.245       -         -       0.23      0.00
 1-10  0.998  -0.182       -         -         -         -
 1-11  0.998  -0.190       -         -         -         -
 1-12  0.997  -0.206       -         -         -         -
 1-13  0.997  -0.200       -         -         -         -
 1-14  0.997  -0.211       -         -         -         -
 1-15  0.997  -0.219       -         -       0.24      0.00
 1-16  0.998  -0.145       -         -         -         -
 1-17  0.998  -0.123       -         -         -         -
 1-18  0.997  -0.220       -         -         -         -
 1-19  0.997  -0.220       -         -       0.24      0.00
 1-20  0.997  -0.211       -         -         -         -
 1-21  0.997  -0.214       -         -         -         -
 1-22  0.997  -0.216       -         -         -         -
                        --------  --------  --------  --------
               Total:     4.52      0.01      4.51      0.00
```

Branch Data

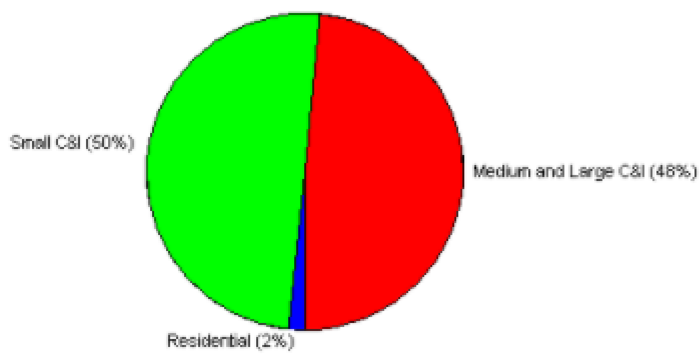
Brnch #	From Bus	To Bus	From Bus Injection P (MW)	From Bus Injection Q (MVAr)	To Bus Injection P (MW)	To Bus Injection Q (MVAr)	Loss (I^2 * Z) P (MW)	Loss (I^2 * Z) Q (MVAr)
1	Sub 1	1-1	-0.85	-0.00	0.85	0.00	0.001	0.00
2	Sub 1	1-7	-0.20	-0.00	0.20	0.00	0.000	0.00
3	Sub 1	1-12	-0.04	-0.00	0.04	0.00	0.000	0.00
4	Sub 1	1-12	-0.04	-0.00	0.04	0.00	0.000	0.00
5	Sub 1	1-16	-0.45	-0.00	0.46	0.00	0.000	0.00
6	Sub 1	1-18	0.23	0.00	-0.23	-0.00	0.000	0.00
7	Sub 1	1-19	0.24	0.00	-0.24	-0.00	0.000	0.00
8	Sub 1	1-20	0.01	-0.00	-0.01	0.00	0.000	0.00
9	Sub 1	1-15	0.05	-0.00	-0.05	0.00	0.000	0.00
10	Sub 2	1-6	1.69	0.01	-1.68	-0.00	0.001	0.00
11	Sub 2	2-1	0.00	0.00	0.00	0.00	0.000	0.00
12	Sub 2	1-9	1.15	0.00	-1.14	0.00	0.003	0.00
13	Sub 2	2-2	0.00	0.00	0.00	0.00	0.000	0.00
14	Sub 2	2-1	0.00	0.00	0.00	0.00	0.000	0.00
15	Sub 2	1-3	1.01	0.00	-1.01	-0.00	0.001	0.00
16	Sub 2	2-3	0.68	0.00	-0.68	-0.00	0.001	0.00
17	1-1	1-2	-0.88	-0.00	0.88	0.00	0.000	0.00
18	1-2	1-3	-1.01	-0.00	1.01	0.00	0.001	0.00
19	1-2	1-4	0.09	-0.00	-0.09	0.00	0.000	0.00
20	1-4	1-5	-0.22	-0.00	0.22	0.00	0.000	0.00
21	1-5	1-6	-1.68	-0.00	1.68	0.00	0.001	0.00
22	1-5	1-7	1.09	0.00	-1.09	-0.00	0.001	0.00
23	1-7	1-8	0.16	0.00	-0.16	-0.00	0.000	0.00
24	1-7	1-10	0.10	0.00	-0.10	-0.00	0.000	0.00
25	1-7	1-11	0.26	0.00	-0.26	-0.00	0.000	0.00
26	1-8	1-9	0.16	0.00	-0.16	-0.00	0.000	0.00
27	1-8	1-10	0.00	0.00	-0.00	-0.00	0.000	0.00
28	1-9	1-10	-0.10	-0.00	0.10	0.00	0.000	0.00
29	2-3	1-16	0.29	0.00	-0.29	-0.00	0.000	0.00
30	2-3	1-17	0.39	0.00	-0.39	-0.00	0.000	0.00
31	1-12	1-13	-0.09	-0.00	0.09	0.00	0.000	0.00
32	1-13	1-11	-0.26	-0.00	0.26	0.00	0.000	0.00
33	1-13	1-14	0.17	0.00	-0.17	-0.00	0.000	0.00
34	1-14	1-15	0.17	0.00	-0.17	-0.00	0.000	0.00
35	1-15	1-22	-0.01	0.00	0.01	-0.00	0.000	0.00
36	1-16	1-1	-0.03	-0.00	0.03	0.00	0.000	0.00
37	1-16	1-17	-0.13	-0.00	0.13	0.00	0.000	0.00
38	1-17	3-1	0.25	0.00	-0.25	-0.00	0.000	0.00
39	1-18	3-2	0.23	0.00	-0.23	-0.00	0.000	0.00
40	1-20	1-21	0.01	-0.00	-0.01	0.00	0.000	0.00
41	1-21	1-22	0.01	-0.00	-0.01	0.00	0.000	0.00
						Total:	0.010	0.01

Appendix: ICE Calculator Parameters and Results

Interruption Cost Estimates

Sector	No. of Customers	Cost per Event (2016$)	Cost per Average kW (2016$)	Cost per Unserved kWh (2016$)	Total Cost of Sustained Interruptions (2016$)
Medium and Large C&I	821	$8,193.5	$111.9	$40.4	$1,076,293.0
Small C&I	4,804	$1,445.4	$516.8	$186.7	$1,111,008.3
Residential	32,734	$7.0	$5.0	$1.8	$36,809.8
All Customers	38,359	$362.4	$116.3	$42.0	$2,224,111.1

Total Cost of Sustained Interruptions by Sector



Input Values			
SAIFI:	0.160	No. of Non-Residential Customers:	5,625
SAIDI (in minutes):	26.6	No. of Residential Customers:	32,734
CAIDI (in minutes):	166.1		
States:	Oregon		