PNNL-36953

Case Study: Port of Anacortes

Evaluating Opportunities for Port Technical Assistance through a Collaborative Research Pilot

October 2024

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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
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EXECUTIVE SUMMARY

Researchers at Pacific Northwest National Laboratory (PNNL) conducted a case study in collaboration with the staff at the Port of Anacortes, Washington, between February and September 2024, focusing on the port’s energy transition efforts. This report outlines the unique aspects of the port, highlights the motivations for decarbonization, and describes initiatives aimed at improving the port's energy resilience and environmental sustainability.

This report explores renewable energy options and evaluates microgrid solutions for the port. It also outlines potential pathways for fuel and equipment transitions for scenarios with targets of reducing greenhouse gas emissions by 2030 and having net-zero emissions at the port by 2050.

Collaborative projects like this at multiple U.S. ports can strengthen critical infrastructure resilience, promote environmental justice, and facilitate the collection of data and best practices for broader implementation. By leveraging expertise from national laboratories, port staff can be better equipped, with insights into various strategies, to improve decision-making for future decarbonization and energy transitions. The findings from this case study can also guide future policy decisions supporting decarbonization in other "hard-to-decarbonize" sectors connected to port activities.

ACRONYMS AND ABBREVIATIONS

AC	alternating current
BESS	battery energy storage systems
CAPEX	capital expenses
CCS	carbon capture and storage
CI	carbon intensity
CO2	carbon dioxide
CO2e	carbon dioxide equivalent
DC	direct current
DOE	Department of Energy
EPA	Environmental Protection Agency
EV	electric vehicle
ft	feet
GHG	greenhouse gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy use in Transportation (model)
IRENA	International Renewable Energy Agency
kW	kilowatt
LCA	Life-cycle Analysis
LNG	liquefied natural gas
m	meters
m/s	meters per second
MCOR	Microgrid Component Optimization for Resiliency (tool)
MDO	marine diesel oil
MW	megawatt
MWh	megawatt hours
NOAA	National Oceanic and Atmospheric Administration
NSRDB	National Solar Radiation Database
O&M	operations and maintenance
OGV	ocean-going vessel
PM	particulate matter
PNNL	Pacific Northwest National Laboratory
PSE	Puget Sound Energy
PV	photovoltaic
RM2	Reference Model 2
RMI	Rocky Mountain Institute
SO2	sulfur dioxide

TRL	technology readiness level
ULSD	ultra-low sulfur diesel
WSDOT	Washington State Department of Transportation

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MOTIVATION

The maritime sector is under increasing pressure to achieve net-zero greenhouse gas (GHG) emissions by 2050, and this transition will require unprecedented action from U.S. ports of all sizes. However, energy transition planning is not a standard activity for ports and their tenants, and many are seeking to better understand the most effective course of action to reduce their emissions. It is important to support the maritime industry's energy transition because of its critical and growing role within the global economy (Stopford 2024). Estimates report that approximately 80 percent of annual global trade by volume is transported via sea and, in North America, 76 percent of all trade involved maritime transportation (MordorIntelligence 2024). The maritime industry has been growing quickly over the past decade (Grzelakowski et al. 2022) and is projected to continue to grow, at a slightly lower rate, over the medium-term (2023–2027) (Sirimanne and Hoffmann 2022). The growth of the maritime sector, combined with an ambitious timeline for maritime decarbonization by 2050, are putting pressure on U.S. ports of varying types and sizes.

U.S. national laboratories have a deep bench of technical capabilities and a history of supporting ambitious energy transition activities that could be leveraged to accelerate maritime decarbonization through a port technical assistance program. Such a program could assist ports' individual needs while simultaneously developing a public repository of resources and best practices. For example, national laboratories can help ports better understand what the demand and supply of alternative fuels will be in their region, how their electrical demand might increase, and how new investments in clean energy technologies could improve operational resilience and environmental justice. A port technical assistance program run by national laboratories would also help build a nationwide repository of best practices, data, and lessons learned in port decarbonization to inform future port efforts and scale action beyond a one-to-one technical assistance model in the future.

CASE STUDY OVERVIEW

This case study overviews a collaboration between the Pacific Northwest National Laboratory (PNNL) and the Port of Anacortes, WA to advance the port's early-stage decarbonization efforts. PNNL aimed to better understand how its technical capabilities could be used to advance port decarbonization by testing them in a real-world example. The Port of Anacortes was interested in accessing the technical capabilities available at a national laboratory to help them navigate the complexities of their energy transition and develop resiliency. The Port of Anacortes was selected for this case study in part because it is a gateway to remote communities on the San Juan Islands and an emergency response site for Skagit County. Though ports will have varying technical assistance needs, this case study provides one example of what technical assistance could look like for a small port that plays an important role in the region's economy and resiliency plans.

The case study was completed from February to September 2024. During this time a core group of PNNL and Port of Anacortes staff met approximately every two weeks. PNNL also attended a port commission meeting and conducted one site visit.

The effort began with multiple introductory meetings to better understand the Port of Anacortes, including its decarbonization ambitions, progress to-date, and potential technical assistance needs. These conversations helped PNNL develop a list of its technical capabilities (**Appendix A**), which were shared with the Port of Anacortes for feedback and prioritization. The Port of Anacortes expressed interest in all the technical capabilities listed and marked the following as their highest priorities:

- **Energy System Resilience** – Support preliminary design of potential microgrid solutions and other resilience strategies, including technoeconomic analysis, for ports to help achieve energy and resilience goals.
- **Renewable Energy Assessments** – Analyze port location(s) for feasibility of implementing various renewable energy options, which could include wind, solar, bioenergy, geothermal, and marine energy.
- **Critical Infrastructure Analysis** – Identify critical port functions and associated infrastructure and energy demands. Assess potential vulnerabilities and provide recommendations to improve resiliency.

The joint team decided to focus limited time and funding on completing renewable energy assessments and an energy system resilience assessment as a part of the case study. The port is constrained in the amount of new electrical capacity it can access, particularly in the next 5 to 10 years. A key motivation for the renewable energy assessments was to better understand how on-site or near-site generation could potentially help the port overcome these electrical constraints and provide a more diverse, localized portfolio of clean energy solutions. To complement this effort, the team decided to focus the energy system resilience analysis on designing a potential microgrid that could integrate promising solutions from the renewable energy assessments. The microgrid could also enhance the resiliency of the port's critical energy infrastructure by providing on-site backup power.

In a parallel effort, PNNL conducted Life-cycle Analysis (LCA) to determine potential decarbonization pathways for Puget Sound ports and included its analysis of the Port of Anacortes within this case study. The LCA uses data from the Puget Sound Maritime Emissions Inventory (Puget Sound Maritime Air Forum 2024) to establish an emissions baseline and life-cycle emissions data on alternative marine fuels from the Greenhouse Gases, Regulated Emissions, and Energy use in Transportation (GREET) model (EERE n.d.) to map how the port could achieve net-zero carbon emissions by 2050. In addition to traditional LCA metrics, the team also evaluated how switching to cleaner alternative fuels could reduce harmful emissions in communities near the Port of Anacortes.

All analyses were discussed regularly with the Port of Anacortes to refine assumptions, address questions, and generate meaningful results. They are explained in further detail in the following sections, along with potential next steps for the port. The case study concludes with a discussion section highlighting lessons learned from these efforts that can be used to inform a future port technical assistance program.

OVERVIEW OF THE PORT OF ANACORTES

The Port of Anacortes is located along the Guemes Channel within the Puget Sound in Washington State. The Puget Sound is a unique fjord system that has many interconnected channels, dozens of islands, and is the second largest estuary in the U.S. (**Figure 1**).

Figure 1. Labeled satellite image[1] of the Puget Sound in Washington State and the location of the Port of Anacortes.

The deep-water Port of Anacortes services nearby island communities, including the San Juan Islands, and plays a critical role as a transportation hub and emergency response site. The port itself is located on Fidalgo Island, which is connected to the mainland via multiple bridges; if a natural disaster compromised these bridges, the Port of Anacortes would be the primary way to receive and distribute goods to the local community. The port is also a municipal corporation that generates economic activity and tourism (Port of Anacortes n.d.[a]) and has access to shipping routes along the Pacific Rim, Canada, and Alaska (Washington State Transportation Commission 2022). The land on which the port operates was home to the Samish and Swinomish tribes before the development of the town of Anacortes in 1879 (Anacortes Washington n.d.).

The Port of Anacortes consists of 80 acres of commercial properties (Port of Anacortes n.d.[a]), a category 1 airport (Washington State Transportation Commission 2022), a marine terminal,

[1] Attribution: Imagery ©2024 Landsat/Copernicus, Data SIO, NOAA, U.S. Navy, GEBCO, Data LDEO-Columbia, NSF, NOAA, Map data ©2024 Google.

and a marina that provide services and mooring to both commercial and private users. **Figure 2** shows an overall view of these areas.

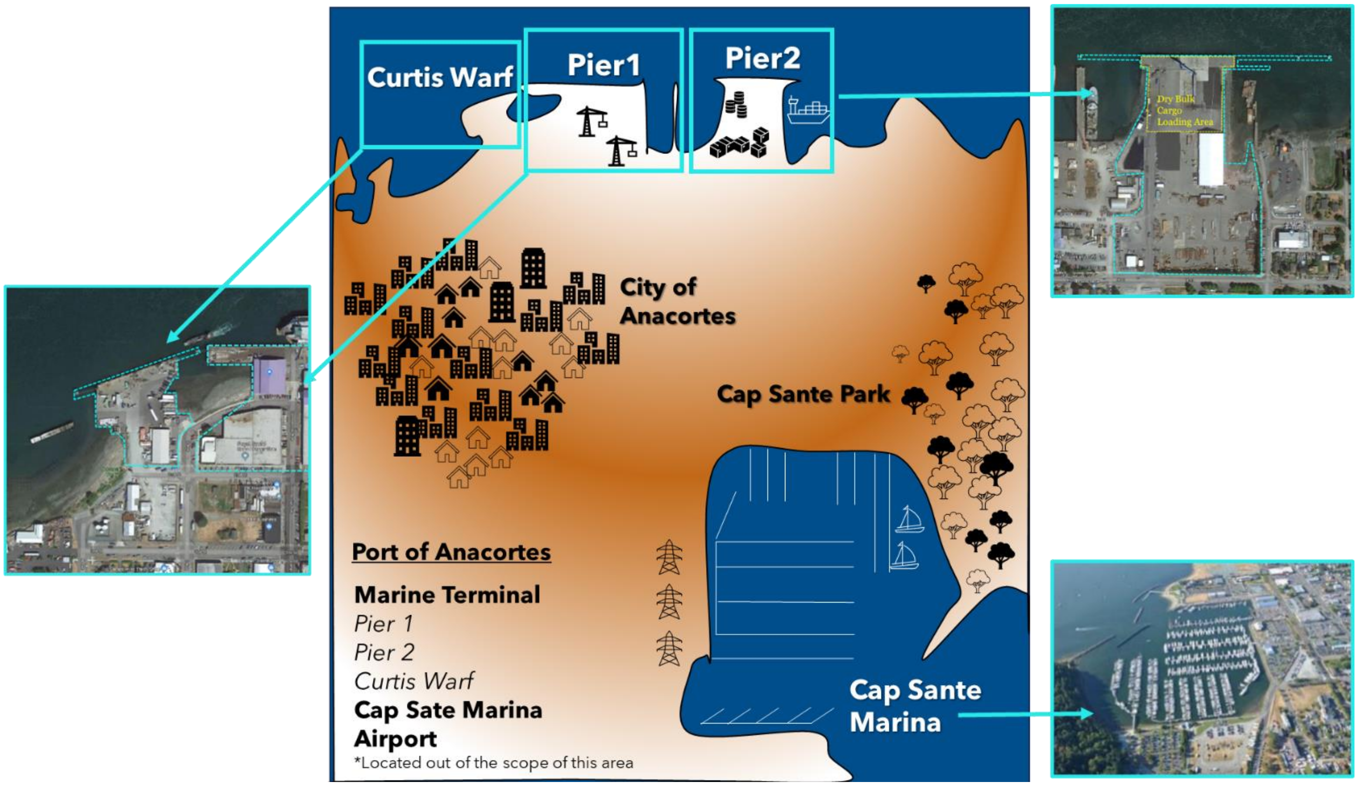


Figure 2. Area map of the Port of Anacortes areas with magnified Satellite images of the marked marina and marine terminal areas (Washington State Transportation Commission 2022).

MARINE TERMINAL

The Port of Anacortes marine terminal is made up of three piers (Pier 1, Pier 2, and Curtis Warf), a shipyard and warehouses.

Pier 1 – This pier is home to the port administrative offices and provides moorage for different vessel types. The floating dry dock is used by the long-term tenant Dakota Creek Industries as a support for its shipbuilding and repair operations. M&M seafood is another long-term tenant that uses Pier 1 as a seafood processing area (Port of Anacortes Commissioners n.d.).

Pier 2 – This pier is the most active part of the marine terminal and is the deepest of the three piers. It is used for high and heavy lift and dry bulk cargo loading (EDASC 2024). The primary bulk products transported at Pier 2 are petroleum coke and prilled sulfur (Port of Anacortes Commissioners. n.d.), which are exported to China, Japan, India, Brazil, and Mexico. Pier 2 also has short-term moorage of vessels, including barges, tug vessels, and vessels up to 1,200 feet in length (EDASC 2024). A short-term assembly tenant of Pier 2 is Transpac Marinas with other tenants leasing smaller buildings to support cargo operations such as Metro Ports, SGS, and the International Longshore & Warehouse Union (Washington State Transportation Commission 2022).

Curtis Warf – This pier includes a seafood processing facility, commercial vessel moorage, and short-term moorage. Its tenants include American Spirit, American Constellation cruise ships, Crowley harbor craft, as well as Pacific Dream Seafoods and Dakota Creek (Port of Anacortes Commissioners n.d.).

MARINA

The Cap Sante Marina has 1,000 boat slips for "local commercial fisherman, tour companies, yacht brokerage firms, and other commercial marine businesses" but a majority is used for recreational purposes. The marina has both permanent and guest moorage and processed 20,400 guest nights in 2022 (Port of Anacortes Commissioners n.d.).

PROPERTIES

In addition to its revenue-generating maritime operations, the port plays a key role in driving economic growth by supporting businesses within the urban area. It manages 80 acres of commercial property, with many tenants holding long-term leases. One notable property is the Port's Seafarers' Memorial Park Building that is often used as a venue for events. The Port also rents out other venue sites and hosts port sponsored events. Future development plans may include building sites to accommodate tenants such as restaurants, hotels, offices, retail shops and other marine-related businesses (Port of Anacortes n.d.[b]).

PORT ECONOMIC ACTIVITY

The Port of Anacortes is a designated small port[2] with an annual tonnage in 2021 of 268,539 total exported metric tons.[3] The port's 2024 budget projected an operating revenue of $20,602,400, including revenue from the airport, marina, marine terminal, and other properties. Marina operations were projected to comprise the majority of the port's operating revenue (56 percent), followed by operating revenue from the marine terminal (31 percent). The primary sources of revenue for the marina are moorage and fuel sales. Most of the revenue generated from the marine terminal is from "cargo shipments, short- and long-term lease of dock space, other ground leases, and transient dockage revenue from the berthing of vessels, barges, and tugboats" (Port of Anacortes Commissioners n.d.). The total operating expenses for the port in 2024 were projected at $17,888,100, with the marina accounting for 57 percent and the marine terminal accounting for 29 percent (Port of Anacortes n.d.[b]; Port of Anacortes Commissioners n.d.).

SUSTAINABILITY EFFORTS

The Port of Anacortes maintains a history of supporting environmental stewardship (Port of Anacortes n.d.[a]) and, in recent years, has increased its focus on reducing harmful emissions from maritime activity. This work is motivated in part by the port's desire to gain a better understanding of their energy footprint and to identify opportunities for future improvements and

[2] Based on the U.S. EPA definition of a small port for the 2024 Clean Ports Program.

[3] Office of the Washington State Auditor, Pat McCarthy, May 6, 2024. Insurance Building, P.O. Box 40021 Olympia, WA.

cost savings. For example, the port recently completed a Marine Terminal Modernization Feasibility Study that recommended upgrades, including the provision of additional shore power for vessels at berth (Port of Anacortes Commissioners n.d.).

The Port of Anacortes voluntarily takes part in multiple efforts to reduce its environmental impact. For example, they participate in a regional maritime emissions inventory called the Puget Sound Maritime Air Emissions Inventory (Puget Sound Maritime Air Forum 2024), along with six other ports in the Puget Sound. In a five-year period (2016–2021) the Port of Anacortes reduced their carbon dioxide (CO_2) equivalent (CO_2e) emissions by 21 percent. The port also reduced other criteria pollutant emissions, including particulate matter (PM_{10} & $PM_{2.5}$), by 31 percent and sulfur dioxide (SO_2) by 29 percent. These reduction values are all reported for 2021 compared to the 2016 baseline. The port is also a certified member of Green Marine, an initiative that drives ports to make changes that target environmental issues like greenhouse gases, community impacts, and water and land pollution (Port of Anacortes Commissioners n.d.).

The port has both invested its own resources in and successfully secured external funding for sustainability efforts. In 2023, the Port of Anacortes was awarded $500,000 in funding for port electrification through the Washington State Department of Transportation (WSDOT) and is using the funding for electric fleet vehicles, charging infrastructure, and electric infrastructure for commercial vessels at its Curtis Wharf (Port of Anacortes Commissioners n.d.; Port of Anacortes 2024). In 2024, the port was awarded $1.03 million in funding from WSDOT through its new Port Electrification Grant Program, which it plans to use for shore power and zero-emission equipment (Matkin 2024).

PORT ENERGY LANDSCAPE

The Port of Anacortes' primary source of energy is electricity, and it also uses a small amount of natural gas. Both electricity and natural gas are provided by Puget Sound Energy (PSE), the local investor-owned utility. The port operates under PSE's Commercial 25 rate schedule for electricity.[4] In 2021, the port became part of PSE's Green Power Program (Port of Anacortes 2021), which allows the port to purchase electricity that is matched 100 percent with renewably generated electricity (PSE n.d.). Natural gas data was not available and, therefore, is not included in the scope of this study. Port operations also require liquid fuels (e.g., gasoline, diesel, ultra-low sulfur diesel [ULSD]), which are provided directly to customers and tenants through the port's fuel dock, which is operated by the port. Some large customers and tenants also purchase fuel directly from third-party fuel providers and the fuel is delivered via truck.

CURRENT ELECTRICITY USAGE

The port primarily manages its accounts with PSE and passes through the cost of electricity to its moorage customers and other tenants. However, some port tenants hold their own accounts with PSE, and their electricity usage is, therefore, not captured within the port's annual electricity usage used for this study.

[4] PSE's Commercial 25 rates schedule is for commercial or industrial customers with a demand greater than 50 kW but less than or equal to 350 kW.

Table 1 summarizes the port's electricity usage for 2019, 2020, and 2021 for its airport, marina, marine terminal, and other properties.[5] Its total annual usage over these years ranged from 1,309 to 1,453 MWh. The marina and marine terminal consistently account for the largest portion of total electricity usage at the Port of Anacortes. The electricity usage at the airport and properties are significantly lower compared to the marina and marine terminals. The distribution of electricity usage for 2021 is shown in **Figure 3**, listed by location. Note the airport electricity, though incorporated in this section, is not included in the rest of the analyses. This is because the airport is geographically separated from the maritime port facilities and primarily serves a different customer base.

Table 1. Reported electricity usage at the Port of Anacortes (2019–2021) by port area.

Electricity Usage (MWh)	2019	2020	2021
Airport	99	112	105
Marina	788	760	690
Marine Terminal	510	514	416
Properties	37	67	98
Total	1,433	1,453	1,309

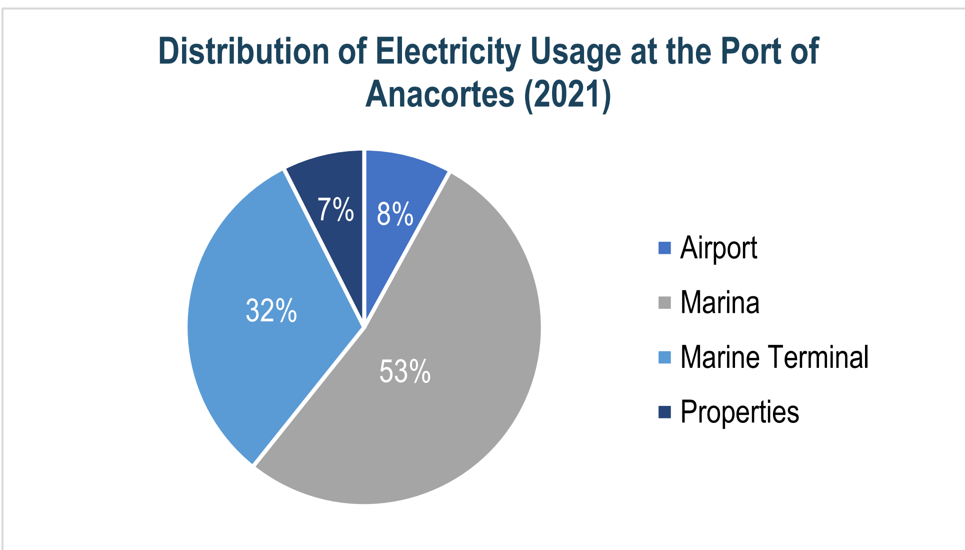


Figure 3. Distribution of the electricity usage at the Port of Anacortes in 2021 by port area.

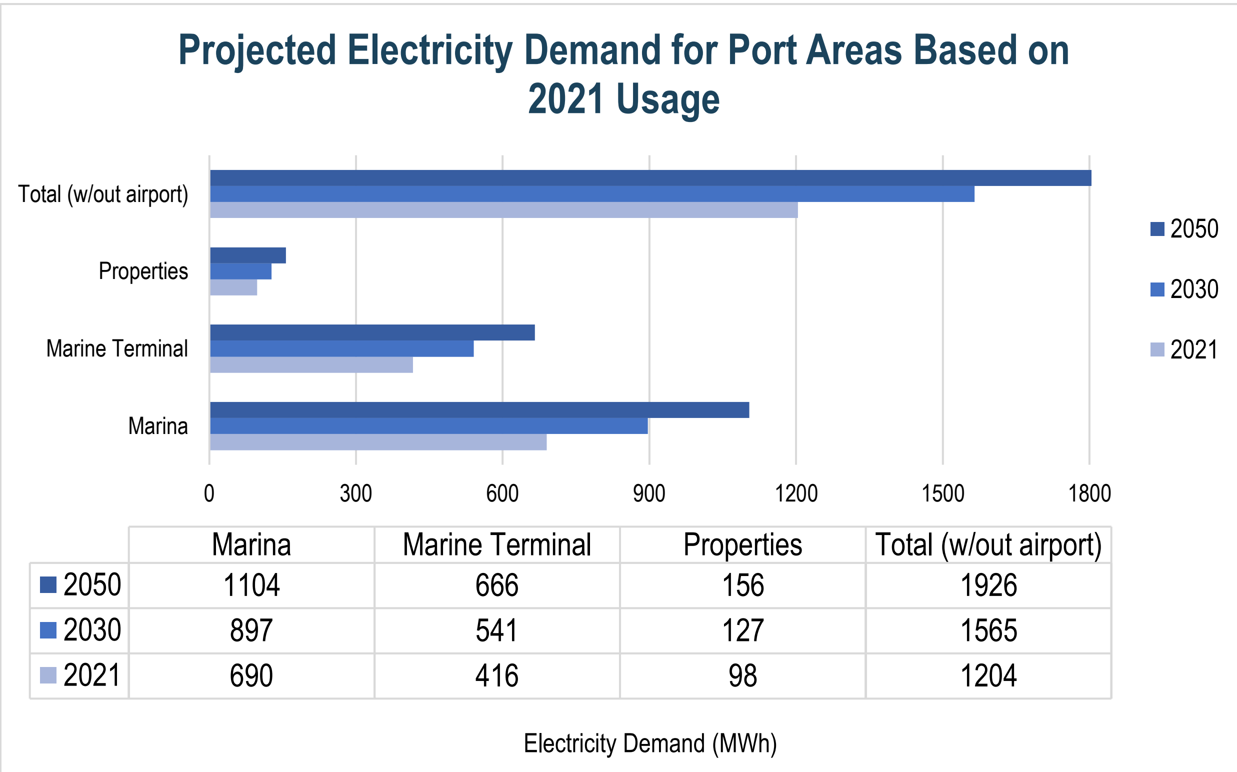
PROJECTED FUTURE ELECTRICITY DEMANDS

Ports are developing electrical infrastructure in anticipation of emission reduction goals within the maritime sector. In tandem, global shipping demands are projected to increase in the

[5] Electricity usage for years 2019, 2020, and 2021 were provided directly by the Port of Anacortes.

coming decades. The result is an overall increase in energy demand at ports to operate at this higher capacity and power new electrical loads.

The International Renewable Energy Agency (IRENA) published a report that outlined potential future scenarios for the increase in maritime shipping demand and energy needs (Castellanos et al. 2021). Researchers chose to use growth rates from the study's moderately progressive scenario (referenced in the study as the Transforming Energy Scenario) to estimate electricity demand for the Port of Anacortes. The Near-term (2030) scenario incorporated a 30 percent increase in port energy demand compared to the 2021 baseline, and the Long-term Standard (2050) scenario incorporated a 60 percent increase in port energy demand compared to the 2021 baseline. These growth rates were incorporated into the Port of Anacortes electricity demand projections for 2030 and 2050, depicted in **Figure 4**.



	Marina	Marine Terminal	Properties	Total (w/out airport)
2050	1104	666	156	1926
2030	897	541	127	1565
2021	690	416	98	1204

Figure 4. Historic electricity usage (2021) and projected future electricity demand in 2030 and 2050 for the Port of Anacortes.

CURRENT AND PROJECTED FUEL DEMANDS

Liquid fuels are another key energy source at the Port of Anacortes, supplied to tenants and customers by third-party providers. According to the 2021 Puget Sound Maritime Emissions Inventory (Puget Sound Maritime Air Forum 2024), ocean-going vessels (OGVs), harbor vessels, recreational vessels, locomotives, heavy-duty vehicles, and fleet vehicles operating at the port all use liquid fuels. The total energy demand for their related operations in 2021 is estimated at 18.41 TJ/year. This was supplied primarily by fossil fuel energy sources—gasoline, marine diesel oil (MDO), and ULSD—and some hybrid technology.

Based on the abovementioned scenario projections, the energy demand of OGV, harbor vessels, recreational vessels, locomotives, heavy-duty vehicles, and fleet vehicles operating at the port is expected to reach approximately 24 TJ/yr in 2030 and approximately 30 TJ/yr in 2050. It is also expected that fossil fuels will be largely replaced by cleaner alternative fuels (e.g., renewable diesel) and other low- or no-emission energy sources (e.g., electrification). The **Decarbonization Life-cycle Analysis** outlines the projected energy sources for each in-scope vessel/vehicle at the Port of Anacortes in 2030 and 2050, along with associated life-cycle carbon emissions reduction benefits. For example, in 2030, OGV operating out of the Port of Anacortes are projected to primarily use biodiesel and renewable diesel, and recreational vessels are projected to use renewable gasoline, biodiesel, and renewable diesel. By 2050, technological and regulatory advancements are expected to enable the widespread use of alternative fuels like methanol, ammonia, and hydrogen for OGVs. Recreational vessels are projected to further electrify by 2050, while some continue to use renewable gasoline and renewable diesel.

Figure 5 provides a breakdown of the historical and projected energy demand by energy type based on the energy technology adoption assumptions included in the Decarbonization LCA, for high-level planning and comparison purposes. It should again be noted that third-party providers are responsible for delivering liquid fuels to the tenants, customers, and visitors who operate out of the Port of Anacortes. Therefore, the port has limited opportunity to influence the provision of future fuels. However, in cases where energy demand is expected to transition from fossil fuel sources to electricity, the port would most likely be responsible for procuring this additional electric service.

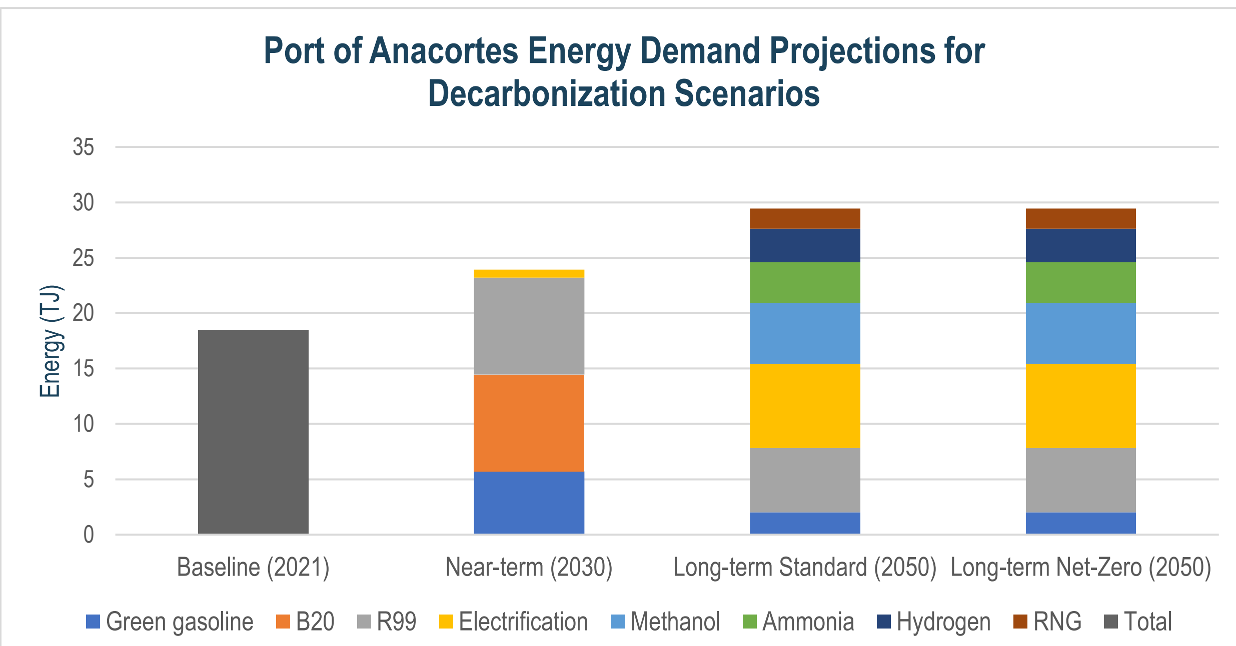


Figure 5. A breakdown of the historical and projected energy demand by energy type for mobile emissions sources at the Port of Anacortes. The Baseline (2021) scenario includes primarily fossil fuel energy sources—gasoline, MDO, ULSD—and some hybrid technologies.

The clean alternative fuel demand estimates provided above were cross-referenced against findings on cost and sustainability for alternative fuels in a 2024 report by Rocky Mountain

Institute (RMI) (Pandey et al. 2024). This report highlighted potential zero-emission fuels (ZEFs) to serve Washington’s shipping sector. ZEFs were defined as those capable of reducing emissions by at least 90 percent compared to traditional fossil fuels and included e-fuels, such as e-methanol, e-ammonia, e-liquefied natural gas (e-LNG), and biofuels such as bio-methanol and bio-LNG.

Bio-Conventional FAME (fatty acid methyl ester) biodiesel is already widely used in commercial applications, primarily in road transport, with millions of tons produced within the U.S. However, second-generation feedstocks, such as forestry and agricultural and municipal residues, are more scalable waste products. These feedstocks have the potential to meet the maritime industry’s growing biodiesel demand, though they are currently limited in commercial availability. Washington has a rich supply of agriculture and forestry feedstocks but also competition from other sectors such as aviation.

The RMI study estimates that, in 2030, the second-generation-waste biofuels, like bio-methanol and bio-LNG, will have production costs between 2 to 4 times that of current Very Low Sulfur Fuel Oil (VLSFO) (per energy-equivalent). For e-fuels produced in the U.S. Wind Belt and delivered to Seattle or Tacoma, the final cost of production and delivery was estimated to be around 2.5 times the cost of VLSFO fuel (Pandey et al. 2024). Ultimately, the availability and cost of ZEFs in Washington will be highly dependent on advancements in technology and supportive policies. Biofuel production costs are influenced by technology, manufacturing configurations, and unknowns involving competition for feedstock assets. E-fuel production costs are largely impacted by the IRA tax credit 45V, which makes the U.S. a low-cost place to produce hydrogen.

CONSIDERATIONS FOR THE FUTURE

The projected increases in electricity demand could be challenging for the Port of Anacortes to meet for multiple reasons. The port anticipates that PSE will be limited in the amount of new electricity it can provide within the next five years and potentially beyond. PSE is facing growing electricity demands from the maritime industry and many other sectors. At the same time, the Clean Energy Transformation Act requires Washington’s electric utilities to achieve GHG neutrality by 2030, and the Climate Commitment Act is seeking a reduction of emissions by 95 percent by 2050. This means PSE will need to generate (through purchasing or developing) 6,700 megawatts of renewable electricity by 2030, in part to replace its current generation via coal and natural gas (Zhou 2024). Meeting these unprecedented demands may limit the amount of additional electricity available to the port in the coming years. On-site and near-site renewable energy generation, load management strategies, and clean alternative fuels could help the port meet its increasing energy needs despite anticipated constraints from the electric utility.

RENEWABLE ENERGY ASSESSMENTS

Given anticipated energy demand increases and potential constraints in future supply, the port was interested in understanding how deploying its own on-site or near-site renewable energy generation could help meet its projected energy demand increases, diversify its energy supply, and enhance its resiliency. Researchers focused their analyses on solar, wind, and tidal renewable energy technologies based on port interests and available resources at the port’s geographical location.

RESULTS SUMMARY

Out of the three renewable resources evaluated in this case study—solar, wind, and tidal—the implementation of solar photovoltaics (PV) showed the most promise in the near-term because of its high technology readiness, relatively low installation costs, and estimated generation potential. The Port of Anacortes could match its annual electricity demand through solar PV alone and is also uniquely positioned to generate additional energy via tidal turbines in its adjacent Guemes Channel. A summary of the projected energy needs and corresponding renewable resources is shown in **Figure 6**.

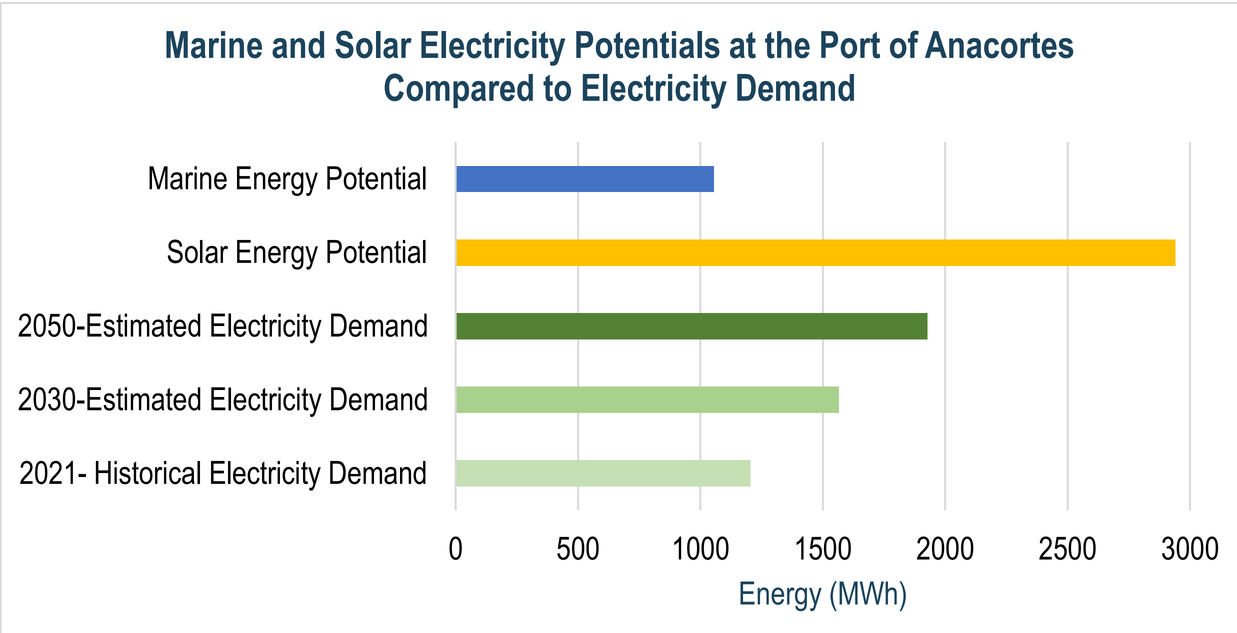


Figure 6. Estimated marine and solar energy potentials for the Port of Anacortes compared to the port's historic electricity usage (2021) and projected electricity demands (2030 and 2050).

In 2021, the Port of Anacortes had a total annual electricity consumption of 1,204 MWh for the marina, marine terminal, and port properties.[6] Installing solar PV at all locations of interest discussed with the port[7] would generate an average of 2,941 MWh of energy, equal to 244 percent of the total electrical energy usage for the port in 2021. Based on the projected growth assumptions (**Projected Future Electricity Demands**) for 2030 and 2050, solar PV could cover approximately 188 percent and 153 percent of total electrical demand for the Port of Anacortes. The total averaged capacity of the 15 possible solar locations (2,919 kW) and corresponding capital expenses ($6.2 million) yields a price for solar installation of approximately $2,140/kW.

Researchers also investigated the marine energy resource potential from tidal energy in the Guemes Channel, located just outside the Port of Anacortes. They evaluated the placement of

[6] The total electrical energy consumption for the port excludes the airport because it is outside the geographical scope of this analysis.
[7] Locations of interest in 11 locations at the marina and 4 locations in the marine terminal, as depicted in **Figure 5** and **Figure 6**.

12 tidal turbines (100 kW/turbine) across the channel based on recommended staggering distances between turbines and between respective rows of turbines. The proposed turbine configuration could produce an estimated 1,056 MWh of energy annually, if the turbines were installed at a depth of 15 feet (ft) from the surface (at lowest tide). This energy production could cover 88 percent of the port's electrical demands in 2021. For the future energy scenarios with increasing energy demand, marine resources would meet 68 percent and 55 percent, of the port's total electrical demand in 2030 and 2050, respectively. It is difficult to report an estimated cost for this type of technology because it is still relatively new with little data available for comparison. The Port of Anacortes is uniquely located in an area with significant marine energy resource potential. However, this technology is still in earlier stages of technology readiness, particularly compared to solar PV, and so it is most feasible to consider marine energy as a potential part of the port's longer-term energy transition strategy.

The wind resource was also evaluated in the marina and marine terminal areas. The annual average wind speed in these areas was approximately equal to the minimum threshold considered feasible for wind energy projects (5.0 meters [m] per section at 50 m above ground level). Therefore, the installation of wind turbines could potentially be an economically viable option for the port, but the area does not have a particularly strong wind resource. The port was less interested in wind turbine installation compared to other renewable energy options due, in part, to its borderline resource availability, spacing requirements for wind turbines, and visual impacts of turbine placement, as well as general complexity of siting wind turbines in the relatively urban landscape within which the Port of Anacortes is located.

More information on the analysis methodology and results for individual renewable energy assessments (i.e., solar, marine, and wind) is included in the following sections. PNNL also developed a Renewable Energy Calculator (Excel worksheet) that summarizes the energy output of various combinations for solar, wind, and marine energy deployments available to the port. It can be used to estimate the possible energy generation and the percent coverage of present and future energy demands.

SOLAR ENERGY ASSESSMENT

ASSESSMENT OVERVIEW

Solar power is a renewable source of electricity generated by harnessing the radiant energy emitted by the sun, commonly through the use of PV solar panels. PV solar panels consist of semiconductor materials that release electrons when exposed to sunlight, generating a direct current (DC) that can be converted into alternating current (AC) for use in homes, businesses, and industries. Solar power helps ports reduce their GHG emissions associated with utility electricity, which generally still heavily relies on fossil fuels to generate. While utility power in the Pacific Northwest relies heavily on hydropower (another form of renewable energy), solar PV, paired with battery storage, also provides increased resiliency for ports by having a supply of electricity separate from the main grid.

Solar PV development in coastal areas has a unique advantage because of its adaptability in placement and power supply. While utility-scale PV farms can have an expansive footprint, PV can also be installed into areas that do not require major infrastructure changes, such as rooftops or carports (**Figure 7**), which allows ports to customize PV to their needs.

Figure 7. Solar PV array on the Port of Seattle headquarters, in Seattle, Washington.

Solar PV modules generate the most power when it is sunny but will still generate some power when it is cloudy or overcast. Pairing battery storage with solar PV allows energy to be stored to meet loads when the sun is not shining. This flexible distribution of energy can offset grid spikes from large power loads or can provide a low-level supply to power auxiliary vessel functions or building operations. When integrated within a microgrid, solar PV and battery storage can help power critical port operations during a bulk power system outage.

The following solar assessment for the Port of Anacortes evaluates the solar resource available and provides annual energy estimates for rooftop- and carport-mounted solar PV at 15 locations within the west and north basins of the port. Nine of these locations were assessed for carport PV in existing parking lots, and six were assessed for rooftop PV on existing Port of Anacortes rooftops, per guidance from the Port of Anacortes on locations of interest.

Overall, this assessment estimates up to 3.7 MW_{DC} of solar PV could be deployed at these sites, generating 2.7–3.2 GWh of electricity annually, with a total cost of $6.2 million.

SOLAR ASSESSMENT RESULTS

This analysis utilized the National Renewable Energy Laboratory (NREL)’s National Solar Radiation Database (NSRDB), which contains decades of solar radiation data covering Anacortes (Sengupta et al. 2018). The NSRDB distills many years of radiation data into a single typical meteorological year, which is a year of hourly data that represents median weather conditions over many years. Since solar radiance varies interannually, a parametric analysis of the solar resource over the decade of available data was conducted using NREL’s System Advisor Model (SAM) software to model solar PV output over the range of weather conditions experienced by Anacortes from 1998 to 2020.

Anacortes has a solar resource that averages 3.16–3.61 kWh/m^2/day. This resource is seasonal since there is more solar energy available during the spring and summer and less during the fall and winter when cloud cover is more frequent. **Figure 8** displays the average monthly solar radiation available in Anacortes for a typical year.

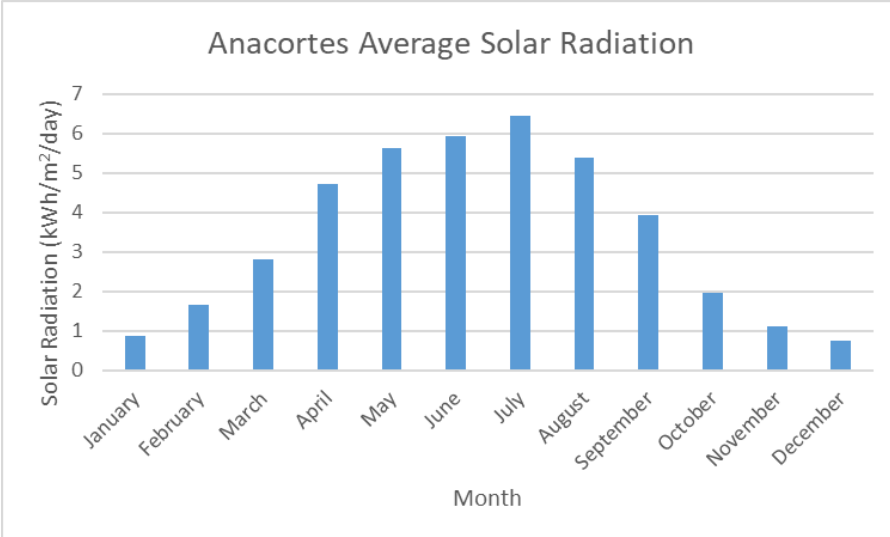


Figure 8. Monthly variation of solar radiation available in Anacortes (NSRDB).

Using the solar radiation profile depicted in **Figure 8**, solar energy estimates were calculated for a hypothetical 1 MW_{DC} PV array, which would take up ~3 acres if carport-mounted or ~2.3 acres if rooftop mounted. The solar estimates are provided in **Table 2**. These estimates are for 1 MW_{DC} of fixed axis roof-mount and fixed axis carport arrays facing due south with no shading losses. Typically, rooftop solar PV is installed flush to the existing rooftop. If the rooftop is horizontal, the PV array can be tilted for optimum annual electricity production (~30° for Anacortes). As such, outputs for 15° and 30° tilt angles for roof-mount solar are provided in **Table 2**. Carport solar is commonly installed at a 5° tilt angle.

Table 2. Solar energy estimates for the Port of Anacortes.

PV Array Type	Fixed Axis (Roof-Mount)	Fixed Axis (Roof-Mount)	Fixed Axis (Carport)
Nameplate Capacity (MW_{DC})	1	1	1
Tilt Angle	30°	15°	5°
Annual Energy Estimate (MWh)	1,009–1,196	967–1,127	908–1,042
Cost ($/kW)	1,561	1,561	2,670

Through conversations with Port of Anacortes staff, 15 potential locations (**Table 3**) for carport or rooftop solar PV were identified in the west and north basins. Nine of these locations are for carport PV, and six are for rooftop PV (**Figure 9**, **Figure 10**). Overall, this assessment estimates that up to 3.7 MW_{DC} of solar PV could be deployed at these sites, generating 2.7–3.2 GWh of electricity annually. Additionally, Port of Anacortes staff indicated that four parking lots (sites 3, 4, 5, and 6) would be particularity good fits for solar, as well as sites 12 and 13 because they are being re-roofed during summer 2024. **Table 3** provides a summary of the acreage, capacity, generation estimates, and capital expenses (CAPEX) for each location.

Table 3. Locations within Port of Anacortes evaluated for rooftop or carport solar PV, with information about acreage, capacity, estimated annual electrical output, and estimated capital expenses for each parcel.

Parcel	Site	Type	Area (acre)	Capacity (kW)	Annual Output (MWh)	CAPEX ($)
Lower Parking	1	Carport	0.3	71	65–74	190,714
Upper Parking 1	2	Carport	1.2	171	156–179	457,714
Upper Parking 2	3	Carport	1.4	200	182–208	534,000
Upper Parking 3	4	Carport	1.4	200	182–208	534,000
Upper Parking 4	5	Carport	2.0	286	259–298	762,857
Upper Parking 5	6	Carport	3.3	471	428–491	1,258,714
Upper Parking 6	7	Carport	0.3	44	40–46	118,243
Medium Parking 1	8	Carport	0.2	30	27–31	80,100
Medium Parking 2	9	Carport	0.4	50	45–52	133,500
Weblocker 1	10	Rooftop	0.3	106	102–126	164,842
Weblocker 2	11	Rooftop	0.3	99	96–119	154,851
Marine Terminal 1	12	Rooftop	1.7	544	526–651	849,184
Marine Terminal 2	13	Rooftop	1.0	320	309–383	499,520
Marine Terminal 3	14	Rooftop	0.7	224	192–219	349,664
Marine Terminal 4	15	Rooftop	0.3	102	88–100	159,846
Total			**14.8**	**2,919**	**2,697–3,185**	**6,247,750**

Figure 9. West Basin with locations 1–11.

Figure 10. North Basin with locations 12–15.

PORT-SPECIFIC CONSIDERATIONS

SOLAR ENERGY RESOURCE

An ideal site for solar PV development in the northern hemisphere has a south-facing orientation, a proximity to existing roads and electrical infrastructure, and minimal shading from buildings, trees, or other obstacles. For rooftop solar, it is typically advisable to consider roofs with a projected lifespan of at least 15 years and the capacity to bear an additional load of approximately 2–4 lbs/ft^2. Solar carports should be rated to support the added weight of the modules.

Solar can be utilized to cover diverse loads. Some ports operate only during the daytime and some operate 24/7. Since solar power is generated during the day, PV could be strategically placed on buildings where complementary loads exist (e.g., office buildings) to provide power when those loads need to be met. Solar PV could also be coupled with battery storage to provide power to non-complimentary loads (e.g., terminal lighting at night).

Solar PV could also help curb the peak loads associated with large, port-specific loads, such as shore power and medium-duty and heavy-duty vehicle charging. These loads have the potential to create large and sudden energy demands that spike the electricity supply. Solar PV, deployed in conjunction with energy storage, can provide load management and reduce electricity costs. For example, electric vehicles (EVs) could be charged during off-peak times with stored energy from the solar PV arrays, or solar PV could be used for peak shaving when providing shore power, reducing port utility bills, since demand charges can be significant contributors to the cost of electricity for commercial customers.

INSTALLATION COSTS

Capital costs for installing solar PV typically range around $2,800/kW for carport solar (including the cost of the structure), and $1,500/kW for commercial-scale rooftop solar. Installation costs for solar PV in coastal locations could be higher than for those deployed further inland, should the owner opt for corrosion-protecting add-ons and materials, such as protective coatings. Many ports are spatially constrained so it is likely that solar PV would be installed on existing buildings or land historically used for other industrial purposes, which could include brownfield sites. The U.S. Environmental Protection Agency (EPA) reports that brownfield sites pose complications—for expansion on, redevelopment, or reuse—because of the presence or potential presence of a hazardous substance. Ports will need to evaluate potential installation risks including brownfield complications on a case-by-case basis.

ENVIRONMENTAL IMPACTS

Solar PV arrays do not generate air pollution or greenhouse gas emissions while operating. While some of their components (i.e., metal, glass) are energy intensive to manufacture, PV systems can provide the energy associated with their manufacture within a few years. Additionally, some module technologies use heavy metals, which may require special handing at project end-of-life.

COMMUNITY ACCEPTANCE

Solar PV has a high technology readiness level and is often well-received by adjacent neighborhoods as a potential source of renewable, clean energy. There are also environmental benefits to near-port communities, who have been historically exposed to higher levels of harmful air pollutants. When solar PV is combined with port electrification efforts it can reduce the consumption and resulting emissions from fossil fuels that traditionally power port activities. It is important to discuss potential benefits and impacts of clean energy projects with the community and integrate their feedback into project decisions. Many ports have established channels for community engagement that could be used to facilitate conversations regarding solar PV and other clean energy opportunities.

LAND USE, ZONING, AND PERMITTING

Ports are unique because they often have large areas of land that could be used for co-located solar. For example, ports have parking areas available for light-duty or heavy-duty vehicles. PV arrays could be mounted on these canopies and provide dual benefits of sun and rain protection to the vehicles, while also producing power. The canopy-mounted PV could also supply power to the EV charging stations. Additionally, some ports have large, covered boatyards, marinas, or docks. These canopies could also potentially be used to mount solar PV, although further research is warranted since few examples of such systems exist. Port facilities, such as large warehouses, could also offer ample space for roof-mounted solar PV systems.

OPERATIONS AND MAINTENANCE

Operations and maintenance (O&M) for solar PV are relatively simple, especially for fixed axis systems, since they have no moving parts. O&M tasks include periodic cleaning of the modules, corrosion and/or vegetation management, system inspection, and corrective maintenance. At the Port of Anacortes, regular rainfall may be sufficient to keep panels clean during the winter months.

Salt is a corrosive agent that oxidizes metal and can lead to the erosion of metal surfaces, removing paint and finishes, and overall reducing the surface material’s integrity. Several factors influence the corrosion rate of aerosolized salt air on metal, including wind speed and direction, coastal topography, humidity, and wave height. Corrosion from sea salt deposition can significantly impact the longevity of exposed electrical infrastructure, such as solar PV modules.

Measures to reduce the impact of salt air include using galvanized steel fasteners that have very low corrosion rates and frames/structures that are made of materials that do not corrode. Although stainless steel, aluminum, copper, and galvanized steel have corrosion-resistant properties, they require a specialized metal finish designed for coastal areas to avoid reactions with salty air and oxygen. Some PV arrays use synthetic rubber strips to separate panels from aluminum rails to mitigate the effect of salty air and rust. Equipment should be rated to NEMA 4X and IP65 ratings for resistance to corrosion and water ingress.

OWNERSHIP

Some ports manage all activities at their facility, while others hold long-term leases with tenants who manage their own activities and may have their own accounts with the electrical utility. Solar PV installations at ports could be owned and operated by multiple parties, including the port authority, tenant, electric utility, or a third-party provider. The ideal ownership model will depend on the port management structure, desired installation location, intended electrical loads, and other agreement terms (e.g., lease terms). For resiliency purposes, landlord ports may want to coordinate across multiple tenants to verify solar PV and other clean, resilient energy technologies are designed to support critical port loads during an unexpected power outage, regardless of the ownership structure for individual assets.

POTENTIAL NEXT STEPS

1. Determine most feasible locations for solar PV installation, taking into consideration future construction, building integrity, and maximum energy output. Create more detailed solar PV models for selected locations, taking into account shading losses, which will generate a more accurate estimate of the solar PV array output.
2. Investigate what loads could be powered by solar PV and infrastructure needed to integrate solar PV into a port’s microgrid. Prioritize solar PV locations by feasibility, including proximity to the potential microgrid location.
3. Discuss solar PV installation processes and potential supportive mechanisms with the electric utility, including a potential relationship and distribution method for re-selling excess power to local the utility.

WIND ENERGY ASSESSMENT

ASSESSMENT OVERVIEW

Wind turbines are customizable to the energy needs of businesses, homeowners, communities, and utilities. Wind turbines vary in size with turbine generator heights (hub heights) ranging from 15 m to more than 100 m and blade lengths ranging from 1.5 m to 60 m or more. Also, they have ranges in generating capacity with less than 1 kW to greater than 10 MW. Wind energy development in coastal areas offers unique opportunities—in wind resource and transportation opportunities—and unique challenges—mainly for land availability, environmental considerations, and service provider availability. Wind turbines in coastal areas have been deployed both on land (e.g., small turbines offsetting 66–90 percent of the annual energy consumption of the Central Maui Landfill Refuse and Recycling Center in Hawaii [Krueger 2015]) and on piers extending into water (e.g., small turbines that offset 20 percent of the energy needs of Jennette's Pier in North Carolina [Brindley Beach Vacations & Sales 2022]).

The following wind assessment for the Port of Anacortes evaluates the available wind resource at two areas of interest, the Marine Terminal and the West Basin, and provides annual energy estimates for a range of commercially available wind turbine options. The assessment concludes by listing important considerations for wind energy deployment, such as cost, O&M information, and environmental and community concerns, along with potential next steps and research areas for potential adopters of wind energy at ports.

WIND ASSESSMENT RESULTS

Four wind resource datasets provide the wind estimates for the Port of Anacortes: Global Wind Atlas 3 (Global Wind Atlas 2024, WIND Toolkit (NREL n.d.; Draxl et al. 2015), NOW-23 (Bodini et al. 2024), and Wind Report (New Roots Energy 2024). Multiple wind datasets are considered in this to provide a range of wind resource expectations. The highest resolution map, Global Wind Atlas 3, shows the highest wind resource at Cap Sante Park and the lowest wind resource at the Marine Terminal, West Basin, and westward through the town of Anacortes (**Figure 11**). The wind will predominantly come from the southeast, with secondary and tertiary frequencies from the southwest and north.

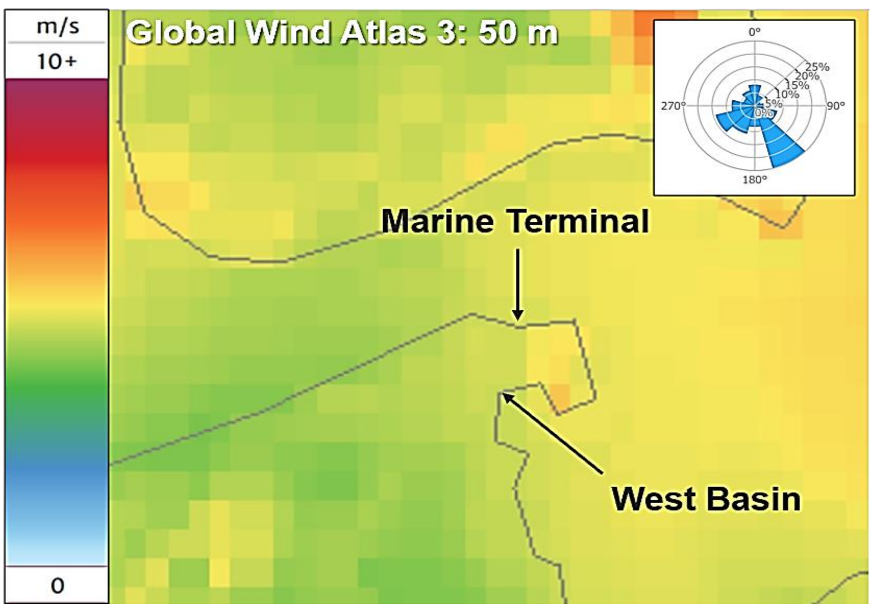


Figure 11. Annual average wind speed at 50 m above ground level at the Port of Anacortes and surrounding areas (Global Wind Atlas 3).

As a rule of thumb, an annual average wind speed of 5.0 meters per second (m/s) is considered feasible for wind energy development at a height of 50 m above ground level. The four datasets agree that the annual average wind speed at 50 m at both the Marine Terminal and the West Basin hovers right at the rule of thumb threshold, between 4.8 m/s and 5.3 m/s (**Table 4**).

Table 4. Annual average wind speed estimates for the Marine Terminal and West Basin.

Wind Model	Marine Terminal	West Basin
Global Wind Atlas @ 50 m	4.9–5.3 m/s	4.9–5.3 m/s
Wind Toolkit @ 50 m	5.2 m/s	5.2 m/s
NOW-23 @ 50 m	5.3 m/s	5.3 m/s
Wind Report @ 50 m	4.8 m/s	4.8 m/s

The ranges of wind speed estimates are adjusted to typical wind turbine hub heights for five commercially available wind turbines ranging from 15 kW in capacity to 2.3 MW (**Table 5**). The annual energy estimates for a single wind turbine installed at the Marine Terminal or the West Basin range from 18–23 MWh if using a 15 kW turbine, to 5,000–6,000 MWh if using a 2.3 MW turbine. The wind energy estimates include a loss factor of 19 percent to account for a variety of influences leading to wind turbine underperformance, including maintenance-related outages, extreme weather outages, and line and transformer loss.

Table 5. Annual energy estimates for an average wind resource year for the Marine Terminal and West Basin.

Turbine Manufacturer and Model	Bergey Excel 15	Eocycle EOX S-16	Northern Power Systems 100-28	EWT DW 54-900	GE 2 MW-116
Nameplate capacity	15 kW	25 kW	100 kW	900 kW	2.3 MW
Hub height	37 m	24 m	37 m	50 m	80 m
Marine Terminal: Annual energy estimates	18–23 MWh	32–41 MWh	146–177 MWh	1,020–1,273 MWh	4,990–5,814 MWh
West Basin: Annual energy estimates	18–23 MWh	32–42 MWh	147–177 MWh	1,032–1,288 MWh	5,038–5,852 MWh

PORT-SPECIFIC CONSIDERATIONS

WIND ENERGY RESOURCE

Ports tend to be in areas that were selected to avoid high winds to mitigate damage and passage challenges for marine vessels and marina infrastructure. The reduced wind resource in these locations poses a potential challenge for the economic feasibility of wind energy at ports. To optimize the amount of wind accessible to a wind turbine deployed at a port, there are some optimization options to consider in terms of altitude and geography. First, since wind speed increases with height above ground, taller turbines can provide an opportunity to produce more wind energy. However, it should be considered that installation costs also increase with higher heights above ground for deployed wind turbines. Second, placing turbines in less sheltered areas near a port, such as a breakwater, can also increase the amount of wind exposure for turbines to convert to energy. However, it should be considered that increased proximity to the salt or brackish water can result in increased corrosion probability and relatedly increased maintenance events and expenses.

INSTALLATION COSTS

Installation costs for distributed wind turbines have been decreasing over the last decade. Installation costs include the wind turbine equipment costs, installation, foundation, electrical labor, transportation, taxes, zoning, permitting, engineering and design, interconnection, and inspection (Orrell et al. 2023). For a small distributed wind turbine (≤ 100 kW in capacity), installation costs from the years 2020 to 2023 ranged from $2,200–$10,600/kW, with an average of $6,200/kW. For midsize and large distributed wind turbines (> 100 kW), installation costs from 2020 to 2023 ranged from $1,500–$5,300/kW, with an average of $2,750/kW (PNNL n.d.). Installation costs for coastal wind turbines are anticipated to be higher than for those deployed further inland, should the turbine owner opt for corrosion-protecting add-ons and materials, such as protective coatings.

ENVIRONMENTAL IMPACTS

Wind turbines, particularly large wind turbines, impact bird and bat populations. Environmental impacts can be mitigated with proper siting of wind turbines away from known migratory paths, nesting grounds, caves, and wetlands.

COMMUNITY ACCEPTANCE

Community acceptance can be a challenge when adding wind to an energy portfolio. Two recommendations regarding distributed wind in community engagement efforts include the following. First, it can be helpful to explain that wind energy is not limited to hundreds of giant wind turbines in a wind farm. Some opponents of wind are willing to consider smaller distributed wind projects, such as a single small wind turbine powering a local operation. Second, positive conversations can be facilitated by explaining the benefits of distributed wind, namely that it keeps the energy produced local rather than transmitting it, too far away cities and states.

Many ports have established channels for community engagement that could be used to facilitate conversations regarding distributed wind and other clean energy opportunities. Some near-port communities may be concerned about wind turbines impeding their water views. On the other hand, the clean energy generated by wind turbines can reduce the need for fossil fuel combustion at ports and create direct health benefits for near-port communities. It is important to discuss potential benefits and impacts of distributed wind with the community and integrate their feedback into project decisions.

LAND USE, ZONING, AND PERMITTING

For a small distributed wind turbine (≤ 100 kW in capacity), a minimum of one acre is typically required to allow for setbacks from neighbors and property lines to mitigate human environment impacts such as noise and shadow flicker. Local zoning and permitting committees can provide the restrictions specific to your area.

The minimum of one acre of land can be used for additional purposes beyond a wind turbine. Wind turbines have a relatively small land use footprint, which allows for surrounding land co-use with parking lots, farming/ranching operations, community parks, and other purposes. To mitigate the effects from obstacles such as trees, buildings, cranes, and other port equipment that could reduce the available wind resource due to turbulence, it is recommended that the lower blade tip of the turbine rotor be at least 10 m higher than any obstacles within a 150 m radius (DOE n.d.).

Wind turbines with tip heights (hub height plus blade length) exceeding 61 m must file a *Notice of Proposed Construction* with the Federal Aviation Administration (FAA). Depending on the proximity to aviation facilities, turbines with tip heights lower than 61 m may also require FAA notification (American Clean Power Association 2020).

OPERATIONS AND MAINTENANCE

Operations are a significant expense for wind farms and large distributed wind projects, but are typically minimal or nonexistent for small distributed wind projects. All types of wind projects, however, require maintenance, which can be scheduled or unscheduled. O&M costs are approximately $35/kW/year for small distributed wind turbines and approximately $20/kW/year for midsize and large distributed wind turbines.

The availability of distributed wind turbine service providers is a significant challenge, particularly in the Pacific Northwest. As an additional challenge, proximity to the salt or brackish water can result in increased corrosion probability and relatedly increased maintenance events and expenses.

POTENTIAL NEXT STEPS

1. Determine whether the energy estimates available would provide valuable offsets of port energy usage, keeping in mind that wind energy is very complimentary to solar energy—wind energy production peaks at night and in the winter, while solar energy production peaks during the day and in summer.
2. Consider gathering on-site wind measurements in a specific location of wind energy interest at or near a turbine hub height of interest.
3. Community engagement regarding wind energy opportunities, with a particular focus on the range of wind turbine size and design options.
4. Consult with a wind energy developer to provide a detailed site assessment and engineering design plan.
5. Keep aware of potential Department of Energy (DOE)-funded opportunities to facilitate the gathering of on-site wind measurements.
6. If the Port of Anacortes expresses further interest in wind energy opportunities, expand wind energy estimates to monthly, interannual, and diurnal estimates.

MARINE ENERGY ASSESSMENT

ASSESSMENT OVERVIEW

Marine energy is an emerging renewable energy technology that may be able to support port infrastructure and energy goals. Energy can be created from waves, tides, or thermal gradients. For Port of Anacortes, the most likely source of power is the tides. As the tide rises, water is pushed through channels, like those in Guemes Channel or around the San Juan Islands, which creates a current that can be used to power turbines underwater (**Figure 12**Error! Reference source not found.). These devices are typically called tidal turbines or tidal energy generators. Tidal energy varies daily with the position of the sun and moon but is predictable for years into the future. Predictable and consistent power is an added benefit for resiliency with tidal power, as many renewables fluctuate significantly.

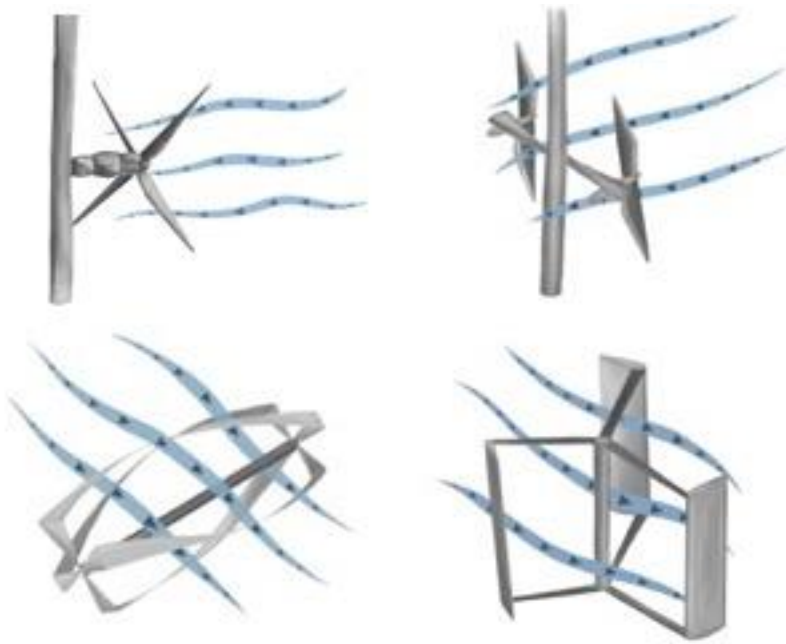


Figure 12. Illustrations of different potential designs of tidal turbines.

Wave energy is unlikely to be a potential energy source for Anacortes, as wave energy generation typically requires waves that develop over a long period, such as on the outer coast of Washington. Both wave and tidal technologies are still emerging technologies and pre-commercial. The advantage of a pre-commercial product is that there may be opportunities for grant funding for demonstration projects.

MARINE ASSESSMENT RESULTS

PNNL identified Guemes Channel as a potential location for tidal energy for the Port of Anacortes. General marine energy potential can be assessed on the Marine Energy Atlas, which shows marine energy average potential for both wave and tidal energy. To determine power generation, we wanted hourly tidal velocity data that could show the amount of generation over the course of a month. To quickly estimate the potential tidal energy available in Guemes Channel, we used data from National Oceanic and Atmospheric Administration (NOAA) measurements of tidal velocities in Guemes Channel that were taken in 2017 (NOAA 2017). Two months of data (**Figure 13**) were taken with an acoustic doppler current profiler (ADCP); this data can now predict currents for the channel accurately into the future. We used one month of this data to estimate power generation in Guemes Channel. There are also computer models of tidal current velocity that could be used to estimate power at other locations.

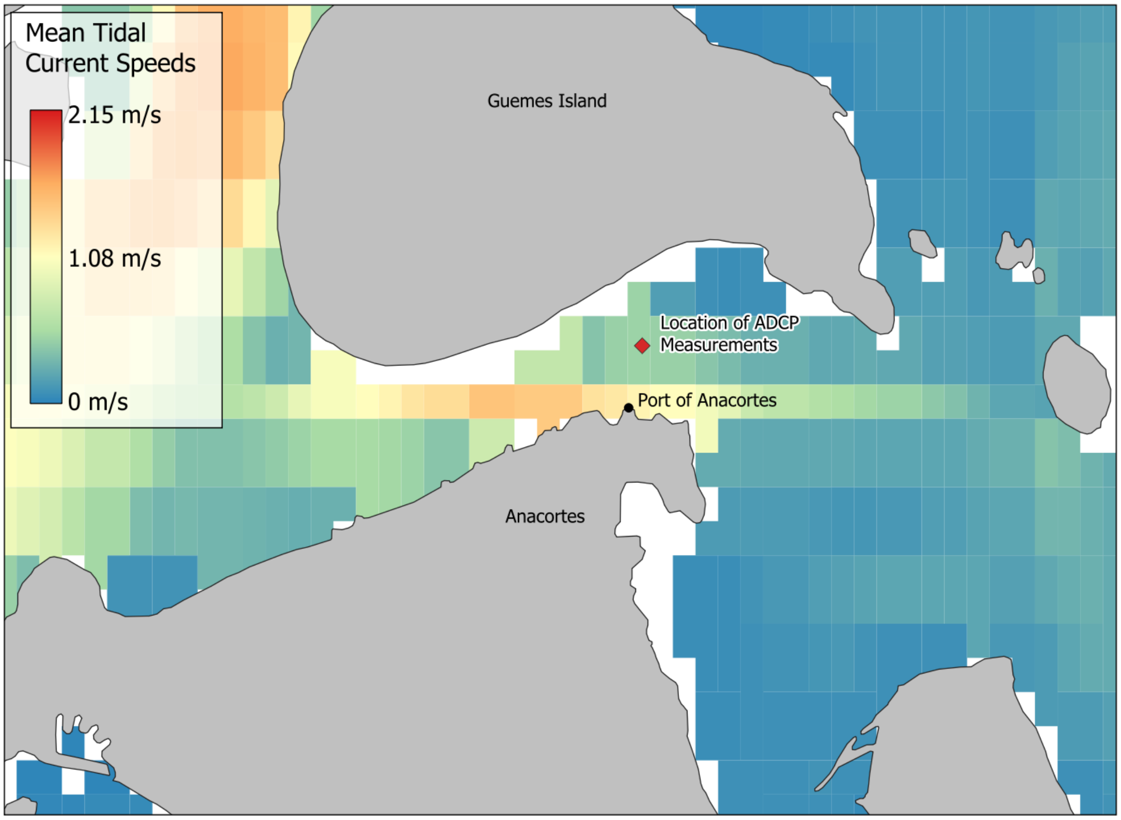
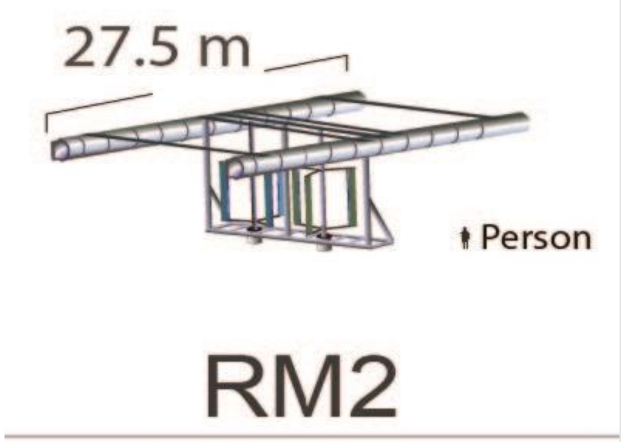


Figure 13. Tidal currents (m/s) in Guemes Channel, with location of ADCP measurements from June 24 to August 26, 2017, shown.

At the identified point, Guemes Channel is 60 ft deep. A tidal turbine could be placed at a variety of depths, but the tidal velocity is typically highest at the surface. We analyzed a turbine placed at two depths: one where the top of turbine would be at the surface, and one where it would about 15 ft below mean lower low water. For a turbine near the surface, the maximum current is about 2.04 m/s and average of 0.74 m/s, while the lower depth has a maximum of 1.96 m/s and average of 0.71 m/s.

To calculate power, we used a “Reference Model” turbine, which is a generic turbine that has data about how much energy it produces. The turbine chosen was Reference Model 2 (RM2), which is a small turbine that would be appropriate for rivers or small tidal channels (Neary 2010) (**Figure 14**). This turbine operates whenever the current is greater than 0.7 m/s and less than 2.6 m/s. With two rotors, the turbine is rated at 100 kW. The power generation is estimated hourly using the velocity data and the rated power per rotor shown in **Figure 14**. Using one month of data, and assuming the tidal power is roughly the same over the course of the year, the yearly production for this turbine is 102 MWh at the surface and 88 MWh at the deeper location. Larger turbines or an array of turbines could generate more power.



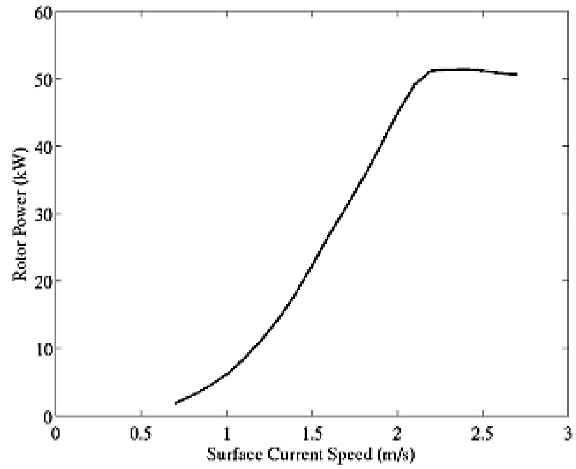


Figure 14. Left figure shows an illustration of Reference Model 2 (RM2), a 100 kW tidal turbine with two rotors that are each 15 ft tall and mounted with surface floats, but a similar size device could also be located deeper in the water column. Right figure shows power generation at different current speeds for this device. Both figures from Reference Model Documentation (Neary 2010).

SCALING TO MULTIPLE DEVICES OR LARGER DEVICES

Multiple devices could be placed in Guemes Channel to increase the potential production. Hydrodynamic modeling of the channel can provide more accurate representation of how closely the turbines could be placed and optimal staggering, but a review of multiple studies suggested that a reasonable place to start would be turbines placed in rows, with three turbine diameters between turbines in the same row and five turbine diameters between rows.

Guemes Channel is about 1.1 km (3498.69 ft) wide (**Figure 15**). About 12 of the 100 kW devices could fit across the channel, assuming they are about 20 m wide and would have 60 m between (three times the rotor diameter). Larger turbines would also fit in the space and may provide more power than many small turbines. For example, the Orbital Marine Energy Device, which is under consideration for installation in the San Juan Islands by Orcas Power and Light Company, can provide 2 MW of electricity, with dimensions of 72 m long and about 60 m width. This device has some surface expression, but the turbine rotors are underwater. Guemes Channel may not be deep enough for this device but is large enough for a device bigger than Reference Model 1.

Figure 15. Distance across Guemes Channel from the Port of Anacortes.[8]

PORT-SPECIFIC CONSIDERATIONS

MARINE ENERGY RESOURCE

Ports tend to be located in areas that are selected to avoid high currents and waves in order to mitigate damage and passage challenges for marine vessels and marine infrastructure. The reduced marine energy resource in these locations poses a potential challenge for the economic feasibility of marine energy at many ports. While some ports, including the Port of Anacortes, are located near (< 5 miles) a significant source of marine energy (e.g., just outside the port breakwater), other ports nearest the source of significant marine energy are many miles away. Delivering electricity generated from marine energy across longer distances may be cost prohibitive from an economic perspective, as underwater transmission is costly. However, for the portion of ports that are located near a significant source of marine energy, using it to power port operations could offer multiple benefits. Delivering energy from underwater devices to on-shore ports can offer a relatively short path for energy delivery, reducing economic and environmental costs and minimizing potential load losses during energy transmission.

Furthermore, marine energy can offer ports resource predictability and geographic isolation of energy infrastructure (i.e., because most infrastructure is underwater as opposed to on land

[8] Imagery ©2024 Airbus, TerraMetrics, Imagery 2024 Airbus/CNES/Airbus, Landsat/Coperniucus, Maxar Technologies, USDA/FPAC/GEO, Map data ©2024 Google.

and, therefore, not subject to some land-based threats) that can enhance the resilience of a port's energy system.

INSTALLATION COSTS

As of 2024, tidal energy is an emerging field with no permanent installations in the U.S. Because of this, installation, operations, and maintenance costs are unknown. Tidal energy will be more expensive than other options, but federal grants may be available to pursue a demonstration project.

ENVIRONMENTAL IMPACTS

Installing tidal energy may have environmental effects, some of which can be mitigated. A list has been compiled among scientists after a decade of research for the most relevant stressors and environmental impact from marine energy (Garavelli et al. 2024). The findings show that the largest degree of impact is for marine animals, including that noise from the turbine can impact navigation and communication with nearby marine animals, magnetic fields induced by electric currents within the cables can impede marine animal movement and behavior, collision risks with the turbine, and displacement or changes in habitat. Interestingly, recent research has found that fish avoid the turbines when operating. Evidence has been documented in both laboratory and field settings (Smith 2021; Yoshida et al. 2022). Other impacts could include changes in ocean processes (e.g., the hull of the turbine could provide a form that attracts major growth of organisms, disrupting the competition and balance of that local ecosystem).

Scientists are still studying the potential environment effects and ways to minimize the impact; a summary of the most up-to-date research is published every four years.[63] In choosing a tidal turbine, some may pose different risks. For example, a turbine placed at a certain depth may impact fish that typically migrate at that depth. Stakeholder and community engagement is essential to determine what potential environmental effects are acceptable, as well as what unknowns will need to be monitored around the site.

COMMUNITY ACCEPTANCE

Many communities that may be suitable for tidal energy development are not aware of tidal turbine technologies, so early engagement is necessary to understand their concerns and constraints. Potential constraints from the community may be around fishing locations or vessel traffic that may be impacted by the turbine site. Local Tribes often have rights to their usual and accustomed fishing areas, so Tribal buy-in is essential for a successful project.

LAND USE, ZONING, AND PERMITTING

The Port of Anacortes highlighted that the channel near the port is a working channel and needs to retain access for transiting vessels. This likely means that a device placed lower in the water column is a better fit for port communities.

OPERATIONS AND MAINTENANCE

Tidal turbines are likely to need yearly maintenance that requires a vessel and specialized training, such as diving, to remove biofouling and clean the device.

POTENTIAL NEXT STEPS

1. Determine if this developing technology will meet the port's needs to cover future energy demands and resiliency goals.
2. Consider gathering more information about the channel to determine which locations have the highest currents and estimate projected energy generation.
3. Consider the pros/cons of the installation locations, including, but not limited to, shipping lanes, distance to shore, and locations of places to connect to the existing grid.
4. Explore stakeholder engagement to determine whether the potential environmental effects of these emerging technologies can be mitigated in their area. Different designs may have different environmental impacts based on their location in the water column and method of connection to the sea floor.
5. Monitor the project and development of the Orcas Power and Light Company (OPALCO) marine energy demonstration project in Rosario Strait. Consider potentially consulting with OPALCO for advice and lessons learned.

MICROGRID ANALYSIS

ASSESSMENT OVERVIEW

DOE 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. Loads powered by a microgrid can range from a single building to an entire neighborhood or campus.

Microgrids require a supply of energy, energy storage, loads, controls, and, optionally, a utility interconnection. Energy can be supplied by distributed renewables like solar PV, distributed wind, or marine energy, or other resources, such as a biomass plant or fossil-fired generation. Battery energy storage systems (BESS) or thermal storage provide energy storage capacity for intermittent renewables. Controls allow the microgrid to balance power supply and demand. Finally, unless the microgrid is in a remote site or isolated from the grid, a utility interconnection provides coupling with the grid. During normal operations, the microgrid is connected to the utility grid, drawing power from the grid when its own energy supplies are not sufficient to meet the load. During grid blackouts, microgrids can "island," or disconnect from the utility grid, continuing to provide power to critical loads.

The Port of Anacortes was interested in understanding how microgrid technology could increase resiliency of the port's critical infrastructure, particularly in the event of an unexpected power outage that could last multiple days. The port determined its most critical infrastructure includes the fuel dock, commercial docks (A & B), boat launch, and cranes, all located in the Cap Sante Marina. These assets would be necessary to facilitate the delivery of supplies to neighboring island communities and/or the delivery of supplies to the Fidalgo Island community (where the port is located) if land-based transportation systems connecting Fidalgo Island to the mainland were down. The port was also interested in maintaining functionality of certain infrastructure at its marine terminal locations, but these were not included in the scope of this microgrid assessment. This is because the port's marine terminals are geographically and electrically separate from its marina by multiple city blocks. Furthermore, some tenants at the marine terminals hold their own electric utility accounts with PSE, so there was limited data to support a microgrid analysis for these locations. A microgrid analysis for the marine terminal locations could be a focus of future efforts for the port.

This preliminary feasibility analysis investigated the potential for a microgrid powered by solar PV, with a BESS and backup fossil-fired generation to provide resilience to selected port loads at the Cap Sante Marina during a three-day power outage. The microgrid would cover the fuel dock, boat launch, A dock, B dock, T dock cranes, and future electric vessel charging at the A dock, as shown in **Figure 16**. Solar PV could potentially be mounted on carports in existing parking lots.

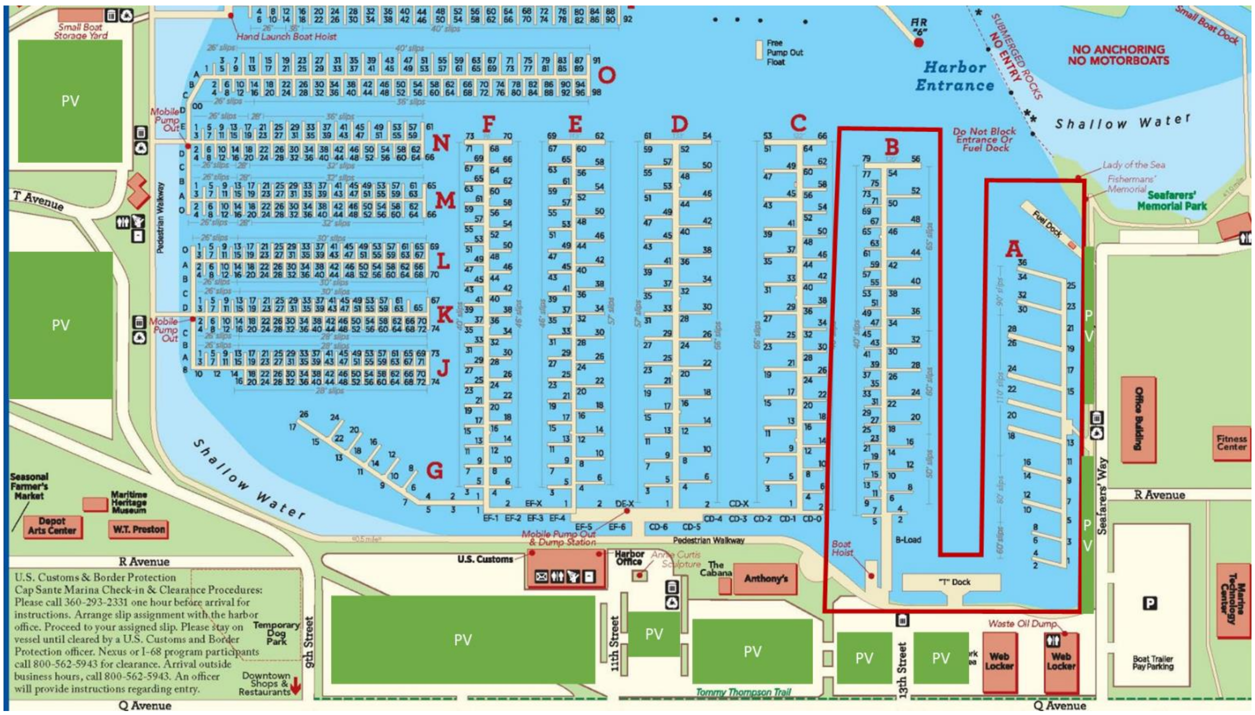


Figure 16. Proposed microgrid boundary (red) and potential solar PV locations (green).

To characterize current loads, an hourly load profile for the port was generated based on information provided by port staff. Port staff provided monthly electricity consumption data for the fuel dock, boat launch, A dock, and B dock. No load data was provided for the T dock cranes or planned A dock electric vessel charging. The monthly electricity consumption data for the fuel dock, boat launch, A dock, and B dock was converted to an hourly load by estimating usage patterns for each load. Since no nameplate rating or usage patterns were provided for the two Kone Crane T dock cranes, an educated guess was made based on crane power for similar models and hypothetical usage patterns. It was assumed a 1-ton crane requires 0.75 kW of power draw, and that both cranes are in use for 30 minutes out of the hour, 3 hours a day (for a total of 90 minutes per crane per day). To estimate future electric vessel charging loads, the future A Dock electric vessel charger used a plug-in EV load profile from the Northwest Power and Conservation Council, scaled to charge PNNL's 50 ft plug-in hybrid research vessel, the *RV Resilience*, which has a 113 kWh battery.

Table 6 outlines the main loads covered by the microgrid, annual consumption (actual or estimated), and hourly load profile assumptions, and **Figure 17** shows the load profiles for each load for a typical week. As expected, given the annual electricity usage, loads are dominated by the boat launch, B dock, and A dock.

Table 6. Microgrid loads, annual consumption, and load profile assumptions.

Load	2021 Electricity Usage (kWh)	Load Profile Assumptions
Fuel Dock	26,520	90% of load between 8 a.m.–6 p.m. daily, 10% of load otherwise for lighting at 24/7 operations.
Boat Launch	146,600	90% of load between 8 a.m.–6 p.m. daily, 10% of load otherwise for lighting at 24/7 operations.
T Dock Cranes	820 (estimated)	0.75 kW power draw for 1 ton chain hoist. Each crane operates for ½ hour, 3 hours a day, between 8 a.m.–6 p.m.
A Dock	126,800	90% of load between 5 a.m.–8 p.m. daily, 10% of load otherwise for lighting at 24/7 operations.
A Dock Electric Vessel Charging	45,400 (estimated)	Adapted from plug-in EV load profile from Northwest Power and Conservation Council, scaled to battery for PNNL's plug-in hybrid vessel *RV Resilience* (113 kWh battery).
B Dock	294,400	90% of load between 5 a.m.–8 p.m. daily, 10% of load otherwise for lighting at 24/7 operations.

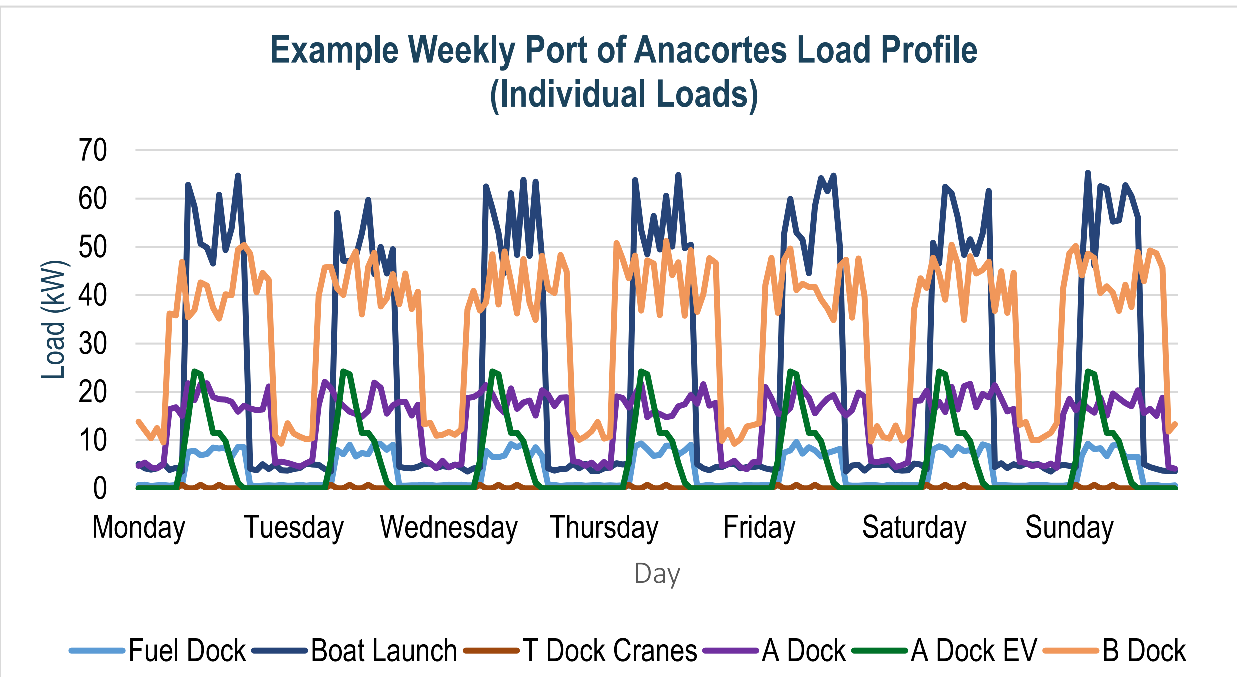


Figure 17. Example weekly Port of Anacortes load profile within the proposed microgrid boundary.

Figure 18 shows a typical week of the net-load for the port within the proposed microgrid boundary. Peak loads occur during the middle of the day, with some loads occurring at night, accounting for lighting and some 24/7 operations. The port's modeled annual consumption is approximately 640 MWh, with a peak load of 172 kW.

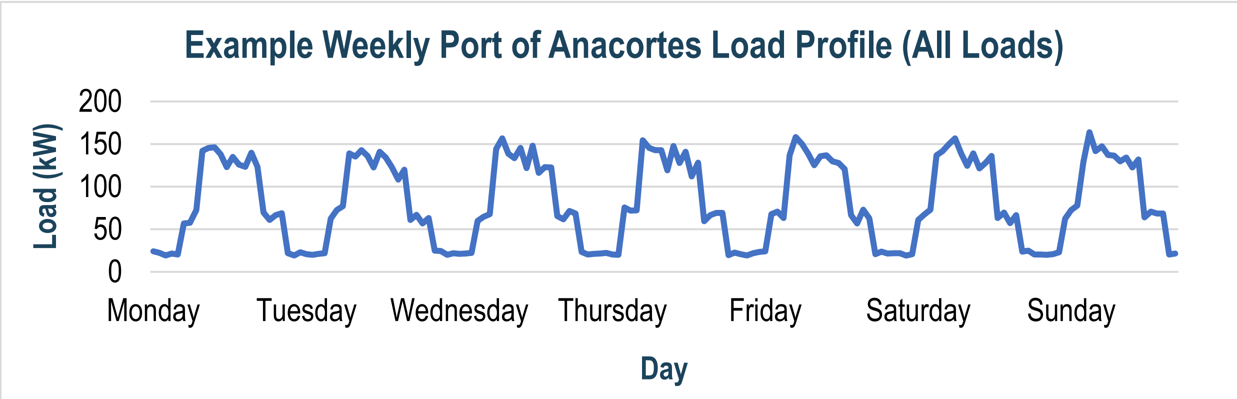


Figure 18. Example of weekly net-load for the Port of Anacortes.

The hourly load profile was used as an input for the technical and economic evaluation of a solar PV, BESS, and fossil-fueled generation microgrid at the port. This evaluation used PNNL's Microgrid Component Optimization for Resiliency (MCOR) tool to generate several microgrid configurations that could provide resilience for a three-day outage at the port. The results from the MCOR analysis are provided in the following section.

MICROGRID ANALYSIS RESULTS

MCOR is an open-source Python tool that simulates microgrid performance under a large range of outage conditions and returns several potential system configurations that meet a site's loads for a specified outage duration. MCOR produces high-level sizing estimates for viable microgrid configurations and does not perform detailed power electrics modeling, assumes no constraints in the distribution system, no distribution losses, and does not model transient electrical effects. MCOR's primary purpose is to help size the generation and energy storage resources to meet the performance requirements of the microgrid, as will be described in the next paragraph; further detailed study is needed to examine the actual siting, deployment, and operational performance of the microgrid.

Table 7 displays selected outputs from MCOR for a three-day outage at the Port of Anacortes given the modeled hourly load profile; full results are available on request. MCOR provides various configurations of these technologies and associated metrics that can be used to weigh possible systems configurations against each other, including capital and maintenance costs, payback period, and breakdowns of how different resources are meeting the site's electric load. Payback period is calculated based on capital cost, O&M costs, and annual benefits (net metering and reduction in demand charges).

Table 7. Selected MCOR outputs for a three-day outage at the Port of Anacortes.

PV capacity	Battery capacity	Battery power	Generator power	Capital cost	PV capital	Battery capital	Generator capital	PV O&M	Battery O&M	Generator O&M	Simple payback
kW	kWh	kW	kW	$	$	$	$	$/year	$/year	$/year	years
878.1	0.0	0.0	132.5	$1,525,376	$1,440,160	$0	$76,400	$13,172	$0	$3,554	17.4
878.1	417.3	104.3	127.9	$1,784,625	$1,440,160	$259,250	$76,400	$13,172	$1,006	$3,554	20.6
878.1	834.6	208.7	98.8	$2,043,875	$1,440,160	$518,499	$76,400	$13,172	$2,011	$3,554	23.9
400.5	417.3	104.3	134.1	$1,001,236	$656,771	$259,250	$76,400	$6,007	$1,006	$3,554	26.2
878.1	1,251.9	313.0	80.8	$2,303,125	$1,440,160	$777,749	$76,400	$13,172	$3,017	$3,554	27.3
800.9	1,251.9	313.0	83.2	$2,176,506	$1,313,541	$777,749	$76,400	$12,014	$3,017	$3,554	28.4
878.1	1,669.2	417.3	74.6	$2,552,825	$1,440,160	$1,036,999	$66,850	$13,172	$4,023	$3,251	30.5
800.9	1,669.2	417.3	77.0	$2,426,206	$1,313,541	$1,036,999	$66,850	$12,014	$4,023	$3,251	31.9
400.5	834.6	208.7	119.1	$1,260,485	$656,771	$518,499	$76,400	$6,007	$2,011	$3,554	33.9
0.0	0.0	0.0	158.4	$85,215	$0	$0	$76,400	$0	$0	$3,554	-

These results indicate that a solar PV + BESS + generator microgrid could provide power to the port. None of the scenarios require more than ~900 kW of solar PV, and there is up to ~1.5 MW of solar PV capacity available on parking lots in and around the Cap Sante Marina.

For example, a microgrid with ~900 kW of solar PV, a ~100 kW/400 kWh BESS, and a 128 kW diesel generator would cost ~$1.8 million, with a payback of approximately 21 years. Another option (400 kW of solar PV, ~200 kW/800 kWh BESS, 119 kW diesel generator) has a lower capital cost (~$1.3 million) but has a longer payback period (34 years). Port staff can assess the various configurations in the attached spreadsheet to decide which one could be pursued based on the port's energy goals, values, and priorities.

POTENTIAL NEXT STEPS

Next steps the port would need to take to implement a microgrid include:

1. Defining a microgrid boundary and identifying locations where an islanding switch can be installed.
2. Identifying locations for the energy generation and storage components (i.e., solar PV, BESS, backup generation).
3. Contacting PSE's interconnection or grid integration department to obtain interconnection process information and gauge their areas of support or concern.
4. Explore options for connecting the microgrid generation and load resources during islanded operations, such as leveraging existing wiring and panels, including potential use of PSE infrastructure.

DECARBONIZATION LIFE-CYCLE ANALYSIS

Ports decarbonization can generate a variety of benefits for ports and near-port communities and help address climate change. Those who live and work near ports are impacted inequitably by harmful emissions from current port operations that are linked to respiratory and cardiovascular diseases, lung cancer, and premature mortality (Bailey and Solomon 2004). Using cleaner energy to power port operations reduces these harmful impacts and advances environmental justice. This analysis aims to better understand potential pathways to decarbonize the maritime sector in short-term (2030) and longer-term (2050) scenarios, focusing on the Port of Anacortes within the Puget Sound Region in Washington State. The port energy transition pathways described in this report were developed in collaboration with the Port of Anacortes to align with Washington State, U.S., and International Maritime Organization decarbonization goals, which call for a 95 to 100 percent reduction in GHG emissions by 2050.

METHODOLOGY

Researchers conducted an LCA-guided decarbonization opportunity assessment for the Port of Anacortes. The analysis used direct GHG emissions data for maritime applications provided by the 2021 Puget Sound Maritime Air Emissions Inventory Report (Puget Sound Maritime Air Forum 2024). This dataset, as summarized in **Table 8**, explains the energy sources for key mobile emissions sources at the Port of Anacortes and was used as the baseline for the decarbonization opportunity assessment.

Table 8. Direct GHG emissions based on current practices at the Port of Anacortes, reported in tons per year (tpy) from the Puget Sound Maritime Air Emissions Inventory (2024).

Emissions Source	CO_{2e} (tpy)	Energy Source
Ocean-going vessels	841	MDO
Harbor vessels	0	N/A
Recreational vessels	433	Gasoline, ULSD
Locomotives	0	N/A
Cargo-handling equipment	21	ULSD
Heavy-duty vehicles	8	ULSD
Fleet vehicles	19	Hybrid
Total	1,322	

In the past, small GHG emission reductions have been demonstrated via operational efficiencies and more strict fuel standards. These include, for example, the use of ULSD with less than 15 parts per million sulfur, and marine gas oil (MGO)/ MDO with less than 0.1 percent sulfur. Continuing port decarbonization at a similar rate would reduce GHG emissions but not at the pace required to achieve net-zero GHG emissions by 2050. The ultimate solution to achieve net-zero GHG emissions in the maritime sector is to replace fossil-fuel-based energy with low-carbon renewables (i.e., biofuels, hydrogen, renewable electricity, etc.) and/or to implement carbon capture and storage (CCS) technology at either the energy production stage or combustion stage.

Although many low-carbon technologies have been studied in the past decades, they vary in technology readiness level (TRL), decarbonization potential, and application requirements. Therefore, the adoption of low-carbon technologies in this analysis varies between near-term and long-term scenarios and across maritime applications (e.g., OGVs, harbor craft, locomotives). Technologies with higher TRL, closer to commercialization, or already commercialized are preferred for near-term application. Technologies with lower carbon intensity (CI) are preferred for long-term scenarios, regardless their TRLs, assuming these emerging technologies will ultimately be commercialized. **Table 9** gives a summary of current practices and leading low-carbon technologies for maritime sector applications, along with their TRL, CI, and applicability to near- and/or long-term scenarios.

In **Table 9**, CI data were collected from Argonne National Laboratory's GREET LCA database and open literature (Wang et al. 2022; Huang et al., under review), which represents the cradle-to-grave GHG emissions for each megajoule (MJ) of energy used in maritime applications. TRL ranges from 1 to 9, where 1 and 9 represent research concept and fully commercialized technologies, respectively.

Table 9. Key metrics for current and alternative energy sources considered for the Port of Anacortes, including which technologies are most likely applicable to each of the analysis scenarios.

Energy Source	CI grams CO_{2e}/MJ	TRL	Drop-in Fuel	Current Practice	Near-term (2030)	Long-term Standard (2050)	Long-term – Net Zero (2050)
Conventional gasoline	93	9		✓			
Conventional diesel	92	9		✓			
Conventional MGO	95	9		✓			
Renewable gasoline	18	7	✓		✓	✓	✓
Biodiesel	27	9	✓		✓		
Renewable diesel – HEFA*	34	9	✓		✓		
Renewable diesel – sludge HTL*	-19	6	✓			✓	✓
Renewable diesel – Fischer-Tropsh	16	7	✓			✓	
Renewable diesel – Fischer-Tropsh with CCS	-42	6	✓				✓
Bio-methanol	18	7				✓	✓
E-methanol	15	8				✓	✓
Green ammonia	1.6	7				✓	✓
Electricity – 2022 WA Mix	32	9			✓		
Electricity – 2050 WA Mix	0	9				✓	✓
Green hydrogen	15	8			✓	✓	✓
Renewable natural gas	11	8				✓	✓

* Acronyms:
HEFA – Hydroprocessed Esters and Fatty Acids
HTL – Hydrothermal Liquefaction

Researchers examined decarbonization potentials across the three scenarios described below. **Table 10** lists the assumptions in near- and long-term low-CI energy penetrations in the maritime sector for the Port of Anacortes. These were loosely based on the U.S. National Blueprint for Transportation Decarbonization, as well as industry and regional knowledge and direct conversation with the port. The Near-term (2030) scenario also incorporates a 30 percent increase in port energy demand compared to the 2021 baseline, and the Long-term Standard (2050) and Long-term Net Zero (2050) scenarios incorporate a 60 percent increase in port energy demand compared to the 2021 baseline. These growth rate assumptions were based primarily on a report from the IRENA, which outlined potential future scenarios for the increase in maritime shipping demand and energy needs. Researchers chose to use growth rates from the study's moderately progressive scenario (referenced in the study as the Transforming Energy Scenario).[9]

Near-term (2030) – This scenario represents the port's continued ambitions to decarbonize operations over the coming half decade and the pathways described within are assumed to be supported by public funding (e.g., EPA Clean Ports Program) and enabling policies (e.g., Washington State's Clean Fuel Standard). This scenario excludes methanol and ammonia fuels, which are not expected to come online in substantial quantities before 2030. It includes electrification of a limited portion of equipment and vessels based on constraints in both technology availability and electrical supply that are anticipated to last until at least 2030. In some cases, although electric technologies (e.g., vessel shore power) are available today, the electrical upgrades required to support the equipment may be difficult to implement by 2030. However, the Port of Anacortes anticipates its fleet of cargo-handling equipment could potentially be 100 percent electric by 2030. In addition, this near-term scenario only considers renewable diesel derived from HEFA pathways as the drop-in alternative for R99, as other technologies are assumed to be not yet fully commercialized.

Long-term Standard (2050) – This scenario is an extension of the Near-term (2030) scenario out until 2050 and assumes a similarly supportive policy and funding environment. By 2050, methanol, ammonia, hydrogen, and renewable diesel are expected to be available at commercial scales and most of the maritime applications that were operating on B20 in 2030 will likely have transitioned to these cleaner fuel choices (except for locomotives, which use B20 for 16 percent of their total fuel supply in 2050). Electrification also plays a more prominent role in this scenario, as technology availability and electrical supply constraints impacting adoption by 2030 are expected to be largely addressed by 2050. In this scenario, emerging biofuel production technologies with a CI much lower than that of commercialized HEFA pathways are taken into consideration. It is assumed that the R99 in 2050 consists of 50 percent wet waste HTL renewable diesel and 50 percent woody biomass FT renewable diesel.

Long-term Net Zero (2050) – This scenario demonstrates a potential pathway to net-zero GHG emissions by 2050 to align with Washington State, U.S., and International Maritime Organization decarbonization goals. The Long-term Standard (2050) was used as a baseline for this scenario and modified where reasonable to reach the intended emissions outcome (100 percent emissions reduction). While the other two scenarios represent ambitiously realistic pathways, this final scenario is even more ambitious. CCS plays can critical role in ultimately reaching net-zero GHG emissions. CCS is used during the production processes for a portion of the renewable diesel (i.e., Renewable Diesel – FT with CCS) included in this scenario.

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[9] https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Oct/IRENA_Decarbonising_Shipping_2021.pdf

Table 10. Assumptions regarding the adoption of low-CI energy technologies within each maritime application for the Near-term (2030), Long-term Standard (2050), and Long-term Net Zero (2050) scenarios at the Port of Anacortes.

Energy Share %	Renewable Gasoline	B20*	R99**	Electrification	Methanol***	Green Ammonia	Green Hydrogen	Renewable Natural Gas
Near-Term (2030)								
Ocean-going vessels	0%	50%	50%	0%	0%	0%	0%	0%
Harbor vessels	0%	50%	50%	0%	0%	0%	0%	0%
Recreational vessels	70%	15%	15%	0%	0%	0%	0%	0%
Locomotives	0%	30%	30%	30%	0%	0%	10%	0%
Cargo-handling equipment	0%	0%	0%	100%	0%	0%	0%	0%
Heavy-duty vehicles	0%	50%	50%	0%	0%	0%	0%	0%
Fleet vehicles	0%	0%	0%	100%	0%	0%	0%	0%
Long-term Standard (2050)								
Ocean-going vessels	0%	0%	20%	10%	30%	20%	10%	10%
Harbor vessels	0%	0%	20%	25%	20%	10%	25%	0%
Recreational vessels	20%	0%	20%	50%	0%	0%	10%	0%
Locomotives	0%	16%	17%	33%	0%	0%	33%	0%
Cargo-handling equipment	0%	0%	20%	60%	0%	0%	20%	0%
Heavy-duty vehicles	0%	0%	30%	10%	0%	0%	60%	0%
Fleet vehicles	0%	0%	0%	100%	0%	0%	0%	0%
Long-term Net Zero (2050)								
Ocean-going vessels	0%	0%	20%	10%	30%	20%	10%	10%
Harbor vessels	0%	0%	20%	25%	20%	10%	25%	0%
Recreational vessels	20%	0%	20%	50%	0%	0%	10%	0%
Locomotives	0%	0%	33%	33%	0%	0%	33%	0%
Cargo-handling equipment	0%	0%	20%	60%	0%	0%	20%	0%
Heavy-duty vehicles	0%	0%	30%	10%	0%	0%	60%	0%
Fleet vehicles	0%	0%	0%	100%	0%	0%	0%	0%

* B20: 20% biodiesel/80% petroleum diesel
** R99: 99% renewable diesel/1% petroleum diesel
*** Methanol: 50% bio-methanol, 50% e-methanol

RESULTS

With the low-CI technologies summarized in **Table 9**, and the expected penetration/share of each technology in each maritime category for both near- and long-term scenarios in **Table 10**, the expected decarbonization potential was calculated for each scenario for the Port of Anacortes. The results are shown in **Table 11**. Please note that all GHG emissions reported in **Table 11** are the life-cycle emissions, including direct emissions at the final combustion stage in **Table 8** and upstream emissions related to feedstock, conversion, and distribution. The results suggest that the selected combination of low-carbon technologies and their proposed penetration across maritime applications can potentially reduce life-cycle GHG emissions associated with in-scope sources at the Port of Anacortes by 50 percent in the near-term (before 2030) and ultimately achieve net zero by 2050. Note that a significant amount of renewable fuels and electricity will be needed to support the proposed decarbonization strategy and ultimately enable the GHG emission reduction, which will likely require policy support to achieve economic feasibility and overcome potential supply chain challenges.

Table 11. Estimated decarbonization potentials for the Port of Anacortes as a percentage decrease in emissions from the baseline scenario (2021).

	Life-cycle GHG Emissions Reduction (%)		
Emissions Source	**Near-term (2030)**	**Long-term Standard (2050)**	**Long-term Net Zero (2050)**
Ocean-going vessels	38%	92%	99%
Harbor vessels	38%	95%	101%
Recreational vessels	68%	100%	106%
Locomotives	53%	97%	109%
Cargo-handling equipment	71%	103%	109%
Heavy-duty vehicles	38%	91%	101%
Fleet vehicles	71%	110%	110%
Total	50%	95%	100%

Researchers also calculated the estimated energy demands by fuel type to achieve the abovementioned emissions reductions, which are also depicted in **Figure 5**. The Near-term (2030) scenario would consume 6 TJ of green gasoline, 9 TJ B20, 9 TJ R99, and 1 TJ electricity per year. The Long-term (2050) Standard scenario would consume 2 TJ green gasoline, 6 TJ R99, 8 TJ electricity, 6 TJ 50 percent bio-/50 percent e-methanol, 4 TJ green ammonia, 3 TJ green hydrogen, and 2 TJ renewable natural gas per year. The Long-term (2050) Net Zero scenario would consume 2 TJ green gasoline, 6 TJ R99, 8 TJ electricity, 6 TJ 50 percent bio-/50 percent e-methanol, 4 TJ green ammonia, 3 TJ green hydrogen, and 2 TJ renewable natural gas. The Long-term (2050) Net Zero scenario also requires access to operational CCS facilities at the fuel production site.

DISCUSSION

The results of this analysis indicate that there are pathways to significant emissions reductions for the maritime sector and Port of Anacortes in the coming decades that could ultimately achieve net-zero GHG emissions by 2050. However, these pathways would require significant adjustments to the current energy system by 2030, and a complete replacement of conventional fossil fuels by clean fuel alternatives and electrification by 2050. The assumptions underpinning this analysis, including the penetration rates of different clean fuels for different maritime end uses, should be further vetted with ports and stakeholders and adjusted over time as market conditions evolve and additional research becomes available.

Researchers identified a potential pathway to achieving decarbonization objectives through replacing conventional fuels with lower CI energy sources and integrating CCS at the point of fuel production. An additional tool to help achieve decarbonization objectives could include CCS technology at the point of combustion (e.g., onboard a vessel), which is being piloted in California. Future analysis could test how onboard CCS technology might serve as a bridge technology to achieve near-term emissions reductions while reliable supplies of clean alternative fuels are being established. Onboard CCS could also reduce the projected demand for some clean alternative fuels, helping to overcome potential future supply constraints. It is possible that both lower CI fuels and onboard CCS will play a role in achieving maritime decarbonization.

The magnitude of clean fuels and electric infrastructure required to achieve modeled pathways in this analysis is unprecedented. Future research should more closely evaluate the feasibility of achieving modeled clean fuel supplies and infrastructure deployments at the Port of Anacortes, accounting for feedstock availability, projected supply and demand for clean fuels (including demand from other industries), and potential guiding policies. Though highly ambitious, this analysis demonstrates a pathway to desired emissions reductions at the Port of Anacortes that could help inform future research and policy decisions.

LESSONS LEARNED FOR PORT TECHNICAL ASSISTANCE

This case study with the Port of Anacortes helped confirm the value of port technical assistance and identify key considerations for future program design, including potential challenges and associated solutions. Though each port is unique, lessons learned from working with the Port of Anacortes are particularly relevant for small- and medium-sized ports, which are anticipated to the be the focus of a future port technical assistance program.

Values to Ports

- **Foundational research –** This case study and associated analyses provide foundational research for the Port of Anacortes' energy transition. The port plans to build on these efforts in the future through a combination of internal and external funding support. For example, the port is planning to use these results and analyses to inform future grant applications and would like to develop externally facing communication materials. The port is also interested in moving beyond preliminary feasibility analysis for promising technologies identified in this case study, including on-site solar and port microgrids. The case study collaboration helped the port establish its bearings in the energy transition space, which will help unlock future investments and accelerate the port's adoption of cleaner energy technologies.
- **Technical expertise –** Connecting ports to national laboratory scientists leverages existing technical expertise to help ports navigate complex energy topics such as microgrids, electrification, and clean alternative fuels. It also can provide ports access to certain national laboratory tools and datasets. Most ports do not have dedicated in-house subject matter experts in these research areas, nor the demand to hire full-time staff in these research

areas, but they will need to access this type of expertise in a part-time capacity to inform their energy transition activities.

- **Trusted advice –** National laboratories provide unbiased science-based analysis of clean energy solutions. This is valuable to ports that are often approached by various vendors with sometimes conflicting recommendations and ports that are navigating complex political environments.
- **Internal capacity building –** By working in close partnership with participating ports, a technical assistance program will help build internal capacity for energy transition work. The case study with the Port of Anacortes included presentations on port-identified priority topics such as renewable energy, microgrids, and port resiliency. As a result, port staff are now more knowledgeable about these topics, aware of available resources they can leverage to continue evaluating these topics, and more comfortable making decisions regarding these topics for the port. Port technical assistance could also help ports identify potential demands for internal workforce development and/or hiring to meet future energy transition goals.

Public Values

- **Advance decarbonization and environmental justice goals –** Transitioning ports away from fossil fuels and toward lower emissions technologies can help address climate change and environmental justice. Although many ports aim to reduce their emissions and advance these public benefits, they often lack the in-house capacity, technical expertise, and funding to develop projects and programs toward this end. Port technical assistance provides a low-risk opportunity for ports to engage with national experts on these topics and generate foundational strategies for future efforts and investments in port energy transition activities. Port technical assistance can also help ports quantify the expected public benefits (e.g., emissions reduction benefit) of their choices and motivate action.
- **Increase the resiliency of the nation's critical infrastructure –** Without advanced planning and coordination, port energy transition activities could exacerbate grid constraints, generate a patchwork of investments, and strain regional energy landscapes. On the other hand, with advanced planning and coordination across ports, utilities, and other stakeholders, port energy transition activity and investments could be leveraged to develop more resilient energy infrastructure that not only provides emissions reduction benefits, but also benefits local economies, communities, and national security. A port technical assistance program can help facilitate the ladder approach.
- **Build a nationwide repository of data and best practices –** As more ports participate in a technical assistance program, national laboratories will develop a repository of data, research, and best practices. This information can be shared with other ports and stakeholders—for example, via an online portal—as feasible, to avoid duplicating efforts and to broaden the impact publicly funded research.
- **Inform a more scalable approach to port energy transitions –** While, in the beginning, port technical assistance will likely require a bespoke approach for each participating port, eventually national laboratories would develop a suite of resources and a deeper understanding of similarities across ports that influence port energy transitions. This information could be used to inform a more scalable approach to technical assistance, which could, for example, group ports by certain characteristics or direct them to publicly available resources once published, to reduce the need for one-on-one support in every situation.
- **Strengthen industry connections and feedback loops –** A port technical assistance program will strengthen relationships between national laboratories, DOE, and maritime

ports and stakeholders. It will also help establish new relationships with ports, particularly small- and medium-sized ports, that have not worked with national laboratories and DOE in the past. Collaborating with a diverse group of ports generates a more accurate understanding of the nationwide status of port energy transition activities. A port technical assistance program would also generate valuable feedback loops with ports that can inform broader research efforts.

- **Inform future policy decisions based on real-world data and examples –** Supportive policies are crucial to driving emissions reductions across U.S. ports, particularly those that would help address high switching costs and the generally higher cost of clean energy technologies compared to fossil fuel technologies. However, the data to inform such policy development is limited. For example, very few U.S. ports publish publicly available emissions inventories and those that do use varying methodologies to calculate and report their emissions. Working closely with ports nationwide through a technical assistance program provides an opportunity to fill existing data gaps and advance data standardization to better inform future policy decisions.
- **Generate learnings that can inform efforts in multiple "hard to decarbonize" sectors –** Ports by nature exist at the intersection of multiple transportation modes and industries. Facilitating energy transitions at ports will involve coordination across these transportation modes and industries and can generate benefits well beyond port boundaries. For example, drayage vehicles, locomotives, and OGV travel beyond port boundaries impacting communities across their routes. Furthermore, technologies and strategies leveraged in maritime port decarbonization could inform similar approaches at inland ports, airports, and other industrial centers that may use similar equipment and face similar challenges and opportunities.

Potential Challenges and Solutions

The case study collaboration, as well as conversations with other ports interested in technical assistance, revealed potential challenges that a future port technical assistance program may face and should aim to proactively address. The challenges can be divided into four categories—data, resources, coordination, and diversity—and are outlined in **Table 12**, along with potential solutions.

Table 12. Potential challenges and solutions to consider in developing a port technical assistance program.

Category	Potential Challenge	Potential Solution
Data	Availability – Some ports may not have standard practices to collect emissions or even operational data to inform technical analyses.	For ports without available data from previous years, use proxy data from other ports and research, as available, to generate estimates.
	Sensitivity – Some port and tenant data may be business sensitive. It may require protections to share or not be shareable.	Identify any potentially sensitive data sources and work to establish proper protection (e.g., non-disclosure agreement) to enable data sharing, as feasible.
	Accessibility – Ports do not always have direct access to relevant data, such as tenant electricity consumption or operational data.	Partner with port tenants on technical assistance projects to access relevant data and/or gain a better understanding of operations in order to generate necessary assumptions.

Category	Potential Challenge	Potential Solution
Resources	Port staff capacity – Many ports, especially small ports, lack dedicated environmental staff to support new projects such as a port technical assistance project.	Require a designated port leader for each project. The port leader does not need deep subject matter expertise but does need reasonable capacity and organizational knowledge to manage and socialize the project.
	National laboratory staff capacity – Technical experts are typically engaged in multiple research projects and may not have available capacity at the time it is requested from ports.	Track research interests from port applications and match with national laboratory capacities. In gap areas, evaluate the benefit of onboarding additional staff.
Coordination	Conflicting timelines – While technical assistance would operate on a programmatic timeline, port timelines are not always as predictable. Incorporating internal feedback and gaining support (e.g., from a port commission) can sometimes take much longer than expected but is very important for a project's success.	Offer multiple potential timeline options (e.g., 12 months, 18 months) to ports and work to verify flexibility in timelines to accommodate unexpected delays.
	Utility coordination – While technical experts can offer research supported solutions, ports will need to work with their electric utility and other stakeholders to confirm feasibility and next steps. Utilities operate on their own timelines and in their own regulatory environments, and some may require financial support to engage in projects and/or provide relevant data.	Encourage applicants to partner with their electric utility on port technical assistance and/or have the electric utility provide a letter of support for their application. This signals the utility and port have already established some form of communication and collaboration.
	Political support – Public ports are typically beholden to their port commission's priorities, which can be difficult to predict for a variety of reasons, including economic uncertainties and commissioner turnover. Energy transition projects will likely be most successful if there is support and at all levels of a port organization.	Encourage applicants to share their plans for working with their commission on a port technical assistance project and to provide any relevant examples of how the proposed work aligns with established port priorities.
Diversity	Engaging small-/medium-sized ports – Large ports have historically been more engaged in energy transition activities for a variety of reasons. Port technical assistance could be designed to help even the playing field and engage more small/medium ports in these activities. However, it could be challenging to attract small/medium ports that do not have dedicated environmental staff.	Conduct program outreach targeted at small and medium ports and integrate priority toward small and medium ports in selection critera, as feasible (e.g., target 80% of awardees are small and medium ports).
	Engaging geographically diverse ports – Ports on the East and West Coasts have historically been more engaged in energy transition activities for a variety of reasons. Port technical assistance could be designed to help even the playing field and engage more geographically diverse ports in these activities. However, it could be challenging to attract ports in regions that do not have policies in place to motivate port action.	Conduct program outreach toward geographically diverse ports and integrate geographic diversity into selection criteria, as feasible.

CONCLUSION

This case study provides an example of what technical assistance could look like for a small port that plays an important role in the region’s economy and resiliency plans. Assisting ports, especially small and medium sized ports, in their decarbonization efforts can accelerate the adoption of clean energy technologies and the achievement of national and international emissions reduction goals. In partnership with the Port of Anacortes, PNNL researchers identified existing capabilities at national labs that can be leveraged for technical assistance and applied them to the maritime port environment. Though no two ports are exactly alike, results and lessons learned from this case study can inform the development of a more permanent and expansive port technical assistance program. They can also be integrated into a public repository that would be built out over time to inform other port efforts and create a more scalable approach to technical assistance. This case study provided significant value to the Port of Anacortes. The port has shared that the collaboration was foundational to its energy transition journey, and that it plans to continue this work with a mix of internal and external funding. These efforts at scale across multiple U.S. ports can also provide a suite of public benefits such as increasing the resiliency of the nation’s critical infrastructure, advancing environmental justice and decarbonization goals, and generating learnings that can accelerate emissions reductions across the multitude of industries and activities that intersect at maritime ports.

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Appendix A – Highlighted Port Technical Assistance Capabilities

Activity	Description
Strategic Energy Transition Planning	Capacity for high-level planning to develop port-specific strategies to accomplish clean energy and emission reduction goals.
Critical Infrastructure Analysis	Identify critical port functions and associated infrastructure and energy demands. Assess potential vulnerabilities and provide recommendations to improve resiliency.
Capacity Building: Decarbonization	Work to build the organization's internal capacity and knowledge base related to port decarbonization to enable the port to shape its own energy transition. Topics may include clean energy options, resiliency planning, alternative marine fuels.
Workforce Development Assessment	Assess relevant workforce opportunities associated with the port's clean energy transition. This can include opportunities for job creation and continuing staff education and can focus on identifying equitable job transitions to support future clean energy technologies.
Fuel Transition Planning	Baseline existing fuel types and amounts being used at the port and develop a strategy to transition toward cleaner alternatives. This could include assessing alternative fueling infrastructure options for ports that supply fuels and/or assessing how ports could prepare for and support vessels that sail on alternative fuels.
Renewable Energy Assessments	Analyze port location(s) for feasibility of implementation of various renewable energy options, which could include wind, solar, bioenergy, geothermal, and marine energy.
Energy System Resilience	Support preliminary design of potential microgrid solutions and other resilience strategies, including technoeconomic analysis, for ports to help achieve energy and resilience goals.
Green Corridors Analysis	Identify key traffic flows to/from the port and opportunities for provisioning clean fuels to reliably serve certain routes.
Energy Auditing	Conduct energy audits of select port properties and/or equipment.
Cost Benefit Analysis/Technoeconomic Analysis	Support analysis of costs/benefits for planning scenarios and technology deployment options.
Hydrogen Safety Panel	The Hydrogen Safety Panel can contribute expertise to help enable the safe use and implementation of hydrogen technologies proposed for ports. This may include 1–2 meetings during early concept review, a 30% design review, and participation in the project's Hazard and Operability assessment.
Energy Baseline & Load Forecasting	Using data provided by the port and electric utility, establish energy baselines for port activities. Forecast potential load growth scenarios, including status quo, select electrification projects, and wide-scale port electrification.
Environmental Justice – Life-cycle Analysis	Conduct Environmental Justice LCA on proposed port decarbonization activities, assessing cradle-to-grave impacts through standard LCA, overlayed with additional socioeconomic considerations that can also highlight potential areas of unintended burden shifting.
Technology Validation	Use lab tools and equipment to assess performance of technologies for baseline or validation purposes. This could include validating/developing load profiles for electrified equipment, for example.
Joint Innovation Project Support	Facilitating collaboration with external stakeholders to support the development of joint innovation projects related to port decarbonization.

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