U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

8 Coastal Resiliency and Disaster Recovery

Powering the Blue Economy: Exploring Opportunities for Marine Renewable Energy in Martime Markets

April 2019

8. Coastal Resiliency and Disaster Recovery

Key Findings

- Coastal areas support a large part of the human population but are under stress from sea level rise and increases in storm frequency and intensity. These areas are also prone to extreme events, such as tsunamis, tropical storms, and flooding. Deterioration of coastal areas can threaten the safety of the populations, including disruptions to communities, such as limiting access to freshwater and electricity for extended periods of time. These threats can result in displacement of human populations and public health risks.

- Coastal communities are addressing threats to coastal areas by focusing on hazard mitigation, preparedness for extreme events, response and recovery operations, and by improving the resiliency of critical infrastructure and emergency assets.

- Coastal resilience can be improved by fortifying natural shorelines like beaches and marshes, and by putting in place assets like distributed power generation sources to support local microgrids.

- Marine energy devices could be integrated into coastal infrastructure, such as piers, jetties, groins, and breakwaters, providing the dual benefit of shoreline protection and power generation.

- Marine energy could also contribute to coastal microgrids, increasing generating source diversity and reducing reliance on hard-to-find diesel fuel during emergencies. Marine energy could be used to support other emergency needs, such as water treatment and supply (e.g., emergency desalination).

Opportunity Summary

Roughly one-third of human populations live within 100 kilometers of a coastline and continued migration toward coastal areas is expected to increase this proportion to one-half by 2030 (Small and Nicholls 2003; MEA 2005). The close proximity of populations to the coast, along with the potential impacts of climate change and sea level rise on storm intensity and frequency, will require communities to plan for events that will place more residents, homes, and businesses in the path of increasingly dangerous and costly storms (Texas A&M undated). Coastal communities must integrate resiliency and disaster recovery planning into decision-making processes, facilitating the understanding of where and how communities are vulnerable to loss from coastal hazards, and adapting planning and development practices to mitigate these vulnerabilities (Texas A&M undated). There are opportunities for marine energy to support coastal resiliency and disaster recovery planning and prevention.

Increases in the frequency of extreme weather events and the threat of future sea level rise has prompted the need for increased shore protection in the form of beach nourishment and the construction of coastal structures to reduce shoreline impacts (National Oceanic and Atmospheric Administration [NOAA] 2017b, 2018; U.S. Global Change Research Program 2014). Shoreline protection structures, such as breakwaters, could also house marine energy devices, providing power to marinas and small ports. Following coastal disasters, such as hurricanes, flooding events, earthquakes, or tsunamis, there may be an immediate need for emergency power, as well as safe drinking water and process water for essential services, including heating and fire suppression systems. Isolated portions of a coastal grid may be susceptible to extended loss of power and could require a boost for grid restart, referred to as a “black start.” Typically, the Federal Emergency Management Agency (FEMA) and/or state or community emergency services provide diesel generators for emergency power sources. As of 2014, FEMA had 1,012 generators in its fleet comprising 103 generator sizes, ranging from 1.5 kilowatts (kW) to 1.825 megawatts (MW) (Danjczek 2014), requiring that shipments of diesel be continually delivered into disaster zones. Marine energy could be used to augment or replace power from diesel generators, as well as provide black-start capability to isolated portions of the grid. All coastal areas are at risk from these natural disasters and could benefit from marine energy. Isolated grids (e.g., coastal Alaska) have less resiliency than areas with neighboring grids and could benefit the most from having an independent source of power from the sea. FEMA’s Disaster Relief Fund is one of the main funding sources for emergency response and disaster recovery, receiving base funding of $615 million in Fiscal Year (FY) 2017 and an additional $6.7 billion for major declarations (PolitiFact 2017).

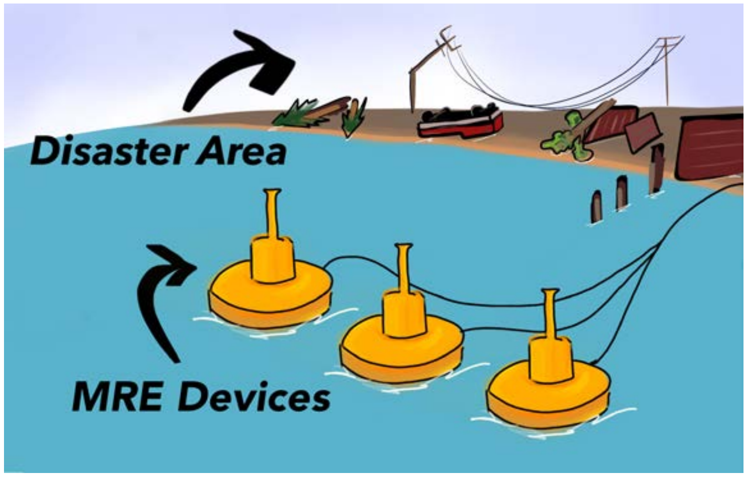

Figure 8.1. Marine energy application overview for emergency response. *Image courtesy of Molly Grear, Pacific Northwest National Laboratory*

Application

Description of Application – Shoreline Protection

Coastal resiliency consists of actions planned and executed to defend against storms, sea level rise, tectonic events and resulting tsunamis, and other hazards, some of which are sudden and unexpected (such as storms and tsunamis), while others are slower and more predictable.

Before a disaster strikes, it is possible to prepare coastal communities to be more resilient to coastal disasters using marine energy, both by augmenting natural defenses, like beaches, and integrating power generation into existing or future shoreline protection infrastructure.

Shoreline protection and defense of coastal environments is a growing necessity in the face of sea level rise and more intense storms. The development of breakwaters, berms, groins, storm surge barriers, and other similar coastal structures will increase globally, presenting the opportunity for the integration of marine energy devices, as well as retrofitting into existing structures (Figure 8.2). The power generated could be delivered to marinas, ports, local communities, or aid in sand replenishment of beaches.

Shore protection solutions can be classified as either hard or soft approaches. Hard approaches include groins, breakwaters, jetties, seawalls, and revetments. Soft approaches include beach nourishment, living shorelines, and sand-filled geotextiles.

Beach Nourishment

Beach nourishment (or replenishment) is the U.S. Army Corps of Engineer’s (USACE’s) preferred approach to shore protection for beaches and shorelines with open wave exposure as it does not harden the shoreline and is the only protection approach that adds sediment to the existing coastal system (USACE 2018a). Sand placement is designed and engineered to be naturally distributed over time. Once the new engineered beach profile reaches equilibrium, the wider beach gently slopes offshore, assuming a more natural form. The longevity of a beach nourishment is a function on the geometry of the project, the nature of the fill material, and the wave climate to which the project will be exposed during its lifetime (Dean and Dalrymple 2002). As a result, many sites may need to be renourished periodically, including beaches that are directly affected by sea level rise. Typically, nourishment activities take place as part of a scheduled project or in response to a coastal storm.

The selection of equipment for nourishment projects is a function of the location and character of the sediment borrow area.[13] If the borrow area is within 20,000 ft of the beach site, then the most economical dredging method generally entails use of cutter suction dredges that pump material through pipelines. For borrow areas farther away from the beach site, trailing suction hopper dredges mine the sediment, travel to a hook-up point, and discharge the material onto the beach via pipelines, sometimes using boosters to augment the power of the hopper dredge (Great Lakes Dredge and Dock 2018).

Shore Protection Structures

Hard shore protection structures are designed and constructed to prevent further erosion of a beach or to impede the motion of sediment along a shoreline (Dean and Dalrymple 2002). Examples of hard shore protection structures include groins, breakwaters, artificial headlands, revetments, seawalls, bulkheads, and jetties. Common construction materials include concrete, steel, timber, stone (quarried and armor units), and geotextiles (USACE 1984).

Shore protection structures provide a means for integration with renewable energy devices. Mustapa et al. (2017) provides a review of the integration of wave energy devices with marine facilities. A main driver for integrating wave energy converters (WECs) with shore protection structures is better economic viability through cost sharing on construction, installation, maintenance, and operation. In addition, the integration of WECs into shoreline protection structures may increase social acceptance of these projects. Integrated devices are beneficial for remote locations as they help to reduce the use of diesel fuel for electricity production and protect the shore through wave dissipation.

As discussed in Mustapa et al. (2017), oscillating water column devices consist of two elements: the reinforced concrete structure that acts as an oscillating chamber and a group of turbine generators. The first integrated oscillating-water-column breakwater was constructed at Sakata Port, Japan. In 2008, the first multiturbine facility consisting of 16 chambers integrated with vertical breakwaters was successfully constructed at the port of Mutriku, Spain (Figure 8.2). In 2012, construction began on the biggest oscillating-water-column-breakwater integration project, the Resonant Wave Energy Converter 3, in the harbor of Civitavecchia, Italy (Figure 8.3). Currently, only eight of 17 caissons are constructed.

---

[13] A sediment borrow area is the location of the offshore source of beach fill material. For a typical beach nourishment project, an investigation takes place that identifies potential sediment borrow areas that have sediment of a suitable grain size, sufficient volume, and are within a reasonable distance from the nourishment site.

Figure 8.2. Mutriku, Spain, oscillating-water-column-breakwater integration. *Source: obs/Voith GmbH*

Figure 8.3. The Resonant Wave Energy Converter 3 Device in Civitavecchia Port, Italy. *Photos from Maestrale (2017)*

Storm Surge Barriers

Storm surge barriers (flood barriers) are another form of coastal protection designed to prevent storms from causing flooding in the protected area behind the barrier. In most cases, the barrier consists of a series of movable gates that remain open under normal conditions to let the flow pass but are closed when storm surges are expected to exceed a certain level (USACE 2018c). During normal conditions, these barriers are typically opened to allow for navigation and saltwater exchange with the estuarine areas landward of the barrier (USACE 2018c). These structures are often chosen as a preferred alternative to close off estuaries and reduce the required length of flood protection measures behind the barrier (USACE 2018c). The largest flood protection project in the world is Delta Works in the Netherlands. Delta Works consists of a number of surge barriers, including Oosterscheldekering (Figure 8.4), the largest storm surge barrier in the world (5.6 miles long). Oosterscheldekering, known as the Eastern Scheldt, has also been equipped with five tidal turbines, with a total capacity of 1.2 MW, enough generation to power 1,000 Dutch households (M Power 2018).

Figure 8.4. Oosterscheldekering storm surge barrier in the Netherlands. *Photo from Amazing Planet (2014)*

Figure 8.5. Five tidal turbines integrated with the Oosterscheldekering storm surge barrier in the Netherlands. *Photo from HydroWorld.com (2015)*

Power generated from marine energy devices could be used to supplement other energy sources during emergency response and disaster relief activities, offsetting the heavy reliance on diesel generators (Table 8.1). The reliance on diesel requires it to be shipped to areas ravaged by disaster, creating logistical and financial challenges. Further, using diesel generation close to communities creates environmental health and safety issues, as a result of storing and burning diesel in those areas. Medium to large marine energy devices could be used to aid in grid restart, whereas smaller devices could improve the resiliency of isolated grids in response to severe storms or other disrupting events.

Description of Application – Disaster Recovery

In 2016, the U.S Department of Homeland Security (DHS) published the *National Response Framework* (DHS 2016), which provides a guide on how the nation responds to disasters and emergencies. The framework describes specific authorities and best practices for managing incidents that range from serious, local events to large-scale terrorist attacks or catastrophic natural disasters.

As discussed in the framework, once an incident occurs, efforts focus on saving lives; protecting property and the environment; and preserving the social, economic, cultural, and political structure of the jurisdiction. Depending on the size, scope, and magnitude of an incident, local, state, tribal, territorial, and insular area governments (and in some cases, the federal government) may be called to action. The response core capabilities are the activities that generally must be accomplished in incident response regardless of which levels of government are involved. Table 8.1 provides a summary of each response core capability and the critical tasks to achieve its objective.

Table 8.1. Requirements for Marine Energy Power To Meet Core Capabilities After a Coastal Disaster, as in the National Preparedness Goal. *Source: DHS (2016)*

Task	Power Needs
Planning	No power required; tasks carried out in advance of disasters
Public information and warning	Electricity needed for communications systems, radio systems, and cell towers to equip personnel to provide ongoing information to the community
Operational coordination	Electricity needed for emergency management centers, including lighting, heating/cooling, and communications
Infrastructure systems	Electricity needed to augment fuel for hybrid and electric vehicles, communications, debris removal equipment, communications, and debris disposal
Critical transportation	Augment fuels for vehicles and other means of evacuation, including boats, delivery of vital supplies, heating/cooling, lighting for evacuees, processing drinking water, and communications
Environmental response/ health and safety	Supply electricity and clean water for medical assistance, lighting, heating/ cooling, and communications
Fatality management services	Provide refrigeration for morgues, transportation for medical personnel and bodies, and communications
Fire management and suppression	Provide power for water pressure and pumping, lighting, and communications for fire crews
Mass care services	Provide power for constructing temporary shelters, processing clean drinking water, distributing food and services, heating/cooling, lighting, and providing emergency first aid
Mass search and rescue operations	Augment fuel for search and rescue vehicles, lighting, and communications
On-scene security, protection, and law enforcement	Provide power for emergency equipment, including lighting, communications, and medical care
Operational communications	Provide power for communications among rescue personnel, field crews, emergency centers, and local and regional authorities; provide power for tools to rebuild communications infrastructure
Logistics and supply chain management	Augment fuel for vehicles to deliver supplies, transport the injured or ill, and provide power for communications equipment and lighting
Public health, healthcare, and emergency medical services	Provide power for essential medical equipment, lighting, heating/cooling, and communications; provide power to produce clean drinking water and process water for sterilization
Situational assessment	Provide power for communications and lighting

Electrical Grid Blackstart

As described in Feltes and Grande-Moran (2008), electrical grids are designed to be resilient and maintain operations and consistent voltages over time. However, system power outages occasionally occur because of human error or natural occurrences, such as lightning strikes, hurricanes, or electromagnetic pulses. When a portion of the grid goes down, it is restored with assistance from a neighboring area of the grid. In circumstances in which there is an isolated portion of the grid, or a widespread blackout occurs and there is no neighbor to assist, a situation known as a black start becomes necessary. A black start involves restoring the system from a preselected, reliable generating asset. For large grid operations, these black-start generators might be isolated coal-fired plants or other power sources. In more isolated grids, black-start generators might include fuel cells, microturbines, wind generators, or photovoltaic panels (Lopes et al. 2005).

As outlined by the Federal Energy Regulatory Commission (2016), electric utility companies develop their own bulk power system recovery and restoration plans that would be implemented following a widespread outage or blackout. In 2014, the commission, in partnership with the North American Electric Reliability Corporation, reviewed these plans for restoration and recovery of nine registered entities with significant bulk power grid responsibilities. The findings of the review are presented in Federal Energy Regulatory Commission (2016).

In the United States, the 2003 blackout that left close to 50 million people across the Great Lakes Region without power was the most devastating of its kind to hit the U.S. industrial complex (U.S. Department of Energy 2015). The blackout was so widespread and severe that black-start procedures were required to bootstrap the affected electrical grid. Outages spread northeast from the Great Lakes through Pennsylvania, New York, and into Ontario. The event contributed to at least 11 deaths and cost an estimated $6 billion (Minkel 2008).

To increase grid resiliency and prepare for potential black-start operations in the event of a blackout, several states and other countries are instituting black-start power alternatives. In 2016, the utility Imperial Irrigation District demonstrated the use of a 33-MW lithium-ion battery energy storage system in California to provide a black start to a combined-cycle natural gas turbine from an idle state (Colthorpe 2017). Also, in 2016, a 5-MW utility-scale battery park in Germany was able to restore power to the local grid (Colthorpe 2017).

Microgrids

As discussed in International Electrotechnical Commission (IEC) (2014), a microgrid is a system of geographically grouped, distinct distributed resources, such as generators or loads, that represent a single generator or load to the wider electricity system. Microgrids may be connected to the wider electricity grid or operate as distinct islands for which no connection point between the utility grid and microgrid exists, and are called isolated microgrids.

Microgrids are inherently suitable for maintaining electricity needs during or after a disaster, as described in IEC (2014). For example, microgrids can dramatically improve the reliability of centralized power systems; isolated microgrids can continue operation, maintaining local power supply autonomously. Microgrids can also reduce the load on the wider grid or export power from the microgrid to a broader area, in addition to helping with voltage and frequency control in such situations.

Power and energy storage technologies associated with microgrids include microturbines, batteries, flywheels/supercapacitors, fuel cells, renewable generators, and combined heat and power systems. Wind turbines are the most utilized renewable energy generation technology in microgrids around the world. There is a reasonable distribution of microgrid sizes, ranging from microgrids that generate less than 20 kilowatts to those that produce more than 60 MW (IEC 2014).

North America has become the dominant player in microgrid research, which is a partial response to renewed government interest after a series of crippling blackouts (IEC 2014). Marine energy technologies could become a significant player in microgrids associated with recovery of generation in coastal areas.

Power Requirements

Beach Nourishment

As discussed earlier, energy generated from integrating marine energy with shore protection structures could potentially be used to supplement power needed for beach nourishment projects. Being that nourishment activities take place both offshore (e.g., pumping sediment from the borrow area) and nearshore (e.g., pumping sediment onto the beach), marine energy devices may need to be easily mobilized so that power can be used in either location. Table 8.2 presents the estimated power consumption for various offshore vessels used for beach nourishment projects. All estimations are based on equipment owned by Great Lakes Dredge and Dock.

Table 8.2. Estimated Power Requirements for Beach Nourishment Vessels

Beach nourishment Vessels	Estimated Power Consumption
Trailing suction hopper dredge[14] Cutter section dredge[15]	Propulsion power: 3,000 horsepower (hp)–13,404 hp (2,238 kW–9,995.4 kW) Dredge pump power: 1,700 hp–10,000 hp (1,268 kW–7,457 kW) Total installed power: 9,395 hp–28,625 hp (7,009 hp–21,345.7 kW)
Booster pump[16]	Cutter power: 250 hp–4,500 hp (187 kW–3,357 kW) Total installed power: 1,665 hp–21,380 hp (1,242 kW–15,949 kW)
Hydraulic unloader[6]	Main pump power: 3,600 hp–14,400 hp (2,686 kW–10,742 kW)
Trailing suction hopper dredge[17]	Total installed power: 6,800 hp (5,073 kW)

Disaster Recovery

Each of the critical tasks outlined by DHS for emergency response will require power to run medical equipment, communication networks and devices, lighting, heating/air conditioning, refrigeration, and many other necessary services. As discussed in IEC (2014), when power is constrained (as in after a disaster), low-priority loads may be shed to maintain supply to critical infrastructure. Following an emergency, there will also be extensive needs for energy to power communities; for shoreline communities, this power could be supplied by marine energy devices off the coast. For communities along sizable rivers, riverine devices could supply power in the same manner. Power needs include air traffic control, communications (e.g., cellular, internet), emergency lighting, emergency response operations and activities, refrigeration (e.g., food, ice, medicine), residences and businesses, sewage and sanitation systems, and shelters.

Markets

Description of Markets – Shoreline Protection

With threats from sea level rise and increases in coastal storm intensity and frequency, communities are protecting their shorelines and coastal infrastructure through the development and construction of shore protection strategies. USACE is the nation's leading agency responsible for protecting coastal infrastructure, with specific priorities to serve mandated functions. The USACE FY19 budget (USACE 2018b) includes $1.930 billion for the study, design, construction, operation, and maintenance of inland and coastal navigation projects. The Flood Risk Management Program is funded at $1.491 billion, which is a collaborative effort that integrates and synchronizes the flood risk management projects, programs, and authorities of USACE with those of other federal, state, regional, and local agencies. The program helps to reduce the risk of loss of life and property damage from riverine and coastal flooding and to increase the resilience of local communities through structural and nonstructural measures.

USACE projects follow legislation, which follows public demand, after devastating coastal storms (USACE 2003). USACE shore protection projects are constructed only where public access to the beach is assured, adequate parking is provided, and only after thorough studies have determined a positive benefit-to-cost ratio.

The majority of USACE's shore protection projects are located on the Atlantic Coast, with the rest distributed fairly evenly along the remainder of the coastal areas. Between 1950 and 2000, USACE constructed 71 specifically authorized shore protection projects at over $1.2 billion. Of this $1.2 billion, about 43% is attributed to initial beach restoration, another 43% to periodic nourishment, 12% to structures, and 2% to emergency costs.

As a steward of the U.S. Outer Continental Shelf energy and mineral resources, the Bureau of Ocean Energy Management (BOEM) oversees access to offshore areas where sand and other materials are mined for beach nourishment projects. As of July 2015, BOEM has executed 48 leases and agreements for coastal restoration projects and conveyed more than 109 million cubic yards of sediment to restore more than 269 miles of coastline in seven states (New Jersey, Maryland, Virginia, North Carolina, South Carolina, Florida, and Louisiana) (BOEM 2016). Additionally, BOEM is engaged in new negotiated noncompetitive agreements for offshore sand resources for projects along the Atlantic Coast and in the Gulf of Mexico (BOEM 2016).

As discussed in Manasseh et al. (2017), there are several factors that favor the use of marine energy for shoreline protection, with the greatest potential at the local community scale, including (1) isolated island or coastal communities that are largely dependent on imported fossil fuels, combined with a need for shoreline stabilization; and (2) low-lying coastal communities that are at the greatest risk of inundation from sea level rise (NOAA 2017b).

Description of Markets – Disaster Recovery

FEMA's Disaster Relief Fund plays the largest role in U.S. disaster recovery efforts, in cooperation with other federal and state agencies. As summarized by PolitiFact (2017) each year, Congress sends two distinct portions of funds to the Disaster Relief Fund. The first portion is the fund's base funding for FEMA operations and routine events ($615 million in FY17), and major declarations ($6.7 billion in FY17). When disaster recovery outstrips FEMA's available funds, as in the case of Hurricane Harvey, Congress can release more funds in the form of supplemental appropriations. Following Hurricane Harvey, Congress approved more than $15 billion for additional relief, of which $7.4 billion was appropriated for the Disaster Relief Fund.

Figure 8.6 summarizes the amount of federal funds spent on hurricane disaster relief in the United States in relation to the total economic damage (generated before economic data from Hurricane Harvey and Hurricane Irma were made available). Since Hurricane Katrina, federal recovery spending has covered 62% of estimated damages on average, peaking at 72% of Katrina's damages and 80% of Sandy's damages (Struyck 2017). Additionally, Congress made 14 supplemental appropriations from 2004 to 2013, totaling $89.6 billion, which included $43 billion in 2005 alone, the year that Hurricanes Katrina, Wilma, and Rita hit the United States (PolitiFact 2017).

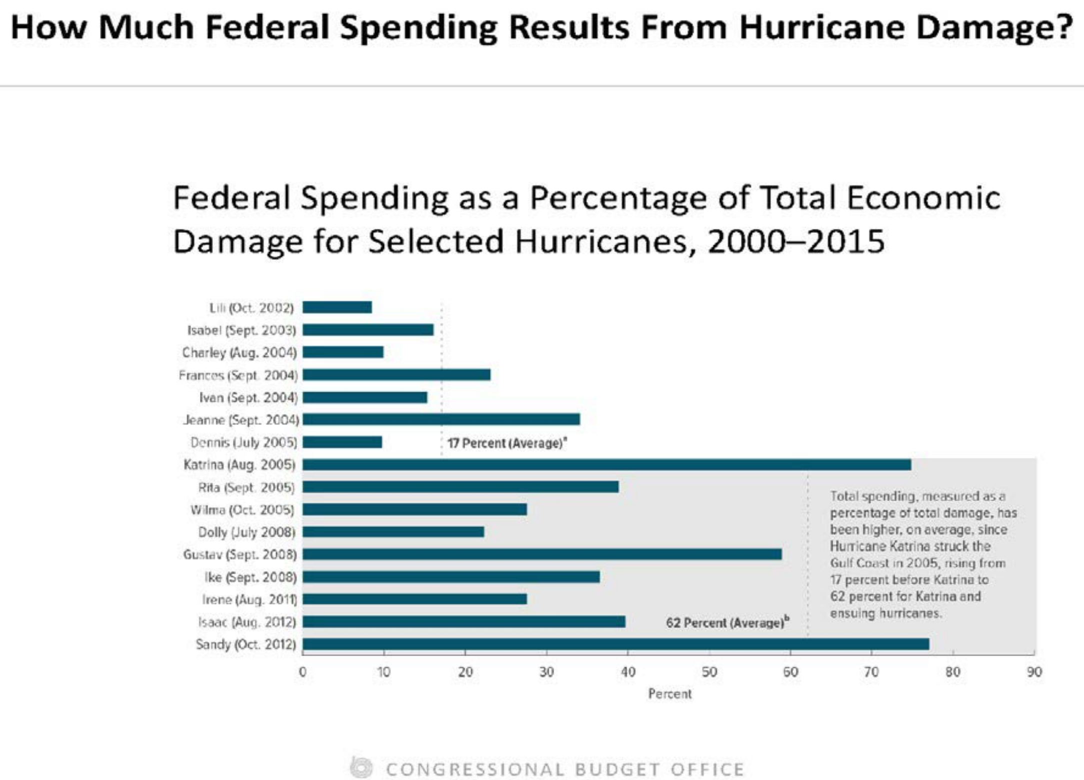

Figure 8.6. Federal government hurricane recovery dollars. *Image from Struyck (2017)*

Increases in extreme weather events and sea level rise (NOAA 2017b, 2018; Melillo et al. 2014) are affecting the resilience of local communities and the operational demands placed on emergency management systems. This can affect core emergency management mission areas and reduce physical and economic loss from disasters in three ways: (1) impacts on mitigation, preparedness, response, and recovery operations; (2) resiliency of critical infrastructure and various emergency assets; and (3) triggering indirect impacts—population displacement, migration, and public health risks —that increase mission risks and will have far-reaching effects on emergency response and disaster relief efforts. In 2010, 39% of the nation's population lived in counties directly on the coastline; this population is expected to increase by 8% from 2010 to 2020 (NOAA 2017a). These extreme events, in combination with budget constraints and increased coastal populations, may force emergency response and disaster relief efforts to push the limits of government funding, driving communities to rely more heavily on local relief, and adjust how emergency response is valued in the future. Communities need to understand all the potential risks and look ahead to become more resilient (McKay 2014). Facing future events, and perhaps anthropogenic disasters, such as terrorist attacks on the electrical grid or other essential services, local relief efforts may become the front line for recovery. Marine energy technologies could provide valuable supplemental power to businesses, residences, and government facilities to improve recovery time and grid resiliency.

Power Options

Diesel generators, solar energy, and battery energy storage systems are the main sources of competition to marine energy for disaster recovery. For example, Tesla has provided solar panels to deliver power to some areas of Puerto Rico that were still without power after Hurricane Maria in 2017 (BBC 2017). Tesla also installed a new solar-powered microgrid on the American Samoan island of Ta'u, shifting the entire island's energy generation from 100% diesel fuel to 100% solar (Lin 2017). The system was built with the capability of withstanding a Category 5 hurricane. Marine energy must prove reliability that is equal to or greater than other renewable technologies in order to be competitive.

Geographic Relevance

The application of marine energy devices for disaster recovery is potentially relevant for all ocean, river, and Great-Lake-adjacent emergency response activities in the United States and globally. Along the U.S. West Coast, large magnitude earthquakes from the Cascadia Subduction Zone that are likely to create large tsunamis that may threaten the coasts of British Columbia, Washington, Oregon, and Northern California (Pacific Northwest Seismic Network 2018). These areas along U.S. coastlines have strong marine energy resources that could contribute to power needs for emergency recovery, including power needed for air traffic control, communications, emergency lighting, emergency response operations and activities, refrigeration, residences and businesses, and sewage and sanitation systems.

Marine Energy Potential Value Proposition

Shoreline Protection

Marine energy devices could be integrated with coastal protection structures, such as breakwaters, groins, revetments, and storm surge barriers to provide energy to local areas with little additional infrastructure cost. Nearshore marine energy devices may also de-energize and reduce the destructive forces of storm-driven waves, thereby mitigating damage to coastal infrastructure. In response to threats of sea level rise and increasing frequency and intensity of coastal storms, many new coastal structures will be constructed or improved, providing an opportunity for marine energy integration. Power from integrated marine energy devices could be used to power local communities, marinas and ports (e.g., navigation lights, recharging electric boats), or to supplement power for beach nourishment activities.

As discussed in Mustapa et al. (2017), the benefits obtained from the integration of breakwater and wave energy devices over the stand-alone wave energy device are as follows:

- Offers cost-sharing benefits including construction, installation, and maintenance; in 2011, the installation cost for a single commercial prototype of wave and marine current energy conversion technology ranged between $11 and $15 million
- Provides energy extraction and coast protection services
- Limits potential environmental impacts thought to be associated with marine renewable energy installations by using an existing breakwater structure as an integrated platform
- Improves WEC device reliability, allowing energy extraction to occur during heavy wave conditions; this is different than stand-alone offshore wave energy devices that need to be retracted for safety reasons
- Improves ease of maintenance and device lifetime; access to the device for routine and emergency maintenance will be improved compared to turbines or WECs deployed at sea
- Provides additional strength for the wave energy device to operate and withstand high wind and wave conditions.

Disaster Recovery

Marine energy devices on standby could be configured to contribute to the power needs for emergency recovery and grid restart along coastlines prone to natural disasters, such as large storms (hurricanes), seismic activity, tsunamis, and flooding. A mix of renewable energy sources has the potential to replace diesel generation traditionally used to respond to emergency power needs and to restart isolated portions of coastal grids from a black start. Marine energy could also contribute to coastal microgrids or a more diversified macrogrid to increase resiliency. During emergency recovery and grid restart efforts, easily transported and deployed devices are advantageous. For example, Marine Power Systems is developing and testing a wave energy device called WaveSub that can be deployed by barge (Marine Power Systems 2018).

Depending on the constraints of the location and needs of a community or grid, marine energy devices could be hardened or prestaged for quick deployment after a disaster. Hardened marine devices would need to be designed to withstand severe precipitation, wind, extreme wave heights, and currents. Prestaged marine energy devices might need to be designed to be rapidly deployed to supply power to critical infrastructure.

Rising sea levels and extreme weather events have challenged communities to become more resilient and rely more heavily on locally available, alternative energy sources. Marine energy can help coastal communities respond immediately to emergencies and provide the necessary power to keep critical infrastructure running. In addition to critical electrical systems needing power, marine energy could be used to support other emergency needs, such as water treatment and supply (e.g., emergency desalination).

An obvious example of the potential for marine energy to support power needs in coastal communities can be found in Puerto Rico following Hurricanes Irma and Maria in 2017. In addition to the fragility of the electrical grid and the need for power on the island, the lack of black-start grid capability continues to plague the island's utility and people.

Coastal communities could be a direct customer of marine energy during emergency response periods. Federal agencies such as FEMA, USACE, and DHS could also use the energy harvested by marine energy devices to supplement emergency power during response efforts. Additionally, civilian and volunteer organizations, such as the American Red Cross, could use marine energy to aid their response efforts. Isolated coastal grids often depend on opportunistic availability of generation sources (Lopes et al. 2005), which may include small coal or natural gas plants, solar, wind, fuel cells, or biomass digesters. Local and regional utilities could see marine energy as a viable means to carry out a black start of isolated coastal grids, allowing for investment in ready standby wave devices in strategic locations nearshore. For example, Oregon passed legislation that increased the state's renewables portfolio standard to 50% renewables by 2040, which includes wave, tidal, and ocean thermal energy (Oregon Department of Energy 2018), with explicit reliance on marine energy and other renewables to assist in coastal recovery and grid black start (Oregon Department of Energy 2011).

Path Forward

Path Forward – Shoreline Protection

Integrating marine energy devices with shore protection structures will require early engagement with public and private agencies to identify opportunities to colocate devices with coastal infrastructure, during the design phase of new construction or the redesign of existing structures for improvements and upgrades.

Potential mission-driven partners include USACE, state environmental management agencies, municipal public works departments, and port authorities. For example, Port of Los Angeles officials have instituted a renewable energy program, including marine energy, as part of their Energy Management Action Plan.

Offshore Wind and Wave Generation Feasibility

The Harbor Department could initiate feasibility studies for offshore wind and wave farm projects in partnership with federal, state, and regional agencies and other stakeholders. The studies could assess the technical and economic feasibility of various technologies for the Southern California offshore environment, as well as the potential impacts of the projects on the environment and human uses, including commercial shipping and recreational boating. If feasible, offshore wind or wave opportunities are identified, the Harbor Department could begin the process of engineering, design, and demonstration of a test system (Port of Los Angeles 2014).

Shore protection alternatives in the form of beach nourishment, living shorelines, and/or hard structures are being instituted by communities to provide resiliency to coastlines and the electrical grid.

Studies predict an increase in the transportation of goods by ship and increases in shipboard passengers, which calls for an appropriate adaptation of the existing marina and port infrastructure to meet these needs (Siemens

2017). There is also movement toward electricity as a source of energy in port operations (Siemens 2017). Port operators are aiming to reduce carbon dioxide emissions (Siemens 2017). Regulations in Europe stipulate that the European Union's carbon dioxide emissions from maritime transport must be reduced by at least 40% by 2050, or even 50% if possible, as compared to 2005 levels. This could provide an opportunity to supplement electrical power with energy generated from marine energy devices integrated into coastal protection structures in the vicinity of a port or harbor.

Although many turbine and WEC designs may be readily adapted for placement in breakwaters and other coastal protection structures, there is a need to refine and test devices to ensure their robust operation and survivability, as well as to optimize energy production to meet coastal community and port/marina needs.

Challenges including establishing the perfect compromise among storm resistance, technical reliability, environmental friendliness, and cost effectiveness need to be addressed (de Almeida 2017). de Almeida (2017) suggests that new WEC concepts should rely on some already existing scaled-up technologies to reduce future costs and time to market, as well as to increase reliability.

Several novel concepts are currently under development and being tested. For example, the Renewable Electric Energy From Sea concept developed by de Almeida (2017) consists of a nearshore fixed submerged caisson placed on the seafloor at low depth. The design and porosity of the structure allows water to flow inside the structure, thereby driving a low head hydropower turbine. The structure can also contribute to shore protection by dissipating waves. A series of scaled model experimental tests were conducted in a wave flume, and researchers concluded that the model captured about one- to two-fifths of the power that it would capture if it were installed in a small-scale river dam. The model demonstrated evidence that the Renewable Electric Energy From Sea structure was successful at breaking/dissipating waves. Another novel concept is being developed by Zyba, a British wave energy startup, which integrates a new curved wave energy device (CCell) with artificial coral reefs to provide both renewable energy and coastal protection for islands (Lempriere 2017).

In 2015, SINN Power installed a WEC module at the Port of Heraklion in Greece to measure generated electricity and evaluate the long-term functionality of components with the aim of using wave energy to power the port's facilities (Balkan Green Energy News 2016). SINN Power received a $1.2 million grant in 2017 from the German Federal Ministry for Economic Affairs and Energy to install other WECs on a breakwater in the port (Harris 2017). Results from tests conducted from the grant will be used to inform an 18-module array that may soon be located near the port.

Power generated from marine energy devices integrated with coastal protection structures could also supplement grid resiliency efforts, in addition to being used to support water desalination (Manasseh et al. 2017), coastal/nearshore aquaculture operations, or emergency response efforts.

Path Forward - Disaster Recovery

Emergency managers and officials at the federal, state, and local levels should be made aware of the potential for marine energy to contribute to the mix of power sources they might call upon for emergency response. This awareness can be accomplished through education and outreach as well as demonstration projects at relevant locations susceptible to frequent outages or disasters. Tests are needed to ensure that the power from marine energy devices can be conditioned and made available on a reliable basis, in conjunction with storage solutions, to pave the way for adding marine energy to the emergency management toolkit. As a first step, areas with known sufficient marine energy resources for generation should be mapped to local disaster needs and strategies, along with a potentially high-impact demonstration project to support a disaster management scenario.

Following Oregon's lead, coastal states could examine the potential for explicitly adding marine energy to the list of renewables and other energy sources used for emergency response and grid restart. As an example, Verdant Power completed an extensive analysis of the weather and water dynamics of Superstorm Sandy in Long Island Sound and at its East River RITE site where a tidal turbine had previously been deployed and tested. Findings indicate a benign impact of an extreme storm on a commercial array of tidal turbines at the test location (Corren et al. 2014). Additionally, coordination will be needed among local communities, FEMA, and state emergency managers to ensure that marine energy is available as a disaster recovery energy option.

Planning and testing the placement of standby-ready marine energy devices in strategic locations would be needed to ensure that deployment, operation, delivery to the grid, retrieval, and refurbishment of the devices is feasible. Significant development and testing would need to be conducted to ensure that the power or freshwater generated by marine energy devices will be efficiently distributed to the grid or other relevant consumers in the event supplemental power is needed.

If marine energy devices were deployed along coastlines, when the power is not being used for emergency response and disaster relief efforts, it can be distributed to the local grid, used for coastal/nearshore aquaculture operations, desalination operations, or stored for future emergency response uses.

A coastal disaster resilience field experiment is being planned at Camp Rilea in the spring of 2019. This experiment will use marine energy to provide electricity and desalinized water to a field hospital (Oregon National Guard 2013).

Potential Partners

Various coastal management and engineering organizations could be relevant partners. This includes federal agencies such as NOAA, BOEM, USACE, and FEMA; state and local coastal and port/harbor planning and management organizations; international organizations with relevant pilot projects; and offshore supply chain members, such as engineering, design, and build firms and dredging companies. Other potential partners include civilian and volunteer organizations, such as the American Red Cross.

Regional and state-level utilities might invest in marine energy to ensure that small isolated coastal grids have black-start ability. Microgrids are inherently suitable for maintaining power supply during or after a disaster (IEC 2014) and integrating marine energy as a power source would improve grid resiliency. Marine energy devices could be used in bigeneration microgrids alongside diesel.

References

Balkan Green Energy News. 2016. SINN Power testing wave energy conversion in Heraklion. https://balkangreenenergynews.com/sinn-power-testing-wave-energy-conversion-in-heraklion/.

BBC. 2017. "Tesla solar power arrives in Puerto Rico." Accessed April 2, 2018. http://www.bbc.com/news/technology-41747065.

Bureau of Ocean Energy Management. 2016. *Stewardship of U.S. Outer Continental Shelf Energy and Mineral Resources: Strategic Framework*. https://www.boem.gov/Strategic-Framework/.Colthorpe, Andy. 2017. "California battery's black start capability hailed as 'major accomplishment in the energy industry.'" *Energy Storage News*. https://www.energy-storage.news/news/california-batterys-black-start-capability-hailed-as-major-accomplishment-i.

Corren, D., J. Colby, and M.A. Adonizio. 2014. Superstorm Sandy and the Verdant Power RITE Project. Proceedings of the 2nd Marine Energy Technology Symposium. April 15-18, 2014, Seattle, Washington.

Danjczek, Peter. 2014. "Mass-Power Outage in Disasters: Addressing Inefficiencies in FEMA's Generator Mission." Johns Hopkins University.

de Almeida, JPPG Lopes. 2017. REEFS: An artificial reef for wave energy harnessing and shore protection - A new concept towards multipurpose sustainable solutions. *Renewable Energy*, Vol. 114, 817-829. https://doi.org/10.1016/j.renene.2017.07.076.Dean, Robert G., and Dalyrmple, Robert A. 2002. "Coastal Processes with Engineering Applications." *Cambridge University Press*.

Federal Energy Regulatory Commission. 2016. Report on the FERC-NERC-Regional Entity Joint Review of Restoration and Recovery Plans. https://www.ferc.gov/legal/staff-reports/2016/01-29-16-FERC-NERC-Report.pdf.

Feltes, James W., and Carlos Grande-Moran. 2008. Black Start Studies for System Restoration. IEEE 2008. Pp. 8.

Great Lakes Dredge and Dock. 2018. Shore Protection & Beach Restoration. Accessed February 23, 2018. https://www.gldd.com/wp-content/uploads/2016/01/GLDD_Shore-Protection-and-Beach-Restoration_Letter.pdf.

Harris, Michael. 2017. SINN Power gets grant to continue wave energy device research. HydroWorld.com. http://www.hydroworld.com/articles/2017/08/sinn-power-gets-grant-to-continue-wave-energy-device-research.html.

HydroWorld.com. 2015. "World's largest 5-turbine tidal array installed in the Oosterschelde barrier, The Netherlands." September 30, 2015. Accessed on November 9, 2018. https://www.hydroworld.com/articles/2015/09/world-s-largest-5-turbine-tidal-array-installed-in-the-oosterschelde-barrier-the-netherlands.html.

International Electrotechnical Commission (IEC). 2014. Microgrids for disaster preparedness and recovery with electricity continuity plans and systems. http://www.iec.ch/whitepaper//pdf/iecWP-microgrids-LR-en.pdf.

Lempriere, Molly. 2017. "CCell: the energy to save coral." *Power Technology*. https://www.power-technology.com/features/ccell-energy-save-coral/.Lin, Daniel. 2017. "How a Pacific Island Changed from Diesel to 100% Solar Power." *National Geographic*. https://news.nationalgeographic.com/2017/02/tau-american-samoa-solar-power-microgrid-tesla-solarcity/.

Lopes, J. A. Peças, C. L. Moreira, and F. O. Resende. 2005. Microgrids Black Start and Islanded Operation. N Proceedings of the 15th PSCC, Liege, 22-26. Pp. 7.

M Power. 2018. Tidal Power Plant in Dutch Delta Works. Accessed February 28, 2018. https://www.mpower-energy.com/projects/eastern-scheldt/.

Maestrale. 2017. Newsletter n.2: April/2017. Accessed on November 9, 2018. https://maestrale.interreg-med.eu/fileadmin/user_upload/Sites/Blue_Growth/Projects/MAESTRALE/Library/Deliverables1streport/MAE_D.2.2.1_Newsletter_2_EN_2017-04.pdf

Marine Power Systems. 2018. "WaveSub: The Future of Energy." Accessed August 10. http://marinepowersystems.co.uk/.

Maritime Journal. 2011. First Commercial Wave Power Plan Opens. July 14, 2011. Accessed November 9, 2018. https://www.maritimejournal.com/news101/marine-renewable-energy/first-commercial-wave-power-plant-opens

McKay, J. 2014. "5 Trends for Emergency Management and Public Safety for 2014 and Beyond." *Emergency Management*. http://www.govtech.com/em/disaster/5-Trends-Emergency-Management-2014.html.

Millennium Ecosystem Assessment. 2005. *Ecosystems and Human Well-Being*. Island Press

Melillo, Jerry M., Terese (T.C.) Richmond, and Gary W. Yohe, Eds., 2014: Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program, 841 pp. doi:10.7930/J0Z31WJ2

Minkel, J. R. 2008. "The 2003 Northeast Blackout-Five Years Later." *Scientific American*. https://www.scientificamerican.com/article/2003-blackout-five-years-later/.

Mustapa, M.A., O.B. Yaakob, Y.M. Ahmed, C. Rheem, K.K. Koh, and F.A. Adnan. 2017. Wave energy device and breakwater integration: A review. *Renewable and Sustainable Energy Reviews* 77, 43-58. https://doi.org/10.1016/j.rser.2017.03.110NOAA. 2017a. "What percentage of the American population lives near the coast?" Accessed April 2, 2018. https://oceanservice.noaa.gov/facts/population.html.

NOAA. 2017b. Climate Change: Global Sea Level. https://www.climate.gov/news-features/understanding-climate/climate-change-global-sea-level.

NOAA. 2018. Extreme Events. https://www.ncdc.noaa.gov/climate-information/extreme-events

Oregon Department of Energy. 2011. Distributed Energy Resilience Study. Prepared by R.W. Beck for Oregon Department of Energy. Pp.148.

Oregon Department of Energy. 2018. "Renewable Portfolio Standard." Accessed on March 7, 2018. http://www.oregon.gov/energy/energy-oregon/Pages/Renewable-Portfolio-Standard.aspx.

Oregon National Guard. 2013. Initiate Conceptual Design for Camp Rilea Ocean Renewable Energy Program. Prepared for Oregon National Guard under OWET agreement OIC1113.MDS2A2.10.

Pacific Northwest Seismic Network. 2018. "Tsunami Overview." Accessed October 8, 2018. https://pnsn.org/outreach/earthquakehazards/tsunami.

PolitiFact. 2017. "How the U.S. Funds Disaster Recovery." Accessed April 2, 2018. http://www.politifact.com/truth-o-meter/article/2017/sep/14/how-us-funds-disaster-recovery/.

Port of Los Angeles. 2014. Port of Los Angeles Energy Management Action Plan. https://www.portoflosangeles.org/DOC/DRAFT%20POLA%20E-MAP_July%202014.pdf.

Siemens. 2017. Totally Integrated Power-Innovative power distribution for ports & harbors-Concept for profitable and safe electric power distribution. http://w3.siemens.com/powerdistribution/global/EN/consultant-support/download-center/tabcardpages/Documents/Planning-Manuals/Innovative-Power-Distribution-for-Ports-and-Harbors.pdf.

Small, C and Nicholls, R. 2003. "A global analysis of human settlement in coastal zones." *Journal of Coastal Research.* 19 584-599

Struyck, Ryan. 2017. "What past federal hurricane aid tells us about money for Harvey recovery." CNN. https://www.cnn.com/2017/08/31/politics/hurricane-harvey-recovery-money/index.html.

Texas A&M. Undated. "Coastal Resilience." Accessed on January 14, 2019. https://coastalresilience.tamu.edu/.

U.S. Army Corps of Engineers (USACE). 2003. The Corps of Engineers and Shore Protection. National Shoreline Management Study. IWR Report 03-NSMS-1.

USACE. 2018a. Beach Nourishment: Restoring our coast and reducing flood damage risk. Accessed February 23, 2018. http://www.nad.usace.army.mil/Portals/40/docs/Sandy%20Related%20Docs/BEACH%20NOURISHMENT.pdf.

USACE. 2018b. "President's Fiscal 2019 Budget for U.S. Army Corps of Engineers Civil Works Program released." Accessed April 3, 2018. http://www.usace.army.mil/Media/News-Releases/News-Release-Article-View/Article/1438488/presidents-fiscal-2019-budget-for-us-army-corps-of-engineers-civil-works-progra/.

USACE. 2018c. Risk Management Strategies. Accessed on March 13, 2018. http://www.nad.usace.army.mil/CompStudy/Risk-Management-Strategies/.

USACE. 2018d. FACT SHEET - Sea Bright to Manasquan, NJ Beach. U.S. Army Corps of Engineers (USACE). 1984. Shore Protection Manual. Vicksburg, Mississippi, USA.

U.S. Department of Energy. 2015. *United States Electricity Industry Primer*. DOE/OE-0017. https://www.energy.gov/sites/prod/files/2015/12/f28/united-states-electricity-industry-primer.pdf.

U.S. Department of Homeland Security. 2016. *National Response Framework*. Third Edition. Pp. 58. Washington D.C.

U.S. Global Change Research Program. 2014. "National Climate Assessment." https://nca2014.globalchange.gov/.