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# Marine Energy Microgrid Feasibility for a Resilient North Olympic Peninsula

September 2026

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U.S. DEPARTMENT of ENERGY

Prepared for the U.S. Department of Energy
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# Executive Summary

The North Olympic Peninsula of Washington State is subject to frequent and often lengthy power outages due to its remote location and the topology of the distribution and transmission systems feeding its power. However, it also has ample marine energy (ME) resource potential from both tidal and wave energy. This report describes a case study feasibility analysis for the installation of marine-energy-fed microgrids located in two communities on the North Olympic Peninsula—Sequim and Port Townsend.

The locations of the case studies were determined through a rigorous stakeholder engagement process, which incorporated both the interests of the communities and the proximity of ME resources. The specific sites for the microgrid within the communities were also informed by community feedback, as well as the topology of the distribution system and the location of the proposed tidal energy generators. Although wave energy was initially considered, it was not included in the analysis, as tidal resources are much stronger for the chosen case study locations.

For each of the case study locations, a microgrid feasibility analysis was performed and produced several different microgrid sizes for each location, including a combination of photovoltaic (PV) and tidal resources as well as a battery and back-up diesel generation. The different sizes offer different potential benefits and would need to be weighed based on the priorities of the community, such as a desire to be independent from fossil-fuel resources, which need to be stored, or overall project installation costs.

A distribution system analysis was also performed for the Sequim case study location, providing a hosting capacity analysis, an estimate of interconnection costs, and a grid-connected simulation. The hosting capacity analysis demonstrates the effect of additional renewable energy generation on the existing distribution system grid and outputs the capacity limits at which the additional generation could cause violations on the grid if mitigation strategies are not employed.

For the Sequim location, the chosen microgrid location, Guy Cole Center, is located almost two miles from the proposed location of the tidal generator, at the mouth of Sequim Bay. This distance would result in significant interconnection costs if the community wanted to install a new distribution line to directly connect the tidal generator and the microgrid. As such, it is recommended that a different microgrid location is chosen if the City of Sequim wants to pursue this project or that they install a microgrid at Guy Cole Center with only PV resources, which can be located on site and would be sufficient to supply power to the building.

The Port Townsend microgrid location at the wastewater treatment plant is located closer to the proposed tidal generator location. However, a distribution system analysis was not able to be performed for this site and would be necessary to make further recommendations with respect to interconnection costs. While this site has much stronger tidal resources than those for the Sequim site, there is little space available for the installation of solar panels. Thus, it is recommended to only include tidal resources in a microgrid at this location unless another nearby site is identified for solar panel installation.

Both case studies provide a starting point for the communities to explore installing a microgrid to improve community resilience. Next steps would involve a more detailed design process, the acquisition of funding, and environmental reviews. This analysis could also be replicated for

other communities interested in installing microgrids or extended for the same communities by exploring different buildings or even several buildings connected by networked microgrids.

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# Acronyms and Abbreviations

| | |
|---|---|
| BESS | battery energy storage system |
| BPA | Bonneville Power Administration |
| CEDS | Comprehensive Economic Development Strategy |
| D-STATCOM | distribution static synchronous compensator |
| DER | distributed energy resource |
| DG | distributed generation |
| DHI | diffuse horizontal irradiance |
| DNI | direct normal irradiance |
| EPRI | Electric Power Research Institute |
| GHI | global horizontal irradiance |
| LTC | load tap changer |
| MCOR | Microgrid Component Optimization for Resilience tool |
| ME | marine energy |
| NODC | North Olympic Peninsula Resource Conservation & Development Council |
| NOP | North Olympic Peninsula |
| NLR | National Laboratory of the Rockies |
| OLTC | on-load tap changer |
| PCC | point of common coupling |
| PNNL | Pacific Northwest National Laboratory |
| PUD | Public Utility District |
| PV | photovoltaic |
| QSTS | quasistatic time series |
| RM2 | Reference Model 2 |
| SVC | static var compensator |
| WWTP | wastewater treatment plant |

# Contents

Executive Summary ..... ii
Acknowledgments ..... iv
Acronyms and Abbreviations ..... v
1.0 Introduction ..... 1
2.0 Background ..... 2
2.1 North Olympic Peninsula Energy Landscape ..... 2
2.2 Collaboration with North Olympic Development Council ..... 2
2.3 Marine Energy on the NOP ..... 3
2.4 ME-Based Microgrids ..... 3
3.0 Methodology ..... 5
3.1 Community Engagement ..... 5
3.1.1 Identifying Case Study Locations ..... 5
3.2 Microgrid Resource Resilience Evaluation ..... 6
3.2.1 MCOR Tool ..... 6
3.2.2 New ME Resource Models ..... 7
3.2.3 Case Study Parameters ..... 8
3.3 Distribution System Analysis ..... 10
3.3.1 Hosting Capacity ..... 11
4.0 Results ..... 14
4.1 Guy Cole Center ..... 14
4.1.1 Microgrid Modeling ..... 14
4.1.2 Distribution System Modeling ..... 19
4.2 Port Townsend WWTP ..... 24
4.2.1 Microgrid Modeling ..... 24
5.0 Discussion ..... 31
5.1 Analysis Takeaways ..... 31
5.1.1 Limitations ..... 31
5.1.2 Recommendations for Community Microgrids ..... 32
5.2 Applications to Future Work ..... 33
6.0 References ..... 35
Appendix A ..... A.1

# Figures

Figure 1. Transmission line infrastructure on the North Olympic Peninsula. Source: https://hifld-geoplatform.hub.arcgis.com/ ..... 2

Figure 2. Tidal resource characterization (as tidal velocity in m/s) in the North Olympic Peninsula (Yang et al. 2021). ....6
Figure 3. High-resolution tidal resource characterization (tidal velocity in m/s) at (a) Admiralty Inlet and (b) Sequim Bay (Yang et al. 2021). ....7
Figure 4. Map of the Port Townsend region with the chosen tidal turbine location (yellow dot) along with the tidal power density, main vessel transit lanes, and critical salmon habitat. Data from Marine Energy Atlas and Marine Cadastre. ....10
Figure 5. Workflow for the DER hosting capacity analysis using the pyHCA module. ....12
Figure 6. Electrical feeder map of the Sequim distribution system without a tidal generator. ....13
Figure 7. Electrical feeder map of the Sequim system showing the locations of the Guy Cole microgrid, distribution line, and tidal generator. ....13
Figure 8. Depiction of different sets of simulations that were run. As shown in the outer circle, different outage lengths were included; the middle circle describes how several different system sizes were produced by each outage length, and the innermost circle depicts the different simulations that were run for each system size and outage length—both 400 random outages and the specific November storm outage. ....14
Figure 9. Dispatch plots for the Sequim microgrid for a 1-week outage, showing sample microgrid operation for different outage conditions: the PV-only, large battery system under (a) favorable and (b) poor PV conditions and the PV + tidal, large battery system with (c) favorable and (d) poor PV conditions. For all figures, orange represents PV generation, blue represents tidal generation, green represents battery discharge, red represents generator use, and the gray line represents the building load. ....16
Figure 10. Average percentage of the load met by each resource across different systems for (a) 4-hour, (b) 8-hour, and (c) 1-week outages. The generator load is shown as red, PV generation contributions are shown as orange, tidal generation contributions are shown as blue, and battery discharging is shown as green. ....17
Figure 11. Percentage of the load met by each resource across different systems for the storm simulation 1-week outage. The generator load is shown as red, PV generation contributions are shown as orange, tidal generation contributions are shown as blue, and battery discharging is shown as green. ....18
Figure 12. Dispatch plots for the Sequim microgrid for a 1-week outage showing sample microgrid operation during the November 4, 2022, storm: (a) PV-only, large battery system and (b) PV + tidal, large battery system. For all figures, orange represents PV generation, blue represents tidal generation, green represents battery discharge, red represents generator use, and the gray line represents the building load. ....18
Figure 13. Electrical design of the microgrid at Guy Cole Center. ....19
Figure 14. Microgrid PCC voltage for different scenarios. ....22
Figure 15. Power exchange between the microgrid at Guy Cole Center and the distribution system under different scenarios. ....23

Figure 16. Power loss in the distribution line connecting the tidal generator with Guy Cole Center under different scenarios. ..... 23

Figure 17. Depiction of different sets of simulations that were run. The table on the left shows the grid of simulations that were run for the two sensitivity parameters—turbine depth and outage length. For each combination of turbine depth and outage length, 13 different microgrid system sizes were modeled. For each of those sizes, simulations were run for the 400 random outage scenarios and the specific November storm scenario. ..... 24

Figure 18. Dispatch plots for the Port Townsend microgrid for a 1-week outage, showing sample microgrid operation for different outage conditions: PV + 2-turbine, large battery system under (a) favorable and (b) poor tidal resource conditions; PV + 3-turbine, large battery system with (c) favorable and (d) poor tidal resource conditions. For all figures, orange represents PV generation (though barely noticeable), blue represents tidal generation, green represents battery discharge, red represents generator use, and the gray line represents the building load. ..... 26

Figure 19. Average percentage of the load met by each resource across different systems for (a) 8-hour and (b) 1-week outages. The generator load is shown as red, PV generation contributions are shown as orange, tidal generation contributions are shown as blue, and battery discharging is shown as green. ..... 27

Figure 20. Tidal energy generation for a 1-turbine system located in Admiralty Inlet for an example 1-week period. Green shows the generation for a turbine sited at a depth of 19.5 m; orange, 16.5 m; and blue 13.5 m. ..... 28

Figure 21. Percentage of the load met by each resource across different systems for the storm simulation 1-week outage for the Port Townsend microgrid. The generator load is shown as red, PV generation contributions are shown as orange, tidal generation contributions are shown as blue, and battery discharging is shown as green. ..... 29

Figure 22. Dispatch plots for the Port Townsend microgrid for a 1-week outage, showing sample microgrid operation during a November 4, 2022, storm: (a) PV + 2 tidal turbines, large battery system and (b) PV + 3 tidal turbines, large battery system. For all figures, orange represents PV generation, blue represents tidal generation, green represents battery discharge, red represents generator use, and the gray line represents the building load. ..... 30

Figure A.1. Fuel usage for different microgrid systems for Sequim for a 1-week outage. For each system, the box represents the first to third quartile of scenario runs with the central line as the median. The whiskers show the full range of data with outliers depicted as separate dots. ..... A.3

Figure A.2. Fuel usage for different microgrid systems for Port Townsend for a 1-week outage. For each system, the box represents the first to third quartile of scenario runs with the central line as the median. The whiskers show the full range of data with outliers depicted as separate dots. ..... A.7

# Tables

Table 1. Site-specific parameters for the microgrid analysis for Sequim. ....8
Table 2. Site-specific parameters for the microgrid analysis for Port Townsend....9
Table 3. Microgrid component sizes for the 400-outage simulation for Guy Cole Center for a 1-week outage....15
Table 4. Hosting capacity limits....20
Table 5. Range of reconductoring costs incurred for placing a new distribution line connecting the tidal generator with Guy Cole Center. ....20
Table 6. Transformer costs for interconnecting the tidal generator with Guy Cole Center....21
Table 7. PV and tidal capacities used for grid-connected analysis. ....21
Table 8. Microgrid component sizes for the 400 scenario simulation for the Port Townsend WWTP for a 1-week outage....25
Table A.1. Output metrics for the Guy Cole Center analysis for the 400-outage simulation of a 1-week outage.... A.2
Table A.2. Output metrics for the Guy Cole Center analysis for the storm simulation of a 1-week outage. .... A.3
Table A.3. Output metrics for the Port Townsend WWTP analysis for the 400-outage simulation of a 1-week outage.... A.5
Table A.4. Output metrics for the Port Townsend WWTP analysis for the storm simulation of a 1-week outage.... A.6

# 1.0 Introduction

Remote coastal communities often face unique challenges due to their radial connection to the transmission system, which makes them particularly vulnerable to weather-driven power outages. Unlike more centrally connected regions, these areas suffer from more frequent and prolonged disruptions in power supply. Marine energy (ME) technology presents a promising solution to these challenges by offering a consistent and reliable local source of energy generation. When integrated into a microgrid, ME technology could significantly enhance resilience, especially if it can outperform other distributed generation (DG) sources such as photovoltaics (PVs) that are less reliable during storm events or provide a complimentary energy source that is available at different times than other resources.

Despite its potential, there are significant barriers to the widespread adoption of ME technology. The industry, which includes utilities, ME developers, and community stakeholders, lacks comprehensive methods to study the benefits of ME projects. Those benefits are especially critical for remote communities with weak grids that have limited support from the bulk power system and often encounter local power congestion issues. These grid limitations pose challenges to hosting higher levels of distributed energy resources (DERs), including ME.

Bhatnagar et al. (2021) highlighted ME's considerable potential in the United States, estimating it could supply over 57% of the electricity generated in 2019. Newman et al. (2022) illustrated how wave energy could boost microgrid efficiency, potentially replacing biofuel generation. ME presents viable solutions for coastal communities by offering reliable energy and socioeconomic advantages (Kazimierczuk et al. 2023). Given the relatively low technological maturity of wave and tidal energy systems, there has been minimal focus on their grid connection in scientific research to date (Noble et al. 2021). Consequently, technical assessments often fail to adequately address the performance of ME and the resilience needs of the grid, limiting the industry's capability to quantify the benefits of ME projects and make informed decisions.

This work builds upon existing open-source, lab-developed software tools to develop an analytical framework that enables stakeholders to evaluate the technical, economic, and social impacts and opportunities of ME. Our team assessed the suitability of ME in helping fulfill the energy resilience needs of two remote coastal communities on the North Olympic Peninsula (NOP): Port Townsend and Sequim. These case studies used Pacific Northwest National Laboratory's (PNNL's) Microgrid Component Optimization for Resilience (MCOR) tool to perform a microgrid analysis for Guy Cole Center, an event center and resilience hub for the city of Sequim, and the Port Townsend Wastewater Treatment Plant (WWTP). These analyses were used to determine possible microgrid configurations incorporating ME that could be installed and to demonstrate how these systems could improve resilience for each site. A distribution system analysis was also performed for the Sequim microgrid using the open-source tool OpenDSS to evaluate how the proposed microgrid would interact with the distribution system while still connected to the grid.

Additionally, our team partnered with the North Olympic Peninsula Resource Conservation & Development Council (NODC) and local community stakeholders. This effort engaged local groups to identify and quantify a comprehensive set of metrics and value streams, ensuring that the tools and approaches discussed in this report meet community needs, especially those of tribal communities with nuanced renewable resource siting concerns.

# 2.0 Background

## 2.1 North Olympic Peninsula Energy Landscape

The NOP is a geographically isolated area of western Washington. This rural area struggles with frequent power outages and infrastructure damage. In the NOP, power generation primarily comes from hydroelectric facilities, and one of the significant producers is the Bonneville Power Administration (BPA). The BPA sells power from 31 hydroelectric dams in the Columbia River Basin, supplying electricity to various public utilities including those in the NOP (BPA 2013). Additionally, local Public Utility Districts (PUDs) like Clallam County PUD and Jefferson County PUD may also engage in or facilitate local renewable energy projects to meet regional demands. The power distribution system begins with two 230 kVA lines in Olympia, eventually ending with a single 69 kVA line in Neah Bay and south of Forks (see Figure 1). Customers in the area commonly experience power outages, mainly from tree limbs falling on the distribution lines.

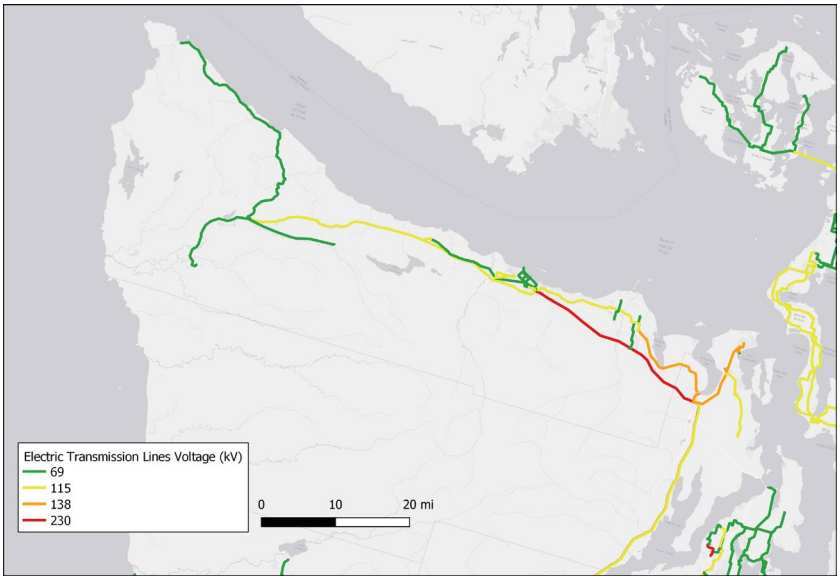



Figure 1. Transmission line infrastructure on the North Olympic Peninsula. Source: https://hifld-geoplatform.hub.arcgis.com/.

## 2.2 Collaboration with North Olympic Development Council

To ensure that this project considered community needs, PNNL partnered with NODC to engage the community. They are ideal partners for this effort given their experience collaborating and engaging with a variety of stakeholders on the peninsula.

As the federally-designated Economic Development District for Jefferson and Clallam Counties, NODC is a collaborative, innovative effort among member governments, community organizations, Tribes and businesses to advance regional economic development in the region through:

- Cross-jurisdictional regional planning for economic development and community and environmental resilience
- Support for economic development in key sectors such as farm and food, forest products, marine trades, and the innovation economy
- Development of economic building blocks such as broadband, workforce development, and energy resilience
- Convening discussions and building broad partnerships and collaborative projects to address key needs and opportunities (NODC, 2026).

By building on and leveraging work done through its ongoing energy planning process, NODC adapted a multicriteria assessment approach previously used for critical emergency planning. This approach was used to get stakeholder input on the potential benefits and challenges for both ME and microgrids for their communities and will be discussed in more detail in Section 3.1.

## 2.3 Marine Energy on the NOP

ME is a renewable energy resource where energy is captured from the hydrokinetic energy in the ocean. This is typically divided into wave energy and tidal energy, though energy can also be created from gradients in temperature or salinity. Wave energy devices capture the movement of the waves through many motions, such as up and down or side to side. Tidal energy typically refers to capturing energy in places where water is flowing quickly because of constrictions. Tidal energy captures the energy of moving water as the tide rises and pushes water from one place to another. These devices often look like wind turbines underwater but can vary in the number of blades, the material for the blades, or the sizes of the blades; unlike wind energy, tidal energy technology has not converged to a single technology archetype.

Both wave and tidal energy require certain ocean conditions to be considered viable options, so the first step in evaluating ME options is to evaluate the tidal current speeds and wave energy generation potential to determine what type of ME may be feasible and where. Viable areas for utility-scale tidal energy typically have average current speeds greater than 1 m/s, although community-scale projects require smaller average current speeds. Suitable areas for utility-scale wave power have an average omnidirectional wave power greater than 30 kW/m. These are not firm requirements, but general guidelines for suitable areas.

Wave energy is not feasible in the Strait of Juan de Fuca off the northern coast of the NOP; wave energy development typically requires open ocean conditions, such as the west coast of the NOP. Tidal energy requires constrictions like straits or inlets, such as Admiralty Inlet.

## 2.4 ME-Based Microgrids

The U.S. Department of Energy defines a microgrid as “a group of interconnected loads and distributed energy resources that acts as a single controllable entity with respect to the grid” (Ton and Smith 2012). In simple terms, a microgrid is a small power system that can operate connected to the larger grid or by itself in stand-alone mode. A microgrid consists of the combination of power generation and storage resources (renewables, batteries, fuel-fired generators, etc.), distribution infrastructure (wires, switchgear, protective devices, transformers,

etc.), and loads being supplied with electricity. Loads powered by a microgrid can range from a single load or building to a small town or large campus.

Microgrids can enhance power grid resiliency, particularly during extreme events and emergencies (Egbue et al. 2016; Liu et al. 2017). They can operate in both grid-connected and islanded modes, providing backup power and improving operational flexibility (Mishra et al. 2020; Stasinos et al. 2022). Several resilience indices have been proposed to measure the impact of extreme events on power grids with integrated microgrids (Liu et al. 2017). Microgrids can enhance resilience through both long-term measures, such as infrastructure hardening and resilience planning, and short-term operational measures applied before, during, and after events (Stasinos et al. 2022). The integration of microgrids in power systems can significantly improve the grid's ability to anticipate, withstand, adapt, and recover from high-impact, low-probability events, ultimately bolstering the overall resilience of critical infrastructure systems (Egbue et al. 2016; Stasinos et al. 2022). However, studies on the resilience of ME-based microgrids have been limited because of the immature state of ME technologies.

Microgrid technology emerged to address reliability concerns and ensure that critical power infrastructure remained operational even during power grid failures. Consequently, the majority of early microgrids were primarily fueled by fossil fuels. Over time, a broader range of generation resources has increasingly been incorporated. This diversification can reduce reliance on any single energy source and provide greater flexibility in managing fuel availability, operating requirements, and extended outages. In some remote areas, access to sufficient fuel during an extended power outage can be limited, and maintaining a diverse mix of generation resources, including locally abundant resources, can extend the time a microgrid can continue to power loads while disconnected from the grid. Typically, microgrids are configured to operate either in parallel with a utility grid or autonomously if there is a grid outage or if there is no utility feed available.

Microgrids require consistent generation resources to provide reliable and resilient electricity on the NOP. Tidal energy is predictable and consistent—there are usually two high tides and two low tides a day, and they can be predicted far in advance with a high level of accuracy. This research aimed to evaluate how ME—specifically, tidal energy—might fit into microgrids on the NOP. This involved working with local stakeholders to identify potential microgrid locations, getting community input on locations and designs, and modeling how tidal energy devices paired with microgrids can improve resilience for two case study locations.

# 3.0 Methodology

## 3.1 Community Engagement

As the project's community engagement lead, NODC consulted with stakeholders on the Olympic Peninsula to identify key needs, concerns, and priorities related to energy development and ME project siting. NODC formed two steering committees: one solely for tribes and a larger steering committee that also includes tribes. The tribal steering committee provided a space for tribes to discuss concerns nation to nation and to provide feedback on the community engagement process and the larger project.

Throughout the project, NODC facilitated regular steering committee meetings to provide updates on the project and solicit feedback. NODC also held two place-based roundtable discussions in Sequim and Port Townsend, as well as four virtual, interest-group-based roundtables to collect input, guide framework development, and eventually share and get feedback on results.

After these initial roundtables, NODC led a regional convening on ME in Sequim, which included presentations on ME and microgrids from PNNL staff, an update of the results of the work done thus far to understand regional priorities and preferences around ME technology and an opportunity to provide input and feedback on the work to date. The convening was attended by elected officials, staff, and volunteers from local, state, and federal governments; Tribes; PUDs; and environmental, fishery, and recreation nonprofit organizations.

### 3.1.1 Identifying Case Study Locations

Two project locations were chosen by the steering committees for the microgrid analysis through an iterative process. These were chosen based on community interest, tidal resource potential, and site suitability. Initially, communities on the west coast of the NOP with wave resources were also considered, but the steering committee ultimately decided not to include wave power.

To inform this process, PNNL used tidal resource maps to demonstrate resource availability for potential project locations. Figure 2 shows the tidal resource for the NOP (Yang et al. 2021). Only locations with constrictions, such as channels through islands, or narrow straits have sufficient tidal velocity to host a productive tidal turbine. On the NOP, Admiralty Inlet, Sequim Bay, Neah Bay, and Port Angeles met that criterion. However, there was less interest from the communities located in Neah Bay and Port Angeles in exploring the tidal resource, so only locations near Admiralty Inlet and Sequim Bay were considered for the case study.

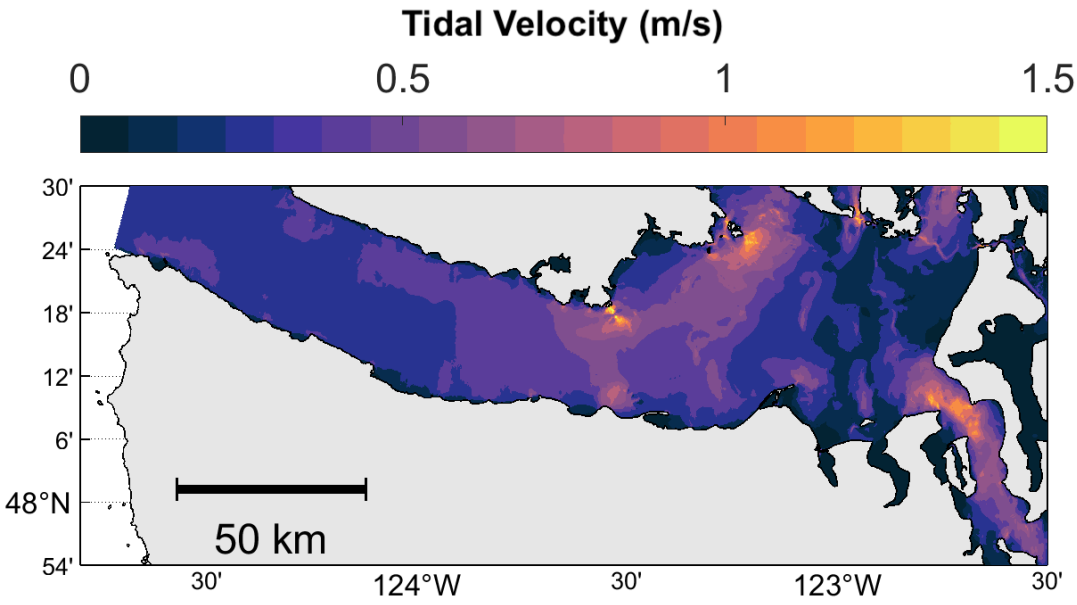



Figure 2. Tidal resource characterization (as tidal velocity in m/s) in the North Olympic Peninsula (Yang et al. 2021).

Based on the tidal resources and community interest, steering committee members suggested several sites in Sequim and Port Townsend, including fire stations and emergency resilience hubs. The PNNL team then assessed these locations for suitability, considering proximity to the tidal turbine (within 1–3 miles), the desire to be on the same distribution feeder as the tidal turbine, existing or planned distributed generation at other sites, and distribution infrastructure constraints to further narrow down the list for the steering committees. Ultimately, the steering committees chose Guy Cole Center, an event center and resilience hub for the city of Sequim, and the Port Townsend WWTP.

## 3.2 Microgrid Resource Resilience Evaluation

To help meet the resilience needs of the communities for the chosen case study locations, a microgrid analysis was performed for each site. These analyses were used to determine possible microgrid configurations that could be installed and demonstrate how these systems could improve resilience for each site.

Microgrids can include many different energy resource types for the generation of energy to meet site or building load. They can also include energy storage and backup fossil-fuel generation. To determine the optimal combination of possible resources for the two case study locations discussed in this report, a PNNL-developed tool called MCOR tool was used. Several different resources were considered, including tidal energy, PVs, battery energy storage, and backup diesel generation.

### 3.2.1 MCOR Tool

MCOR was developed at PNNL to help site owners and managers perform feasibility analyses for resilience-focused microgrids. It performs a suite of simulations to help size the components of a microgrid and models performance during a large range of outage conditions. It also provides economic calculations to demonstrate how the renewable energy components of the

microgrid could be used to generate revenue year-round when connected to the grid. Newman et al. (2020) provides a detailed description of the MCOR methodology.

### 3.2.2 New ME Resource Models

For this analysis, a new MCOR capability was developed to model tidal energy resources in addition to PV resources. For PV modeling, MCOR uses a statistical resource model to develop a set of potential outage scenarios and the associated resource conditions (e.g., solar global horizontal irradiance [GHI], direct normal irradiance [DNI], diffuse horizontal irradiance [DHI], and cloud cover) during those outages. This allows users to model microgrid performance during a large range of conditions outside of what is considered “typical” weather. However, as tidal resources are fairly predictable as compared with solar, it was determined that developing a statistical resource model was not necessary for tidal energy. Therefore, the new MCOR tidal resource capability leverages existing modeling work to develop power production profiles used in the tool.

For the analyses completed here, the data come from (Yang et al. 2021) and are used to develop 19-year tidal epochs (using the UTide software), from which individual periods are sampled to be used for simulating outage periods. These data are analogous to those contained in the Marine Energy Atlas but have a much higher spatial resolution, which is necessary to properly capture the tidal velocity potential in lower-velocity areas, such as Sequim Bay. Figure 2 shows the tidal resource for the Salish Sea overall, while Figure 3 shows higher resolution tidal resource maps for Admiralty Inlet and Sequim Bay.

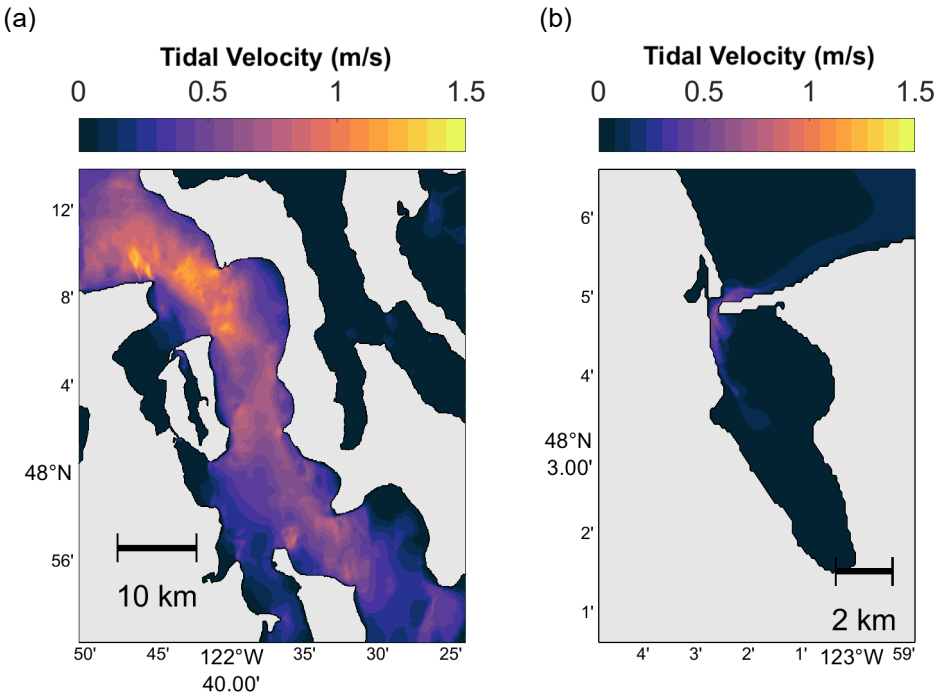



Figure 3. High-resolution tidal resource characterization (tidal velocity in m/s) at (a) Admiralty Inlet and (b) Sequim Bay (Yang et al. 2021).

To calculate tidal energy production during modeled outages, MCOR provides a list of tidal turbine device models for the user to choose from. These should be selected from based on the specifics of the site, such as the water column depth, the average tidal velocity, and other siting

constraints. The chosen model will determine the turbine rated power, number of rotors, rotor diameter, and cut-in and cut-out velocities. These parameters along with the depth of the turbine within the water column and the number of installed turbines will determine the hourly tidal energy production of the installed system.

### 3.2.3 Case Study Parameters

#### 3.2.3.1 Sequim

The specifications for the case study analyses were determined from a combination of feedback from the communities and site constraints. A summary of site-specific parameters is shown in Table 1. As discussed in Section 3.1.1, the location of the microgrid was chosen by the community representatives and constrained by the distribution system topology and proximity to suitable tidal turbine siting locations. For Sequim, Guy Cole Center was chosen as a suitable resilience hub and load and utility rate data were provided by Clallam PUD.

Table 1. Site-specific parameters for the microgrid analysis for Sequim.

| Parameter | Value |
|---|---|
| Location | Guy Cole Center |
| Outage lengths | 4 h, 8 h, 168 h |
| PV max capacity | 94 kW |
| PV tilt, azimuth | 5°, 180° |
| Tidal turbine location | 48.078, 123.043 |
| Tidal turbine depth | 2.7 m |
| Tidal turbine model | RM2* |
| Max # turbines | 1 |

*Reference Model 2

Outage lengths of 4 hours, 8 hours, and 1 week were chosen for the analysis based on feedback from community meetings about the types of outages that were typical in their community, as well as the desire to include a longer outage that would represent a more extreme weather-related event. In addition to modeling these outage lengths for several hundred unique and randomly generated scenarios, a specific outage was modeled starting on November 4, 2022, at 10 p.m. to reflect a weeks-long outage that affected much of the NOP following a severe windstorm.

The site for tidal turbine installation was chosen based on the location of the maximal tidal velocity at the inlet of Sequim bay. The selected model, Reference Model 2 (RM2) (Neary et al. 2014) was chosen as the only example tidal turbine small enough to fit in that location. With the same siting constraints, a maximum number of turbines of one was chosen, and a depth at the center of the channel of 2.7 m was used.

To assess the space available at Guy Cole Center for solar panels, a rooftop and carport analysis was performed using satellite imagery. Locations for rooftop-mounted PV panels were identified on the south-facing aspect of the Center's roof, and carport-mounted PV panels over

parking spots could be mounted with little potential shading. Based on this analysis, a total of 94 kW of solar panels could be installed between the Guy Cole Center roof and the adjacent parking lot with carport mounting. Tilt and azimuth angles of 5° and 180°, respectively, were chosen to represent the carport siting.

#### 3.2.3.2 Port Townsend

As for the Sequim case study, the parameters for the Port Townsend case study (summarized in Table 2) are derived from both the community feedback and site-specific constraints. Several potential microgrid sites were identified by the community, but the WWTP was chosen based on its large, consistent power needs and proximity to ideal tidal turbine locations. Load and utility data for the building were provided by Jefferson PUD.

Table 2. Site-specific parameters for the microgrid analysis for Port Townsend.

| Parameter | Value |
|---|---|
| Location | Wastewater treatment plant |
| Outage lengths | 4 h, 8 h, 168 h |
| PV max capacity | 13.6 kW |
| PV tilt, azimuth | 30°, 180° |
| Tidal turbine location | 48.157, −122.766 |
| Tidal turbine depth | 13.5 m, 16.5 m, 19.5 m |
| Tidal turbine model | Tidal Energy Ltd Deltastream |
| Max # turbines | 3 |

The same outage lengths and prototypical extreme event were used for Port Townsend as were used for Sequim.

There was more flexibility in turbine siting for Port Townsend than for Sequim as the nearby channel contains many locations with strong tidal resources and the average channel depth is much deeper (see Figure 3). The chosen location was selected based on (1) its proximity to the wastewater treatment site to limit installation costs, (2) avoidance of nearby critical salmon habitat, and (3) avoidance of main vessel transit lanes. Limiting the environmental impact was one of the key priorities identified from the Port Townsend community roundtable. Figure 4 shows the location of the chosen site along with the peak tidal resources and key areas to avoid.

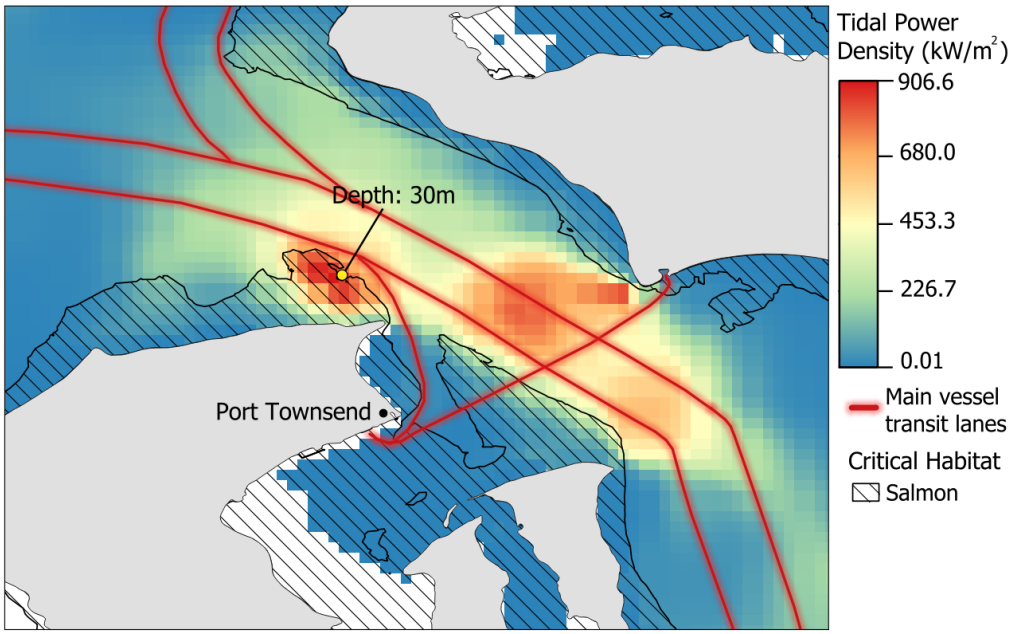



Figure 4. Map of the Port Townsend region with the chosen tidal turbine location (yellow dot) along with the tidal power density, main vessel transit lanes, and critical salmon habitat. Data from Marine Energy Atlas[1] and Marine Cadastre[2].

The tidal turbine model was selected to avoid surface expression, which was one of the key community requirements, and is an ideal size for the location and local tidal velocity. Three different depths were studied to evaluate the differences in power production while still allowing the turbine to remain fully below the water surface.

The WWTP building had very limited solar panel installation opportunities and no carport space available, for a total maximum solar panel capacity of 13.6 kW.

## 3.3 Distribution System Analysis

To understand how the proposed microgrid would operate while connected to the distribution system during normal operations and the potential costs for interconnection of the different renewable resources, a distribution system analysis was performed. This entails creating a mathematical model of the system that allows us to calculate power flow across the entire system. The determination of the power flow in various branches of the network is essential to understanding the interaction between the proposed microgrid and the rest of the distribution system. The interaction is studied in terms of the power exchange between the microgrid and the distribution system and the voltage at the microgrid. This was only done for the Sequim microgrid and not for Port Townsend, as it was not possible to obtain distribution system data for Port Townsend in time for the analysis.

This analysis leverages the Electric Power Research Institute (EPRI) OpenDSS simulation software to model the operation of the distribution system. The analysis is carried out by creating a 12.47 kV unbalanced three-phase model of the distribution system in the Sequim region. The distribution system model is developed in OpenDSS and consists of three-phase

[1] https://maps.nlr.gov/marine-energy-atlas
[2] https://hub.marinecadastre.gov/

and single-phase lines, single-phase loads, and a three-phase substation load tap changer (LTC) modeled as three single-phase autotransformers. The model also comprises three-phase and single-phase transformers, reactors, fuses, switches, and control objects. A model of the microgrid system at Guy Cole Center in Sequim is developed in OpenDSS and consists of a battery energy storage system (BESS), a PV system, and an off-site tidal generator, which is connected to the Guy Cole Center through a dedicated distribution service line. The total length of the line connecting the tidal generator with Guy Cole Center is roughly 9,400 feet (~1.8 miles).

The microgrid's performance is evaluated by running quasistatic time series (QSTS) simulations in grid-connected mode. In this mode, the power exchange between the microgrid (Guy Cole Center) and the distribution system is monitored. Additional metrics such as the microgrid voltage, network power loss, and battery capacity are also monitored at each simulation time step.

### 3.3.1 Hosting Capacity

The first step in the distribution system analysis involves the determination of the hosting capacity of the system at a specified location. Hosting capacity refers to the amount of generation that can be added to the system at a location before control changes or system upgrades are required to safely and reliably add more generation. Hosting capacity is highly locational and does not represent a hard limit on the amount of generation that can be added to the distribution system. In the context of microgrid design and control, determining the hosting capacity is important for ensuring safe limits for the added renewable capacity. In this study, we determine the hosting capacity of the Guy Cole Center microgrid based on the voltage and thermal limits. The estimate of the hosting capacity is derived using snapshot simulations at different generation capacities of the PV and tidal generators and does not incorporate the impact of control equipment such as LTCs, switched capacitors, and smart inverters. Since the microgrid consists of one building, which is located at a fair distance from the substation LTC, a snapshot-based estimate of the hosting capacity is sufficient to determine the DER capacity limits reasonably. The overall process of determining the hosting capacity is illustrated in Figure 5. The hosting capacity uses a graph theory approach that utilizes the Networkx package[1] and pyHCA (Poudel and Peerzada 2024) in Python 3.12. pyHCA is a Python module that performs the numerical calculations to determine the hosting capacity of the distribution system. This method represents the distribution system as a network of nodes (buses) and edges (line segments connecting buses).

The tidal hosting capacity is determined by adding a new line segment to the network graph in two steps. In the first step, the distance between the target node (generator hosting node) and the microgrid (Guy Cole Center) is determined using the lengths of the edges. In the second step, the line segment is modeled in OpenDSS using the impedance matrix of the line with a similar length. The existing connections of the target node with other nodes are terminated in a way that does not impact power flow convergence. In this manner, a dedicated distribution line connecting the tidal generator and Guy Cole Center is added to the feeder design.

[1] https://networkx.org/

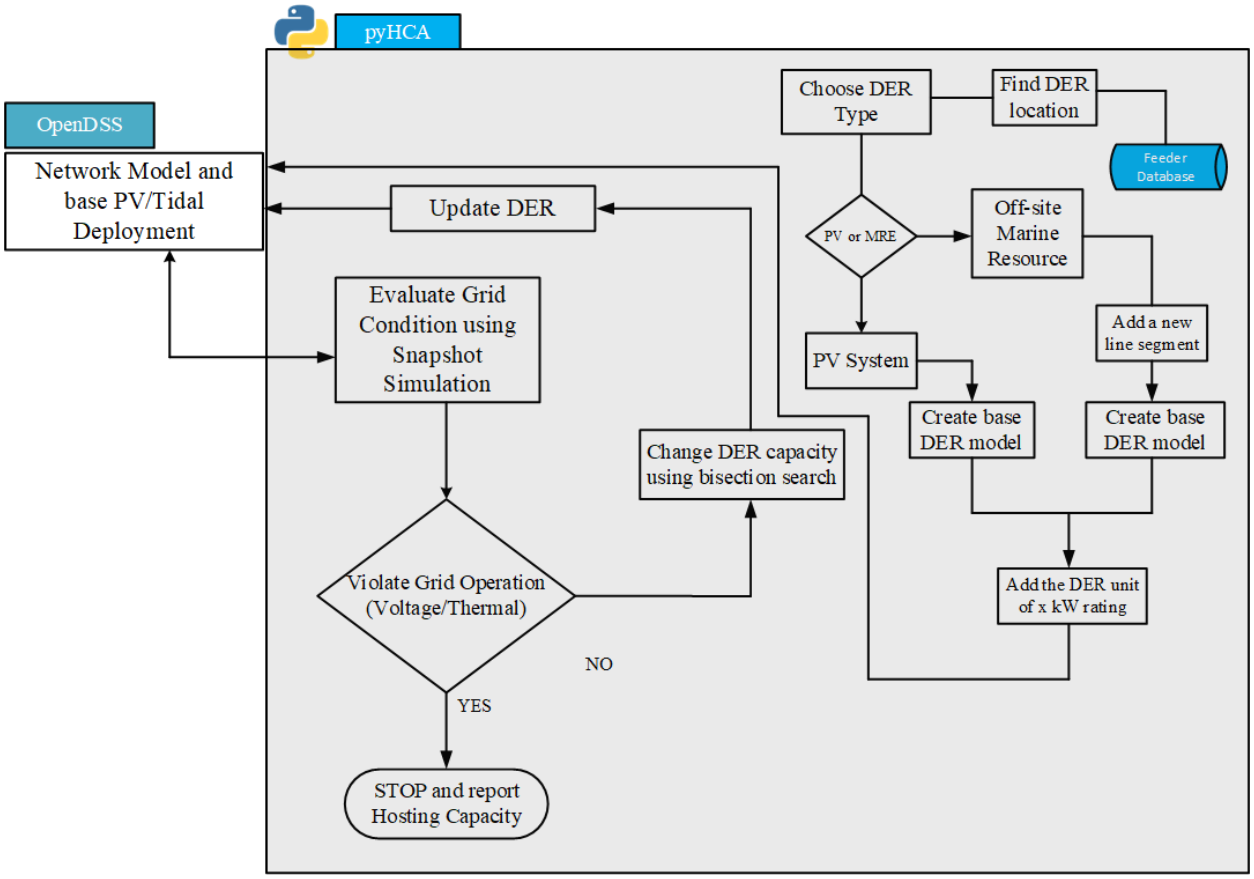



Figure 5. Workflow for the DER hosting capacity analysis using the pyHCA module.

Electrical one-line diagrams of the distribution system without and with the new line added are shown in Figure 6 and Figure 7. Note that in Figure 7, the total length of the newly modeled line that connects the tidal generator with the microgrid is roughly 9,400 feet. Since the microgrid under consideration is a building whose electrical load is modeled as a single-phase constant power load with no dependence on the voltage, the distribution line that serves the tidal power to the building is also modeled as a single-phase line. The tidal hosting capacity is also calculated in the absence of a dedicated distribution line between the tidal generator and the microgrid. In both cases, a tidal generator of increasing capacity is modeled at the tidal site until network violations (voltage or thermal) prohibit increasing the capacity.

Since the output of a PV system is less constrained by the location, the PV hosting capacity is determined by modeling a PV system interfaced with an inverter at the microgrid location. In this case, no new lines are added to the feeder design. For both tidal and PV generators, the hosting capacity is determined using a bisection search algorithm. The algorithm is initiated by assuming a fixed interval of generation capacity, which is repeatedly halved until convergence is met. At the limit, the method yields the maximum generation capacity that can be added to the feeder while satisfying the feeder constraints. The hosting capacity results for PV and tidal with and without dedicated distribution lines are presented in Section 4.0.

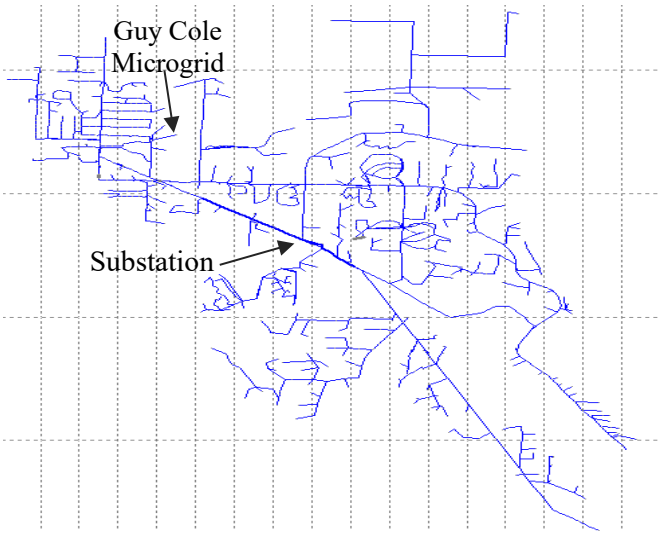



Figure 6. Electrical feeder map of the Sequim distribution system without a tidal generator.

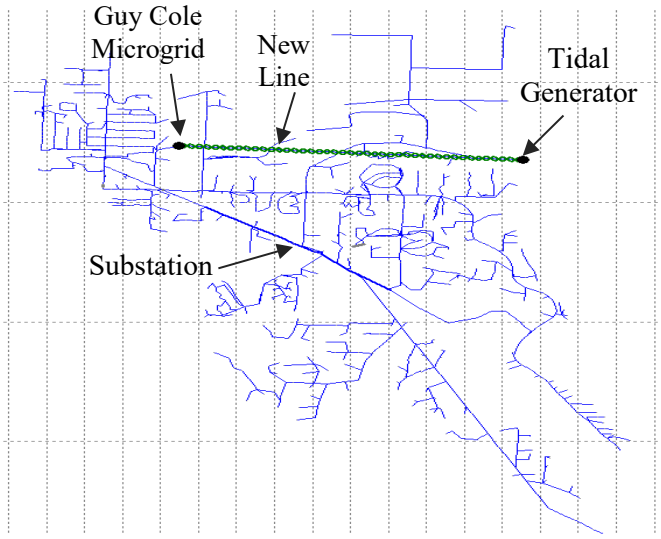



Figure 7. Electrical feeder map of the Sequim system showing the locations of the Guy Cole microgrid, distribution line, and tidal generator.

# 4.0 Results

## 4.1 Guy Cole Center

### 4.1.1 Microgrid Modeling

As described in Section 3.2, MCOR was used to develop possible microgrid systems to allow Guy Cole Center to serve as a resilience hub and continue to power critical loads during a utility outage. Several different simulations were run, each of which provided a suite of options that could be used in a microgrid with renewable energy, battery storage, and backup diesel generator components of varying sizes.

The first set of simulations modeled microgrid behavior during 400 hypothetical outage scenarios using weather and resource conditions derived from historical and modeled data. A sensitivity study was run to model outages of 4 hours, 8 hours, and 1 week. Each outage length resulted in a different set of microgrid sizes that would meet all the load for the duration of the outages. The second set of simulations focused on the outage caused by a November 2022 windstorm on the NOP. Figure 8 depicts the hierarchy of different simulations that were run.

For each outage length, several different potential system sizes were determined by MCOR, and for each of those sizes, microgrid simulations were run for the 400 random scenarios and the storm scenario. Each of these potential microgrid system sizes can meet the site's load during an outage. Different simulations could be used to answer different questions about the suitability of the microgrid to meet community needs. For example, the 400-outage simulation could describe how the microgrid system performs under a range of weather conditions, while the one-outage storm results show how the system performs during a particularly bad storm. The differing outage lengths show what type of system you would need to keep the lights on during outages of different lengths. Finally, the different system sizes show different ways you can meet your energy needs by varying the respective sizes of the components in the microgrid, and these sizes are listed in the tables below.

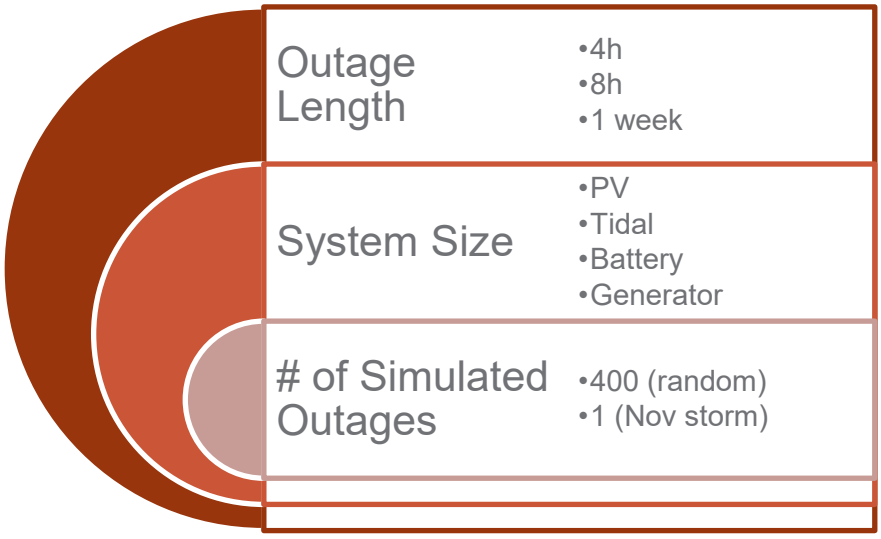



Figure 8. Depiction of different sets of simulations that were run. As shown in the outer circle, different outage lengths were included; the middle circle describes how several different system sizes were produced by each outage length, and the innermost circle

depicts the different simulations that were run for each system size and outage length—both 400 random outages and the specific November storm outage.

Most of the results presented below are for a 1-week outage (for both the 400-outage simulation and the storm simulation), but a comparison for shorter outages is also included.

**Renewable Energy Component Sizes**

The sizes for the PV and tidal energy components were largely constrained by the available space and technologies, as described in Section 3.2.3.1. Given those constraints, MCOR produced seven different possible microgrid configurations:

- one with no renewable energy and only a backup diesel generator
- three with PV as the only renewable energy resource (at the maximum allowed capacity given siting constraints) and with three different battery sizes
- three with one tidal turbine along with PV and with three different battery sizes.

To size the systems with both tidal and PV resources, the tidal capacity was based on a single turbine, and the PV capacity was determined to allow the entire system (PV + tidal) to produce the same amount of energy over the course of the year as the total annual building load. For both PV only and PV + tidal systems, three different battery capacities were included: one designed to be large enough to supply all load not met directly by the renewable resources (assuming there is enough charge), one designed to meet 75% of the unmet load, and one designed to meet 50% of the unmet load. The battery power ratings are based on the maximum amount of load that could be charged into the batteries at any given hour. These three battery sizes are slightly different for the PV only and PV + tidal systems, as they generate different amounts of renewable energy and at different times of day.

Table 3 shows the resulting component sizes for a 1-week outage. Each row represents a different system configuration and includes the PV, tidal, battery, and generator sizes required to meet all loads during an outage across all 400 simulations.

Table 3. Microgrid component sizes for the 400-outage simulation for Guy Cole Center for a 1-week outage.

| System name | PV capacity (kW) | Tidal capacity (kW) | Battery capacity (kWh) | Battery power (kW) | Generator capacity (kW) |
|---|---|---|---|---|---|
| Generator only | 0.0 | 0.0 | 0.0 | 0.0 | 40.0 |
| PV, small battery | 94.0 | 0.0 | 352.8 | 34.2 | 40.0 |
| PV, med battery | 94.0 | 0.0 | 529.2 | 51.2 | 40.0 |
| PV, large battery | 94.0 | 0.0 | 705.5 | 68.3 | 40.0 |
| PV + tidal, small battery | 21.9 | 90.0 | 224.3 | 42.5 | 40.0 |
| PV + tidal, med battery | 21.9 | 90.0 | 336.5 | 63.8 | 40.0 |
| PV + tidal, large battery | 21.9 | 90.0 | 448.7 | 85.1 | 40.0 |

### Comparison Across Systems

Several different metrics were used to compare systems. These include fuel usage during an outage, the percent of load met by each resource in an outage, total installation costs, potential net-metering revenue, and the storage recovery. These are presented in table form in Appendix A.1, as well as a figure of the fuel usage for different microgrid systems.

Figure 9 shows example dispatch plots to demonstrate how the microgrid could meet the site load under varying weather conditions for two of the microgrid systems listed in Table 3. For the scenarios with favorable PV resources, all the load is met by a combination of renewable energy and battery discharge, but for the scenarios with poor PV resources, the generator must be turned on after only a few days.

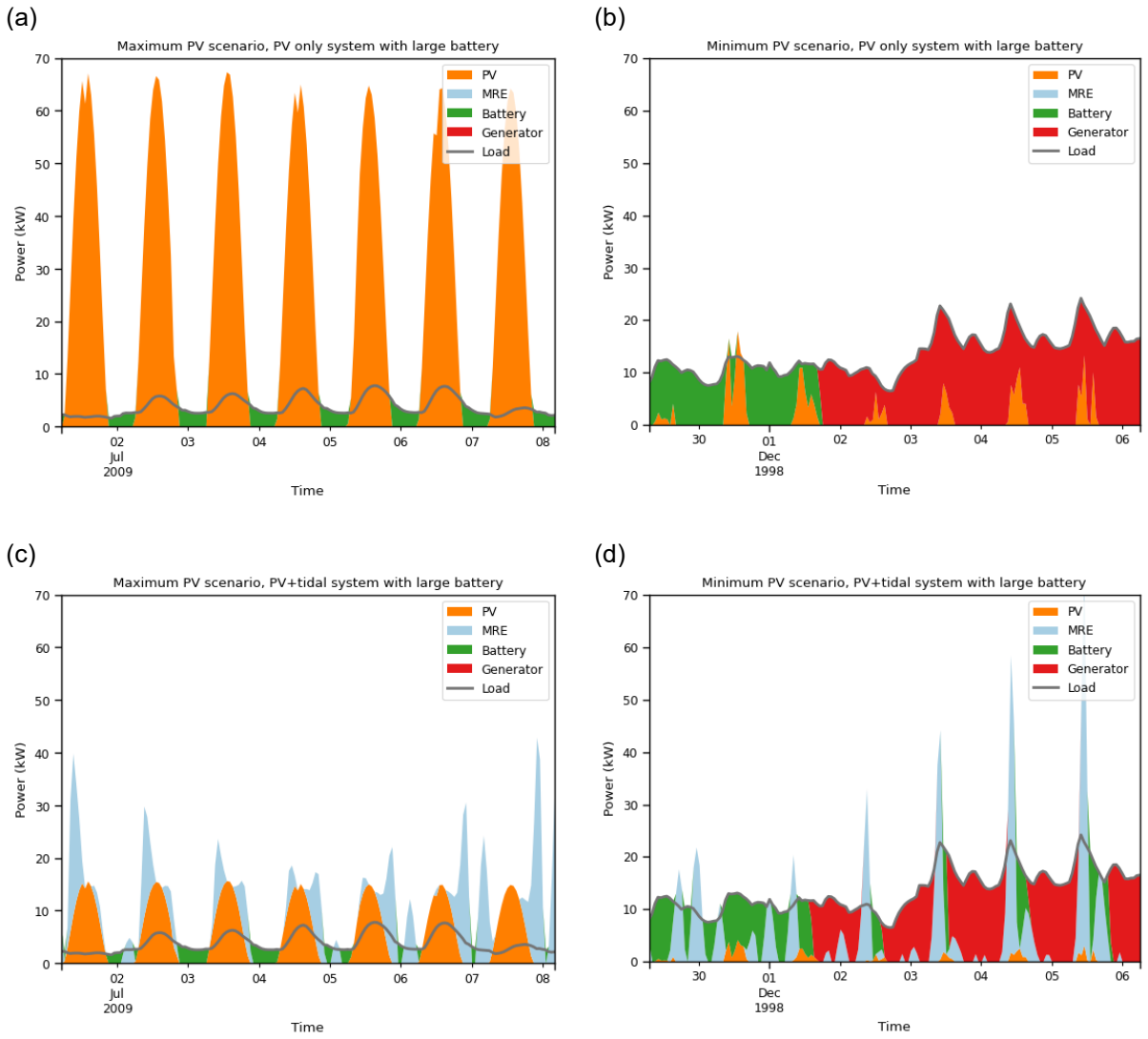



Figure 9. Dispatch plots for the Sequim microgrid for a 1-week outage, showing sample microgrid operation for different outage conditions: the PV-only, large battery system under (a) favorable and (b) poor PV conditions and the PV + tidal, large battery system with (c) favorable and (d) poor PV conditions. For all figures, orange represents PV generation, blue represents tidal generation, green represents battery

discharge, red represents generator use, and the gray line represents the building load.

### Outage Length Sensitivity Analysis

While the results above are all for the 1-week outage simulation, shorter outages of 4 and 8 hours were also simulated. Figure 10 compares the average percent contribution of each resource to meet the load for the seven different systems and the three different outage lengths. For the 4- and 8-hour outages, all of the load can be served by the renewable and battery components for all 400 scenarios, but for the 1-week outage, the generator is used for at least some of the scenarios. As for the fuel usage, for a given renewable energy resource capacity, there is not much difference in resource contribution to the load across the different battery sizes. There is a slight reduction in the generator contribution to the load for the 1-week outage as the battery size is increased, but it is relatively small given that the battery capacity is doubled from the "small" to the "large" size.

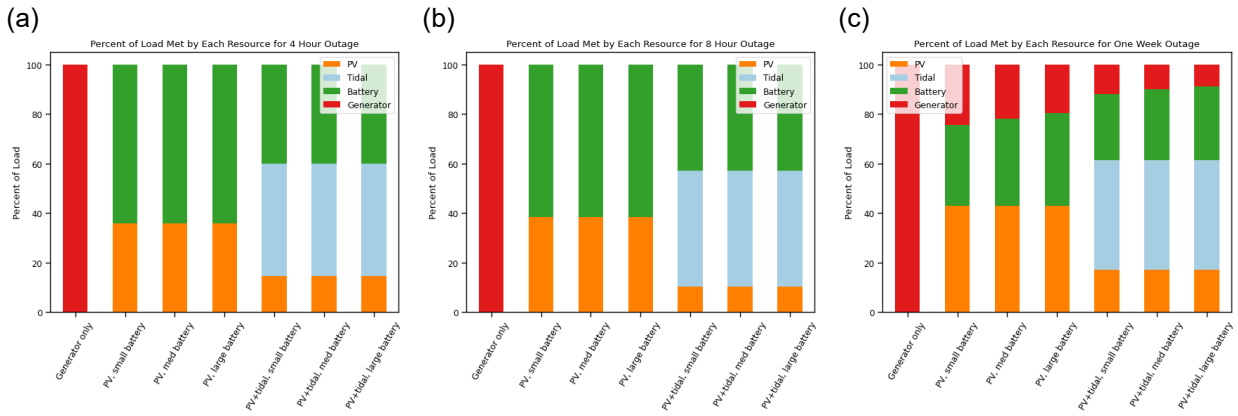



Figure 10. Average percentage of the load met by each resource across different systems for (a) 4-hour, (b) 8-hour, and (c) 1-week outages. The generator load is shown as red, PV generation contributions are shown as orange, tidal generation contributions are shown as blue, and battery discharging is shown as green.

### Storm Modeling

In addition to simulating microgrid operation under a large range of conditions by running and aggregating the results from 400 scenarios, MCOR was also run for a specific storm by simulating an outage that started at 10 p.m. on November 4, 2022, to represent the windstorm that occurred at that time.

Figure 11 shows the percentage of load met by each resource across the seven systems, with the full results shown in Appendix A.1. As compared with the 400 scenario simulation, the microgrid relies much more heavily on the generator for the storm simulation.

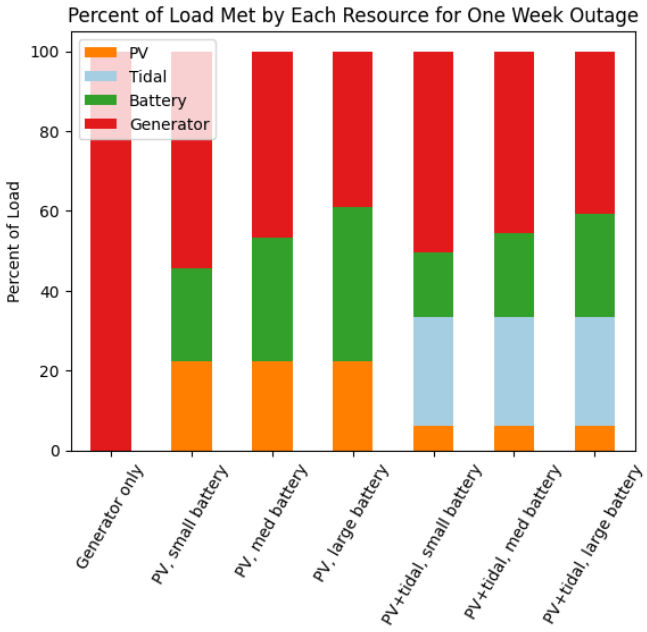



Figure 11. Percentage of the load met by each resource across different systems for the storm simulation 1-week outage. The generator load is shown as red, PV generation contributions are shown as orange, tidal generation contributions are shown as blue, and battery discharging is shown as green.

Figure 12 shows how the load is met by each resource during the 1-week storm outage for both the PV only, large battery system and the PV + tidal, large battery system. Both systems require significant generator use after a few days. Even with the large battery, there is not enough renewable generation to recharge it beyond a few hours of use.

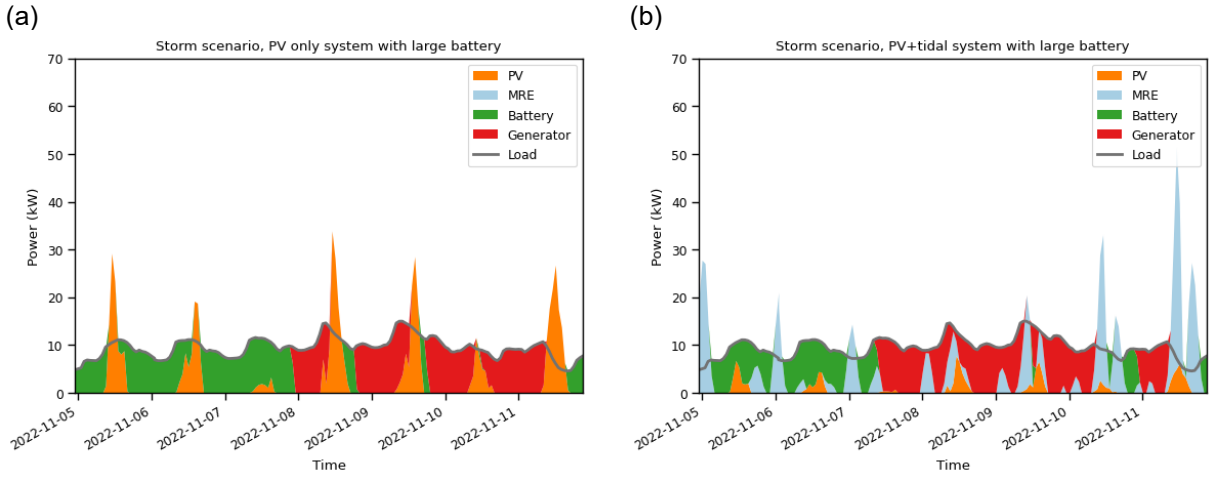



Figure 12. Dispatch plots for the Sequim microgrid for a 1-week outage showing sample microgrid operation during the November 4, 2022, storm: (a) PV-only, large battery system and (b) PV + tidal, large battery system. For all figures, orange represents PV generation, blue represents tidal generation, green represents battery discharge, red represents generator use, and the gray line represents the building load.

A comparison of the results from the 400-scenario simulation and the storm simulation is helpful to understand how a microgrid might perform under a large range of conditions versus a specific extreme event that caused widespread power outages in the region. Even if the microgrid system can supply power with little to no diesel fuel during most outages, the backup generator would still be critical for more extreme outages.

### 4.1.2 Distribution System Modeling

**Hosting Capacity**

A detailed, unbalanced three-phase model of the Sequim distribution feeder was created in OpenDSS to evaluate the microgrid performance in grid-connected mode. The model includes the design of the microgrid at Guy Cole Center, which consists of a PV system, a BESS, and an off-site tidal generator. A wye–delta transformer is used to connect the BESS and tidal generator with the microgrid. The base load of the microgrid consists of the building load, which is modeled as a single-phase load with constant power characteristics. An outline of the microgrid design at Guy Cole Center is shown in Figure 13. The directions of the arrows marked in the diagram represent the flow of power. The microgrid is connected with the distribution system at the point of common coupling (PCC) bus. The bidirectional arrow at the PCC bus alludes to the fact that power can either be exported or imported from the main grid subject to the changes in the local generation and load within the microgrid.

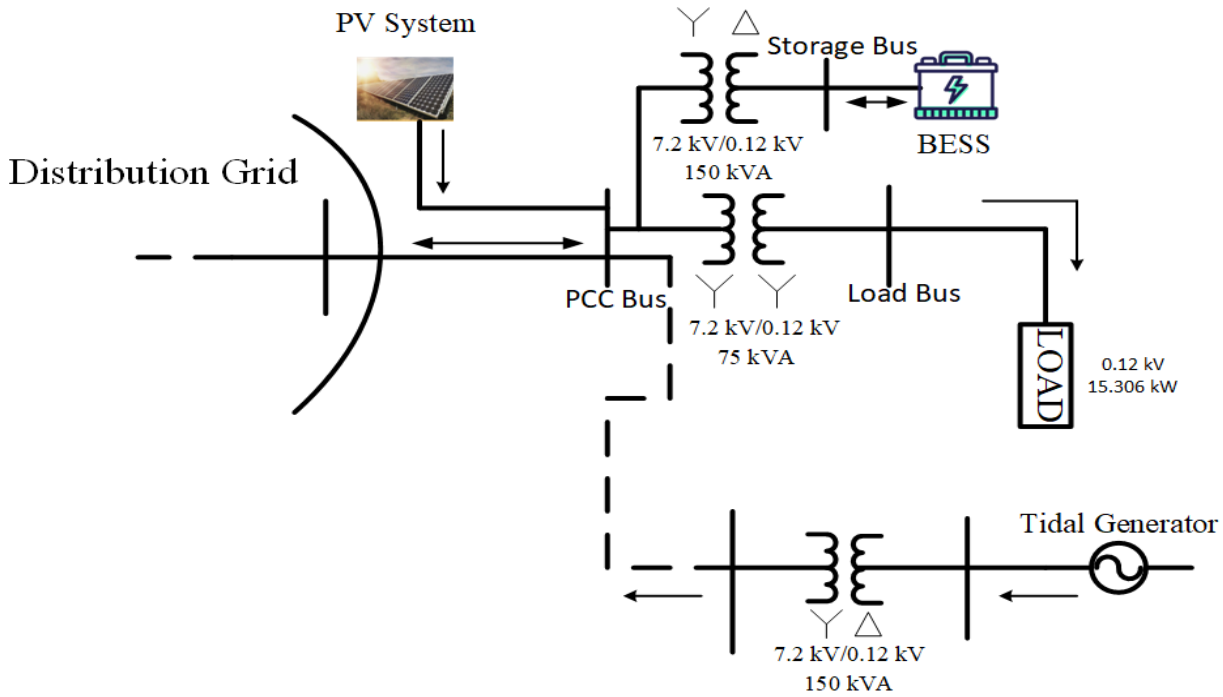



Figure 13. Electrical design of the microgrid at Guy Cole Center.

The dashed line within the microgrid in Figure 13 represents the new line that is added to the system to connect the tidal generator with the microgrid. A hosting capacity analysis was performed prior to simulating the microgrid operation. The results of the hosting capacity analysis are essential to ensure that the sizes of the generators in the microgrid don't violate the network constraints. The results of the hosting capacity analysis are given in Table 4.

Table 4. Hosting capacity limits.

| Generator Type | Hosting Capacity Limit for Voltage Violations | Hosting Capacity Limit for Thermal Violations |
|---|---|---|
| PV system | 30 kW | 3,144 kW |
| Tidal without dedicated line | 390 kW | 3,560 kW |
| Tidal with dedicated line | 102 kW | 12,509 kW |

From the results in Table 4, it is clear that voltage violations are more restrictive than thermal violations and the limits for the PV system are more conservative than for the tidal generator. The analysis considers the voltage constraint in the range of 0.90 per unit and 1.05 per unit. The thermal overloading constraint is imposed by the current carrying capacity limits of the distribution lines. A comparison of the hosting capacity limits and the PV and tidal capacities used for the proposed microgrid is given in Section 5.0.

**Tidal Generator Interconnection Costs**

Since installing a tidal generator is largely constrained by the location of the turbine and necessitates the construction of a new line, there is a significant capital investment involved in connecting the tidal generator placed in Sequim Bay with Guy Cole Center. Table 5 gives approximate estimates of the cost involved in placing a new distribution line. The cost estimates in Table 5 are based on the National Laboratory of the Rockies (NLR) cost distribution guide (Horowitz 2019). It is important to note that the unit costs of installing new lines and the range of reconductoring costs found in the NLR database can be quite large.

Table 5. Range of reconductoring costs incurred for placing a new distribution line connecting the tidal generator with Guy Cole Center.

| Line Length | Low Estimate [$130/ft] | Medium Estimate [$178/ft] | High Estimate [$258/ft] |
|---|---|---|---|
| ~9400 ft | $1,222,000 | $1,673,200 | $2,425,200 |

In this report, we consider the generation scheduling of the microgrid in the grid-connected mode of operation. Since the microgrid is assumed to be connected to the main grid at all times, the operation of the BESS is not considered in this analysis. Although the BESS is part of the microgrid topology, as shown in Figure 13, its operation is fully modeled in the islanded mode of operation in Section 4.1.1 and is not part of this analysis. For the grid-connected analysis, the scheduling of intermittent resources such as PV and tidal is considered. The PV system is modeled as a generator with unity power factor operation. The output of the PV system is constrained by the weather and the total apparent power capacity of the PV inverter. A wye–delta transformer is used to connect the single-phase tidal generator with the distribution system. The transformer performs the dual operations of providing electrical isolation and the required voltage level for the tidal generator. An approximate estimate of the costs involved in installing a new transformer are given in Table 6. Note that the unit costs are based on the NLR cost guide (Horowitz 2019), which provides transformer costs based on power levels of 0–50 kVA and 50–150 kVA. The high cost estimate for 0–50 kVA is not given as it is not available in the aforementioned cost guide.

Table 6. Transformer costs for interconnecting the tidal generator with Guy Cole Center.

| Transformer kVA | Number of Phases | Low Cost Estimate | High Cost Estimate |
|---|---|---|---|
| 0–50 kVA | Singe-phase or three-phase | $10,400 | N/A |
| 50–150 kVA | Single-phase or three-phase | $15,600 | $49,300 |

The line connecting the tidal generator and the microgrid is single phase and is carefully designed to allow all the power from the tidal generator to feed the load at the microgrid. In cases where there is a surplus of generation feeding into the microgrid, the surplus power is exported to the rest of the distribution system. The bidirectional nature of the power flow between the microgrid and the distribution system may impact the operation of the protection relays and other protection equipment such as circuit breakers. While a detailed analysis of microgrid protection schemes is outside the scope of this report, it is an important consideration that should be taken into account.

**Grid-Connected Simulations**

In grid-connected operation, it is important to monitor the voltage at the PCC bus and the power exchange between the microgrid and the distribution system. Other important considerations are the network power loss, the real power loss in the distribution line connecting the tidal generator with the microgrid, the output of PV system and tidal generator, and the microgrid demand. These metrics are evaluated by running a week-long QSTS simulation in OpenDSS. The microgrid generator schedule is based on the MCOR output, and the electrical parameters are obtained as solutions to the time series power flow equations that model the power exchange in the distribution system. The grid-connected analysis considers three scenarios. The first scenario does not consider any local generation, and as such, the entire load within the microgrid is supplied by importing power from the distribution system. The remaining two scenarios consider local generation in the form of PV and the combination of PV and tidal. Table 7 lists the capacities of the generation sources used in each scenario.

Table 7. PV and tidal capacities used for grid-connected analysis.

| Generating Resource | Scenario 1 | Scenario 2 | Scenario 3 |
|---|---|---|---|
| PV | 0 kW | 94 kW | 94 kW |
| Tidal | 0 kW | 0 kW | 90 kW |

The time series voltage at the microgrid PCC bus for the November storm simulation is shown in Figure 14. It is important to note that the microgrid voltage is confined within the acceptable limits for all the scenarios. As such, no voltage control actions are required to regulate the voltage. In grid-connected operation, LTC operation at the substation is sufficient to regulate the microgrid PCC voltage.

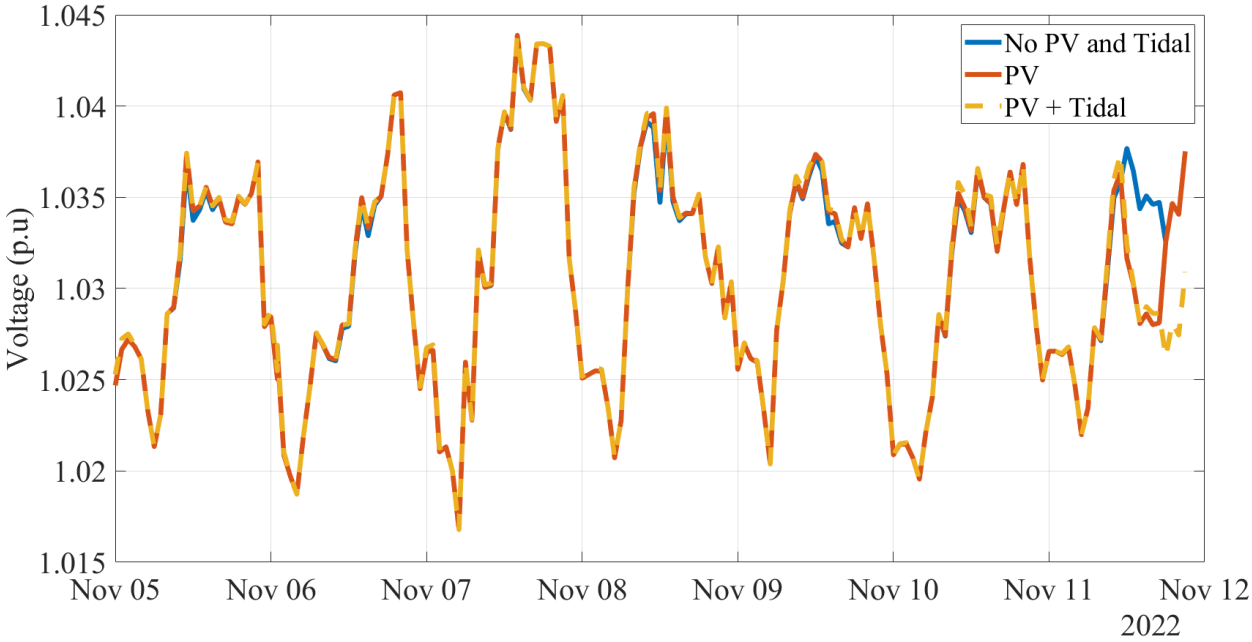



Figure 14. Microgrid PCC voltage for different scenarios.

The power exchange between the microgrid and the distribution system is shown in Figure 15. Positive values in the power profile refer to power being imported, while negative values refer to surplus power exported back to the distribution system. Power exchange is an important indicator of the self-sufficiency of the microgrid. Ideally, scenarios that increase the power exported to the grid and hence decrease the dependency on the distribution system would be preferred. From Figure 15, it is apparent that more power is exported to the grid in the scenario that considers PV and tidal, and less with PV only. In the scenario with no local generation in the microgrid, all the power that is needed to meet the load is imported from the distribution system.

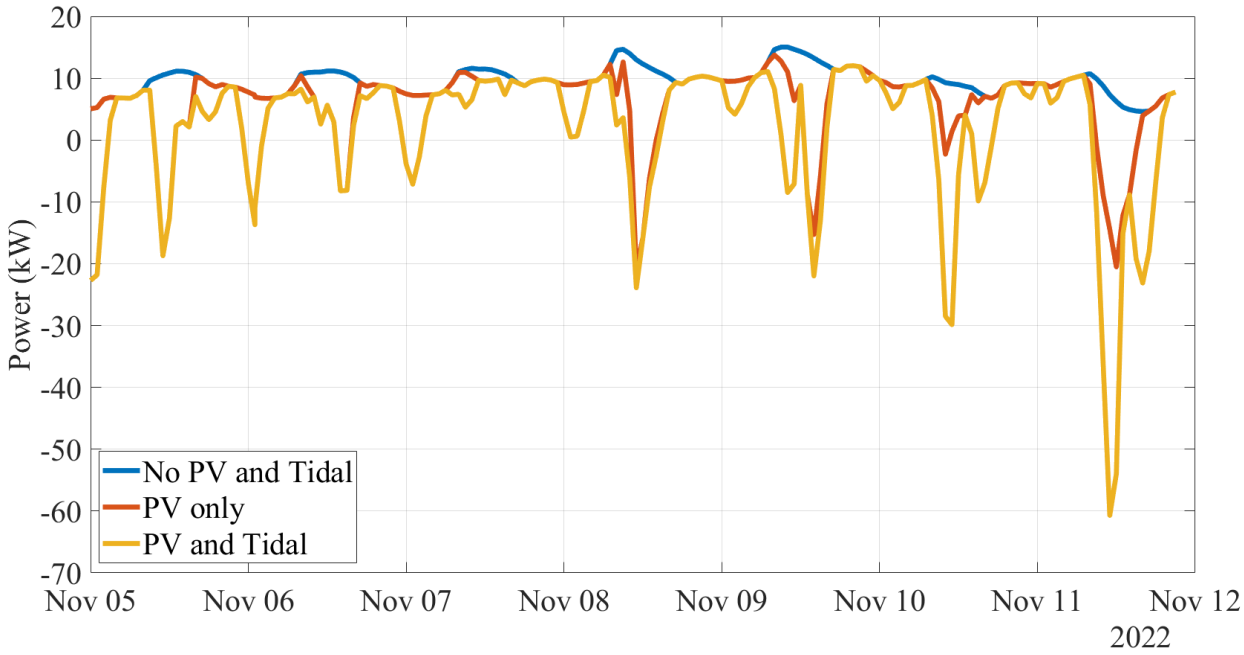



Figure 15. Power exchange between the microgrid at Guy Cole Center and the distribution system under different scenarios.

Figure 16 shows the time-series power loss profile in the distribution line connecting the tidal generator with the microgrid. Since the line connects the tidal resource with the microgrid and does not connect with other loads or other sources of generation, the losses in this line are reported only when the tidal generator is producing power. It is important to note that while power loss occurs, it is not significant enough to impact the operation of the microgrid.

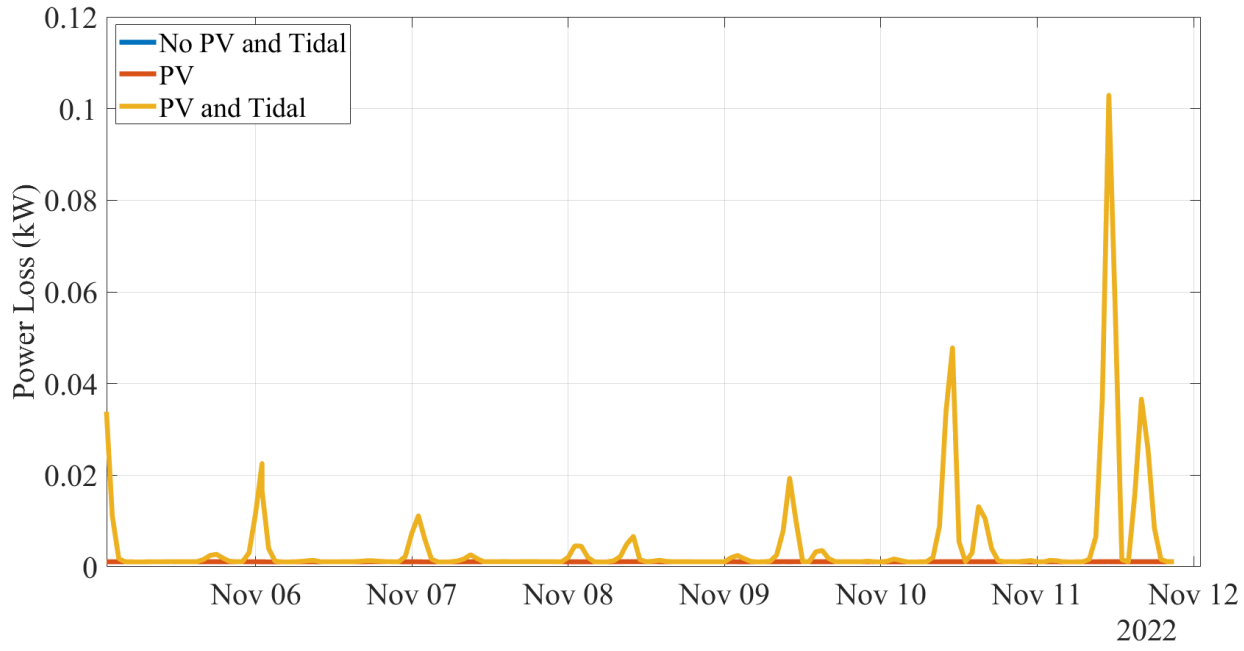



Figure 16. Power loss in the distribution line connecting the tidal generator with Guy Cole Center under different scenarios.

## 4.2 Port Townsend WWTP

### 4.2.1 Microgrid Modeling

The microgrid analysis for the Port Townsend WWTP was similar to that for Guy Cole Center in Sequim, with a few key differences. First, since there is more flexibility on the siting of the tidal turbines in Admiralty Inlet as compared with Sequim Bay, more than one turbine was considered as well as a range of siting depths. These different depths are included in the sensitivity analysis discussed below. In addition, as distribution system data were not obtained in time for the analysis, any constraints on the microgrid from the larger system, such as the hosting capacity, are not considered here.

Figure 17 depicts the different simulations that were run for the Port Townsend sensitivity analysis. The range of parameters used for the sensitivity analysis allows for readers to compare how the microgrid system should be sized and would perform for different design choices.

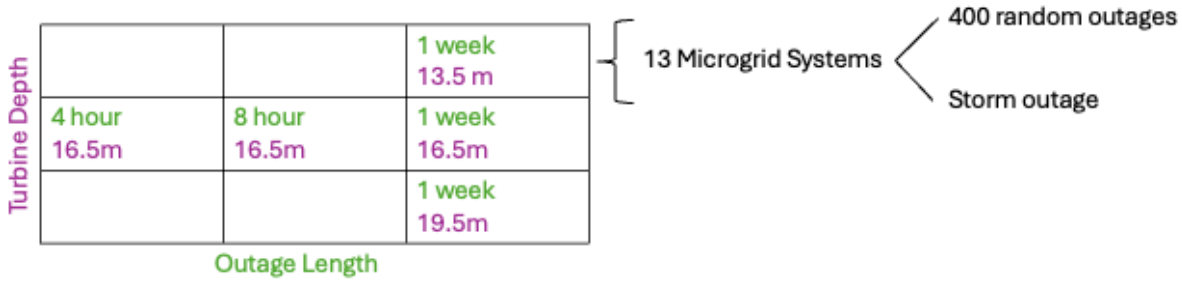



Figure 17. Depiction of different sets of simulations that were run. The table on the left shows the grid of simulations that were run for the two sensitivity parameters—turbine depth and outage length. For each combination of turbine depth and outage length, 13 different microgrid system sizes were modeled. For each of those sizes, simulations were run for the 400 random outage scenarios and the specific November storm scenario.

**Renewable Energy Component Sizes**

The available footprint for installing PV at the wastewater treatment plant is very limited; thus, even in systems for which PV is included, the resource contributes very little to the microgrid production. However, given the available space for installing tidal turbines in Admiralty Inlet, up to three tidal turbines were included for the analysis. Given these constraints, MCOR produced 13 different possible microgrid configurations:

- one with no renewable energy and only a backup diesel generator
- three with PV as the only renewable energy resource (at the maximum allowed capacity given siting constraints) and with three different battery sizes
- three with one tidal turbine along with PV and with three different battery sizes
- three with two tidal turbines along with PV and with three different battery sizes
- three with three tidal turbines along with PV and with three different battery sizes.

To size the systems with both tidal and PV resources, the tidal capacity was based on the number of turbines, and the PV capacity was determined as the maximum available capacity based on available space. The three different battery sizes were calculated in the same way as for the Sequim analysis.

Table 8 shows the resulting component sizes for a 1-week outage and the central of three depths that were modeled (16.5 m). Each row represents a different system configuration and includes the PV, tidal, battery, and generator sizes required to meet all the load during an outage across all 400 simulations. Note that the system with only PV + backup diesel generation does not include a battery power rating, as there is never enough PV generation to charge the batteries after meeting the critical load. These systems are not recommended, as the renewable generation is far below that needed to supply the load and it performs almost identically to the generator-only system.

Table 8. Microgrid component sizes for the 400 scenario simulation for the Port Townsend WWTP for a 1-week outage.

| System name | PV capacity (kW) | Tidal capacity (kW) | Battery capacity (kWh) | Battery power (kW) | Generator capacity (kW) |
|---|---|---|---|---|---|
| Generator only | 0.0 | 0.0 | 0.0 | 0.0 | 400.0 |
| PV, small battery | 13.6 | 0.0 | 2306.7 | 0.0 | 400.0 |
| PV, med battery | 13.6 | 0.0 | 3460.0 | 0.0 | 400.0 |
| PV, large battery | 13.6 | 0.0 | 4613.4 | 0.0 | 400.0 |
| PV + 1 turbine, small battery | 13.6 | 400.0 | 1877.3 | 153.1 | 400.0 |
| PV + 1 turbine, med battery | 13.6 | 400.0 | 2816.0 | 229.7 | 400.0 |
| PV + 1 turbine, large battery | 13.6 | 400.0 | 3754.6 | 306.2 | 400.0 |
| PV + 2 turbines, small battery | 13.6 | 800.0 | 1646.5 | 323.6 | 400.0 |
| PV + 2 turbines, med battery | 13.6 | 800.0 | 2469.8 | 485.5 | 400.0 |
| PV + 2 turbines, large battery | 13.6 | 800.0 | 3293.1 | 647.3 | 400.0 |
| PV + 3 turbines, small battery | 13.6 | 1200.0 | 1458.2 | 494.2 | 400.0 |
| PV + 3 turbines, med battery | 13.6 | 1200.0 | 2187.3 | 741.2 | 400.0 |
| PV + 3 turbines, large battery | 13.6 | 1200.0 | 2916.4 | 988.3 | 400.0 |

### Comparison Across Systems

A full list of all simulation output metrics is included in Appendix A.1, along with a figure comparing the fuel usage across microgrid systems.

Figure 18 shows example dispatch plots to demonstrate how the microgrid could meet the site load under varying resource conditions for two of the microgrid systems. For the scenarios with favorable tidal resources, all the load is met by a combination of renewable energy and battery discharge, but for the scenarios with poor tidal resources, the generator must be turned on after only a few days.

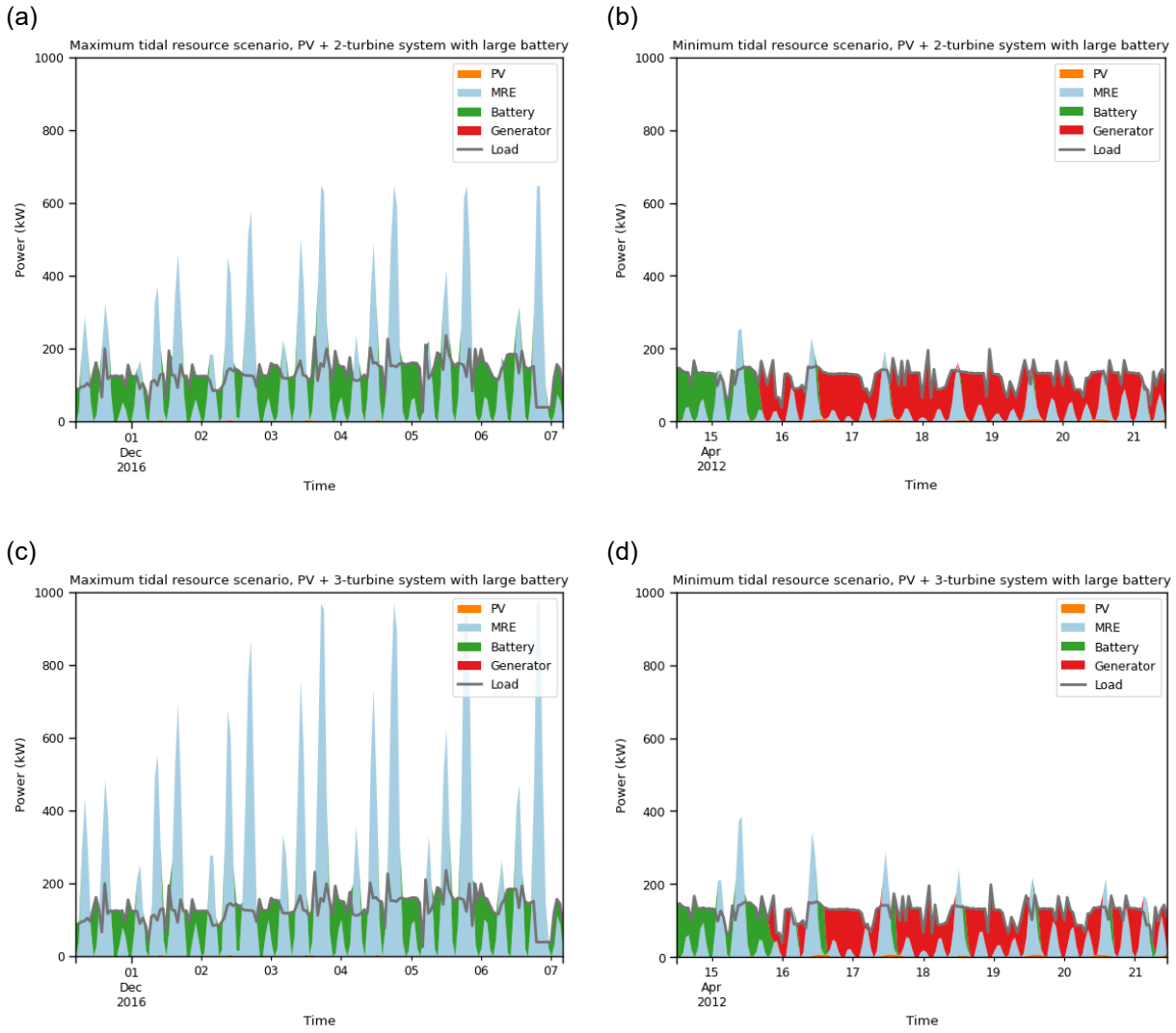



Figure 18. Dispatch plots for the Port Townsend microgrid for a 1-week outage, showing sample microgrid operation for different outage conditions: PV + 2-turbine, large battery system under (a) favorable and (b) poor tidal resource conditions; PV + 3-turbine, large battery system with (c) favorable and (d) poor tidal resource conditions. For all figures, orange represents PV generation (though barely noticeable), blue represents tidal generation, green represents battery discharge, red represents generator use, and the gray line represents the building load.

### Outage Length and Depth Sensitivity Analysis

Two different sensitivity analyses were run for the Port Townsend microgrid. First, the simulations were run for 4-hour, 8-hour, and 1-week outages. Second, the 1-week outage was simulated for three different tidal turbine depths. Figure 19 shows the average percentage of load (across the 400 scenarios) met by each of the microgrid resources for the 13 different component size options for both 8-hour and 1-week outages. For the 8-hour outage, the renewable energy and battery resources are able to meet all of the load for the PV + tidal systems, except for 1% of the load that needs to be met by the generator for the 1-turbine, small

battery system. In contrast, for the 1-week simulation, between 13% and 60% of the load needs to be met by the generator for the PV + tidal systems.

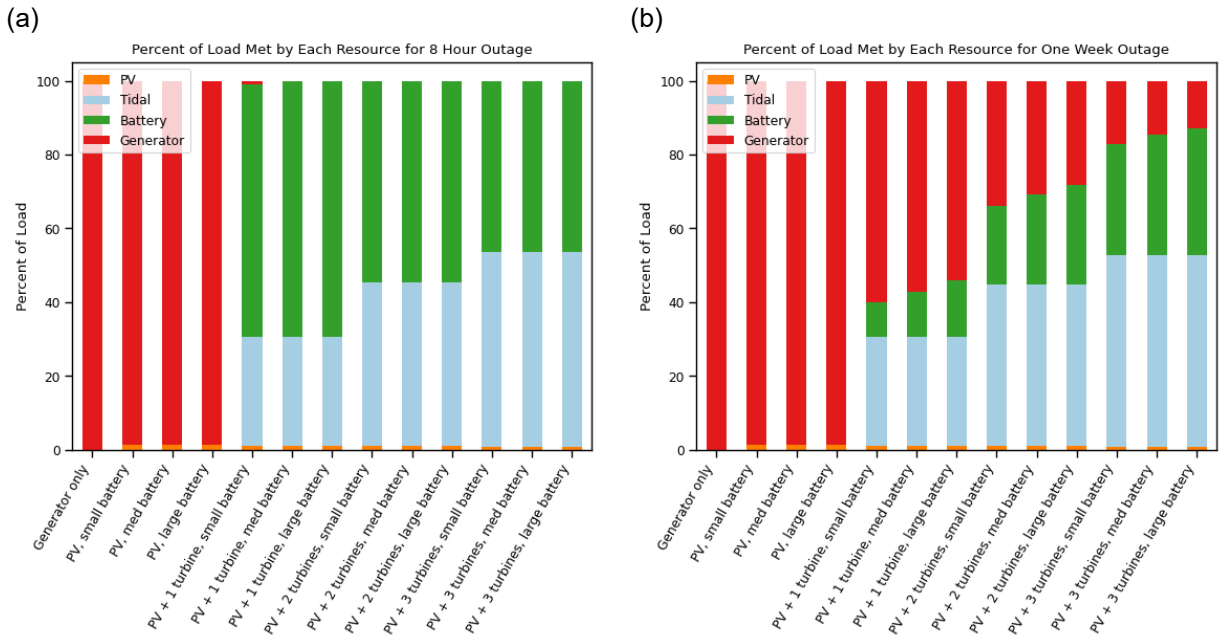



Figure 19. Average percentage of the load met by each resource across different systems for (a) 8-hour and (b) 1-week outages. The generator load is shown as red, PV generation contributions are shown as orange, tidal generation contributions are shown as blue, and battery discharging is shown as green.

There is not a meaningful difference in microgrid performance for the three different depths considered for tidal turbine siting, and Figure 20 shows the tidal energy generation for the three depths for an example 1-week period.

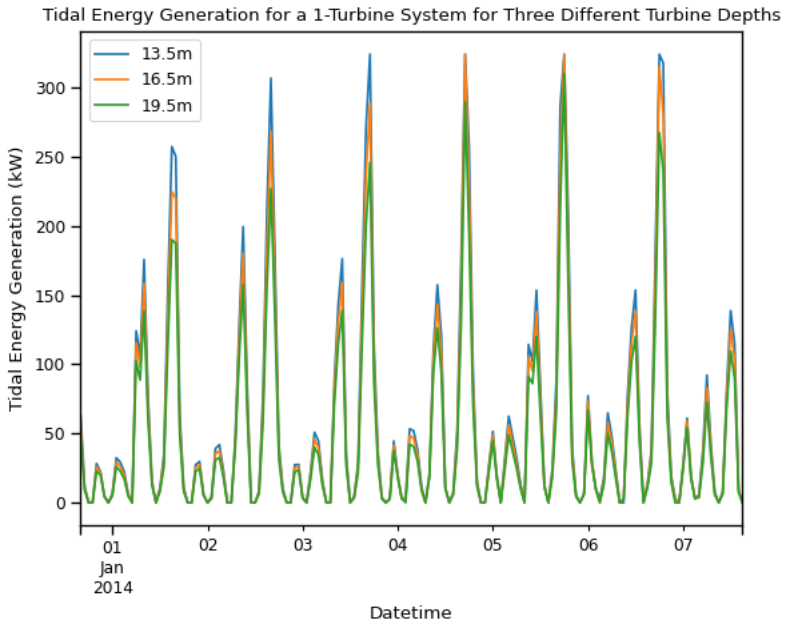



Figure 20. Tidal energy generation for a 1-turbine system located in Admiralty Inlet for an example 1-week period. Green shows the generation for a turbine sited at a depth of 19.5 m; orange, 16.5 m; and blue 13.5 m.

**Storm Modeling**

The same November storm that was simulated for the Sequim location was also simulated for Port Townsend. Figure 21 shows the percentage of load met by each resource across the 13 systems, with the full results included in Appendix A.1. As compared with the 400 scenario simulation, the microgrid relies much more heavily on the generator for the storm simulation.

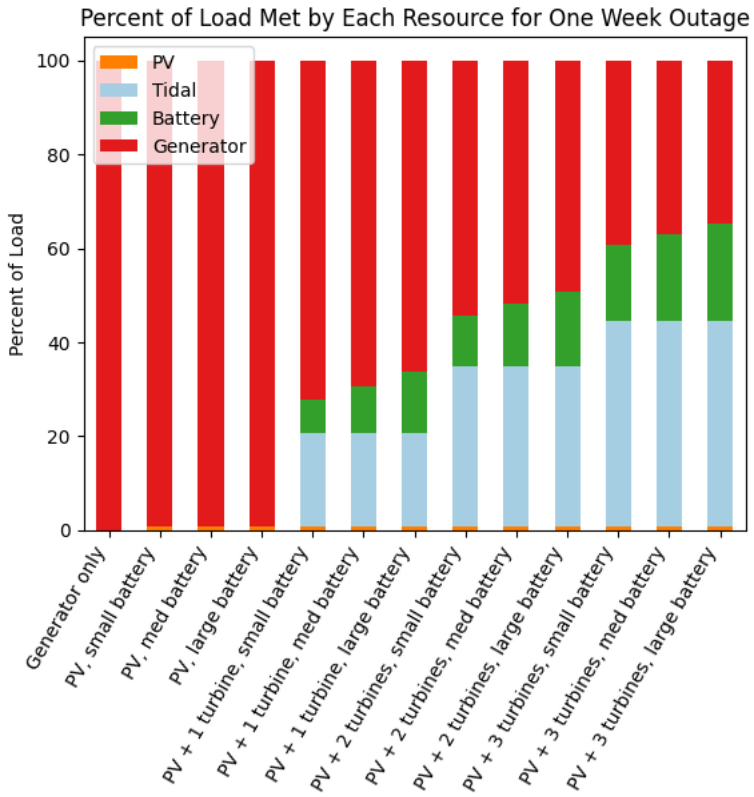



Figure 21. Percentage of the load met by each resource across different systems for the storm simulation 1-week outage for the Port Townsend microgrid. The generator load is shown as red, PV generation contributions are shown as orange, tidal generation contributions are shown as blue, and battery discharging is shown as green.

Figure 22 shows how the load is met by each resource during a 1-week storm outage for the PV + 2 tidal turbines, large battery system and the PV + 3 tidal turbines, large battery system. While the addition of a third tidal turbine makes almost no difference in the amount of energy the battery is able to discharge to meet the load, the amount of generation supplied by the diesel generator is decreased by 28%.

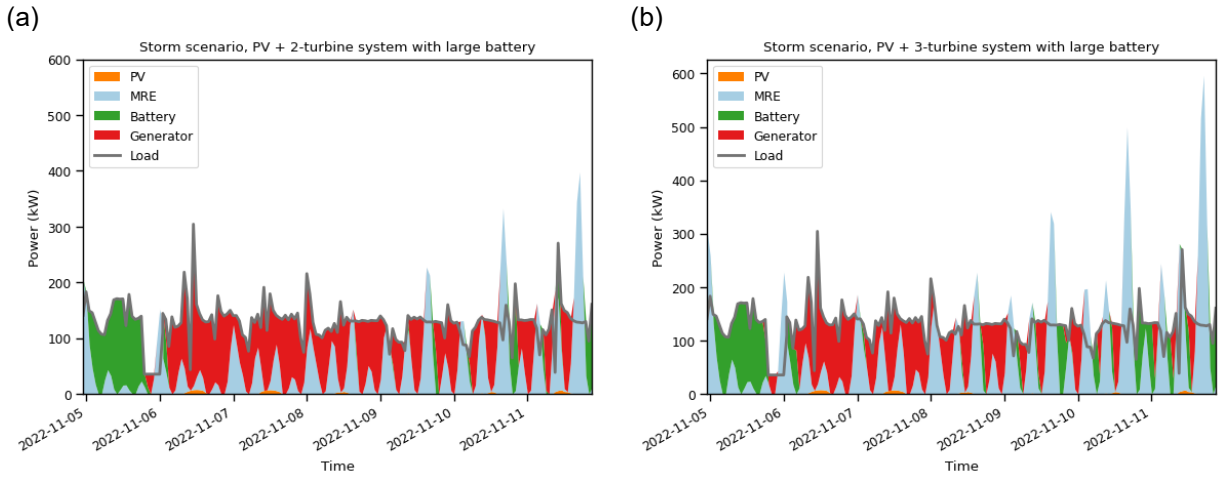



Figure 22. Dispatch plots for the Port Townsend microgrid for a 1-week outage, showing sample microgrid operation during a November 4, 2022, storm: (a) PV + 2 tidal turbines, large battery system and (b) PV + 3 tidal turbines, large battery system. For all figures, orange represents PV generation, blue represents tidal generation, green represents battery discharge, red represents generator use, and the gray line represents the building load.

# 5.0 Discussion

## 5.1 Analysis Takeaways

### 5.1.1 Limitations

The analysis presented above illustrates how microgrids could help power the load at Guy Cole Center and the Port Townsend WWTP during a utility outage. However, it is important to understand the limitations of both the analysis and the data used as an input.

The costs for installing the microgrids, which are included in Appendix A for each of the microgrid system sizes, are approximations, and the actual costs would be highly dependent on local labor and transportation costs. In addition, as tidal energy is still a developing technology, the costs for the tidal system are highly uncertain and likely much higher than they will be in several years as the technology matures and the production of tidal turbines increases in scale. Finally, the costs included in Appendix A are only for the generation and storage equipment and do not include the costs for any distribution system upgrades that would be required to connect the system to the grid. This includes additional lines or switches to connect the tidal generator to Guy Cole Center, which are presented in Section 4.1.2.

The microgrid system could also be used to generate revenue in the normal grid-connected mode. Appendix A.1 includes an estimate of net-metering revenue for each of the 7 sizes for the Sequim microgrid and 13 sizes for the Port Townsend microgrid. However, the simulation does not include operation of the battery in the grid-connected mode, and it could be possible to generate additional revenue by allowing the battery to supply grid services to the local distribution utility, depending on the market products locally available.

Data availability was a challenge for this project. The project team assumed that we would get access to distribution system data for both Port Townsend and Sequim, but we were not able to get that data for Port Townsend from Jefferson PUD because of project timeline constraints. As a result, estimates of distribution system installation costs are not included for the WWTP, and no distribution system analysis was conducted.

Another example of data availability challenges relates to the Sequim microgrid analysis. Since Guy Cole Center does not have a smart meter, only monthly usage data were available from the PUD. These monthly data were scaled to a publicly available load profile for an office building from the NLR's ComStock™ dataset (Parker et al. 2023). As the load data are a critical input for the analysis, any deviation between the modeled load and the actual load could have a large impact on the recommended microgrid system sizes and their performance. In addition, even if it were possible to obtain hourly load data for Guy Cole Center, behavior during an outage when the Center is serving as a resilience hub could be very different from normal operation.

The load data for the Port Townsend WWTP, however, are much more detailed than those used for Guy Cole Center. Jefferson PUD provided hourly load data for an entire year, so assuming that the load does not significantly deviate from year to year, those data provide an accurate baseline for microgrid performance during an outage.

As previously noted, there is not much rooftop solar potential at the WWTP. The modeled PV capacity of 13.6 kW makes almost no contribution to the overall generation of the microgrid.

Unless a larger site is found that can house a much larger solar array, it is not recommended to install a PV array at the site.

Finally, a very detailed pilot project[1] for a tidal turbine array located in Admiralty Inlet was previously conducted and ultimately did not move forward. The location and scope of that project were different than those modeled for Port Townsend here, but many of the challenges and environmental requirements for that project would likely apply to this one as well.

### 5.1.2 Recommendations for Community Microgrids

**Sequim – Guy Cole Center**

Several different microgrid system sizes were presented in this analysis. If the City of Sequim intends to install a microgrid at Guy Cole Center, they will have to weigh different priorities and constraints when deciding among them. As discussed in Section 4.1.2, Guy Cole Center is located almost two miles from the point of interconnection of the tidal generator, and the cost for connecting the generator and the rest of the microgrid will be significant. For that reason, it may make more sense to install a microgrid with only solar generation or choose a different building located closer to the tidal generator to serve as a resilience hub. In general, as tidal generation can be very expensive, it is ideal for microgrids connected to that resource to be located close to the point of interconnection. Choosing an ideal microgrid location can also be informed by the feeder topology.

Given this distance, it is also possible that in the event of an outage, the connection between the tidal generator and the rest of the microgrid may not be active, depending on what caused the outage, and the microgrid may have to rely on PV generation alone. If both PV and tidal resources are available, they provide more reliable energy together, as they are complementary generation sources that produce energy at different times of the day.

For any of the renewable energy options, it is much more cost effective to install a smaller battery, and there is little difference in the resilience benefits of a small versus larger battery. It is also important to note that this is merely a feasibility analysis, and a more detailed design process should follow before taking additional steps.

The results of the hosting capacity analysis indicate that voltage violations occur at lower PV and tidal capacities than thermal violations. The results in Table 4 show that a PV system with a rated power of 30 kW or more can cause voltage violations (overvoltage) at the microgrid bus. This could hypothetically be an issue for microgrid systems with rated PV capacities of 94 kW but not those with rated PV capacities of 22 kW. However, the actual power generated by a PV system is variable and rarely reaches the rated power. The analysis in Section 4.1.2 uses a PV system with a rated capacity of 94 kW, and the instantaneous output of that PV system rarely exceeds 30 kW during the simulation horizon, albeit that simulation is during November. Moreover, it is also important to note that the results of the hosting capacity analysis are more conservative since they don't consider the operation of voltage control devices such as on-load tap changers (OLTCs), which can mitigate these overvoltage violations. Unlike the hosting capacity analysis, the grid-connected simulations in Section 4.1.2 are not static; hence, they model the time-dependent control changes that are used to regulate the voltage. This is one example of a system upgrade that can increase the hosting capacity limit to specifically mitigate voltage violations. Voltage violations can also be addressed using smart inverters that control

[1] https://tethys.pnnl.gov/project-sites/admiralty-inlet-pilot-tidal-project

the injection of reactive power into the system, switched capacitor banks, and other power electronic devices such as static var compensators (SVCs) and distribution static synchronous compensators (D-STATCOMs). It is also important to note that the proposed tidal generator capacity of 90 kW is less than the capacity at which voltage violations are possible at that distribution system node. Overall, our simulations indicate that the proposed microgrid at Guy Cole Center does not exhibit severe voltage regulation issues with the proposed PV and tidal capacities, and as such, the existing OLTC at the substation is sufficient to regulate the microgrid voltage.

Thermal violations, which refer to the overloading of the lines due to large currents that exceed their current carrying capability, also do not pose a significant threat to microgrid operations. The existing lines within and outside the microgrid have sufficient current carrying capacity to support the proposed PV and tidal capacities. However, our simulations do indicate the bidirectional flow of power between the microgrid and the distribution system in the grid-connected mode. This observation is important to consider when designing protection schemes for the microgrid, such as relays and circuit breakers. It is recommended that the microgrid design incorporate directional overcurrent relays that can differentiate the direction of the fault current and trip when the fault occurs in the designated direction.

**Port Townsend – Wastewater Treatment Plant**

As for the Sequim analysis, several different microgrid system sizes were included in this analysis, albeit with a few more options. Three different tidal turbine depths were modeled, with little difference in microgrid performance. A larger range of depths could be included but would require the turbine to not be fully submerged. As there was little difference in performance, the depth should be chosen based on ease of installation and any other environmental considerations. Three different numbers of turbines were also considered (one, two, or three), and this did have a large effect on microgrid performance. A larger number of turbines could make installation more complicated and would certainly increase the cost but would also increase the amount of revenue that could be generated from net metering during the year and would lower the reliance on the diesel generator during an outage. Any net-metering revenue would be constrained by local net-metering policies. For each PV and tidal turbine capacity, three different battery sizes were included. As for the Sequim analysis, there was not a significant benefit to including a larger battery; thus, the smallest battery size is recommended.

## 5.2 Applications to Future Work

The analysis framework developed here is intended to be replicable to other communities or sites within the studied communities. The community outreach and feedback process developed by NODC could be used to gather the priorities and constraints of communities that would then be used to inform a microgrid and distribution system analysis. The software used to perform these analyses is open source and freely available and could be run by users with the requisite technical expertise.

As was previously mentioned, obtaining accurate high-resolution data is critical for producing realistic results. This includes resource data, such as tidal velocity maps, as well as hourly building load and feeder data.

This project experienced some challenges choosing both communities for the case study and microgrid locations. The project team needed to identify communities of interest to evaluate ME resource potential, but some of these locations ultimately did not have sufficient tidal resources,

leading to potentially interested communities not being chosen for the analysis. In addition, the team needed potential microgrid locations within the identified communities to determine feasibility with respect to the distribution system topology and tidal resource location, but the communities needed more constraints to narrow down potential microgrid locations. This resulted in back-and-forth conversations, extending the timeline for determining project locations. For future work, we suggest providing a list of constraints (i.e., distance from water, area available for solar PV) to help the community narrow down potential microgrid locations. It is also recommended to provide ample communication during the community and site location process to ensure that all participants are aware of the project and siting constraints.

While this analysis only considered individual building microgrids, they can also be used to power multiple interconnected buildings or even entire communities. More than one connected microgrid could have a larger impact on community resilience and could provide more flexibility on microgrid siting with respect to the location of tidal resources. For example, if some of the sites are located closer to tidal resources, they could share those with other sites that are further away.

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# Appendix A

## A.1 Full Microgrid Results

### A.1.1 Sequim – Guy Cole Center

Table A.1 shows the full results for a 1-week outage and 400-scenario simulation. The capital cost includes the cost of the equipment and installation of the microgrid only and does not include any costs required for interconnection to the distribution system or additional lines and switches required to connect the tidal turbine to the rest of the microgrid. The full details of the cost assumptions are included in Appendix A.2. The net-metering revenue is calculated assuming that the photovoltaic (PV) and tidal generators are able to feed energy back to the grid in the normal grid-connected mode. It is assumed that there are no limits on the amount of energy that can be fed back to the grid and that the net-metering rate is the same as the utility rate provided in bills from the Public Utility District (PUD). It is assumed that the battery is not operating in the grid-connected mode. The PV, tidal, battery, and generator percentages shown here represent the average percentage of the load met by each component average across the 400 outage simulations. “Fuel used – average scenario” presents the average amount of fuel used across the 400 outage scenarios, and “fuel used – conservative scenario” presents the maximum amount of fuel used across the 400 scenarios. The storage recovery represents the percentage of the excess renewable generation (PV and tidal) beyond meeting the load that is able to charge the battery during an outage. This is also calculated as the average across the 400 outage simulations.

Table A.1. Output metrics for the Guy Cole Center analysis for the 400-outage simulation of a 1-week outage.

| System name | Capital cost ($) | Net-metering revenue ($/yr) | PV percentage (%) | Tidal percentage (%) | Battery percentage (%) | Generator percentage (%) | Fuel used – average scenario (gal) | Fuel used – conservative scenario (gal) | Storage recovery (%) |
|---|---|---|---|---|---|---|---|---|---|
| **Generator only** | $24,095 | $0 | 0 | 0 | 0 | 100 | 193.3 | 430.4 | 0 |
| **PV, small battery** | $517,683 | $9,400 | 43 | 0 | 33 | 25 | 69.7 | 319.3 | 64 |
| **PV, med battery** | $616,426 | $9,400 | 43 | 0 | 35 | 22 | 62.7 | 303.0 | 64 |
| **PV, large battery** | $715,170 | $9,400 | 43 | 0 | 38 | 20 | 56.2 | 288.6 | 64 |
| **PV + tidal, small battery** | $806,968 | $11,649 | 17 | 44 | 27 | 12 | 36.4 | 259.8 | 52 |
| **PV + tidal, med battery** | $873,932 | $11,649 | 17 | 44 | 28 | 10 | 31.3 | 251.8 | 54 |
| **PV + tidal, large battery** | $939,331 | $11,649 | 17 | 44 | 30 | 9 | 27.6 | 240.0 | 54 |

Table A.2 shows the full results for a 1-week outage storm scenario simulation. The metrics are as described above, except not averaged over many simulations, since only one simulation was used. The costs are not included here as they are identical to those listed above.

Table A.2. Output metrics for the Guy Cole Center analysis for the storm simulation of a 1-week outage.

| System name | PV percentage (%) | Tidal percentage (%) | Battery percentage (%) | Generator percentage (%) | Fuel used (gal) | Storage recovery (%) |
|---|---|---|---|---|---|---|
| **Generator only** | 0 | 0 | 0 | 100 | 147.6 | 0 |
| **PV, small battery** | 22 | 0 | 23 | 54 | 81.0 | 100 |
| **PV, med battery** | 22 | 0 | 31 | 47 | 69.2 | 100 |
| **PV, large battery** | 22 | 0 | 39 | 39 | 58.2 | 100 |
| **PV + tidal, small battery** | 6 | 27 | 16 | 50 | 77.1 | 80 |
| **PV + tidal, med battery** | 6 | 27 | 21 | 45 | 69.4 | 81 |
| **PV + tidal, large battery** | 6 | 27 | 26 | 41 | 61.6 | 81 |

Figure A.1 shows how fuel usage varies across the different system options. It is notable that for systems with the same renewable energy capacity, there is not much difference in fuel usage for the different battery sizes, even though the smallest battery size is half of the largest size.

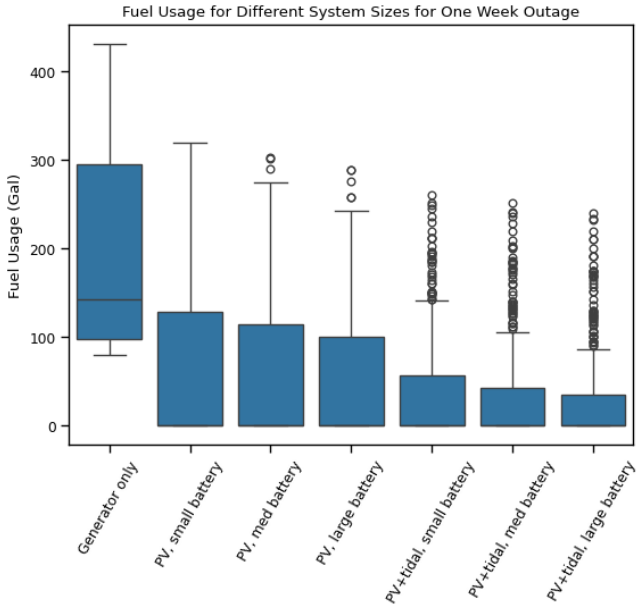



Figure A.1. Fuel usage for different microgrid systems for Sequim for a 1-week outage. For each system, the box represents the first to third quartile of scenario runs with the central line as the median. The whiskers show the full range of data with outliers depicted as separate dots.

### A.1.2 Port Townsend – Wastewater Treatment Plant (WWTP)

Table A.3 shows full results for a 1-week outage, 16.5 m turbine depth, and 400-scenario simulation. The metrics are calculated as described for the Sequim analysis.

Table A.3. Output metrics for the Port Townsend WWTP analysis for the 400-outage simulation of a 1-week outage.

| System name | Capital cost ($) | Net-metering revenue ($/year) | PV percentage (%) | Tidal percentage (%) | Battery percentage (%) | Generator percentage (%) | Fuel used – average scenario (gal) | Fuel used – conservative scenario (gal) | Storage recovery (%) |
|---|---|---|---|---|---|---|---|---|---|
| **Generator only** | $175,650 | $0 | 0 | 0 | 0 | 100 | 1691.6 | 2033.9 | 0 |
| **PV, small battery** | $1,413,478 | $1,511 | 1 | 0 | 0 | 99 | 1669.8 | 2028.4 | 0 |
| **PV, med battery** | $2,014,372 | $1,511 | 1 | 0 | 0 | 99 | 1669.8 | 2028.4 | 0 |
| **PV, large battery** | $2,615,266 | $1,511 | 1 | 0 | 0 | 99 | 1669.8 | 2028.4 | 0 |
| **PV + 1 turbine, small battery** | $2,914,438 | $42,799 | 1 | 29 | 9 | 60 | 1045.7 | 1596.8 | 95 |
| **PV + 1 turbine, med battery** | $3,434,178 | $42,799 | 1 | 29 | 12 | 57 | 990.7 | 1520.7 | 97 |
| **PV + 1 turbine, large battery** | $3,953,919 | $42,799 | 1 | 29 | 15 | 54 | 939.2 | 1468.4 | 97 |
| **PV + 2 turbines, small battery** | $4,532,582 | $84,087 | 1 | 44 | 21 | 34 | 592.8 | 1307.7 | 92 |
| **PV + 2 turbines, med battery** | $5,026,395 | $84,087 | 1 | 44 | 24 | 31 | 536.4 | 1262.4 | 95 |
| **PV + 2 turbines, large battery** | $5,520,207 | $84,087 | 1 | 44 | 27 | 28 | 491.1 | 1215.1 | 95 |
| **PV + 3 turbines, small battery** | $6,172,835 | $125,374 | 1 | 52 | 30 | 17 | 297.5 | 1086.3 | 78 |
| **PV + 3 turbines, med battery** | $6,651,774 | $125,374 | 1 | 52 | 33 | 15 | 253.5 | 1044.2 | 81 |
| **PV + 3 turbines, large battery** | $7,130,713 | $125,374 | 1 | 52 | 34 | 13 | 222.9 | 1004.4 | 82 |

Table A.4 shows the full results for a 1-week outage storm scenario simulation. The metrics are as described above for the Sequim analysis. The costs are not included here as they are identical to those listed above.

Table A.4. Output metrics for the Port Townsend WWTP analysis for the storm simulation of a 1-week outage.

| System name | PV percentage (%) | Tidal percentage (%) | Battery percentage (%) | Generator percentage (%) | Fuel used (gal) | Storage recovery (%) |
|---|---|---|---|---|---|---|
| **Generator only** | 0 | 0 | 0 | 100 | 1752.4 | 0 |
| **PV, small battery** | 1 | 0 | 0 | 99 | 1741.9 | 0 |
| **PV, med battery** | 1 | 0 | 0 | 99 | 1741.9 | 0 |
| **PV, large battery** | 1 | 0 | 0 | 99 | 1741.9 | 0 |
| **PV + 1 turbine, small battery** | 1 | 20 | 7 | 72 | 1315.9 | 100 |
| **PV + 1 turbine, med battery** | 1 | 20 | 10 | 69 | 1265.7 | 100 |
| **PV + 1 turbine, large battery** | 1 | 20 | 13 | 66 | 1211.4 | 100 |
| **PV + 2 turbines, small battery** | 1 | 34 | 11 | 54 | 1000.7 | 96 |
| **PV + 2 turbines, med battery** | 1 | 34 | 13 | 52 | 956.7 | 96 |
| **PV + 2 turbines, large battery** | 1 | 34 | 16 | 49 | 909.3 | 96 |
| **PV + 3 turbines, small battery** | 1 | 44 | 16 | 39 | 725.7 | 94 |
| **PV + 3 turbines, med battery** | 1 | 44 | 18 | 37 | 686.6 | 94 |
| **PV + 3 turbines, large battery** | 1 | 44 | 21 | 35 | 645.0 | 94 |

Figure A.2 shows how fuel usage varies across the different system options.

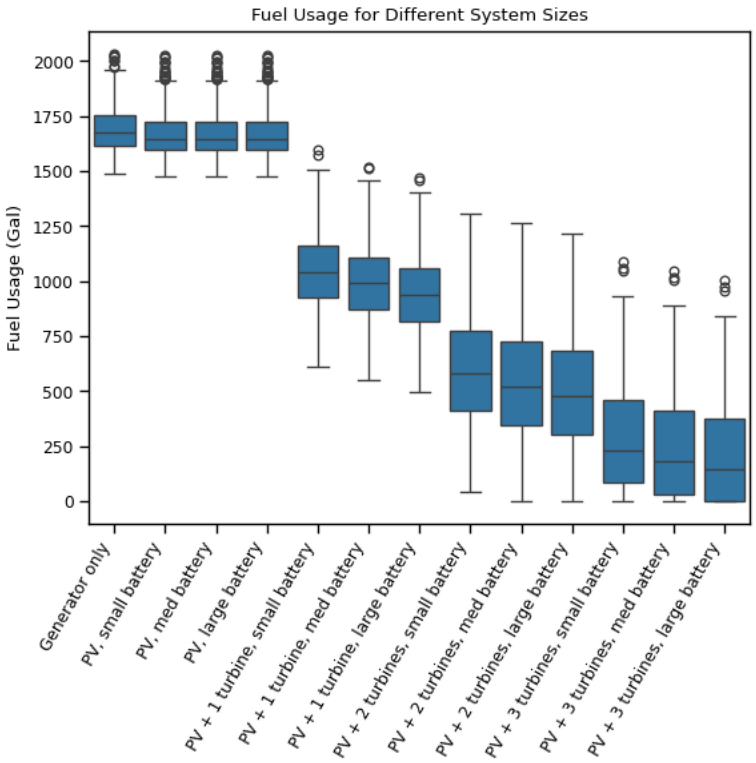



Figure A.2. Fuel usage for different microgrid systems for Port Townsend for a 1-week outage. For each system, the box represents the first to third quartile of scenario runs with the central line as the median. The whiskers show the full range of data with outliers depicted as separate dots.

## A.2 Assumptions

### A.2.1 Cost Assumptions

The listed capital costs include costs for the PV, tidal, and battery systems, as well as a backup diesel generator and adequately sized fuel tank.

**PV Costs**

Roof-mounted costs (for the Port Townsend analysis) are based on the NLR report *U.S. Solar Photovoltaic System and Energy Storage Cost Benchmarks: Q1 2021* (Ramasamy et al. 2021), which lists capital costs for PV systems of various sizes (residential, commercial, and utility-scale). From these costs, adders for different racking types were extrapolated as follows: roof to ground cost adder: +5%. For the size of the system considered here, the cost is $2.65/W. For carport installations (for the Sequim analysis), a carport adder was determined from the *Vermont Solar Cost Study* (Seddon 2016) to be +19% as compared with roof-mounted, for a cost of $3.15/W.

### Tidal Costs

Tidal turbine costs are specific to each device, with costs (converted from euros to dollars) from the research paper “Cost Modelling and Design Optimisation of Tidal Stream Turbines” (Coles et al. 2021).

### Battery Costs

Battery costs are calculated assuming $0.521/Wh for the battery system and construction/commissioning and $0.401/W for the inverter and balance of system costs. These are based on the average of 2018 and projected 2025 costs from *Energy Storage Technology and Cost Characterization Report* (Mongird et al. 2019).

### Generator and Fuel Tank Costs

The cost for generators is based on CAT model costs from the GSA Advantage website[1] and then extrapolated to $191/kW. This is then doubled to $382/kW with the assumption that the total capital cost is twice the cost listed to account for installation costs. The cost for any given system is based on the largest generator size from all of the outage scenarios.

The fuel tank sizes and costs are based on ConVault tank systems with prices from the GSA Advantage website[1].

[1] https://www.gsaadvantage.gov

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