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Pacific
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PORT ELECTRIFICATION HANDBOOK

A Reference to Aid U.S. Port Energy Transitions

May 2024

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

U.S. DEPARTMENT OF
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Port Electrification Handbook

A reference to aid U.S. port energy transitions

May 2024

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DEDICATION

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EXECUTIVE SUMMARY

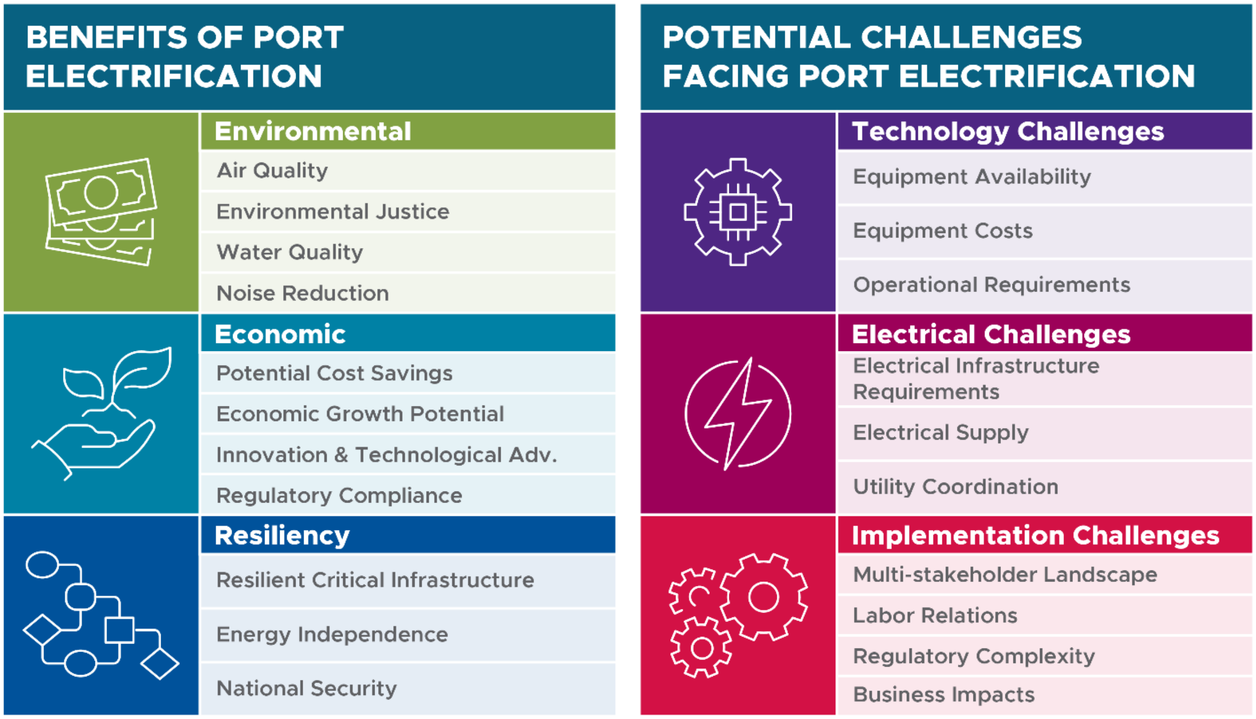
Port electrification can take many forms, such as electrifying cargo handling equipment or deploying a microgrid to power critical port infrastructure. To help evaluate the growing challenge of increased electrification and its impacts on the system, Pacific Northwest National Laboratory developed this Port Electrification Handbook with support from the U.S. Department of Energy, Office of Electricity's Microgrids R&D [research and development] program. The goals of this handbook are the following:

- Help port operators and planners evaluate different electrification technologies
- Explain how these technologies could aid and impact ports and surrounding communities
- Provide step-by-step considerations for port electrification.

Overview of Port Electrification: In most cases, port infrastructure is traditionally powered by fossil fuels (e.g., diesel, natural gas, heavy fuel oil), and the term "electrification" generally refers to powering this infrastructure and equipment by electricity, instead. Electricity can be provided via a battery, hydrogen fuel cell, or through direct connection to an electrical source such as the utility grid or solar photovoltaic panels.

Port electrification 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 diesel exhaust, particulate matter, and nitrous oxides that are linked to respiratory and cardiovascular diseases, lung cancer, and premature mortality.[1] Using clean electricity to power port operations reduces these harmful impacts of port activity and advances environmental justice.

Figure ES.1 describes other potential benefits and challenges of port electrification. Though all ports can benefit from electrification to some degree, the approach will vary port by port based on factors that include a port's location, electricity cost, electricity generation, operations, and operational structure. For example, the environmental benefit of electrification will be more pronounced for ports powered by renewable energy sources compared to ports that rely on utility grids primarily powered by coal or natural gas.



BENEFITS OF PORT ELECTRIFICATION

Environmental
- Air Quality
- Environmental Justice
- Water Quality
- Noise Reduction

Economic
- Potential Cost Savings
- Economic Growth Potential
- Innovation & Technological Adv.
- Regulatory Compliance

Resiliency
- Resilient Critical Infrastructure
- Energy Independence
- National Security

POTENTIAL CHALLENGES FACING PORT ELECTRIFICATION

Technology Challenges
- Equipment Availability
- Equipment Costs
- Operational Requirements

Electrical Challenges
- Electrical Infrastructure Requirements
- Electrical Supply
- Utility Coordination

Implementation Challenges
- Multi-stakeholder Landscape
- Labor Relations
- Regulatory Complexity
- Business Impacts

Figure ES.1. Potential benefits and challenges of port electrification.

The electrification technologies discussed here in the Port Electrification Handbook—including distributed energy resources (DERs), microgrids, and electrified end uses—vary in technology readiness and availability. Similarly, ports also vary in risk tolerance and their associated interest in investing in early-stage technologies. Grants and other financial incentives could help ports and stakeholders overcome some investment risk. Nonetheless, it is valuable to understand technology readiness and availability when planning potential electrification efforts, which is estimated in **Figure ES.2**.

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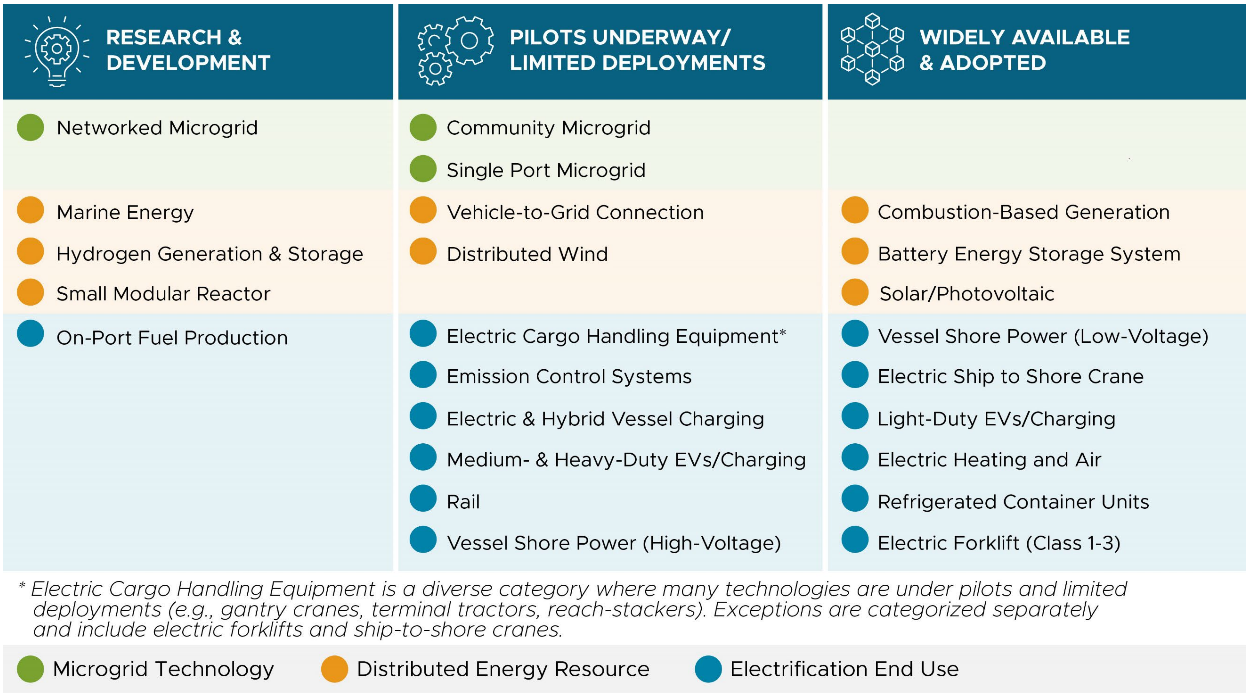
[1] Bailey, D., and G. Solomon. 2004. "Pollution Prevention at Ports: Clearing the Air." *Environmental Impact Assessment Review* 24 (7–8): 749–774. https://doi.org/10.1016/j.eiar.2004.06.005.



RESEARCH & DEVELOPMENT	PILOTS UNDERWAY/ LIMITED DEPLOYMENTS	WIDELY AVAILABLE & ADOPTED
🟢 Networked Microgrid	🟢 Community Microgrid 🟢 Single Port Microgrid	
🟠 Marine Energy 🟠 Hydrogen Generation & Storage 🟠 Small Modular Reactor	🟠 Vehicle-to-Grid Connection 🟠 Distributed Wind	🟠 Combustion-Based Generation 🟠 Battery Energy Storage System 🟠 Solar/Photovoltaic
🔵 On-Port Fuel Production	🔵 Electric Cargo Handling Equipment* 🔵 Emission Control Systems 🔵 Electric & Hybrid Vessel Charging 🔵 Medium- & Heavy-Duty EVs/Charging 🔵 Rail 🔵 Vessel Shore Power (High-Voltage)	🔵 Vessel Shore Power (Low-Voltage) 🔵 Electric Ship to Shore Crane 🔵 Light-Duty EVs/Charging 🔵 Electric Heating and Air 🔵 Refrigerated Container Units 🔵 Electric Forklift (Class 1-3)

** Electric Cargo Handling Equipment is a diverse category where many technologies are under pilots and limited deployments (e.g., gantry cranes, terminal tractors, reach-stackers). Exceptions are categorized separately and include electric forklifts and ship-to-shore cranes.*

🟢 Microgrid Technology 🟠 Distributed Energy Resource 🔵 Electrification End Use

Figure ES.2. Electrification technologies map depicting technology availability for DERs, electrification end uses, and microgrid technologies.

Port Microgrids: With the electrification of maritime ports, the potential (and need) to form microgrids at a port becomes significant.

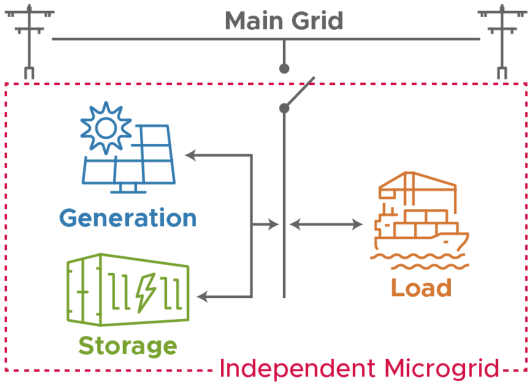


Figure ES.3. Example of an independent port microgrid.

Intermittent disruptions from the bulk power system can interrupt the power supply to the electrified port, resulting in an impact to port operations. Microgrids not only enable a backup source of power for critical facilities, but they can also be used to keep operations running during shorter outages or enable a limited set for disaster recovery. In certain power markets and infrastructure scenarios, microgrids may also be a way to either save feeder upgrade or increased demand charges, or possibly even sell services back to the bulk power system. The Port Electrification Handbook describes different types of microgrids, including independent microgrids (see **Figure ES.3**) and more complex community and networked microgrid designs. It also discusses key planning considerations for microgrids and how to assess their potential value through technoeconomic analysis.

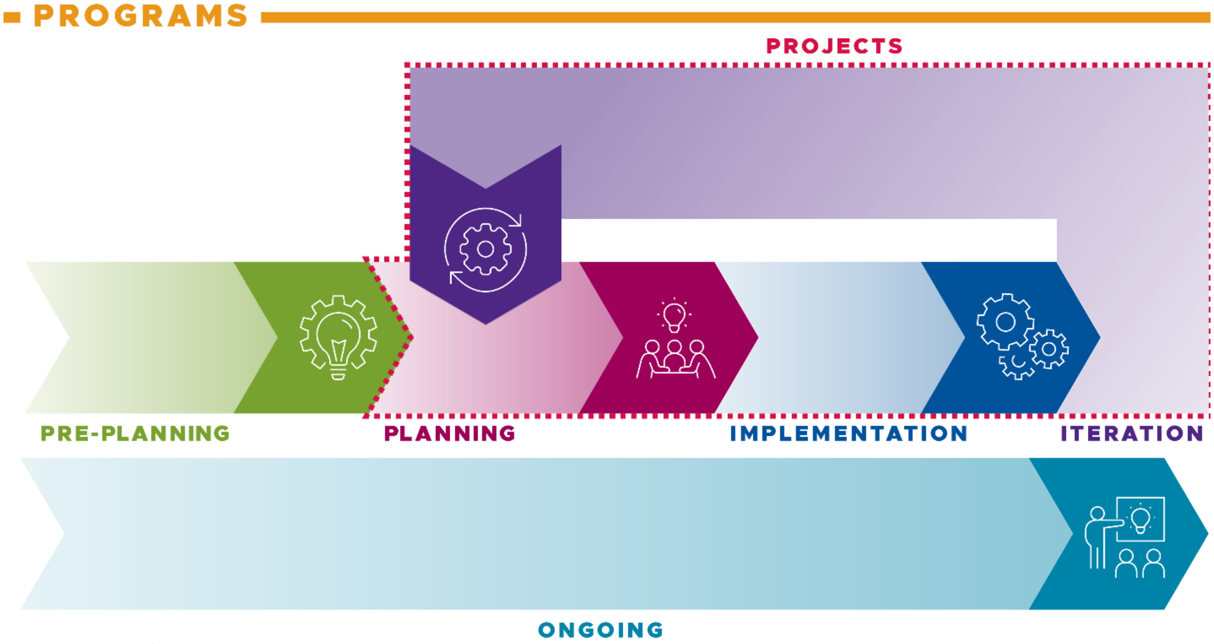
Planning for Port Electrification: The Port Electrification Handbook provides high-level guidance on electrification program planning and implementation, to help inform port, tenant, and other stakeholder efforts. It will not capture every task for every port because each is incredibly unique. Instead, the guidance is intended to provide a template for ports and stakeholders to build on in their respective efforts, a road map of planning phases and tasks to consider within each phase, and potential structure to support the sometimes-ambiguous process of port electrification.

The Port Electrification Program Management Framework, outlined in **Figure ES.4**, summarizes the phases of port electrification and tasks within each phase. It aims to align with the incremental investment process and ongoing iteration that is often undertaken to achieve overarching electrification and decarbonization goals. It includes four defined phases—Pre-planning, Planning, Implementation, and Iteration—and lists ongoing tasks that are important at all phases. Though outlined sequentially and in distinct categories, in practice, the boundaries between the phases blur, and it is highly likely that multiple phases will occur at the same time.

Utility Coordination

Port electrification must be accomplished hand-in-hand with the electric utility.

Ports can design and plan for various electrified end uses, but projects will only move forward if the required electrical service can be made available. Coordinating closely with the electric utility can also offer increased efficiencies, potential cost savings, and partnership and information sharing opportunities.



Pre-planning:
- Establish overarching goals and vision
- Develop energy/emissions baseline and electrification load forecast

Planning:
- Catalogue existing infrastructure/equipment and available alternatives
- Define scope, budget, and project goal(s)

Implementation:
- Secure project funding
- Establish project team and management structure

Iteration:
- Evaluate project performance
- Measure progress toward overarching vision and goals

Ongoing:
- Coordinate with the electric utility
- Manage/build stakeholder and partner relationships

Figure ES.4. Port Electrification Program Management Framework.

The maritime sector is experiencing an unprecedented demand from international, national, and sometimes regional forces to transition toward cleaner energy sources, including electricity. This demand is coupled with an influx of funding, largely from federal sources, that will support port energy transition activities and infrastructure buildout. Though the road ahead is largely unpaved, there is an increasing library of lessons learned from the implementation efforts of industry leaders and resources, such as this handbook, that help guide port efforts. Port electrification, when planned carefully with relevant stakeholders, can facilitate port energy transitions and strengthen the resiliency of the nation's critical infrastructure while advancing environmental justice.

A Regional Approach to Port Electrification

It is often most effective if regional groups of ports move in unison on certain activities. This can enable a systems approach to implementing new technologies and help ports avoid placing themselves at a competitive disadvantage (e.g., by requiring electrification when their neighbor ports do not). A regional approach also helps increase participating ports' influence on regional customers and leverage to advance policies supporting port electrification, for example, in state and federal legislature.

ACRONYMS AND ABBREVIATIONS

AC	Alternating Current
AHJ	Authority Having/Holding Jurisdiction
BCR	Benefit-Cost Ratio
BESS	Battery Energy Storage System
CARB	California Air Resources Board
CCS	Combined Charging System
CEA	Chugach Electric Association
CHE	Cargo Handling Equipment
CIUD	Critical Infrastructure Upgrade Deferral
DC	Direct Current
DCFC	Direct Current Fast Charge
DER	Distributed Energy Resource
DOE	Department of Energy
DOT	Department of Transportation
ECHE	Electric/Electrified Cargo Handling Equipment
EERE	Office of Energy Efficiency & Renewable Energy
EPA	Environmental Protection Agency
ERTG	Electric/Electrified Rubber-Tired Gantry
ESS	Energy Storage System
EV	Electric Vehicle

GHG	Greenhouse Gas
HD	Heavy-Duty
IMO	International Maritime Organization
ITC	Investment Tax Credit
JBER	Joint Base Elmendorf-Richardson
K	Thousand
M	Million
MARAD	Maritime Administration
MASCORE	Microgrid Asset Sizing considering Cost and Resilience
mBESS	Mobile Battery Energy Storage System
MCS	Megawatt Charging System
MD	Medium-Duty
NREL	National Renewable Energy Laboratory
NZE	Near-Zero Emissions
OE	Office of Electricity
PNNL	Pacific Northwest National Laboratory
PoA	Port of Alaska
PRIMRE	Portal and Repository for Information on Marine Renewable Energy
PV	Photovoltaic
RCA	Regulatory Commission of Alaska
RCU	Refrigerated Container Unit
RTG	Rubber-Tired Gantry
SCL	Seattle City Light
SMR	Small Modular (nuclear) Reactor
Sandia	Sandia National Laboratories
STS	Ship-to-Shore
TEA	Technoeconomic Analysis
TEU	Twenty-foot Equivalent Unit
TRL	Technology Readiness Level
UNCTAD	United Nations Conference on Trade and Development
UPS	Uninterruptable Power Supply
U.S.	United States
V2G	Vehicle-to-Grid
XFC	(DC) eXtreme Fast Charging
ZE	Zero Emissions

Photo credit: Port of Seattle.

CONTENTS

FIGURES

TABLES

Photo credit: Port of Seattle.

INTRODUCTION

PURPOSE AND SCOPE OF HANDBOOK

Port electrification can take many forms, such as electrifying cargo handling equipment (CHE) or deploying a microgrid to power critical port infrastructure. To help evaluate the growing challenge of increased electrification and its impacts on the system, Pacific Northwest National Laboratory (PNNL) developed this Port Electrification Handbook with support from the United States (U.S.) Department of Energy (DOE), Office of Electricity's Microgrids R&D [research and development] program. The purpose of this handbook is to help port operators and planners evaluate different electrification technologies, understand how these technologies could aid and impact their port and surrounding communities, and to provide step-by-step considerations for port electrification. It was developed with guidance from seven guiding ports and additional input from ports, stakeholders, and partners nationwide.

OVERVIEW OF PORT ELECTRIFICATION

All ports can benefit from electrifying their operations to some degree, and electrification solutions are as diverse as ports themselves. In most cases, port infrastructure is traditionally powered by fossil fuels (e.g., diesel, natural gas, heavy fuel oil), and the term "electrification" generally refers to powering this infrastructure and equipment by electricity, instead. Electricity can be provided via a battery, hydrogen fuel cell, or through direct connection to an electrical source such as the utility grid or solar panels.

Generally, all ports have access to electricity via connection to the electric grid that has long supported traditional loads, including outdoor lighting and building electricity. For many years, some ports have also been operating select infrastructure, such as ship-to-shore (STS) cranes, via grid connection or plugging in refrigerated container units (RCUs). Although ports are well-equipped to run a portion of their operations on electricity, heavy-duty industrial operations, including drayage trucking and powering oceangoing vessels at berth, have traditionally been accomplished using fossil fuels. Electrifying these types of port operations could reduce environmental impacts of port activities, including greenhouse gas (GHG) emissions and other harmful air pollutants that inequitably impact port workers and nearby port communities. However, electrifying these heavy-duty loads represents a momentous undertaking for ports and their customers and/or tenants, who have not traditionally managed this type of work.

Port electrification is a multi-stakeholder process most effectively viewed through a regional lens. It is driven by not only by port priorities and investments, but also those of port tenants and/or customers and by the regulatory landscape. The electrification technologies and processes described here can be useful to ports but also port tenants, customers, and other stakeholders that will play varying roles in port electrification projects. While the roles each of these groups play (e.g., manager, funder, equipment owner) may shift depending on port and project variables, these organizations must work collaboratively to advance electrification priorities at maritime ports. It also can be beneficial for regional groups of ports to move in unison on certain activities. This can enable a systems approach to implementing new technologies and help ports avoid potential competitive disadvantages (e.g., by requiring electrification when their neighboring ports

Port Electrification Development Process

*The Port Electrification Handbook is one of multiple components within the Resilient Electric Distribution Grid R&D ("Resilient Ports") project. It integrates key aspects of other components—including a resilient microgrids case study and technoeconomic analysis—into a nationwide overview and best practices document. Other elements informing the handbook include policy and market research and extensive outreach with ports and other stakeholders, including port tenants, utilities, and vessel owner/operators. The outreach process solicited input from ports nationwide via an in-person workshop held in February 2024 in Seattle, Washington (**Appendix B – Workshop Summary**), as well as a brief online survey (**Appendix C – Port Electrification Survey Summary**) and one-on-one meetings. The project team also collaborated regularly with seven guiding ports who helped inform the handbook content.*

do not). A regional approach also helps increase participating ports' influence and leverage to advance policies supporting port electrification, for example in state and federal legislature.

Port electrification must be accomplished hand-in-hand with the electric utility. Ports can design and plan for various electrified end uses (e.g., shore power, electric/electrified cargo handling equipment [ECHE]), but projects will only move forward if the required electrical service can be made available. A study commissioned by the Port of Long Beach estimated that full port electrification could generate a 5X increase in the port's annual energy consumption by 2030,[2] but meeting projected demand increases of this scale will be difficult to impossible for many electric utilities. Ports could benefit from energy efficiency upgrades and from exploring non-traditional infrastructure solutions to meet their projected electricity demand (for example, by installing on-site clean generation, which can alleviate some demand on the electric utility and provide enhanced port energy independence).

GUIDING POLICIES

Ports are experiencing an unprecedented demand to decarbonize, driven by international, national, state, and, in some cases, even regional policies. At the international level, maritime decarbonization primarily is driven by the International Maritime Organization (IMO), an organization that promotes cross-governmental coordination toward sustainable shipping. The IMO has managed measures related to energy efficiency and international shipping for over a decade. In 2023, IMO member states adopted an updated GHG strategy that accelerated its decarbonization timeline, now calling for net-zero GHG emissions in international shipping near 2050, with interim targets set for 2030 and 2040. The IMO now is working to develop and establish measures to help achieve these goals. IMO is not an enforcement agency; its members are responsible for enforcing policies within their own jurisdiction.

The U.S. adopted the IMO's updated GHG strategy and has implemented federal policies also calling for achieving a net-zero economy by no later than 2050. Unprecedented amounts of federal funding directed toward zero emissions (ZE) transportation and clean energy investments have supported these ambitions. For example, the Inflation Reduction Act (2022) allocated $3 billion to the Environmental Protection Agency (EPA)'s Clean Ports Program. Other landmark legislation includes the Bipartisan Infrastructure Law (2021) and Infrastructure Investment and Jobs Act (2022), which similarly allocated billions of dollars to support federal programs related to port decarbonization, including the Department of Transportation (DOT)'s Port Infrastructure Development Program and DOE's Regional Clean Hydrogen Hubs. For more information on

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[2] Engie Impact, "Accessing reliability and resilience of power systems at the Port of Long Beach."

federal funding and incentives related to port electrification, see the **Funding Opportunities & Incentives** section. Port decarbonization efforts at the federal level have historically fallen across multiple agencies, including the EPA, DOT, and DOE. There is currently an ongoing joint effort between these and other agencies to develop a Maritime Decarbonization Action Plan that will supplement the U.S. National Blueprint for Transportation Decarbonization.

For many ports, the most influential policies advancing port electrification are implemented at a state or regional level. Such policies vary widely depending on a port's location and often are driven by a state's clean energy and/or emissions reductions goals. In alignment with these goals, states may appropriate funding specific to port electrification or ZE transportation projects and may also enact related regulatory measures. For example, California has paved the way for port electrification in multiple respects by enacting the Ocean-Going Vessels at Berth Regulation that reduces harmful emissions from oceangoing vessels in port, and the Advanced Clean Trucks (ACT) standard, which requires increasing sales of ZE and near-zero emissions (NZE) trucks over time. Other states have adopted the ACT standard, including Maryland, Massachusetts, New Jersey, New York, Oregon, and Washington.[3] Some states have also developed regulations that will decrease harmful emissions from electricity generation over time, such as Washington's Clean Energy Transformation Act, which requires the state's electric utilities to provide 100 percent clean electricity by 2045. This policy and those similar will increase the emissions benefits of port electrification over time. Finally, electric utilities can play a pivotal role in supporting port electrification through guiding policies, including favorable rate structures, streamlining or accelerating permit processing, co-developing programs, providing make-ready infrastructure, and more. Utility coordination is critical for port electrification and discussed further in the **Electric Utility Coordination** section.

Potential Roles of a Port Authority

Two common types of port structures in the U.S. are landlord ports and operational ports:

- ***Landlord ports*** *lease portions of the port property to terminal operators (generally stevedoring companies) that manage operations in that area within the terms of their lease agreement. Terminal operators generally own their own equipment.*
- ***Operational ports*** *manage the maritime activities at their port. They generally own their own equipment and hire their own dockworkers.*

The role a port authority plays in electrifying port operations will vary by port type. Landlord ports have an important, though sometimes indirect, role to play in advancing port electrification. Landlord ports must coordinate with their tenants who, in many cases, are the end-users and owners of electrification technologies. Operational ports have more direct control over their equipment and investments, which can make implementing changes like electrification projects more straightforward. Not all ports will fall squarely into either category, as some maintain a hybrid structure and/or limited operational control over private terminals, for example. More ideas on the potential role of ports in electrification projects can be found in the ***Port Levers to Support Electrification*** *section.*

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[3] McNamara, M. 2023. "Understanding California's Advanced Clean Truck Regulation." RMI. June 27, 2023. https://rmi.org/understanding-californias-advanced-clean-truck-regulation.

POTENTIAL BENEFITS AND CHALLENGES

Though all ports can benefit from electrification to some degree (see **Figure 1**), the approach will vary port by port based on a variety of factors. These include a port's location, electricity cost, electricity generation, operations, and operational structure. For example, the environmental benefit of electrification will be more pronounced for ports powered by renewable energy sources compared to ports that rely on utility grids primarily powered by coal or natural gas. This section identifies potential benefits and challenges of port electrification to inform planning efforts. The **Planning Considerations** section integrates these considerations into generalized, step-by-step guidance for port electrification programs and projects.

BENEFITS OF PORT ELECTRIFICATION

Environmental

- Air Quality
- Environmental Justice
- Water Quality
- Noise Reduction

Economic

- Potential Cost Savings
- Economic Growth Potential
- Innovation & Technological Advancement
- Regulatory Compliance

Resiliency

- Resilient Critical Infrastructure
- Energy Independence
- National Security

Figure 1. Potential benefits of port electrification.

Environmental Benefits: One of the most critical reasons for port electrification is its potential to significantly reduce the environmental impact of maritime activities. By replacing fossil-fuel-powered equipment and vessels with electric alternatives, ports can substantially cut greenhouse gas emissions, curb air and water pollution, and reduce the inequitable environmental and health impacts on port workers and port-adjacent communities.

- Air Quality: Electrification leads to cleaner air around ports and nearby communities. Reduced emissions of harmful pollutants, such as sulfur dioxide and nitrogen oxides, improve air quality, leading to better health outcomes for residents in port cities and surrounding areas.
- Environmental Justice: Those who live and work near ports are impacted inequitably by air pollution and other environmental externalities of traditional port activities. For example, diesel exhaust, particulate matter, and nitrous oxides resulting from port activity are linked to respiratory and cardiovascular diseases, lung cancer, and premature mortality in neighboring communities.[4] Furthermore, near-port communities also are often historically disadvantaged communities. Using clean electricity to power port operations reduces the harmful impacts of port operations and advances environmental justice.

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[4] Bailey and Solomon 2004 (see Footnote 1). https://doi.org/10.1016/j.eiar.2004.06.005.

- Water Quality: Port electrification not only contributes to reducing air pollution, but also plays a crucial role in enhancing water quality in and around ports. Port electrification can significantly decrease the discharge of harmful pollutants into water, leading to cleaner and healthier marine environments. This improvement is not only beneficial for aquatic ecosystems, but also for the sustainability of fisheries and the overall well-being of coastal communities.
- Noise Reduction: Electric equipment and vessels are notably quieter than diesel or gas-powered engines. This reduction in noise pollution benefits both local communities and the well-being of workers on and around the port, contributing to a more harmonious and livable environment.

Economic Benefits: Port electrification projects usually require significant upfront investment but, over time, could provide financial benefits to ports, tenants, or customers.

- Potential Cost Savings: Electrification can result in significant cost savings for port operators in the long run. While the initial investment can be significant, electric equipment is often more energy efficient, is less expensive to maintain, and can generate fuel cost savings that, in combination, can lead to significant reduced operational costs over time. Additionally, if a port generates electricity on-site, there may be programs through the electric utility to sell excess generation back to the grid.
- Economic Growth Potential: Port electrification could stimulate economic growth by attracting sustainability-minded customers, reducing trade barriers related to environmental regulations, and creating job opportunities in manufacturing, maintenance, and technology development related to electrification.
- Innovation and Technological Advancement: Investing in port electrification fosters innovation and drives the development of cutting-edge technologies in energy storage, renewable energy integration, and electric transportation. This innovation not only benefits the ports but also contributes to broader technological advancements, leading to future economic growth.
- Regulatory Compliance: Many countries and regions are implementing stringent environmental regulations and emissions standards for ports. Electrification can help ports comply with these regulations or prepare to comply with potential future regulations, avoiding penalties and trade restrictions.

Resiliency[5] Benefits:

- Resilient Critical Infrastructure: Ports that invest in electrification and microgrid systems gain increased resiliency against power outages and disruptions. These systems can help ensure that critical operations can continue even during adverse conditions.
- Energy Independence: Ports that invest in on-site energy generation benefit from a diversified energy mix that is more prepared to withstand and more flexible to respond to unexpected events.
- National Security: Port electrification can benefit national security by strengthening the nation’s critical infrastructure. Additionally, port microgrids could be designed to operate isolated from the utility grid for enhanced security measures. These types of deployments are common, for example, with the U.S. Navy.

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[5] Resiliency, in the context of the Port Electrification Handbook, refers to the ability of a system to prepare for and adapt to changing conditions and to withstand and recover rapidly from deliberate attacks, accidents, or naturally occurring threats or incidents.

Despite growing interest and funding support, electrifying port operations remains challenging for a variety of reasons (see **Figure 2**).

Potential Challenges Facing Port Electrification

Technology Challenges
- Equipment Availability
- Equipment Costs
- Operational Requirements

Electrical Challenges
- Electrical Infrastructure Requirements
- Electrical Supply
- Utility Coordination

Implementation Challenges
- Multi-stakeholder Landscape
- Labor Relations
- Regulatory Complexity
- Business Impacts

Figure 2. Potential challenges facing port electrification.

Equipment Challenges:

- Equipment Availability: Not all equipment has an electric alternative in today's market. Even if a piece of equipment is available, it may not meet grant requirements—such as Build America, Buy America—or be certified by the Underwriters Laboratories (i.e., UL listed). Additionally, supply chain constraints may cause significant delays (18+ months) in equipment availability for many key items, including electrical transformers and panels.
- Equipment Costs: Electric equipment can be over twice as expensive as traditional fossil-fueled equipment. Depending on the equipment, it may be difficult to impossible to make the business case for added costs of electrification. Across the board, declining costs will accelerate electric equipment adoption.
- Operational Requirements: Even if electric equipment is available, it is not always a one-to-one replacement for fossil-fueled equipment. This could be due to charging requirements, battery lifespan, or operational power demands. Having reliable equipment is of upmost importance to ports to avoid operational interruptions and associated costs.

Electrical Challenges:

- Electrical Infrastructure Requirements: Port electrification generates new electric loads that often require utility infrastructure upgrades. While the equipment is expensive, the electrical infrastructure to support it can be the most expensive and unpredictable project cost. Though these costs may sometimes be supported by grant funding or the electric utility, this is not always the case.
- Electrical Supply: Large-scale port electrification could increase electrical service needs for some ports multiple times over. It will be challenging, and potentially impossible in some cases, for electric utilities to meet electrification loads with traditional infrastructure solutions. Innovative technologies, such as demand-side management and port microgrids, could help alleviate potential bottlenecks in electrical supply.
- Utility Coordination: Although electric utilities have been providing service to ports for decades, port electrification is a new business area for ports and utilities alike. It represents an opportunity for ports and utilities to learn together but also can be a challenging new process to navigate and coordinate.

Implementation Challenges:

- Multi-stakeholder Landscape: Ports may have high ambitions for electrification, but their authority to enact port electrification projects will ultimately be influenced by their operating structure. For example, landlord ports need to coordinate with their tenants among numerous other stakeholders to electrify port operations. In some cases, tenants are the lead for electrification projects at ports.
- Labor Relations: Electrification could generate new workforce opportunities, while at the same time reducing the need for other positions. Therefore, port clean energy transition activities must be coordinated closely with Labor Relations to identify and address any potential workforce impacts.
- Regulatory Complexity: Ports have varying degrees of authority over the activities they support, depending on their structure (e.g., landlord port, operational port) and the regulatory landscape they operate within. Regulation associated with port electrification varies widely at the national and international level, which can also be challenging for ports that serve a diverse set of customers.
- Business Impacts: Ports must consider their customer base and how electrification measures may impact their customers. Electrification could help attract sustainability-minded customers but could also inadvertently push customers to other ports with less stringent requirements related to electrification. This is one reason why it can be beneficial for ports to plan efforts at a regional scale.

ELECTRIFICATION AND THE PORT DECARBONIZATION LANDSCAPE

Electrification is a leading decarbonization solution and one that is most widely available because electricity infrastructure already serves ports nationwide. However, electrification is not always the best solution for all port decarbonization needs. Ports, tenants, vessel owner/operators, and other stakeholders are considering options beyond electrification, including hydrogen, biofuels, renewable fuels, renewable natural gas, and e-fuels. Some might also consider small modular nuclear reactors in the future, but this technology is not anticipated to be available in the coming decade. When choosing between potential decarbonization solutions, ports should consider factors including but not limited to electricity availability, electricity cost, alternative fuel or feedstock availability, spatial constraints, and operational requirements that will influence which decarbonization technology is best suited for a port and use case. A few other alternative fuels and associated resources are highlighted below to help familiarize ports with how electrification fits into the overarching decarbonization landscape.

Hydrogen is an alternative fuel that, when used in a fuel cell electric vehicle (EV), will produce only water vapor and air, resulting in zero tail pipe emissions. However, the overall life-cycle emissions for hydrogen will vary depending on its production pathway. Most hydrogen currently is generated from natural gas through steam methane reforming, though the U.S. is catalyzing cleaner hydrogen production through its Regional Clean Hydrogen Hubs Program. This program, at full scale, aims to annually produce over three million metric tons of clean hydrogen.[6] Hydrogen has a high energy per mass but low volumetric density, which is why it often is stored as a compressed gas (700bar) or cryogenic liquid (-253°C). However, even cryogenic liquid hydrogen is still four to five times less energy dense by volume than conventional liquid hydrocarbon fuels at room temperature.[7] Although hydrogen offers a promising decarbonization solution for heavy-duty industries, storing it—particularly onboard ships—can present challenges related to safety, space, and energy use (to maintain desired storage temperature).

The cost of equipment and the cost of hydrogen fuel are both significant barriers to the adoption of hydrogen technologies at ports. DOE's Hydrogen Shot aims to reduce the cost of clean hydrogen by 80 percent by 2031.[8] Depending on a port's hydrogen demand and access to clean electricity, it may be most cost-effective to produce and store hydrogen on-site. Though hydrogen and electrification can be viewed as competing options in the port decarbonization landscape, it is important to understand how they complement one another as electricity is used to generate hydrogen and hydrogen, when used in a fuel cell, generates electricity. **Table 1** includes other considerations regarding electricity and hydrogen in port applications.

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[6] The White House. 2023. "Biden-Harris Administration Announces Regional Clean Hydrogen Hubs to Drive Clean Manufacturing and Jobs." https://www.whitehouse.gov/briefing-room/statements-releases/2023/10/13/biden-harris-administration-announces-regional-clean-hydrogen-hubs-to-drive-clean-manufacturing-and-jobs.

[7] Keoleian, G. A., G. M. Lewis, C. Buchanan, J. Calzavara, and M. Woody. 2022. *Hydrogen Roadmap for the State of Michigan Workshop Report*. CSS22-17, Ann Arbor, Michigan: University of Michigan. https://dx.doi.org/10.7302/21851.

[8] DOE. 2021. *Energy Earthshots: Hydrogen*. Department of Energy. https://www.energy.gov/eere/fuelcells/articles/hydrogen-shot-introduction.

Table 1. Key considerations for evaluating hydrogen and electricity for port applications.

Consideration	Electricity	Hydrogen
Cost	Electricity rates are generally predictable and vary by region. Consider potential demand charges and specialized rate structures (e.g., shore power).	Prices are currently high and fluctuate but are expected to come down over time. Goal to reach $1/kg in the coming decade.
Operational requirements	Plan for charging time and charging frequency; this may require adjustments to standard operation.	Similar operations and fueling times compared to fossil-fueled equipment.
Weather conditions	Extremely cold weather may impact battery chemistry and performance. Storms may impact grid reliability.	Designed for operation in cold weather (-10°C and lower); however, warmer weather conditions can be challenging.
Spatial constraints	Plan for charging equipment footprint, conduit pathways, and battery storage (if desired).	Plan for fuel storage and associated setbacks, which depend on how hydrogen is stored (e.g., gas or liquid).
Supply	Requires connection to the electrical grid where electrical service upgrades are likely necessary OR establishing an on-site microgrid with on-site generation. In all cases, utility coordination is key.	Requires established hydrogen supplier OR on-site production likely through electrolysis. On-site production requires electricity and likely connection to the utility grid.
Emissions impacts	Overall emissions reduction potential depends on the emission factors for associated electricity generation (e.g., CO_2, NOx, SOx). Electrification of fossil-fueled equipment and transportation at ports reduces Scope 1 emissions, non-point source pollution, and improves near-port air quality.	Overall emissions reduction potential depends on hydrogen feedstocks, production processes, and the emissions factors for electricity used to produce hydrogen. Replacing fossil-fueled equipment and transportation with hydrogen-powered alternatives reduces Scope 1 emissions, non-point source pollution, and improves near-port air quality.
Resiliency	Electrification, coupled with renewable generation and storage (e.g., microgrids), can provide localized energy to ports and benefit national security.	Potential for on-site generation and storage and inclusion in microgrids. Energy storage and generation are separate (similar to fossil fuels), which can provide resiliency benefit. Hydrogen can enable long-term energy storage and grid services.
Safety	Available safety standards for electric equipment operation and charging. Local jurisdictions (e.g., Fire Department) may have additional reviews and restrictions.	Available safety standards for hydrogen generation, storage, and use that continue to be revised and expanded. Local jurisdictions (e.g., Fire Department) may have additional reviews and restrictions.

Biofuels (e.g., ethanol, biodiesel) convert energy from biomass into liquid fuels that can be blended with fossil fuels to provide a drop-in, cleaner fuel replacement. Using biofuels and biofuel blends in existing equipment can avoid the need for significant capital investments in new engine technology. The sustainability of biofuels depends on their feedstocks and production processes. Within the U.S., the EPA approves renewable biofuel pathways under its Renewable Fuel Standard program and sets annual production volume targets. The Alternative Fuels Data Center maintains a Biodiesel information page that includes biodiesel laws and incentives at the federal and state level.

Renewable Diesel, also sometimes commonly referred to as Green Diesel, is a drop-in replacement for conventional diesel fuel, made from feedstocks such as soybean or canola oil. Renewable diesel meets the U.S. and European specifications for petroleum and, unlike biodiesel, can be used in standard diesel engines without any blending with petroleum diesel. The production of renewable diesel has increased over the past decade,[9] and most of the currently available product is used in California due to the financial benefits provided by California's Low Carbon Fuel Standard. The Alternative Fuels Data Center maintains a Renewable Diesel information page with additional information regarding this alternative fuel.

Electrofuels, or e-fuels (e.g., e-methanol, e-ammonia), are produced using electricity to separate hydrogen from water, then combining that hydrogen with other materials—carbon dioxide in the case of e-methanol and nitrogen in the case of e-ammonia—to make alternative fuels that can be drop-in replacements to their fossil-fuel-based counterparts. For example, methanol and ammonia are already produced at industrial scales often using conventional feedstocks such as natural gas. However, they have not been traditional used as marine fuels. E-fuels may be in liquid or gas form and can be used to power internal combustion engines. Creating e-fuels requires a significant amount of electricity, preferably from renewable sources to provide desired emissions-reduction benefits. Although e-fuels offer a promising decarbonization solution, currently there is only limited production of e-fuels in the U.S., with plans for new e-fuel plants to come online in the coming years. In the maritime industry, e-fuels are considered a promising long-term solution to decarbonizing oceangoing vessels, pending the availability of clean electricity to produce them. Methanol is considered a medium-term marine fuel solution (expected to increase in use over the next 5 to 15 years) while ammonia is considered a long-term marine fuel solution (expected to increase in use in 15+ years).[10] According to DNV's Maritime Forecast to 2050, as of July 2023, 8 percent of the ships on order by gross tonnage in the world fleet would be powered by methanol.[11]

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[9] EIA. 2024. Monthly Energy Review, Table 10.4b. https://www.eia.gov/totalenergy/data/browser/index.php?tbl=T10.04B.

[10] Vanderbilt University Climate Change Initiative. 2022. *Pathways to Net-Zero 2050 in the North American Marine Shipping Industry: Fuels and Propulsion Systems*. Blue Sky Maritime Coalition. https://www.bluesky-maritime.org/_files/ugd/8ed502_6b637ee509f349779d6be00660727d86.pdf.

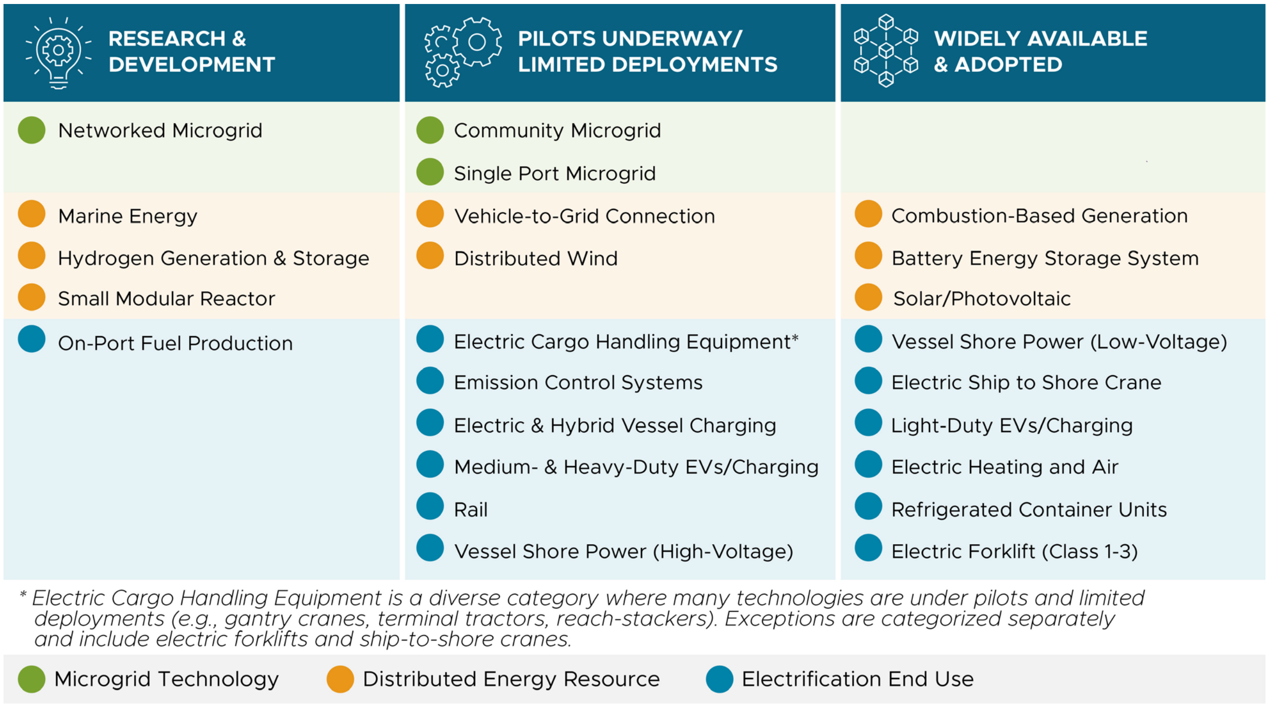
[11] DNV. 2023. *Energy Transition Outlook 2023 – Maritime Forecast to 2050*, https://www.dnv.com/maritime/publications/maritime-forecast-2023/download-the-report.

Photo credit: Port of Bellingham.

PORT ELECTRIFICATION TECHNOLOGIES

Port electrification can involve the deployment of several different technologies. This includes both converting existing equipment and assets to use electricity instead of fossil fuels, as well as deploying additional power generation sources and energy management technologies.

The electrification technologies discussed here—including distributed energy resources (DERs), microgrids, and electrified end uses—vary in technology readiness and availability. Similarly, ports also vary in risk tolerance and their associated interest in investing in early-stage technologies. Grants and other financial incentives could help ports and stakeholders overcome some investment risk. Nonetheless, it is valuable to understand technology readiness and availability when planning potential electrification efforts, which is estimated below in **Figure 3**.



RESEARCH & DEVELOPMENT	PILOTS UNDERWAY/ LIMITED DEPLOYMENTS	WIDELY AVAILABLE & ADOPTED
🟢 Networked Microgrid	🟢 Community Microgrid	
	🟢 Single Port Microgrid	
🟠 Marine Energy	🟠 Vehicle-to-Grid Connection	🟠 Combustion-Based Generation
🟠 Hydrogen Generation & Storage	🟠 Distributed Wind	🟠 Battery Energy Storage System
🟠 Small Modular Reactor		🟠 Solar/Photovoltaic
🔵 On-Port Fuel Production	🔵 Electric Cargo Handling Equipment*	🔵 Vessel Shore Power (Low-Voltage)
	🔵 Emission Control Systems	🔵 Electric Ship to Shore Crane
	🔵 Electric & Hybrid Vessel Charging	🔵 Light-Duty EVs/Charging
	🔵 Medium- & Heavy-Duty EVs/Charging	🔵 Electric Heating and Air
	🔵 Rail	🔵 Refrigerated Container Units
	🔵 Vessel Shore Power (High-Voltage)	🔵 Electric Forklift (Class 1-3)

** Electric Cargo Handling Equipment is a diverse category where many technologies are under pilots and limited deployments (e.g., gantry cranes, terminal tractors, reach-stackers). Exceptions are categorized separately and include electric forklifts and ship-to-shore cranes.*

🟢 Microgrid Technology 🟠 Distributed Energy Resource 🔵 Electrification End Use

Figure 3. Electrification technologies map depicting technology availability for DERs, electrification end uses, and microgrid technologies.

POWER SYSTEM COMPONENTS

Before discussing specific port electrification technologies, it is useful to go over some simple power system terminology. **Figure 4** shows a simplified, traditional power system. Power is produced by large, centralized "Generating Stations" (e.g., coal, nuclear, wind, and large-scale solar—usually 20 MW or greater by National Electric Reliability Corporation standards[12]), shown in red on the left-hand side of the figure. It is stepped up in voltage by the "Generation Step Up Transformer," to then be transmitted over long distances from the power plant to the load centers (cities) using the "Transmission Lines," shown in green. Finally, the power is stepped down to a lower voltage level using the "Substation Step Down Transformer" for local distribution, shown in purple. The local distribution may be broken into specific zone, circuits, or branches, which become "Feeders." Finally, the voltage may be stepped down again to service the load-end load (the icons in blue). DERs are usually installations less than 10 MW[13] and will be connected at either the purple portion of the system or after another transformer at the blue level.

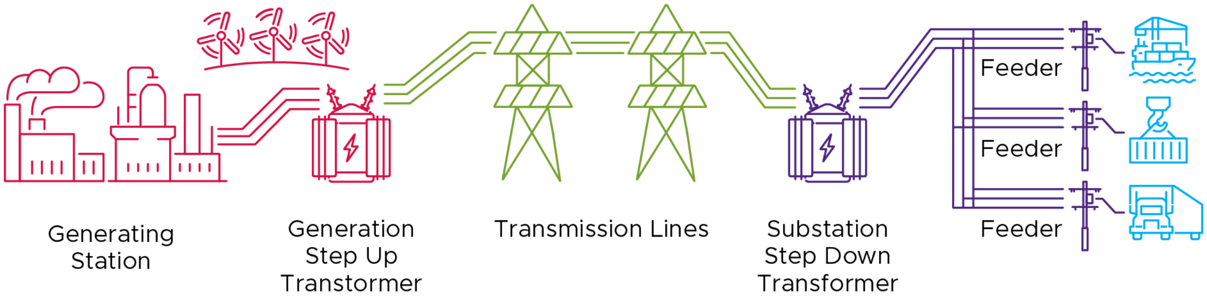


Figure 4. Power system components.

In general, the red and green portions of the diagram refer to the "transmission system" or "bulk electric system." The purple and blue refer to the "distribution system" and the "distribution feeder" connection. Most port electrification technologies will connect as blue icons to the purple or directly to the "Substation Step Down Transformer."

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[12] NERC. 2024. "Glossary of Terms Used in NERC Reliability Standards." National Electric Reliability Corporation. April 1, 2024. https://www.nerc.com/pa/Stand/Glossary%20of%20Terms/Glossary_of_Terms.pdf.

[13] Federal Energy Management Program. 2002. "Distributed Energy Resources: A How-To Guide." National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy02osti/31570.pdf.

DISTRIBUTED ENERGY RESOURCES

DERs typically represent smaller sources of generation on a power system, usually located closer to the load and near the “edges” of the power grid. For port electrification, DERs would often be items like solar photovoltaic (PV) systems on building roofs and energy storage to produce and store additional energy needed by the electrified technologies. DERs can also encompass flexible loads or devices that can both consume and produce electricity. DERs are often deployed to help alleviate power congestion or voltage concerns on the power system, as well as providing a backup power source for a local end use during emergency or outage conditions.

BATTERY ENERGY STORAGE SYSTEM

Overview: Battery energy storage systems (BESSs) are usually lithium-ion-based or lead-acid-based battery systems deployed to the power system. Other battery and storage chemistries exist but are not as popular or widely deployed. BESSs provide a mechanism to store energy from the power grid and discharge it back into the system at a different time. Both when the energy is stored and when it is discharged rely heavily on why the BESS was deployed and what its capabilities include.

BESSs are often deployed to serve two primary purposes—to support energy scheduling and/or to provide backup power. Below are some common definitions/terms for how energy storage may be used in these contexts:

- **Energy Arbitrage** and **Peak Load Shaving** are forms of energy scheduling that involve storing or buying electricity when prices/constraints are low or a resource is available, and then discharging during high prices/constraints. A classic example is storing excess solar energy generated during the day, and then discharging that energy back into the grid in the evening. A similar approach can be used to store electrical energy purchased when a time-of-use price value is low, and then use the stored energy to reduce the overall power draw (or sell it back to the electricity market) during the higher price period.
- **Demand Reduction** and **Demand Charge Reduction** are forms of energy scheduling or energy reserve, where the BESS acts as a buffer to keep the power consumed below a specific threshold. This can help keep the power impact to the electricity grid below a set value where new energy demand charges may trigger (and result in a higher bill/price category for several months), or to limit power to prevent overloading parts of the system during a high power-draw load. The BESS can be used to absorb "spikier" high-power, short duration loads like opportunity charging of EVs and ships by spreading that electric demand over a larger time period. In addition to demand charge mitigation, this approach may also enable higher-power, shorter-duration loads to be deployed near the end of a power system without requiring a larger feeder/infrastructure upgrade.
- **Backup Power/Microgrids** is the ability for the BESS to provide power to assets during an outage of the main power grid. This may be simply riding through normal momentary outages of an unreliable power system or may be providing hours (or days, depending on size) of energy to continue operations of a critical port resource. Which resources the microgrid can power in islanded mode will depend on the on-site generation capacity and BESS sizing. For example, a microgrid may be sized to continue powering critical ECHE during intermittent outages or to provide a backup energy source to RCUs if a prolonged outage has occurred. The BESS must typically have "grid-forming" capabilities to provide this service (the ability to form its own independent microgrid, even if that microgrid is a single device for backup power), unless it is part of a larger microgrid that has those capabilities elsewhere. Some BESS do not have "grid-forming" capabilities, so if backup power is a desired use case, this capability should be confirmed with the equipment provider.

It is important to note that there are other ways of using BESS devices to provide additional grid services, which may help offset the costs either through direct energy market interactions or providing a service to defer an equipment or infrastructure upgrade elsewhere. Furthermore, the backup power/microgrids use case is not necessarily mutually exclusive from the other use cases—it just requires that if the BESS is being used for other "blue sky"[14] operations, a minimum level of state of charge is maintained in case the backup power service is needed.

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[14] "Blue sky" refers to normal operation of the bulk electricity grid, where the system is operating routinely and as expected.

From a pure energy cost/sales perspective, BESS devices may not provide the best economic return. In certain power markets and under appropriate system conditions, they can be a cost-saving and/or profit-generating device on the system. However, BESS deployment typically is justified in other mechanisms, such as providing backup power, avoiding a costly capital upgrade (potentially due to environmental sensitivities or local regulation), or extending the benefits of another technology (e.g., storing on-site solar to help reduce the need to generate or purchase higher-GHG electricity).

Technology Readiness: Lithium-ion and lead-acid-based battery chemistries have a high Technology Readiness Level (TRL) due to being a well-understood technology that has seen significant deployment. Other chemistries may have lower TRL values. Regardless of battery chemistry, the interfacing electronics (the inverter device) have a high TRL and are well-understood. However, even with a high TRL, it is important to engage with local utilities and authorities holding jurisdiction. There may be additional studies/permits associated with batteries, such as larger interconnection studies (even if just being used as an energy buffer), and safety considerations, such as approach boundaries, fire suppression requirements, and spill containment.

BESS deployed as a part of a port microgrid at the Port of Long Beach.
Photo Credit: Port of Long Beach.

Photo credit: Port of Anacortes.

ELECTRIC VEHICLES WITH GRID CONNECTION

Overview: EVs are designed to use electric motors for traction and mechanical processes, with the energy stored in an onboard battery. This usually is done to improve energy efficiency of the process, reduce or eliminate emissions, and potentially reduce fuel and maintenance costs. EV deployments can be as simple as electric forms of light-duty vehicles, like security vehicles, yard operations trucks, or even charging for staff personal vehicles. It can also extend into medium- and heavy-duty operations, such as drayage vehicles and CHE like rubber-tire gantries and top-picks. While this section focuses on the potential to use the energy stored in EVs to support other port energy needs, the **Light-Duty Electric Vehicle Charging** and **Medium- and Heavy-Duty Electric Vehicle Charging** sections provide an overview of EV/ECHE technologies relevant to ports and associated charging infrastructure.

EVs recharge their onboard batteries through one of two mechanisms. The first is hybrid EVs, where an onboard generator set (diesel or other fuel) charges the battery, but some or all vehicle operations are electric. The second is a pure battery EV that requires a plug connection to the electricity grid to recharge the onboard battery. Plug-in vehicles may provide reduced operations costs in lower fuel/electricity costs, as well as reduced maintenance costs due to the lack of a combustion engine.

Depending on the duty cycle and dwell time (how long it is active and when it may be parked/available to charge) of the EV, charging requirements may be significantly different. For example, a rubber-tire gantry may only have a single shift of downtime and require direct current (DC) fast charging (DCFC – 150 kW) or even DC eXtreme Fast Charging (XFC – 350 kW) to completely recharge its battery, whereas a truck used by security may only need slower Level 2 charging (13.2 kW) to refill its battery. Drayage trucks and EVs with larger capacities may even require Megawatt Charging Systems (MCS – up to 3.75 MW currently), potentially needing several megawatts of power at once (for reference, 1 MW of charge power is equivalent to about 125 residential houses running a centralized air conditioner at once). If several megawatt-level chargers (or several hundred Level 2 chargers) are active at the same time, it could exceed limits of the power grid at that location, so it may be necessary to upgrade infrastructure or distribute charging locations throughout the port to connect to different parts of the power system.

Regardless of the power level required (Level 2, DCFC, XFC, or MCS), the charge controller on many EVs can support the ability to adjust the charge rate ("V1G" or Smart Charge Management). This capability allows the EV to adjust its charge rate in response to a higher time-of-use or critical-peak-price in electricity. Rather than being an unresponsive load on the system, the flexibility of the EV charging can become an asset and part of the DER pool to help manage grid conditions and constraints. For example, an EV truck with a longer dwell time may reduce its charging to avoid overloading a nearby transformer with other EVs charging on it, rather than charging at full power for the shorter duration.

DER capability can be further extended if the EV has the ability to discharge back into the grid (Vehicle-to-Grid or V2G capability). V2G requires additional capabilities in both the EV and the EV service equipment—the pedestal/connection the EV plugs into. The battery on the EV needs the capability to discharge through the connected port, and the EV service equipment needs to have the capability to convert the DC power back to alternating current (AC). Some vehicles may have onboard inverters to do this conversion directly, but that is often only for a limited amount of power (e.g., the onboard capabilities of an F-150 Lightning or Rivian R1T). Ideally, the vehicle can be treated as nearly identical to the BESS mentioned previously. In this regard, the V2G-capable vehicle may impose additional interconnection or operational restrictions from the utility, as they may treat it identically to a generator at that point.

In both the managed charging and V2G scenarios, the dwell time of the vehicle will be a key enabler of the flexibility, as well as the appropriate incentive structure. If an EV requires four hours to charge and only has four hours between shifts, it will have little flexibility and will need to charge as fast as it can. If the same vehicle has eight hours between shifts, it may be able to charge slower or even provide power back to the grid for part of the time, so long as it still meets 100 percent state of charge by the eight-hour mark.

For the V2G cases, the ability to discharge may be balanced against overall battery health and longevity. The additional cycles on the battery may shorten the expected service life of the battery, so any financial incentive to discharge back into the grid would need to help offset that cost. Aside from specialized EVs or EVs with a very long dwell time, the primary function of the vehicle may drive the charging cycle and leave little room for V2G flexibility. Furthermore, while EV manufacturers have become more lenient on whether V2G usage violates the battery warranty, not all have adopted this stance or may have specific restrictions on how V2G occurs. Any cost-benefit analysis of V2G capabilities of the EVs needs to factor in such limitations.

Technology Readiness: Technology readiness of EVs varies significantly in the port space. Light-duty vehicles have higher readiness levels and availability, due to leveraging the general consumer market. Medium- (MD) and heavy-duty (HD) vehicles, especially in the context of more specialized port equipment, are at a lower TRL and may have limited availability. Not all equipment may even be available in an electric form, or the battery capacity and longevity under typical port operations are still being evaluated. When available, electric versions of the equipment may be significantly more expensive than the traditional fossil-fuel-based equipment, so approaches to help justify the additional cost are needed. The capability of EVs to do Smart Charge Management or V2G has been demonstrated many times, but overall adoption and incentive mechanisms to encourage their use are still limited and evolving. EVs have significant potential as another DER on the power system, but current implementations are focused more on Smart Charge Management to avoid overloading equipment or additional demand charges from the utility.

COMBUSTION-BASED GENERATION (FOSSIL FUEL AND RENEWABLE FUEL)

Overview: Combustion generation is generally any form of generation resulting from combusting or burning a fuel source to directly run a reciprocating engine or gas turbine. Traditional diesel, gasoline, and natural gas generators are typical examples of this type of DER. Biodiesel and propane-fueled generators fall in this category, as well, but are not as widespread as diesel and natural gas. Direct hydrogen combustion, “hydrogen-enriched natural gas,” and even e-fuels (e-ammonia or e-methanol) still operate on the same principle but are deployed in even fewer numbers at the moment.

For the context of a port, it is assumed the generators are no larger than dozens of megawatts; larger, centralized power plants are in a different category. Combustion generation may be continually connected to the grid to provide power or services, or may only be connected to resources when an outage occurs, like a backup diesel generator (forming a microgrid of a single device). In certain strategic deployments, a distributed generator can be deployed, similarly to the BESS, and provide energy arbitrage or demand charge mitigation capabilities to the system, possibly as capital investment deferral to a larger feeder upgrade. This may be a very niche case, as the generator capital cost, fuel cost, and maintenance costs need to be significantly less than the infrastructure upgrade to be feasible.

For all types of fuel-based combustion generation, important considerations are emissions-related restrictions and potential environmental permitting requirements. The EPA maintains emissions requirements and runtime restrictions for emergency and non-emergency generators. Some states and local jurisdictions have additional regulations. If fuel-based combustion generators will be used in non-emergency situations or as the continual primary source of energy for a system (e.g., as part of an isolated microgrid), emissions regulations are stricter and may require purchasing additional or higher tier equipment.

Technology Readiness: Diesel, biodiesel, gasoline, propane, and natural gas generators are well-understood and are all at high levels of technology readiness. Biodiesel and propane are not deployed as frequently as diesel and natural gas, usually due to fuel availability and fuel costs. Hydrogen-based and e-fuel-based combustion generation is still being demonstrated; commercial deployments are available, but limited deployment numbers and evolving technology mean any deployments may need upgrades as further lessons are learned.

HYDROGEN GENERATION AND STORAGE

Overview: Hydrogen generation and storage has a homonym in the name; "generation" can mean two separate things in this context. Generation can refer to power production from hydrogen using a combustion engine or fuel cell, as well as the generation of hydrogen on-site using electrolysis. Storage encompasses how to maintain hydrogen produced elsewhere or on-site until it can be consumed (either for power generation or as a fuel for another port process).

For the purposes of port electrification, any on-site hydrogen production is assumed to be via electrolysis or catalyst-enhanced electrolysis; the gasification process for forming hydrogen is assumed to happen elsewhere.[15] Electrolysis production of hydrogen currently requires about 50 kWh of electricity to produce 1 kg.[16] Depending on the size of the production facility, this may require infrastructure upgrades or supplemental power sources near the electrolysis plant. Furthermore, the storage method may require additional energy to convert to that form (e.g., compressed gas or liquid hydrogen storage). Environmental considerations may make the use of PV/solar or wind desired in order to make the hydrogen "green."[17]

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[15] EIA. 2023. "Hydrogen Explained: Production of Hydrogen." Energy Information Administration. Last updated June 23, 2023. https://www.eia.gov/energyexplained/hydrogen/production-of-hydrogen.php.

[16] For reference, an RTG crane requires about 45 kg/day, a straddle carrier 46 kg/day, a reach stacker 33 kg/day, a yard tractor 21 kg/day, and a forklift 5 kg/day. (See Steel, L. M., and C. Myers. 2019. "Hydrogen Fuel Cell Applications in Ports: Feasibility Study at Multiple U.S. Ports." PNNL-SA-147032, Pacific Northwest National Laboratory and Oak Ridge National Laboratory. Presentation at H2@Ports International Workshop, San Francisco, September 2019. https://www.energy.gov/sites/prod/files/2019/10/f68/fcto-h2-at-ports-workshop-2019-viii3-steele.pdf.)

[17] National Grid. 2024. "The Hydrogen Colour Spectrum." https://www.nationalgrid.com/stories/energy-explained/hydrogen-colour-spectrum.

The previous paragraph focuses on molecular hydrogen; many port applications are also exploring whether hydrogen-derivatives like e-fuels (e.g., e-ammonia or e-methanol) could be used to replace existing fossil fuels. If those methods are being explored, power requirements for those processes will need to be considered, as well, especially if requirements for "green" sources of electricity are preferred.

Hydrogen storage is primarily done as compressed gas in pressure vessels or as liquid hydrogen kept cryogenically cooled. Methods to store hydrogen in materials (through either adsorption or absorption) are available but not at wide scale. Chemical processes to store hydrogen in a stable but easily accessible form (e.g., formate salts or formic acid[18]) are also being developed but are not on large-scale deployments. For both compressed gas and cryogenic liquid storage, additional power and safety requirements may need to be considered.

Electricity generation from hydrogen is typically via a hydrogen fuel cell. Hydrogen fuel cells provide power to the electric grid in a manner similar to standard chemical batteries, often going through an inverter to convert from the DC voltage to the grid's required AC voltage. Combustion-based generation is theoretically possible but deployed in even smaller numbers due to regulatory limitations, especially around NOx emissions.[19] However, many manufacturers are exploring Hydrogen Internal Combustion Engine (H2ICE) technologies, with meeting regulatory emissions requirements being a main focus.[20] If deployed, it will work similarly to the **Combustion-Based Generation (Fossil fuel and Renewable fuel)** section above, just using hydrogen gas directly or natural gas infused with hydrogen.

Technology Readiness: Electrolysis production of hydrogen gas, the storage of gaseous or liquid hydrogen, and the use in fuel cells are all at high levels of technology readiness. California has had a hydrogen fueling program for over a decade, which can offer key lessons learned, and has commercial offerings for hydrogen-based technology. However, the deployment still is limited, and if ammonia or methanol processes are explored at ports, they are at a lower technology readiness and may have some uncertainty in how they are deployed.

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[18] Autrey, S. 2023. *Enrichment of H_2 to CO_2 Ratio Using Formic Acid as a Hydrogen Carrier – CRADA 581 (Abstract)*. Richland, Washington: Pacific Northwest National Laboratory. https://www.pnnl.gov/publications/enrichment-h2-co2-ratio-using-formic-acid-hydrogen-carrier-crada-581-abstract.

[19] HFTO. 2022. "H2IQ Hour: Addressing NOx Emissions from Gas Turbines Fueled with Hydrogen: Text Version." Hydrogen and Fuel Cell Technologies Office, Office of Energy Efficiency & Renewable Energy, Department of Energy. https://www.energy.gov/eere/fuelcells/h2iq-hour-addressing-nox-emissions-gas-turbines-fueled-hydrogen-text-version.

[20] HFTO. 2023. "H2IQ Hour: Overview of Hydrogen Internal Combustion Engine (H2ICE) Technologies." Hydrogen and Fuel Cell Technologies Office, Office of Energy Efficiency & Renewable Energy, Department of Energy. https://www.energy.gov/sites/default/files/2023-03/h2iqhour-02222023.pdf.

Solar PV array installed at the Port of Bellingham in partnership with the electric utility, Puget Sound Energy. Photo Credit: Port of Bellingham.

SOLAR PHOTOVOLTAIC TECHNOLOGIES

Overview: Solar power generation, or generation from PV cells, is a widely deployed form of DER. Using different semiconductors, the PV cell converts the sun's irradiance into electricity, which can be fed through an inverter and back to the power grid. PV generation typically is coupled with some form of energy storage (usually a BESS) to store excess generation during the day for use at night or when clouds reduce production.

While widely deployed, PV generation does have some considerations for its use in port environments. The first is the land use required for significant generation; solar power generation can require between 5 and 10 acres per megawatt of production capability.[21] With the electrification of more port assets, meaningful solar power production could require significant land area, which may be better used for other port operations.

The second major consideration for PV in a port environment is potential maintenance, primarily periodic cleaning. Depending on the technology deployed and the local weather and wildlife patterns, the PV arrays may require a periodic cleaning to maintain full efficiency and power production. As standard dust, grime, and bird droppings accumulate on the solar cells, power production can drop significantly.

Technology Readiness: Solar PV has a high TRL with many projects deployed and commercial offerings available. The interfacing inverters have high technology readiness, and many adhere to standards required by the local utility to interconnect with their system (e.g., IEEE 1547-2018 or California Rule 21).

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[21] SEIA. n.d. "Land Use & Solar Development." Solar Energy Industries Association. https://www.seia.org/initiatives/land-use-solar-development.

DISTRIBUTED WIND

Overview: Distributed wind represents the deployment of smaller, more dispersed wind turbines (or microturbines) compared to a large-scale wind farm turbine. Individual wind turbines may produce between 5 kW and a few MW of power, with the installation typically smaller than 20 MW[22] (possibly composed of multiple turbines). Distributed wind is typically used in a manner similar to PV, where it is either fed into the power grid to reduce overall power consumption or sell power back to the utility, or it is tied to an energy storage system (ESS) to store excess energy during high production times and utilize it when wind production is low.

The footprint for distributed wind can vary by the type of turbine used, local wind conditions, and any regulatory requirements (environmental and visual). While the actual pylon the turbine is attached to may be relatively small, the space reserved for the distributed wind asset may need to be larger to accommodate nearby structures or meet local noise ordinances.

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[22] WETO. n.d. "How Distributed Wind Works." Wind Energy Technologies Office, Office of Energy Efficiency & Renewable Energy, Department of Energy. https://www.energy.gov/eere/wind/how-distributed-wind-works.

However, it is important to note that most seaports are intentionally sited in lower-wind areas, as high winds can create dangerous conditions for port operations. Therefore, ports may be less likely to have significant distributed wind potential at their working terminals and potentially across their overall property.

Technology Readiness: Distributed wind has a high TRL, leveraging not only many distribution deployments, but also the technologies and findings from larger transmission-scale wind farms. Many commercial products are available to deploy.

A Note on Offshore Wind

The burgeoning U.S. offshore wind industry is expected to play a critical role in providing coastal communities renewable energy. Many ports will inevitably play a role in this industry, for example supporting offshore wind customers and harboring vessels that service and construct offshore wind turbines. Currently, largely due to size and cost, planned and deployed offshore wind sites are utility-scale investments. As it related to port electrification, at this time, offshore wind is not a DER available at a port's scale. However, it may benefit some ports to plan for anticipated electric load growth to support the offshore wind industry.

MARINE ENERGY

Overview: Marine energy is captured from the natural motion of ocean water, with the two most common forms of marine energy being wave energy and tidal energy. Wave energy is captured from the up and down or side to side motion of waves and tidal energy is captured as water flows from one place to another due to shifting tides. Kilcher et al.[23] estimates the U.S.' marine energy technical resource (the theoretical amount that can be captured by existing technologies) to be 2,300 TWh/yr, which is approximately 57 percent of the nation's energy demand. The placement of marine energy devices must be done with caution to avoid significant interference, for example, the destruction of natural habitat or creation of new hazards to marine traffic. Marine energy potential varies widely depending on location. The National Renewable Energy Laboratory (NREL)'s Marine Energy Atlas is an online mapping tool that allows users to explore marine energy potential along much of the U.S. coastline. Additionally, the Portal and Repository for Information on Marine Renewable Energy (PRIMRE) is a comprehensive repository of resources, data, deployments, and additional information related to marine energy.

Technology Readiness: Marine energy is a promising but challenging technology, still primarily under research, development, and testing. One of the largest challenges facing marine energy is the corrosive and generally harsh environment the devices must operate in. Other challenges include high costs, permitting requirements, and addressing potential environmental impacts. However, multiple locations worldwide are testing marine energy, with one wave energy site under development along the Oregon Coast that should begin initial operations by 2025.[24] Marine energy deployments are tracked in PRIMRE's Marine Energy Projects Database. Marine energy is an interesting solution for ports that, by nature, are located on the water. It may be possible for some ports to participate in marine energy demonstration projects today, and ports will more likely find commercially available marine energy options in the next decades.

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[23] Kilcher, L., M. Fogarty, and M. Lawson. 2021. *Marine Energy in the United States: An Overview of Opportunities*. NREL/TP-5700-78773, Golden, CO: National Renewable Energy Laboratory. https://www.energy.gov/sites/default/files/2021/02/f82/78773_3.pdf.

[24] WPTO. n.d. "PacWave: Offshore Wave Energy Test Site." Water Power Technologies Office, Office of Energy Efficiency & Renewable Energy, Department of Energy. https://www.energy.gov/eere/water/pacwave-offshore-wave-energy-test-site.

SMALL MODULAR REACTOR

Overview: Small modular reactors (SMRs) are smaller nuclear power generation devices. SMRs are built as smaller, limited capacity units that can be bundled or chained together to provide the power required. The units are expected to be mostly self-contained, with little required maintenance or intervention from the end user. SMRs are expected to have relatively small footprints for their power production capabilities.[25]

Technology Readiness: The technology readiness of SMRs is currently very low. Several commercial entities are designing and getting approvals for their design. Internationally, some smaller demonstrations of SMRs have occurred. In the U.S., the license approval to build the first commercial SMR prototype was granted in 2021, with an expected operational unit online in 2029. While promising from an energy density and power production standpoint, SMRs are unlikely to be readily available until well into the 2030s or 2040s.

ELECTRIFIED MARITIME END USES

VESSEL SHORE POWER

Overview: Providing shore power to vessels at berth reduces emissions by eliminating the need to run fossil-fueled generators to power their auxiliary systems. Shore power can be provided at high-voltage (6.6–11 KV) or low-voltage (240–480 V) rates. High-voltage systems primarily serve large oceangoing vessels, and the Institute of Electrical and Electronics Engineers (IEEE) has established standards for high-voltage shore power systems to serve container, cruise, and roll-on/roll-off vessels.[26] Low-voltage systems can vary significantly and serve many types of vessels, including harbor craft, fishing vessels, and recreational vessels. Generally, it is easier to develop shore power systems that regularly serve the same vessels. This is because a key challenge with shore power is standardization, as electrical standards exist for some but not all vessel types. The IEEE standard mentioned above (IEC/IEEE 80005-2019) defines many of the electrical characteristics and protection of shore power connections, as well as the connector layout for specific types of vessels. However, not all vessel types are explicitly defined yet, so specific detail may be missing while the standard evolves. Furthermore, plug-in port locations vary across vessels, which can make it challenging to accommodate multiple vessels at one shore power location. There are some mobile shore power solutions that begin to address this challenge.

High-voltage shore power installations often cost multiple millions of dollars, and there is some concern about future stranded assets, particularly if vessels eventually are powered by cleaner alternative fuels and no longer need shore power to reduce their emissions while at berth. This risk can be reduced by integrating a requirement that shore-power-capable vessels plug in at berth. Furthermore, the EPA's recent Shore Power Technology Assessment at U.S. Ports noted a continued increase in the number shore power installations, types of vessels being served by

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[25] Reactor Technologies. n.d. "Advanced Small Modular Reactors." Office of Nuclear Energy, Department of Energy. https://www.energy.gov/ne/advanced-small-modular-reactors-smrs.

[26] IEEE. 2019. "80005-1-2019 – IEC/IEEE International Standard – Utility connections in port – Part 1: High voltage shore connection (HVSC) systems – General requirements." Institute of Electrical and Electronics Engineers. https://doi.org/10.1109/IEEESTD.2019.8666180.

shore power, and number of vessels that are shore power capable in their 2022 evaluation across ports nationwide,[27] signaling promising growth in this segment.

Shore power installations are dependent on electrical service availability and require ongoing coordination with the utility, particularly for high-voltage installations. In some cases, where ports are challenged to meet shore power demand with existing utility service, they have used switch gear to deploy systems that serve multiple berths, but only a portion of berths can be serviced at any given time (e.g., six berths are shore power capable but only three can be powered concurrently). Ports noted that it can be helpful to "think outside the box" when designing shore power solutions, particularly when facing electrical infrastructure or geographical constraints and when planning how to accommodate shore power loads.

California mandates certain vessels at certain ports plug into shore power or use an approved technology to capture emissions while at berth.[28] Outside of California, shore power sometimes is required by ports, for example, within berthing tariffs. The EPA Shore Power Technology Assessment at U.S. Ports[29] provides a comprehensive overview of shore power installations, including costs and lessons learned, from nationwide examples. An associated Shore Power Emissions Calculator provides estimated emissions reductions from shore power installations based on vessels serviced, frequency of usage, and other factors.

Technology Readiness: Shore power technology is widely available and has been deployed for decades, including both high- and low-voltage systems. Within the United States, low-voltage systems are more common, and high-voltage systems are being deployed with increasing frequency. There are some challenges with high-voltage system deployments, including servicing the overall power demand and load shape of shore power sessions that could, at peak, draw approximately 10 MW of load per individual cruise ship (port partners have expressed this could be somewhere between 8 MW and 15 MW). Though high-voltage shore power technology itself is readily available, novel solutions that address challenges with the current systems are being developed and demonstrated. These could include integrating BESS into shore power systems to help manage peak loads, working with the utility to develop shore power specific electric rates, and considering solutions that provide increased mobility for shore power installations, such as rail-mounted systems with extended cables.

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[27] Eastern Research Group, Inc. 2022. *Shore Power Technology Assessment at U.S. Ports 2022 Update*. EPA-420-R-22-037, Transportation and Climate Division, Office of Transportation and Air Quality, Environmental Protection Agency. https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1016C86.pdf.

[28] CARB. 2024a. "Ocean-Going Vessels at Berth Regulation." California Air Resources Board. https://ww2.arb.ca.gov/our-work/programs/ocean-going-vessels-berth-regulation.

[29] Eastern Research Group, Inc. 2022 (see Footnote 27). https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1016C86.pdf.

Figure 5. Compilation of images taken while plugging in a cruise vessel at the Port of Seattle. Photo Credit: Port of Seattle.

LIGHT-DUTY ELECTRIC VEHICLE CHARGING

Overview: Light-duty vehicles are generally defined as having a gross vehicle weight rating of less than 8,500 lb. This category includes many port fleet and staff vehicles, such as passenger vehicles and pickup trucks. Light-duty EVs are commercially available across the U.S. The most commonly available models are compact cars, through there is a growing number of EV sports utility vehicle (SUV) and pickup truck models.

Although the upfront cost of EVs is generally higher than their internal combustion engine counterparts, light-duty EVs, in many cases, have a lower total cost of ownership. This calculation compares lifetime costs and integrates cost savings from available incentives, rebates, maintenance costs, and fuel savings. The DOE Alternative Fuels Data Center's Vehicle Cost Calculator enables cost and emissions comparison across many U.S. vehicle models, including some EVs. A port's electricity rate will influence potential fuel savings costs and some electric utilities offer special EV rates or other incentives to encourage EV adoption.

EVs have zero tail pipe emissions, so electrification of light-duty fleet vehicles will reduce a port's Scope 1 emissions and decrease localized air pollution impacting port workers and neighboring communities. Scope 2 emissions-reduction benefits will depend on any indirect emissions from generating electricity that is used to charge EVs at the port.

Vehicle electrification requires charging infrastructure that can reliably charge vehicles at a rate that meets their operational requirements. There are multiple options for light-duty EV charging described in **Figure 6**. AC charging infrastructure (Level 1 and Level 2) is the least expensive option and may, in the case of Level 1, require little to no upfront investment depending on current electrical availability. DC fast charging equipment requires investment ranging from tens to hundreds of thousands of dollars, with costs increasing as the power level increases (e.g., DCFC at up to 150 kW, XFC at up to 350 kW, and MCS at up to 3.75 MW). Furthermore, as highlighted in **Figure 6**, there may be different connectors and standards associated with the different charging levels, so it is helpful to ensure the vehicle to be charged supports the "speed" and connection available. Depending on the scale of infrastructure installation, a utility permit and electrical service upgrade may be required, which can significantly increase project costs. Managed charging options may help a port charge its vehicle fleet more efficiently, thus decreasing the overall number of chargers required and resulting project costs.

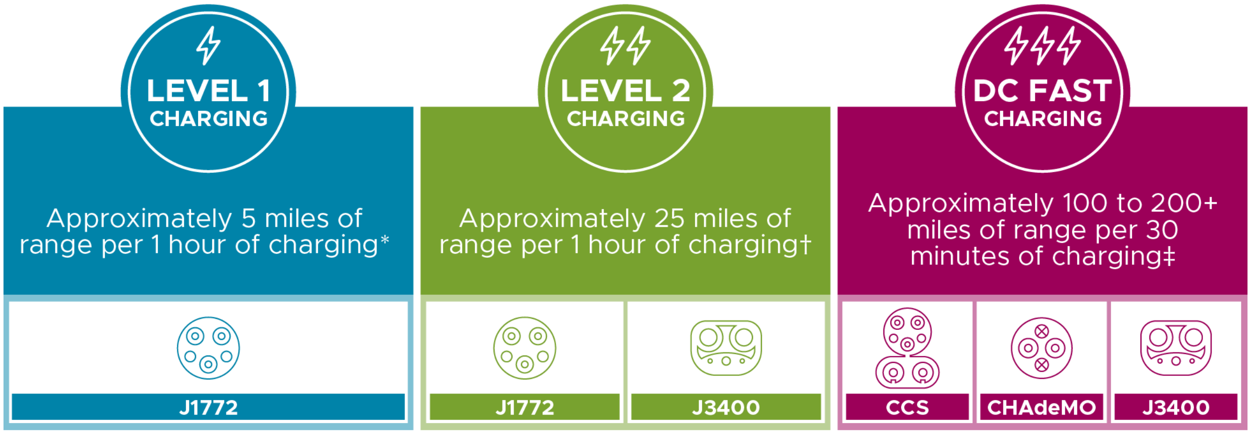

Figure 6. Light-duty EV charging options.

Potential port actions:

- **Prepare for vehicle turnover** – The most cost-effective time to replace a vehicle is at its end-of-life. Ports can catalogue their existing fleet and prepare to purchase EVs when replacements are necessary. Some ports have policies that require purchasing an electric or hybrid vehicle if an option is available.
- **Develop a Fleet Electrification Plan** – Ports can analyze their existing fleet size and usage to determine which vehicles are candidates for electrification and what type of charging infrastructure would be required to meet their operational needs. For example, some ports have found that their security vehicles and/or maintenance trucks are conducive to electrification because they primarily are driven on the port property and have significant downtime for charging. (Example: Port of Seattle – Sustainable Fleet Plan)

- **Install workplace charging** – For port staff who use vehicles to commute to work, providing workplace charging can help them drive an EV, especially if they lack access to reliable home charging. In certain circumstances, it may be possible to use the same charging infrastructure to charge staff vehicles during the day and port fleet vehicles overnight.

Technology Readiness: Light-duty EV charging technology is widely available at Level 1, Level 2, and DC Fast Charging levels (both DCFC and XFC). Megawatt Charging is expected to be available for EVs in future years but is aimed more at medium-duty (MD)/heavy-duty (HD) EVs and is still evolving. There are also many state and federal programs aimed at increasing the deployment of EV charging infrastructure through providing supportive funding and resources, such as the National Electric Vehicle Infrastructure Formula Program.

Electric vehicle charging station (DC Fast Charging and Level 2) installed by Puget Sound Energy at the Port of Anacortes. Puget Sound Energy owns this infrastructure and manages it as part of their own charging network. Photo Credit: Port of Anacortes.

Electric Marine Maintenance vehicle charging, part of the Port of Seattle fleet. Photo Credit: Port of Seattle.

MEDIUM- AND HEAVY-DUTY ELECTRIC VEHICLE CHARGING

Overview: Port operations typically require a mixture of MD/HD EVs, including drayage and terminal trucks. These vehicles are increasingly available in electric, electric hybrid, and hydrogen-powered drive trains. The operational demands of these vehicles will influence which clean energy technology provides the best alternative and the best location for charging placement. For example, terminal trucks that take regular, short trips across port property may be ideal candidates for full electrification, as well as drayage trucks that travel tens of miles from port property to the nearest rail facilities. On the other hand, drayage trucks that regularly travel 100+ miles to warehouse locations and back could be better suited for hybrid or hydrogen technologies in today's technology environment. Battery range and charge times associated with today's MD/HD EV technologies limit potential use cases. Standards like the MCS that provide a common charge interface and power are evolving and moving toward adoption. However, these variables are continuously improving.

HD trucks charging at the Port of Long Beach. Photo Credit: Port of Long Beach.

The ownership model and operational demand of MD/HD vehicles that service a port will influence the role ports play in supporting MD/HD vehicle electrification. Vehicles that currently fuel on port property, such as terminal tractors, would likely require on-site charging to facilitate their electrification. Vehicles that currently fuel off port property, such as drayage trucks owned by third parties, will likely be best served by charging elsewhere, for example, along driving routes or where the truck is parked during off shifts. In any case, ports with spatial constraints will be challenged to identify potential locations for MD/HD EV charging infrastructure, particularly for fleets that, to date, have always fueled elsewhere. If ports are considering providing charging for drayage fleets on port property, they are generally not looking to do this on marine terminals, but rather other properties they own. Some ports with available space are developing on-port charging for drayage fleets to help drive early adoption. Ports are also considering how they can help facilitate MD/HD EV adoption in third-party fleets without installing associated infrastructure on port property.

California's ACT regulation, adopted in 2020, accelerated the demand for ZE trucks and NZE trucks at an unprecedented rate. ACT sets a required percentage sales of ZE and NZE sales for Original Equipment Manufacturers that increases over time. While California led the way with the adoption ACT, multiple other states also have adopted this rule since, including Maryland, Massachusetts, New Jersey, New York, Oregon, and Washington.[30]

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[30] McNamara 2023 (see Footnote 3). https://rmi.org/understanding-californias-advanced-clean-truck-regulation.

Technology Readiness: MD/HD EV charging is available today, primarily leveraging DC Fast Charging solutions, sometimes coupled with energy management software. Today's MD/HD EV charging solutions usually are deployed following the combined charging system (CCS) standard, but a faster charging standard, the MCS standard, is currently under development. The MCS, once finalized, would open new possibilities for EVs to service port operations by further reducing charging times (but at increased power levels). As demand for MD/HD charging solutions increases in California and other states that follow their clean trucks standards, the availability and adoption of MD/HD charging solutions is expected to similarly increase.

ELECTRIC AND HYBRID VESSEL CHARGING

Overview: An increasing number of electric and hybrid-electric vessels are coming to market, including electric work skiffs, harbor tugs, and ferries. With today's technology, full electrification is a promising solution for vessels that travel predictable, short routes (e.g., ferries) while hybrid-electric solutions are better suited for vessels that travel unpredictable or longer routes (e.g., fishing vessels). Electrification is not expected to be a leading solution for the decarbonization of large oceangoing vessels due to the weight and energy density limitations of battery technology. These vessels, instead, likely will transition to clean alternative fuels such as methanol or ammonia. Within the U.S., the Port of Seattle recently received an electric work skiff that now services its Fisherman's Terminal, and the Port of San Diego and Crowley are working together to deploy charging infrastructure to serve a ZE tugboat.

Electric work skiff. Photo Credit: Port of Seattle.

Charging standards for electric and hybrid vessels are still under development. Though standards exist for common shore power applications to power a vessel's auxiliary systems, marine charging standards would apply to powering an electric vessel's primary systems. The MCS, currently under development, is being designed to support the marine industry, among others. There are also no best practices for deploying publicly available vessel charging stations because, thus far, deployments have been associated with specific vessels. However, in the future, it is reasonable to anticipate a demand for publicly available electric vessel charging.

Technology Readiness: Electric vessel technology is available in limited contexts and expected to increase in availability, particularly for vessels that travel predictable, short routes. Both electric vessels and charging infrastructure are in early stages of deployment and encounter some challenges with availability and standardization.

CARGO HANDLING EQUIPMENT

Overview: CHE is used to transfer cargo (e.g., containers, dry materials) on/off vessels, around the port, and eventually onto rail, trucks, or other transportation that carries the cargo away from the port. Ports that typically handle container cargo will use CHE, including STS cranes, gantry cranes, top handlers, side handlers, forklifts, and straddle carriers.[31] For bulk cargo, CHE commonly includes loaders, cranes, and forklifts.[32] CHE can also include terminal tractors and yard trucks, which this report discusses in the **Medium- and Heavy-Duty Electric Vehicle Charging** section. CHE traditionally is powered by fossil fuels, but there are a growing number of alternative fuel CHE options coming to market, including Liquified Natural Gas (LNG), Compressed Natural Gas (CNG), hydrogen, and electric options.

When considering CHE electrification, it may be helpful to start by examining a port's current equipment inventory to determine which assets are the heaviest emitters, are the closest to replacement, and could most easily be converted to electric options. The first factor regarding emissions can be calculated by collecting fuel usage from equipment and calculating its current emissions, for example through the EPA's Greenhouse Gas Equivalencies Calculator. When considering replacement needs, it can be helpful to identify equipment nearing its end-of-life and equipment with aging engine technology. In some cases, even if the equipment will only require repowering, it could be beneficial to replace the entire piece of equipment earlier with an electric counterpart to stay ahead of emissions regulations. Finally, certain CHE operational demands are better suited for electrification than others.

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[31] ANL. 2022. *Cargo Handling Equipment at Ports.* Argonne National Laboratory. https://www.anl.gov/sites/www/files/2022-03/Cargo%20Handling%20Equipment%20At%20Ports%20FINAL%203-23-22b%5B75%5D.pdf.

[32] ANL 2022 (see Footnote 31). https://www.anl.gov/sites/www/files/2022-03/Cargo%20Handling%20Equipment%20At%20Ports%20FINAL%203-23-22b%5B75%5D.pdf.

It may be useful to catalogue and compare the following items across potentially electrified CHE options to develop a prioritization and investment strategy:

- Rolling vs. non-rolling ECHE – Some pieces of equipment operate within a confined area (e.g., some rubber-tired gantries [RTGs]) or are stationary or on rails (e.g., STS cranes). In these cases, it may be possible to establish a direct connection between the equipment and the utility grid, providing reliable electricity and eliminating the need for charging. Rolling ECHE will require some form of energy storage, usually in the form of a battery. Grid connection provides a simple and reliable electric supply with the downside of limited-to-no mobility. Battery-powered options are mobile but introduce a new variable to plan around—equipment charging—that can sometimes create challenges.

Electric Cargo Handling Equipment

The ***Case Study: Electric Cargo Handling Equipment*** *section contains a more in-depth description of an ECHE project deploying two types of electric/electrified rubber-tired gantry (ERTG) Cranes. The case study includes potential implementation steps and lessons learned, based loosely on the experience of the Georgia Ports Authority.*

One of Georgia's ERTGs in operation. Photo credit: Georgia Ports Authority.

- Charging requirements – ECHE that is not grid-connected will require regular charging or battery replacements. A charging schedule will depend on the shift schedule and charging infrastructure specifications. In some cases, the operational demands of CHE are not conducive to charging, primarily because the equipment lacks sufficient downtime. In these cases, the high-power MCS likely will be needed, which is still an evolving standard. The Long Beach Container Terminal has taken an innovative approach to overcome this challenge by using electric, autonomous vehicles to transfer containers at their terminal and battery swapping technology.
- Electrical loads – ECHE conversions will generate new electrical loads it is necessary to plan for. PNNL has developed a load profile spreadsheet to help estimate potential loads from common types of ECHE. The most accurate load profile can be obtained directly from the equipment provider. Ensure load planning also considers potential electricity regeneration that may be captured, for example, when lowering cargo loads.

Technology Readiness: ECHE is a diverse category of assets with varying levels of technology readiness. Some CHE types have offered an electric option for many years (e.g., light-duty forklifts, STS cranes) while others are more recently coming to market (e.g., ERTGs, top-picks). Generally, heavy-duty cargo handling activities are more difficult to electrify. There are fewer available ECHE options in this category, and those that are available are not as well-proven. Light-duty cargo handling activities (similar to light-duty vehicles) are easier to electrify, and options are more widely available and well-proven. One exception is stationary CHE, such as STS cranes, which are easier to electrify because they can be connected directly to the grid.

Matson EV yard hostlers at Port of Long Beach terminal. Photo Credit: Port of Long Beach.

In all cases, ECHE is usually significantly more expensive than fossil-fueled CHE, sometimes over twice as expensive. Federal and other funding support, such as grants, offer critical financial assistance to help close the cost gap. However, it is important to note that some funding opportunities may require equipment to be Build America, Buy America compliant, which may be challenging for certain ECHE that currently is not produced widely in the U.S.

Argonne National Laboratory published Cargo Handling Equipment at Ports in March 2022, which includes information on key CHE for container ports and available fuel options (shown in **Table 2**). Electric versions are available for most equipment reviewed, with the exception of chasis rotators and log stackers. Bulk cargo or liquid product ports, on the other hand, would use other types of equipment such as wheel loaders/front-end loaders, material handlers and cranes, conveyance systems, pumps, and internal bulk trucks that move goods around on-site. Of this list, wheel loaders/front-end loaders are available in small versions (around 4 cubic yards bucket size) but not at the size required to support most port operations (around 10–15 cubic yards bucket size) in the U.S. Conveyance systems and pumps that are stationary can be electrically powered, while portable models are typically powered by a generator. Material handlers and cranes (e.g., clamshell cranes) that would be used in bulk cargo ports are also available in electric versions.

Table 2. CHE and fuel types. Source: Argonne National Laboratory, 2022, *Cargo Handling Equipment at Ports*.

Equipment	Gasoline	Diesel	CNG	LNG	LPG	Hybrid	Electric	Fuel Cell
Automated Guided Vehicle							✓	
Chassis Rotator		✓						
Container Crane		✓					✓	
Forklift	✓	✓	✓		✓		✓	✓
Log Stacker		✓						
Material Handler		✓				✓	✓	
Mobile Crane		✓					✓	
Pallet Jack							✓	
Reach Stacker		✓					✓	
Rubber-Tired Gantry Crane		✓				✓	✓	
Side Handler		✓			✓		✓	
Straddle Carrier		✓				✓	✓	
Terminal Tractor	✓	✓	✓	✓			✓	
Top Handler		✓					✓	

ON-SITE FUEL PRODUCTION

Overview: On-site fuel production in the context of an electrified port is expected to be some form of hydrogen-based fuel source. Depending on the amount of hydrogen a port expects to use, on-site production may be the most cost-effective and reliable hydrogen source in the future. However, it is important to note that on-site fuel production and electric vehicle/equipment charging will be in direct competition for available electricity and that using electricity to charge electric vehicles/equipment is more efficient than using electricity to produce hydrogen and then converting the hydrogen back to electricity for use in a fuel cell. However, in cases where electrification is not feasible, hydrogen-based fuel sources provide an alternative that can enable decarbonization of traditionally hard-to-decarbonize end uses. Ports may use hydrogen for CHE and, in some scenarios, to refuel ships. For example, the first hydrogen fuel cell passenger ferry in the U.S. will be demonstrated in the San Francisco Bay (California).[33] Some details are provided in the **Hydrogen Generation and Storage** section above, especially in the context of using molecular hydrogen gas or liquid to fuel on-site equipment, generators, and fuel cell devices. On-site fuel production will produce the hydrogen via electrolysis from water, using electricity from the power grid for the process. Once separated, the hydrogen needs to be compressed or cooled for storage. Methods to bind hydrogen with other material for storage are available but are not widely deployed and are still being researched. On-site hydrogen production enables the port to have energy independence from a larger supply chain, which provides some resiliency against supply interruptions.

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[33] CARB. 2024b. "LCTI: Zero-Emission Hydrogen Ferry Demonstration Project." California Air Resources Board. https://ww2.arb.ca.gov/lcti-zero-emission-hydrogen-ferry-demonstration-project.

Electrolysis of the water can utilize any electricity source but may have requirements for the full life-cycle emissions to ensure it is reducing greenhouse gases and other emissions. On-site solar PV or distributed wind generation would be suitable sources if energy capabilities were sufficient. Power from the traditional electric grid may be acceptable, though it may have requirements such as having the port buy credits in renewable sources of power under the assumption these would providing the electricity for the hydrogen production.

In addition to the electrolysis of the water and storage requirement, additional filtering and processing of seawater may be necessary, depending on the local seawater conditions and electrolysis devices utilized. These additional processes may require marginal increases in power but also have the potential to incur maintenance and disposal costs. The full hydrogen production cycle should be evaluated through cost-benefit analysis to ensure any maintenance considerations are fully understood.

Space requirements for the electrolysis and storage facilities will be a key consideration for on-site hydrogen fuel production. Operational requirements for the hydrogen fuel needs to be considered and evaluated to determine how much on-site storage is needed, which will translate into pressure vessel or cryogenic tank sizes for storing the hydrogen. Local fire code also likely will require appropriate spacing and easements around the hydrogen facilities, requiring further ground space.

Technology Readiness: On-site fuel production using electrolysis to produce gaseous or liquid hydrogen has a high TRL, but deployment is not widespread. California has over a decade of production and deployment of hydrogen infrastructure, but adoption outside of California has been limited. While the technology has commercial offerings, there may be challenges in sourcing equipment if several ports deploy hydrogen simultaneously. However, DOE’s Hydrogen Hubs program seeks to improve these limitations, including helping to drive down the production cost of hydrogen.

REFRIGERATED CONTAINER UNITS

Overview: RCUs are insulated Conex crates with climate control capability. RCUs plug into a vessel’s power supply to maintain a proper storage temperature for goods while in transit, be that refrigerated, frozen, or even warmed. RCUs are insulated and can maintain temperatures while they are moved around the yard or loaded/unloaded. However, RCUs require some form of power to maintain temperatures for extended periods and, typically, will be plugged in when stored at a port. When plugging in is not an option, a diesel-powered or electric unit is attached to the RCU to power climate control. Electric units are more appealing from an emissions perspective and are required in certain jurisdictions.[34]

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[34] CARB. 2024c. “Transportation Refrigeration Unit (TRU or Reefer) Regulation.” California Air Resources Board. https://ww2.arb.ca.gov/our-work/programs/truckstop-resources/truckstop/regulations/transport-refrigeration-unit-tru-or.

Individual RCUs require around 5.5 kW,[35] which is not a significant load. However, a large collection of refrigerator container units (especially part of an RCU stack of the yard) can present an appreciable amount of load to the port. In more temperate locations, not every RCU will be active at the same time, which will decrease the overall demand. However, in more extreme temperatures, a stack of 100 RCUs could require half a megawatt of power. The circuits and plugs provided for the RCU stacks need to be sized appropriately for this potential load.

Technology Readiness: Electric RCUs have a high TRL, with the devices being in service for many years. Electric RCUs have been used aboard ships and in holding yards, with diesel power units (or a hybrid genset) usually only attached for delivery outside the port. There are numerous commercial options available, including the infrastructure to support RCUs while in port (cord connection pedestals or racks/scaffolding to power stacks of RCUs).[36]

BUILDINGS & LIGHTING

Overview: Ports support a variety of building and lighting types depending on their operations, including warehouses, processing centers, storage facilities, offices, and high-mast lights. Each of these typically connects to the utility grid to, at a minimum, provide basic electrical service (110V , 220V, or 277V) to support standard loads. However, in many cases, it is possible to further electrify buildings by converting non-electric loads over to more efficient electric ones and/or by deploying DERs (e.g., solar PV) on or nearby buildings to help serve their loads. Some outdoor lighting can also be powered without a grid connection through solar PV and batteries.

A first step in considering building electrification is to identify and address any opportunities for energy efficiency improvements. Energy auditing is a common practice aimed at identifying opportunities for energy efficiency improvements and has been used in the building space for many years. Combined heat and power may also be a solution to increase building energy efficiency if e-fuel microgrids are being considered.

Asset Score is a national, standardized, and publicly available tool that supports building energy audits. Particularly with older buildings, improvements, such as adding insulation and LED lighting, may offer quick and cost-effective wins that reduce a building's energy use and save money. It is possible that building energy loads, such as heating/cooling, could be converted to electrical loads with increased efficiency, for example, by switching a gas furnace for a high-efficiency electric heat pump. For more detailed information, NREL's report, *A Guide for Creating a Building-Level Action Plan to Improve Energy Efficiency*, offers detailed guidance on this topic, as well as step-by-step recommendations.[37]

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[35] Trane Technologies. 2013. *Thermo King Operator's Manual: MagnumPlus, Revision 0*. TK-61110-4-OP. https://www.thermoking.com/content/dam/thermoking/documents/products/TK%2061110-4-OP%20Magnum+%20Operators%20Manual%20Rev.0%2011-13%20EN.pdf.

[36] EPRI. 2010. *Electric Refrigerated Container Racks: Technical Analysis*. Washington, DC: Electric Power Research Institute. https://www.epri.com/research/products/1019926.

[37] Better Climate Challenge. 2023. *A Guide for Creating a Building-Level Action Plan to Improve Energy Efficiency and Reduce Carbon Emissions*. DOE/GO-102023-5893, Department of Energy. https://www.nrel.gov/docs/fy23osti/85708.pdf.

Technology Readiness: Building electrification and energy efficiency technologies are well-proven and widely available. There are also federal incentives that help reduce costs of some of these technologies. States, municipalities, and electric utilities sometimes also offer additional resources and incentives.

EMISSION CONTROL SYSTEMS

Overview: Emissions control technology could help reduce harmful emissions from traditionally hard-to-abate sectors and can be viewed as a potential bridge technology between today's fossil-fuel-based economy and a clean-energy-based economy of the future. Emissions control systems include a variety of technologies that can be onboard ships, based on land, or mounted on mobile barges. They work in various ways to remove harmful pollutants, generated through the fuel combustion process, from engine exhaust prior to its release into the environment. Emissions control systems are not used widely but are increasingly of interest as ports worldwide are feeling pressure to reduce the environmental impacts of their operations. Emissions control systems include carbon capture and storage technology.

In all cases, it is important to consider the life-cycle emissions benefits of an emissions control system. Carbon capture and storage systems come in many forms and can be energy intensive. If they require electricity to operate, this electricity should be powered by clean energy sources (e.g., renewable electricity) to capture desired emissions benefits. Emissions control solutions should include an exhaust capture system, emissions treatment system, and a process for storing or repurposing captured materials to avoid their reintroduction into the environment.

Emissions control systems are related to port electrification for multiple reasons. They offer a potential alternative to shore power that could help ports with electrical constraints to still achieve desired environmental improvements. They also offer an alternative for vessels who may not be shore power capable. Emissions control systems may require grid connection to support their operation, for example, when deployed dockside on port property to serve vessels at berth. California's at-berth regulation allows for the use of qualifying emissions controls technologies or qualifying shore power solutions.

Technology Readiness: Emissions control systems are not widely available but are being piloted in limited port contexts. For example, a recent CARB-supported project aimed to demonstrate an emissions control system at the Port of Long Beach, focused on reducing emissions from oil tankers.[38]

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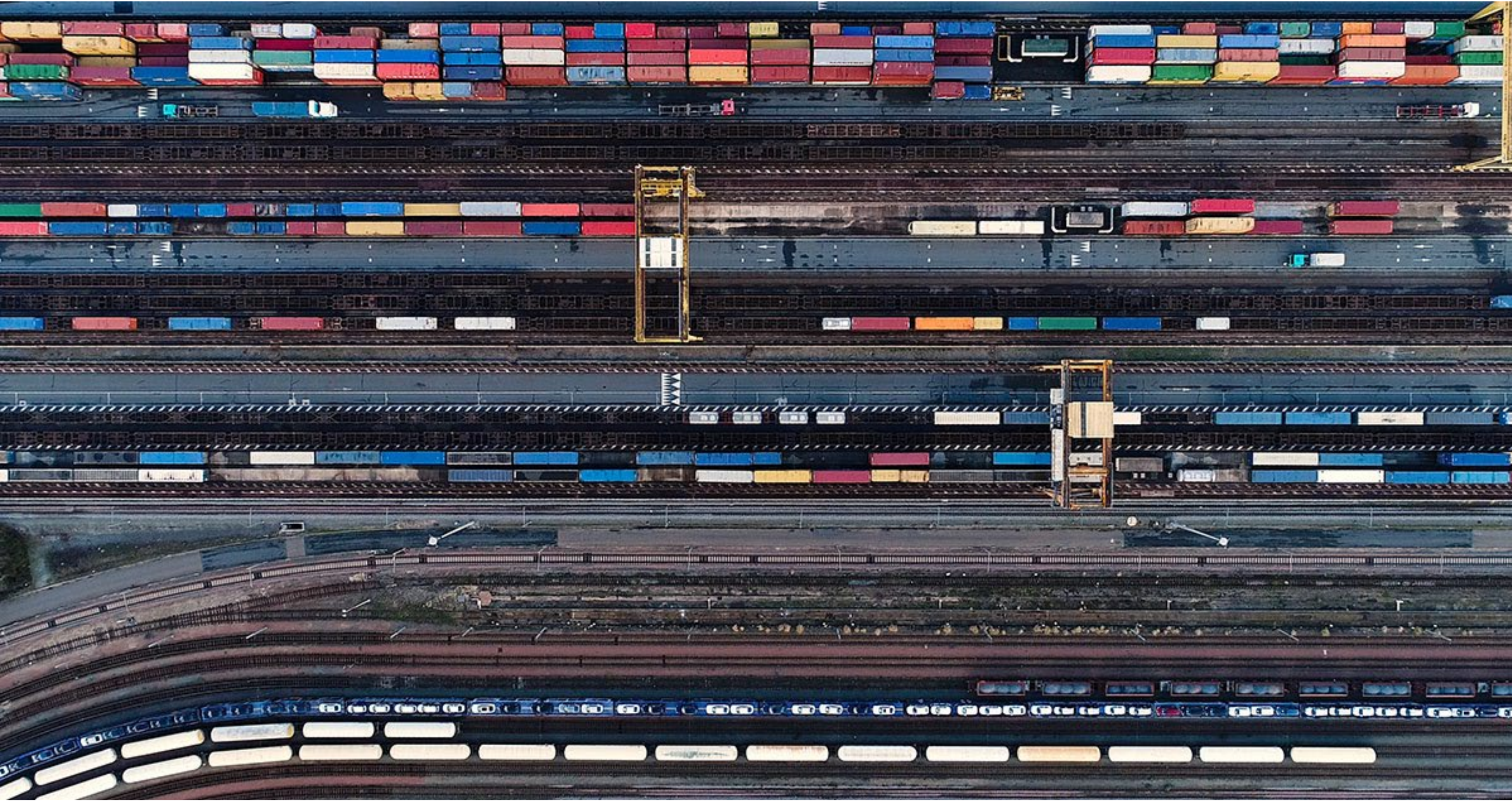
[38] CARB. 2024d. "LCTI: Capture and Control System for Oil Tankers Project." California Air Resources Board. https://ww2.arb.ca.gov/lcti-capture-and-control-system-oil-tankers-project.



RAIL

Overview: Electrified rail technologies have been adopted worldwide, though the most prolific electrified solutions provide passenger and not usually freight transportation, particularly in the U.S. Currently deployed technologies usually include overhead lines (catenary) and third rail electrification systems, but these systems can be challenging for U.S. freight trains that travel long distances. For freight trains in the U.S., three technological pathways to electrification are taking shape—catenary systems, hydrogen fuel cells, and battery-powered locomotives. The demand for these technologies is being driven, in part, by the EPA's emissions-reduction requirements for nonroad engines and vehicles, including locomotives. A study led by Lawrence Berkeley National Laboratory and published in 2021 highlighted the near-term opportunity in converting diesel trains to battery-electric and identified near-future scenarios where battery-electric trains achieve cost parity with their diesel-electric counterparts. The study also asserts that because most U.S. trains already are powered by diesel-electric technology, continuing to use the existing electric motors could simplify battery-electric retrofits.[39]

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[39] Popovich, N. D., D. Rajagopal, E. Tasar, and A. Phadke. 2021. "Economic, Environmental and Grid-Resilience Benefits of Converting Diesel to Battery-Electric." *Nature Energy* 6: 1017–1025. https://doi.org/10.1038/s41560-021-00915-5.

While, in general, the rail sector shows promise for electrification, certain types of locomotives may be easier to convert over others due to their operational demands. Switcher locomotives are used to connect freight cars that eventually are transferred to another locomotive before exiting the yard. Switcher locomotive operations usually are confined to port property and offer a promising near-term case for electrification because their operational demands could align with the available range and charge times of battery locomotives. Since the spring of 2023, an electric switcher locomotive operated by Pacific Harbor Line has been operating between the Ports of Los Angeles and Long Beach as a limited-term demonstration project.[40] Heavy-haul locomotives are more challenging to electrify due to their operational demands. However, Wabtec Corp has developed the "first battery-powered, heavy-haul locomotive that will be used for mainline service."[41] Because most heavy-haul trains are pulled by a group of locomotives, the battery-electric locomotive is planned to replace one diesel locomotive. Energy management software would optimize the load across all locomotives.

Technology Readiness: Today, the electrified rail technology relevant to port operations remains in the development and demonstration phases. However, as Popovich et al.[42] asserts, multiple variables could align soon that would bring battery-electric trains to cost parity with diesel-electric trains. Achieving this future would accelerate industry investment in battery-electric trains and associated technology readiness. Influential variables include battery energy density, battery costs, availability of renewable electricity, electricity costs, and charging infrastructure availability.

PORT ELECTRIFICATION EXAMPLE

Figure 7 shows a variety of the different DER and Electrified End Use technologies laid out on a port. Specific technologies are highlighted, such as a BESS device, solar PV generation, ECHE charging, and light-duty vehicle charging. Also in the figure are electric shore power for vessels, hydrogen production stations, and electric STS cranes. The key takeaway is there are options not only in what technologies a port may deploy, but also the proximity of things like generation sources (e.g., solar PV) to the loads consuming them (e.g., STS cranes and vessel charging). It is also important to consider operational feasibility, along with electrical feasibility, when planning for port electrification. For example:

- Vehicle and equipment charging infrastructure should generally be placed where vehicles/equipment dwell for extended periods of time. As depicted in **Figure 7**, for example, workplace charging is available for staff in the parking lot adjacent to the office building. Equipment charging infrastructure is placed on the terminal where the equipment is typically stored overnight.

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[40] Robinson, A. 2024. "The Port's Futuristic New Train Runs 'Dead Silent.' It May Pave the Way for What's to Come." *Long Beach Post*. Last updated January 9, 2024. https://lbpost.com/news/battery-electric-train-port-long-beach-joule.

[41] Gallucci, M. 2023. "Full Steam Ahead for Electric Freight Trains." Canary Media. https://www.canarymedia.com/articles/transportation/full-steam-ahead-for-electric-freight-trains#:~:text=At%20a%20ceremony%20in%20Erie,country's%20best%2Dselling%20electric%20vehicle.

[42] Popovich et al. 2021 (see Footnote 39). https://doi.org/10.1038/s41560-021-00915-5.

- Stationary or rail-mounted ECHE should be installed on terminals in a location where it can safely operate while not interfering with other port operations. This requires considering not only how the cargo will be loaded/off-loaded, but also ingress and egress of drayage vehicles, support equipment/vehicles, and all other necessary through-traffic for port operations.
- BESS may be installed as part of a port microgrid, in which case they would be located within the microgrid boundaries and, as feasible, near the infrastructure they are intended to serve during a bulk system outage. BESS depicted in **Figure 7** are strategically placed to provide backup power in different terminal areas, with one adjacent to the office/communications center.
- Solar PV could be installed in ground-mounted, roof-mounted, or carport-mounted configurations in areas that have sufficient solar resource available. **Figure 7** depicts multiple arrays of ground-mounted solar PV supplying multiple terminals with renewable electricity.

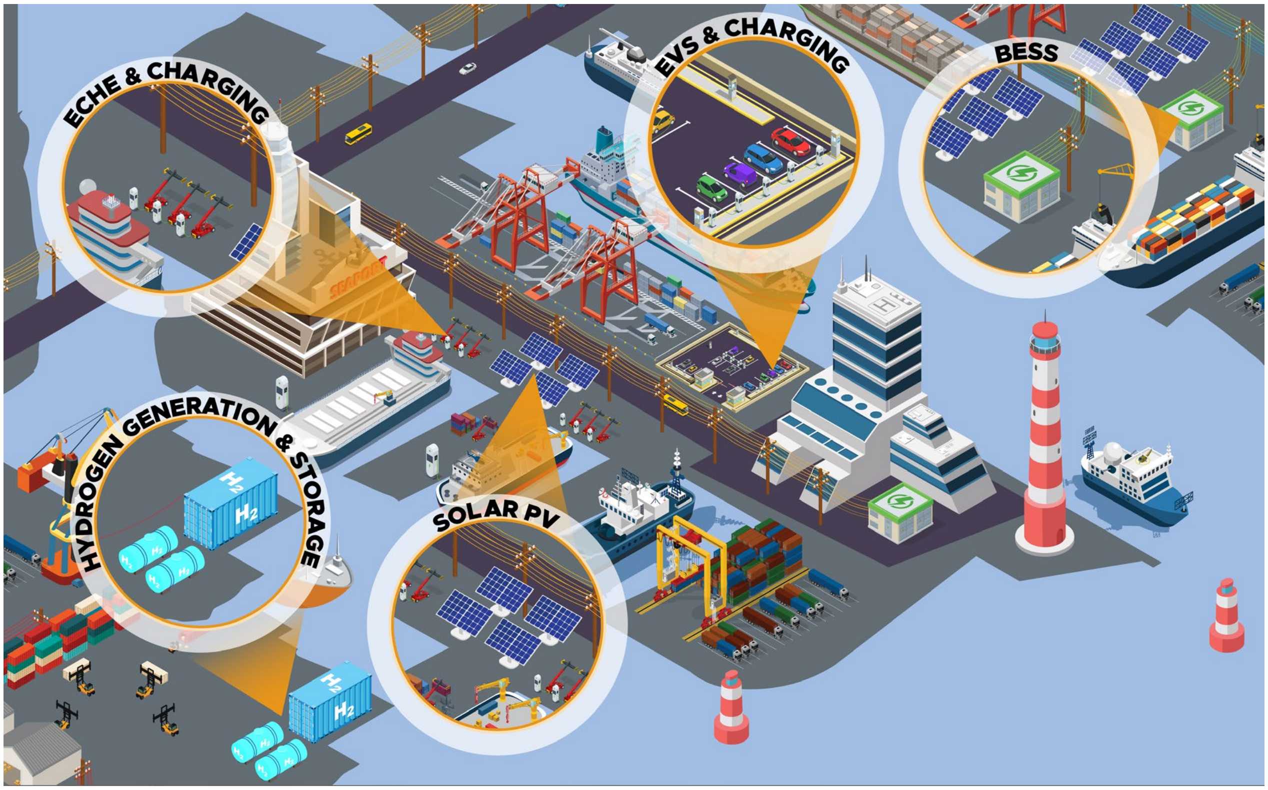

Figure 7. Examples of potential electrification-related deployments at a port, including LD EV charging, ECHE charging, solar PV, vessel shore power, and a BESS.

Port Microgrid Deployment

There are currently limited deployments of microgrids in port applications with many resulting in lessons learned. The ***Case Study: Port Microgrid Deployment*** *section provides an overview of a port microgrid project designed to power critical port infrastructure, including a communications center, in an unplanned power outage. It includes potential project activities and lessons learned, based loosely on the experience of the Port of Long Beach.*

PORT MICROGRIDS

With the electrification of maritime ports and the deployment of DERs on the system, the potential (and need) to form microgrids at a port becomes significant. Intermittent interruptions from the bulk power system due to normal weather effects, distribution outages due to animal intrusion or accidents, or even larger natural disasters can interrupt the power supply to the electrified port. Microgrids not only enable a backup source of power for critical facilities, but they can also be used to keep operations running during shorter outages or enable a limited set for disaster recovery. In certain power markets and infrastructure scenarios, microgrids may also be a way to either save feeder upgrade or increased demand charges or possibly even sell services back to the bulk power system.

Figure 8. Left to right (1) main incoming board for the microgrid, (2) wiring for solar PV panel array, (3) microgrid-extending mobile BESS, and (4) 306 kW DC solar PV array on warehouse roof. Photo Credit: Port of Long Beach.

TYPES OF MICROGRIDS

Microgrids tend to fall into two different types of topologies: independent or networked. This distinction primarily deals with their ability to operate as separate entities.

Independent Microgrids (see **Figure 9**) are the most common type of microgrid commercially deployed today. They could be as simple as a single DER, like a diesel generator serving a single critical building or asset. An independent microgrid may extend further, picking up additional buildings nearby or additional sources of generation. This configuration may be known as a community microgrid (see **Figure 10**). The key distinction for both independent and community microgrids is they form a stable, independent grid, even if that is just a single piece of equipment. Examples would include a microgrid servicing a central security and control office (like the Port of Long Beach Joint Command and Control Center) or a microgrid serving a group of buildings such as a group of warehouses that have RCUs.

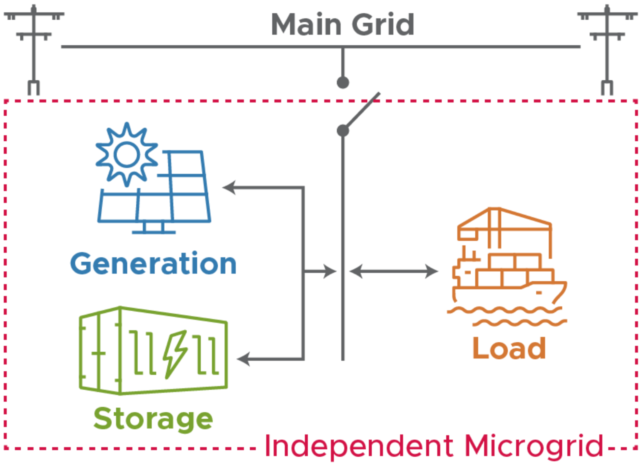

Figure 9. Independent microgrid.

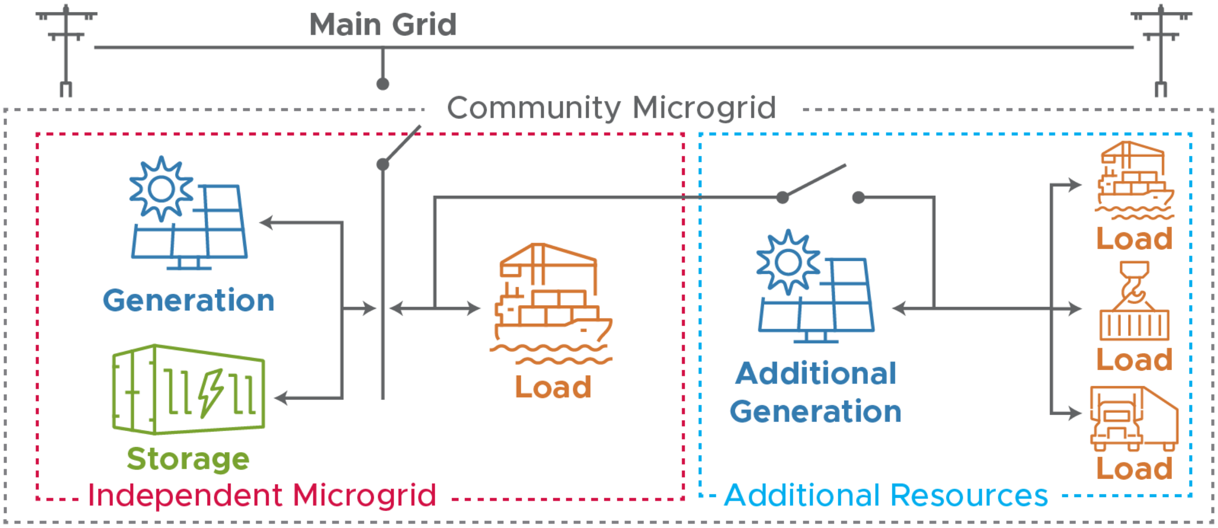

Figure 10. Community microgrid.

Independent microgrids may have configurable sections that give access to additional generation, but those sections do not have the ability to operate independently. Load structures and priorities may be deployed, where certain lower-priority loads may be left without power or disconnected in a longer outage or due to limited fuel supply.

Independent microgrids may operate completely isolated from the bulk power system, or they may be connected to the bulk grid during “blue sky” conditions to support grid operations and islanded only when the bulk grid is stressed or unavailable (i.e., “black sky” conditions). The latter usually is accomplished via some type of switch gear, such as a synch-check relay, sectionalizing switch, or an automatic transfer switch. In all methods, there may be coordination with the local utility before connecting or disconnecting the microgrid from the main power system.

Networked Microgrids (see **Figure 11**) include the connection of two (or more) independent microgrids. The same principles of the independent microgrid apply, but the generation pool and load pool will be larger and more diverse, and the interactions between networked microgrids usually are managed by one or multiple microgrid controllers.

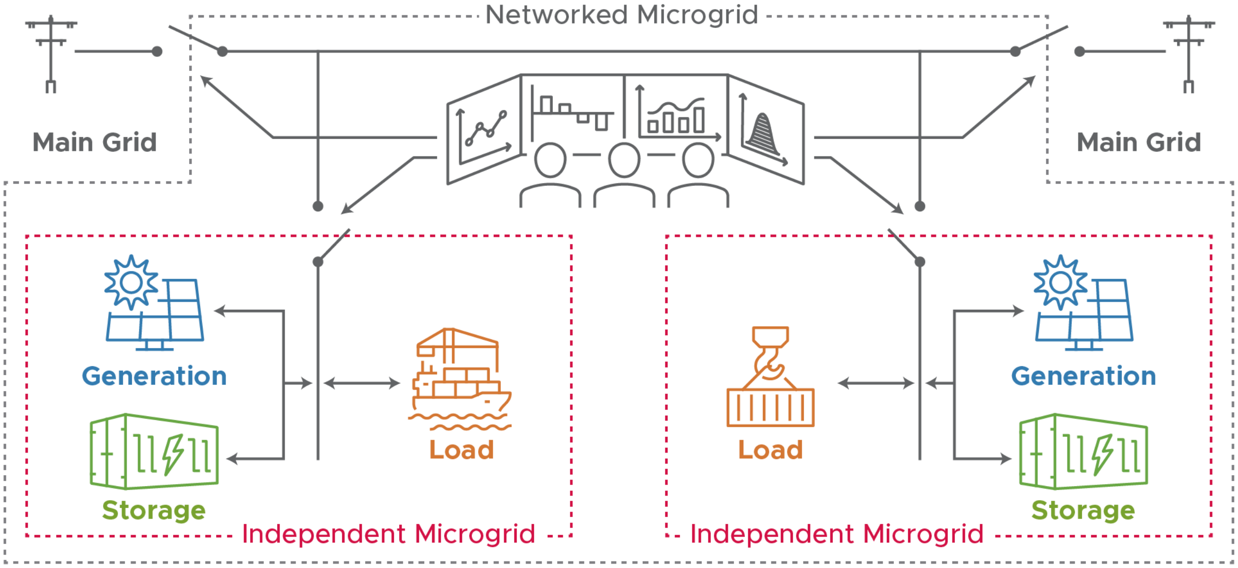

Figure 11. Networked microgrid.

Networked microgrid operations will require additional power system switchgear. In addition to the isolating equipment needed to island an independent microgrid from the bulk power system, switching devices between the independent microgrids also are needed. This typically will be a sync-check relay between the two independent microgrids but could take other forms depending on the topology and composition of the system. Some form of coordination, even if it is a manually controlled adjustment, will be needed between the two independent microgrids as they interconnect.

The advantage of networked microgrids is often the access to additional generation resources and the ability to consolidate and operate these resources more efficiently. For example, two independent microgrids may have diesel generators that are only partially loaded, potentially leading to wet stacking[43] and a loss of overall efficiency. When those two microgrids network, generation could be adjusted so a single diesel generator is serving the whole load. This would put the generator higher on its efficiency curve but also create a redundant/backup generator if the main generator needs to be taken out for maintenance. The efficiency increase may allow the

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[43] Wet stacking is when a generator (especially diesel) is run at too low of an output and fails to reach proper operating temperature. This can lead to unburnt fuel in the exhaust, which can increase emissions and generator maintenance, and decrease efficiency. (See Generac Mobile. n.d. *Diesel Engine: Wet Stacking Fact Sheet*. https://www.generacmobileproducts.com/GeneracMobile/media/20library/downloads/generators/diesel/172143_DieselWetStacking_ONLINE.pdf.)

microgrid to operate for a significantly longer portion of time, as was demonstrated in the SPIDERS microgrid projects.[44]

PORT MICROGRID DESIGN CONSIDERATIONS

For both independent and networked microgrid topologies, there are many aspects that need to go into considering and designing a microgrid for a port electrification scenario. A key first item is to determine the overall purpose of the microgrid. For example, is the microgrid purely providing backup power to a critical asset, or will it be used in normal operations? Knowing the scope of the operational use will help with insights into the other considerations mentioned below.

The **cost** of deploying microgrid assets (e.g., generation sources, power system switch gear, and control elements) can quickly become a major capital cost. Furthermore, maintenance and operation of the microgrid will impose some continuous costs. This often can be justified if backup power is needed for a critical operation (e.g., security or waste management) but will prevent a stance of “deploy microgrids everywhere.”

While microgrids are an option to add increased power capacity and potentially avoid a larger feeder upgrade, the feeder upgrade may make sense for a broader port electrification perspective. The long-term operational costs of the microgrid may not make sense for non-critical loads, especially if electrification has the potential to increase demand for those sections of the feeder in the future. The **Technoeconomic Analysis Tools** section discusses a handful of publicly available technoeconomic analysis tools that could support cost/benefit analysis for port microgrids.

Total load, or how much load a microgrid needs to serve, is one key consideration. Total load includes all the load the microgrid might reasonably provide power to when disconnected from the main grid. It may not be all load in the microgrid footprint, due to either missing connectivity (load intentionally not on the microgrid) or an operational aspect minimizing that load (e.g., seasonal facility). The total load may also change over times of the day and season of the year, so it is important to consider these variations when sizing the components of the microgrid.

Total load may be estimated using existing power bills and metering data, depending on how the system is set up. Building management systems may contain useful load information, as well. If neither is available, power meters may need to be deployed to the system to get an initial baseline. This project created a supplementary “Maritime Port Load and Generation Profile Workbook” spreadsheet that can assist ports in estimating potential loads for common port electrification end uses.

One key aspect of the load evaluation is the “steady state” versus “transient” load of the system. Steady state load represents how much power a device needs when it is running and performing normal operations. Transient load of the system may be a sudden increase in power associated with the device starting up, changing conditions, or having a brief abnormal operation. One of the main loads that requires this consideration is motor-based loads, like pumps and HVAC

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[44] Barr, J. L., F. K. Tuffner, M. D. Hadley, and K. P. Schneider. 2014. *Utility Assessment Report for SPIDERS Phase 2: Ft. Carson (Rev 1.0)*. PNNL-24030. Richland, WA: Pacific Northwest National Laboratory. https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-24030.pdf.

compressors. **Figure 12** shows the power consumption of a small induction motor during start up—the inrush power during the transient is several times the steady state power draw but only lasts 150 ms. The example in **Figure 12** is more pronounced than many motor starts (which are usually only around 4x the power at startup for HVAC compressors[45]) but is not atypical for certain pumps. However, some generators in an islanded or microgrid scenario may not be able to provide that short burst of power and may trip offline, requiring either a different generation source or some extra hardware to operate correctly (e.g., for a motor, a soft start device or variable frequency drive).

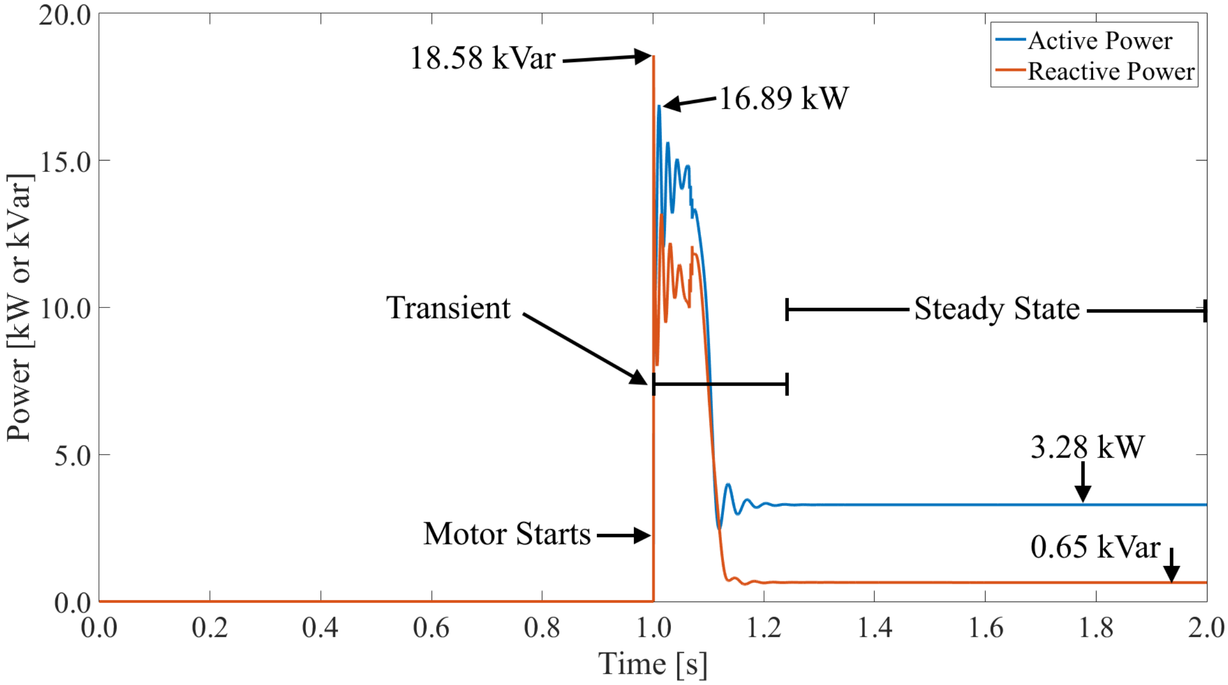

Figure 12. Load inrush example – induction motor start.

Critical loads are a subset of the total load; they represent loads that must be supplied at all times. This could be a critical port operation like security or a process like hydrogen production. Critical loads will be at the highest tier if a load priority structure is put in place. If necessary, multiple feeds between the microgrid generation sources and the critical loads may be in place to provide additional resiliency.

Criticality of loads in a tier structure may change with time and operational conditions. For example, a nearby sewage lift station may be acceptable to lose power for a 15-minute block but could become a critical load afterward to prevent any environmental spilling. A building with a large convening hall may be lower priority in standard day-to-day operations but becomes critical if the microgrid is being used for disaster relief. The load criticality structure will need to be evaluated during the design and consideration process.

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[45] Robles, S. 2015. *Commercial 3-Phase Rooftop Air Conditioner Test Report*. Prepared for Lawrence Berkeley National Laboratory by Southern California Edison. https://certs.lbl.gov/publications/commercial-3-phase-rooftop-air.html.

Microgrid control refers to the direct device control and capabilities and is tied very closely to the overall operational considerations.

- Capabilities of controls at the generator – All generation devices have local controls that manage their behavior. Some devices will have the ability to respond to grid measurements (have the most capabilities and functions), some will maintain commanded set points (require an external control of some sort), and others will just passively try to push as much power as they can (little to no control). Generators that can form a microgrid and provide backup power (even if only to a single device) will have the first category (often call grid-forming and having droop or isochronous controls). Rooftop PV often falls into the final category and has no control or capabilities to work without connection to a larger power system. Depending on the complexity of the microgrid system and operations, it may be able to operate with only the controls at the generator and not require a microgrid controller or other control devices.
- Coordination level of assets needed – This consideration is closely related to the first bullet on capabilities of controls at the generator but in the context of the whole system. If the individual devices have a form of proportional response control on them (droop control is a typical mechanism), the devices will independently adjust to changes (typically load changes) on the system. If they lack this capability, a microgrid controller may be needed to coordinate how the different generators respond. For generators with only set point capabilities (the middle category above), they need a microgrid controller or other coordinating device to adjust to changing microgrid conditions.
- Remote control vs. crew-dispatched changes – This consideration relates to if any “remote” capabilities are needed for the microgrid. Remote in this instance is if the device can change its state using an electronic or communication signal, versus a device that requires an operator or electrician to physically visit it and manipulate the device (local-only control). Remote capabilities may still only be within the microgrid (i.e., a local microgrid controller may have the ability to open/close a switch or start and stop a diesel generator), but there is no communication outside of the microgrid. Remote capabilities could allow the microgrid to be controlled by a single computer/interface, whereas crew-dispatched changes require the operator/electrician to physically visit and perform each individual action.
- Centralized control/dispatch integration – This consideration often means extending the microgrid control beyond the fenceline. If the port has a central operating office and managing authority (possibly even the security office), they may want the ability to control the microgrid or its components remotely. This will often require additional controls at the device and for the microgrid and communication lines between the operations center and microgrid but can allow quick actions by a smaller set of staff.
- Communication needs to operate the microgrid – With any controls beyond those directly attached to the generator or load of the microgrid, there needs to be a way to transmit data between them. For simple, local-only microgrids, this could be a MODBUS connection between the devices or even an isolated ethernet network that only connects those devices. As the size of the microgrid increases, or if a central office control capability is needed, this may start requiring commodity/third-party network services like cellular connections. The criticality of the microgrid and the loads it serves may also require backup forms of communication be available, such as a secondary fiber line or alternative cellular carrier.

Many commercial-off-the-shelf systems are available to connect and control microgrid assets, either autonomously or through a human-in-the-loop dispatch center. A key consideration in any of these scenarios is the requirements of these microgrid controller solutions. If it operates “in the cloud” or requires an external connection, reliable communication needs to be maintained to operate the microgrid. Alternative or backup communication channels can help ensure the microgrid will operate as intended. It is also important to note that, as the communication levels increase, especially once it goes beyond the fenceline of the microgrid to a central office or cloud-based controller, the cybersecurity solutions required will increase, as well.

Operations & Maintenance considerations address how the microgrid assets will be managed within the larger port operational context. Consideration should be given to how the microgrid is expected to operate and who has authority to initiate islanding the system. Even if the microgrid is operated with remote sensors and control, an important aspect of operation is identifying how microgrid notifications will be communicated to relevant parties and what actions, if any, should take place as a result.

Operation of the microgrid also includes training—both for the use of the microgrid assets and maintaining them. Consideration should be given to which personnel need the training, what type of training is needed, and how often it needs to be refreshed. Training requirements should be factored into the cost of the microgrid and staffing plans for operations during an outage.

Finally, the microgrid must be maintained by qualified personnel. This important consideration is sometimes overlooked during the design phase and even during operation, which can inadvertently lead to unexpected failure down the line.

Survivability requirements refer to how likely a microgrid will be able to operate through an outage scenario (e.g., 90 percent survivability during a seven-day outage) and are integrated into the microgrid design process, as they tie directly into the use case of the microgrid. If a microgrid is deployed as a backup power asset, it may need to use generation sources and equipment that can either be hardened against or specifically designed to operate in particular conditions. Examples could be a critical diesel generator requiring a special enclosure for itself and the fuel source to withstand flooding or a battery system requiring a large easement/approach boundary to ensure any nearby structure fires would not degrade its operations.

Microgrids deployed for demand reduction or to increase capacity without a large feeder upgrade may not have the same survivability requirements. If serving a non-critical load, especially one that could be served through a reconfiguration of the power system, the microgrid assets may not need to be as robust.

Survivability requirements may also need to consider longer outages and how the generation sources are “fueled.” For traditional combustion-based generators, this will be evaluating how much fuel storage is needed on-site and whether any special refueling contracts need to be negotiated up front. For more renewable-based microgrids, this may require diversifying the generation sources (e.g., solar and wind) or having a contingency generator (biodiesel) to help charge the battery or provide power if not enough solar or wind energy is generated.

Utility coordination on microgrids is a significant consideration for deploying a microgrid at the port; the utility should be engaged very early in the process. The utility may have specific requirements for where the equipment can interconnect or how it interconnects to the system. There may also be regulatory aspects of the microgrid, such as if it can even operate. The utility may even have incentives or different rate structures associated with services the microgrid provides that may factor into the cost-benefit analysis.

On the equipment and interconnection requirements side, the utility may require specific switch gear to be deployed to island and reconnect the microgrid from their system. This might require equipment in the microgrid to adhere to specific standards when connected to the main power system, or even provisions that it cannot feed power back into the grid. Depending on the utility and expected microgrid use case, a full interconnection study of the system may be required to fully examine the impacts to the surrounding customers or portions of the system.

Regulatory aspects will be another key area to coordinate with the utility. Many utilities and regulatory bodies have explicit rules against providing power across “fencelines” (to other owners) or competing with monopoly clauses the utility may have in place. Exceptions often can be filed, such as the exception with the California Public Utilities Commission so the Port of Long Beach could provide power across the fenceline to the Joint Command and Control Center. Regulations and utility coordination could also require specific communication sequences or “insight” into the microgrid—such as a data feed to the utility or coordination calls every time the microgrid is islanded and reconnected.

Finally, coordination with the utility may reveal some incentives or additional price mechanisms the microgrid could leverage. The port microgrid may be able to serve as a backup staging center or community relief center in larger outages, which the local utility or municipality could leverage as part of their overall disaster recovery plan. The utility may also have provisions for the microgrid to provide grid services to them or the transmission grid, improving overall resiliency to the system and having potential revenue streams during normal operations. This will vary by region, but many utilities are starting to proactively engage customer-owned assets to provide overall benefit to the system. For more, see the **Electric Utility Coordination** section.

Distributed energy resource considerations primarily focus on how the system will be powered and whether any advanced form of DERs will be leveraged. Traditional power system control only adjusts generation sources of the system—basically adjusting it to match the load on the system. However, DERs can include variable loads (such as vehicle charging or temperature setbacks) that may be used as a grid services resource, as well. Leveraging the assets may require additional controls or capabilities on the loads, so will need to be considered early in the process.

From the generation side, DER consideration will be on any additional generation resources on the system, as well as what other types of generation are feasible. More details on the various types of DERs are provided in the **Distributed Energy Resources** section, but a key aspect for the generation will be resource availability. If a large PV array is deployed as the primary power source for the microgrid, but times of the year have significant cloud cover (and, therefore, reduced power output), a supplemental generation source may need to be deployed or a larger BESS purchased. The economics and regulatory requirements of that alternative power source may change the feasibility of the primary generation, which may make other DER options more viable.

The next subsection gives some explicit considerations for ESSs, but it factors into the DER consideration. If the energy storage needs to operate independently from a traditional generation source, the DER needs to have grid-forming capabilities. Much like the fuel considerations of the traditional generation sources, the size of the battery will need to be considered and how to replenish that charge.

Energy storage systems on an electrified port may eventually take many forms, but currently, the leading technology is battery-based energy storage, usually using lithium-ion or lead-acid-based chemistries. Redox flow batteries may be considered but are not as commonly deployed or commercially available.

As mentioned in the DER section, the overall power and energy capabilities of the energy storage must be considered. If the ESS needs to provide 2 MW of power to a microgrid for 30 minutes, a 1 MWh battery would be sufficient, assuming perfect transfer. If more power or surging power (associated with a large motor starting or the inrush associated with a large device switching on) requires higher capabilities, the energy storage inverter and associated battery technology will need to be capable of that, as well.

Directly tied to the DER capabilities of ESSs is how big of a footprint it will need. Two different aspects may need consideration here. The first is how big the battery needs to be and the corresponding equipment—this may be as simple as how many Conex-sized-equivalents the storage requires. The second, larger space consideration must account for any approach and regulatory boundaries. The local electrical code may have required easements or approach boundaries, but the local fire code is likely to have larger abatement zones to both prevent and manage any fires in the batteries. Furthermore, the DER footprint may need to be expanded to accommodate additional fire suppression equipment for the battery technology.

As mentioned above, cost for microgrids is a key consideration and ESSs often are affected by this. Except in very specific power markets, even the ability to provide grid services may not make ESSs economical from a pure cost-benefit perspective. Factoring in and quantifying the backup power, resiliency, and potential emissions reductions need to be part of the consideration to fully justify the expense.

Photo credit: Port of Seattle.

PLANNING CONSIDERATIONS

PORT ELECTRIFICATION PROGRAM FRAMEWORK

OVERVIEW

This section provides generalized, high-level guidance on electrification program planning and implementation, to help inform port, tenant, and other stakeholder efforts. It will not capture every task for every port because each is incredibly unique. Instead, the guidance in this section is intended to provide the following:

- A template for ports and stakeholders to build on in their respective efforts.
- A road map of planning phases and tasks to consider within each phase.
- Potential structure to support the sometimes-ambiguous process of port electrification.

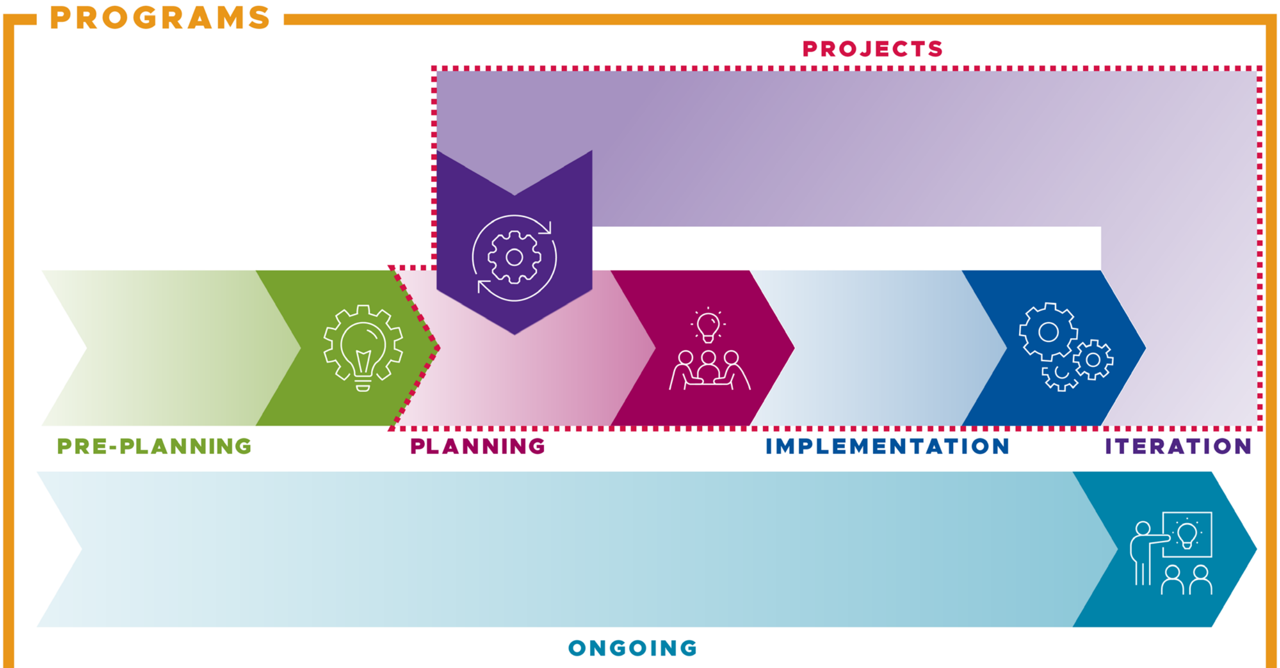
Note: Though in this section we describe efforts from a port perspective, this process could be undertaken by port tenants with minimal adjustment. In key areas where processes may differ between operational and landlord ports, notes are included describing the differences.

The Port Electrification Program Management Framework, outlined in **Figure 13**, summarizes the phases of port electrification and tasks within each phase. It aims to align with the incremental investment process and ongoing iteration that is often undertaken to achieve overarching electrification and decarbonization goals. It includes four defined phases—Pre-planning, Planning, Implementation, and Iteration—and lists ongoing tasks that are important at all phases. Though outlined sequentially and in distinct categories, in practice, the boundaries between the phases blur, and it is highly likely that multiple phases will occur at the same time. For example, during the Planning phase, a port may identify its next electrification project, only later realizing during the Implementation phase that it will need to adjust the project's scope to meet grant requirements, requiring reiteration of some of these Planning phase steps.

A Regional Approach to Port Electrification

A Regional Approach to Port Electrification: *It is also often most effective if regional groups of ports move in unison on certain activities. This can enable a systems approach to implementing new technologies and help ports avoid placing themselves at a competitive disadvantage (e.g., by requiring electrification when their neighbor ports do not). A regional approach also helps increase participating ports' influence on regional customers and leverage to advance policies supporting port electrification, for example, in state and federal legislature.*

One example of a relevant regional approach is the Northwest Ports Clean Air Strategy, a joint effort between the Port of Seattle, Port of Tacoma, Northwest Seaport Alliance, and Port of Vancouver (BC) to reduce harmful emissions related to seaport operations, first adopted in 2008. It is a voluntary effort where participating ports document their progress toward shared objectives in annual implementation reports and an emissions inventory that is completed every five years.



Pre-planning:

- Establish overarching goals and vision
- Develop energy/emissions baseline and electrification load forecast
- Conduct an electric infrastructure assessment
- Identify opportunities for energy efficiency improvements
- Coordinate with the electric utility
- Plan to engage stakeholders and partners
- Assess staffing resources and needs
- Review influential policies, market trends, and lessons learned

Planning:

- Catalogue existing infrastructure/equipment and available alternatives
- Define scope, budget, and project goal(s)
- Coordinate with utility to develop a load forecast, confirm electrical availability, assess costs
- Identify and manage potential impacts (e.g., workforce, economic, and operational impacts)
- Plan to engage project-specific stakeholders and partners

Implementation:

- Secure project funding
- Establish project team and management structure
- Coordinate across other projects underway
- Provide opportunities for meaningful community engagement

Iteration:

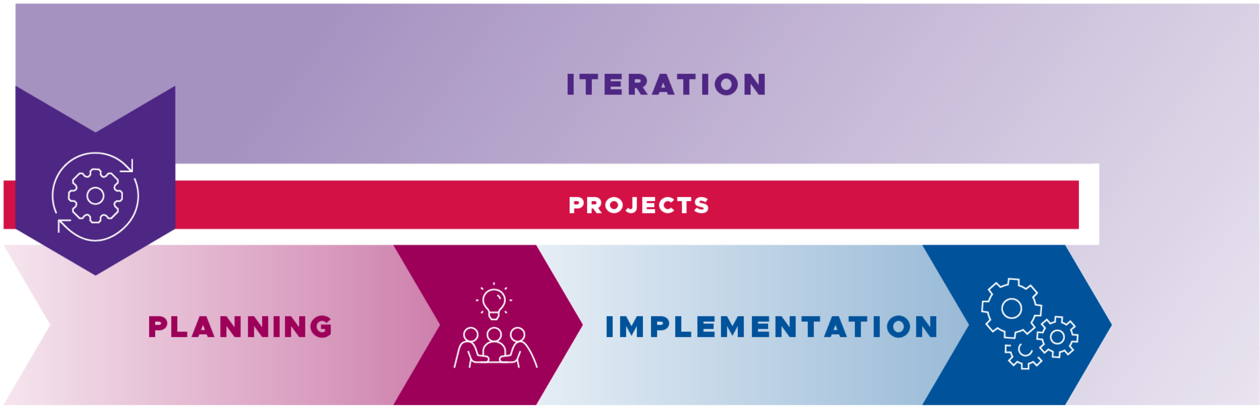
- Evaluate project performance
- Measure progress toward overarching vision and goals
- Discuss results and desired next steps

Ongoing:

- Coordinate with the electric utility
- Manage/build stakeholder and partner relationships
- Advocate for supportive funding and desired policies
- Complete energy efficiency improvements
- Maintain Equipment
- Manage ongoing requirements (e.g., grant requirements)
- Plan for and secure necessary resources

Figure 13. Port Electrification Program Management Framework.

Figure 13 represents port electrification planning at a programmatic level. While the components of each phase are relevant to overall programmatic execution, the Planning, Implementation, and Iteration phases are more directly applicable to individual projects. If multiple projects are occurring at the same time, which is highly likely, coordination between them would be a high priority. The suggested tasks in each phase should be adjusted and further defined depending on individual port context and projects. An example of using the framework to outline phases of an MD/HD EV charging project is shown in **Figure 14**.



Planning:
- Catalogue existing infrastructure and available alternatives
- Coordinate with utility to develop load forecast, assess electrical availability, and estimate costs
- Identify and manage potential impacts (e.g., environmental, workforce, economic, and operational)
- Project-specific stakeholder mapping and engagement

Implementation:
- Secure Resources – USDOT (e.g., NEVI), MARAD PIDP, EPA Clean Ports, State and Local Sources
- Establish project team & management structure
- Plan for funding and reporting requirements (e.g., Buy America)
- Procure permits – electrical, construction, other
- Ongoing coordination with stakeholders including trucking companies and community members
- Establish evaluation and data management plan – EV charging data, fleet conversion data
- Assess performance over project period

Iteration:
- Coordinate with tenants on tenant adoption planning
- Identify potential improved market solutions such as next-gen EV charging technology
- Communicate results with stakeholders and gather feedback on desired next steps

Figure 14. Example of potential steps to design an MD/HD EV charging project.

PRE-PLANNING

The Pre-planning phase sets the foundation and direction for the port electrification program. It includes collecting relevant baseline information, stakeholder input, and reviewing existing policies and market trends. Collectively, the results of these and other tasks are integrated into overarching guidance for the electrification program, which may include a vision and goals, technologies or topics of focus, resource needs, potential projects list, and a stakeholder engagement plan. The overarching guidance may be adjusted throughout the next steps on an as-needed basis or at a predetermined cadence (e.g., annually). It is important to include a diversity of stakeholders in pre-planning conversations, including internal stakeholders at multiple levels within the organization and external stakeholders such as the electric utility, tenants, and community-based organizations. Further detail on stakeholder mapping and engagement can be found in the **Stakeholder and Partner Engagement** section.

As an example, the Port of Seattle and Northwest Seaport Alliance are in the process of completing electrification strategies for their facilities: the Waterfront Clean Energy Strategy and South Harbor Electrification Roadmap, respectively. A regional collaborative strategy—the Northwest Ports Clean Air Strategy—is guiding both efforts. It is important to note that, even while completing these foundational electrification strategy documents, both organizations have electrification projects that are completed already and currently underway. Their efforts exemplify the value and complexity of the pre-planning process and the non-linear nature of working with innovative technologies. While an electrification/clean energy strategy is important to both organizations, they also are implementing some projects while it is under development and integrating lessons learned from these projects into their strategies. Conversations with both organizations helped inform the tasks described in this section.

- **Establish overarching goals and vision** – The ultimate goal or goals of this work will vary by organization, and it is important to establish them early on. Goals may revolve around climate (e.g., reduce greenhouse gas emissions), environmental justice (e.g., help address the negative health impacts from harmful air emissions), economics (e.g., reduce energy costs, attract new customers), resiliency (e.g., increase energy independence), community (e.g., generate new clean-energy-related jobs), or other topic areas. Once set, they represent a North Star to help guide future business and investment decisions. Ideally, port electrification goals cascade from broader port goals, and potentially goals of other relevant organizations such as state agencies or the International Maritime Organization.
- **Develop energy/emissions baseline and electrification load forecast** – This task examines how much energy the port currently uses and associated emissions impacts of this energy consumption. The results of this effort will establish a baseline from which to compare the potential benefits of future projects, such as emissions benefits that often are requested in funding applications. Consider all sources of port energy in establishing an energy baseline. This likely includes electricity and other utilities like natural gas, as well as fuel consumption for fleets and CHE. To establish the emissions baseline, it is important to define the scope and boundaries of the port's emissions profile. The EPA's Port Emissions Inventory Guidance describes widely accepted best practices that can be useful to ports nationwide. Additionally, the EPA's Greenhouse Gas Equivalencies Calculator provides emissions impact estimates from energy usage data. For load forecasting, it may be helpful to project high, medium, and low electrification scenarios and to take into account other clean alternative fuels that the port and stakeholders may adopt in the coming years (see the **Electrification and the Port Decarbonization Landscape** section).

  Note: For landlord ports, depending on the scope of their electrification program, this task may require coordination with tenants who maintain their own utility connections and fuel usage information.
- **Conduct an electric infrastructure assessment** – Coordinate with the electric utility, tenants, and other relevant stakeholders on a port infrastructure assessment to evaluate overall electric availability and develop a comprehensive understanding of infrastructure feeding the port. Identify service upgrade options to meet potential new electric loads. For more detail, see the **Electric Utility Coordination** section.

- **Identify opportunities for energy efficiency improvements** – Electrification projects can be complex and expensive. This exercise helps ensure that projects plan for the most efficient electric loads, saving potential future project and energy costs. Energy auditing is a common practice aimed at identifying opportunities for energy efficiency improvements and has been used in the building space many years. Asset Score is a national, standardized, and publicly available tool that supports building energy audits.
- **Coordinate with the electric utility** – See the **Electric Utility Coordination** section.
- **Plan to engage stakeholders and partners** – See the **Stakeholder and Partner Engagement** section.
- **Assess staffing resources and needs** – Electrification planning and implementation is not a traditional port activity. Where new work is proposed, associated staffing requirements should also be identified, along with other potential resource needs. In some cases, it may be possible to retrain existing staff to take on new tasks, while in other cases, it may be necessary to hire new staff from outside the organization or contract with an external consultant. Consider staffing needs at both a programmatic and project level. Project managers and other staffing costs are sometimes eligible grant costs, so it may be possible to add funding for these positions into future project proposals.
- **Review influential policies, market trends, and lessons learned** – Organizations nationwide and internationally have established policies that apply pressure on ports to decarbonize their operations (see the **Guiding Policies** section). Port electrification strategies should consider and proactively address how these policies may impact future business opportunities and how customers may also demand cleaner energy alternatives in the future. Finally, port electrification strategies and demonstration projects are underway worldwide. New strategies can benefit from and integrate lessons learned from others’ efforts.

PLANNING

Once a strategy is established through the Pre-planning phase, its implementation is often executed at the project level. The next three phases—Planning, Implementation, and Iteration—describe potential project-level tasks that may be adjusted depending on the type of project underway. It is likely that ports will/may have multiple electrification projects underway at the same time, in which case, cross-project coordination is critical. It is also likely that tasks will overlap between the Planning, Implementation, and Iteration phases and sometimes even across multiple projects.

- **Catalogue existing infrastructure/equipment and available alternatives** – The most cost-effective time to replace fossil fuel equipment with an electric alternative is at the end its life. Therefore, it is useful to understand the status of existing infrastructure and equipment and when these assets may need to be replaced. It can also be useful to catalogue the type of engines in existing equipment (e.g., Tier III Diesel) to focus investments on replacing top emitters. Identify market-available electric alternatives, associated costs, and charging requirements. The California CORE Eligible Equipment Catalogue may be a helpful repository of market-available electric technologies, including CHE and forklifts. Some equipment, particularly heavy-duty equipment, may not have an available electric alternative but may have hybrid or hydrogen alternatives.

- **Define scope, budget, and project goal(s)** – Identify the boundaries of the current proposed project, including associated tasks and costs. This can be adjusted as other pieces of information come to light, such as funding availability, grant requirements (if applicable), infrastructure costs, and other stakeholder priorities.
- **Coordinate with utility to develop a load forecast, confirm electrical availability, assess costs** – New electric loads usually require approval and coordination and, sometimes, new service from the electric utility. It is best to coordinate with the electric utility at a programmatic level and project level, to plan around overall electrification goals and project-specific needs. Utilities will require information around projected new loads to assess how these loads may be met and any required infrastructure upgrades. Associated costs can vary widely, and the utility can provide cost information. For more information on utility coordination, see the Electric Utility Coordination.

  Note: For landlord ports, depending on the scope of their electrification project, this task may require coordination with tenants who maintain their own utility connections and fuel usage information.

Load Planning Resource

*To assist with load planning, the Port Electrification Handbook project developed a supplementary **Maritime Port Load and Generation Profile Workbook**. This includes electric loads associated with a handful of common electrification end uses such as shore power, forklifts, and RCUs. Ports will need to generate their own loads for utility planning based on individualized information, such as shift schedule and environmental factors (e.g., temperature), but could use this spreadsheet to develop a generalized sense of load impact from potential electrification projects.*

- **Identify and manage potential impacts** – Once a clearer idea of the intended project scope has been established, consider and quantify (to the extent possible) the potential impacts of these efforts. Ideally, potential positive impacts can be tied directly back to the overarching goals of the electrification program established in the Pre-planning phase. Potential negative impacts could be captured and tracked in a project risk matrix, identifying steps that can be taken to mitigate these risks. Impacts to consider include, but are not limited to, environmental (e.g., emissions benefits), workforce (e.g., new trainings required), economic (e.g., energy cost savings), and operational impacts (e.g., new requirement for workers to plug in equipment after their shift).
- **Plan to engage project-specific stakeholders and partners** – This task is similar to the efforts described during the Pre-planning phase but focused on deeper engagement with a likely narrower group of stakeholders relevant to the project being planned. For more information see the **Stakeholder and Partner Engagement** section.

IMPLEMENTATION

This phase is focused on completing the planned project. Though the boundaries between Planning, Implementation, and Iteration can blur, this phase generally begins at securing funding for a project and ends at project close out.

- **Secure project funding** – For some ports, it may be possible to cover project costs in existing budgets or through integrating them into future capital planning efforts. This is often because the goals of the project clearly advance the overarching goals of the port and/or provide an overall cost benefit. In other instances, it may be necessary to seek external funding support to help cover project costs, most likely in the form of grants/cooperative agreements, or incentives (for more, see the **Funding Opportunities & Incentives** section). It is important to note that federal funding often requires cost share that ports would need to budget and plan for. Federal funding also comes with a variety of requirements that vary by opportunity and can impact what types of tasks, costs, and equipment may be eligible for coverage.

- **Establish project team and management structure** – Identify internal and potentially external (e.g., tenant) stakeholders to include on the project team, as well as a management plan that identifies roles and responsibilities across team members. This task can also include managing the project's scope, schedule, budget, and reporting requirements (if any).
- **Coordinate across other projects underway** – If there are multiple related projects underway, establish regular mechanisms to coordinate across them and share lessons learned. Projects may benefit from streamlining communications with stakeholders, the electric utility, and tenants. As discussed earlier, the Port Electrification Program Management Framework in **Figure 13** represents potential steps at a high level, and it is likely that multiple projects will be ongoing at any given time.
- **Provide opportunities for meaningful community engagement** – Implement engagement efforts defined during the Planning phase. If potential community impacts were identified during the Planning phase, engagement efforts should address these impacts, ideally offering opportunities for two-way communication and for community perspectives to influence project efforts. In some instances, this may result in scope adjustments that would then need to be managed with the funding entity.

ITERATION

Deep decarbonization of maritime port activities will not occur overnight, but rather through a series of incremental investments likely over multiple decades. Each project creates progress toward a port's long-term overall goals and offers lessons learned that can inform future projects and updates to the port's overall electrification strategy. The Iteration phase focuses on evaluating completed projects and documenting outcomes to inform future efforts. Next steps after Iteration may include updating the strategy established during the Pre-planning phase and beginning one or multiple new projects based on recent lessons learned.

- **Evaluate project performance** – Reflect back on the project goals established during the Planning phase. How did the project measure up to the goals it set out to achieve? Communicate any other intended or unintended outcomes as part of the project evaluation, as well as overall lessons learned.
- **Measure progress toward overarching vision and goals** – Revisit the overarching goals established during the Pre-planning phase. How did this project advance these overarching goals? Consider what future efforts could continue to advance progress toward these goals, taking into account lessons learned from this project.
- **Discuss results and desired next steps** – Document and communicate project outcomes with internal and external stakeholders to identify potential next steps. Where possible, solicit stakeholder feedback on project impacts from their perspective. Use available information to identify potential next steps, such as a second phase of the project or a new project that integrates lessons learned from the current project into the upcoming Planning phase.

ONGOING

- **Coordinate with the electric utility** – The importance of utility coordination cannot be overstated and is, therefore, included as an ongoing task. Ports can benefit greatly from developing a partnership relationship with the electric utility that includes coordination outside specific requests and, more broadly, related to achieving overarching and mutual goals. For more information, see the **Electric Utility Coordination** section.
- **Manage/build stakeholder and partner relationships** – See the **Stakeholder and Partner Engagement** section.
- **Advocate for supportive funding and desired policies** – Ports drive national and international economies and can use their political influence to advocate for policies and resources that support their goals. This could include advocating at the regional, state, or federal level, as various policies and funding programs exist at each of these levels that influence port electrification. For example, at the federal level, the 2022 IIJA alone created an unprecedented $3 billion dollar investment in EPA's Clean Ports Program, and some states have set aside funding for electrification to serve ports within their jurisdiction. The policy and funding environment varies greatly by region and requires ongoing effort to understand and engage in related conversations.
- **Complete energy efficiency improvements** – While energy efficiency first was addressed during the Pre-planning phase, it also is included as an ongoing task to encourage ports to evaluate and implement opportunities for energy savings on a regular basis.
- **Manage ongoing requirements** – Grants often have reporting requirements that extend beyond the performance period. This may include, for example, providing data or information on the status of equipment purchased as a part of the project. Because federal funding requirements usually extend beyond the project period, this is considered an ongoing task.
- **Plan for and secure necessary resources** – Port decarbonization requires significant capital and effort, the extent of which can sometimes be overlooked in the early days of program planning. Funding opportunities can be hard to predict and, therefore, plan around; it can be advantageous for ports to seek funding and other resources on an ongoing basis as capacity allows. Securing necessary resources also includes non-financial resources like staff capacity, management capabilities, and analytical tools necessary to support the program.

ELECTRIC UTILITY COORDINATION

Utility coordination is critical at all phases of the electrification process—from initial pre-project planning to final commissioning—as port electrification generates new electric loads that likely require utility infrastructure upgrades and associated permitting. While new electric equipment can be expensive, the electrical infrastructure to support it is sometimes the most expensive and unpredictable project cost. For example, lead times for electrical equipment, such as switchgear and transformers, may be years due to supply chain constraints. Utility timelines for electrical engineering design, equipment procurements, construction, and permitting can also be lengthy and unpredictable. Electric utilities have been providing electrical service to ports for decades, but decarbonization efforts will result in large-scale port electrification that could increase service demands for some ports by over five times,[46] fundamentally impacting established operations.

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[46] Engie Impact, "Accessing reliability and resilience of power systems at the Port of Long Beach."

Port electrification represents a new business focus for ports and utilities alike and an opportunity for organizations to coordinate and learn together.

The logistics of coordination can vary widely utility by utility, but the overall goal is to coordinate as early and often as possible. This coordination ideally occurs at multiple levels across each organization, for example, by establishing a relationship and mutual goals between the utility general manager and port president/port commissioners, as well as establishing ongoing staff-level meetings. Ideally, the port is assigned a single, main utility contact to coordinate the efforts of other subject matter experts within the utility, as necessary. It may be helpful to formally document the intended coordination effort, and an example of this can be found in the Clean Energy Partnering Agreement established between the Port of Seattle, Northwest Seaport Alliance, and Seattle City Light.[47] Landlord ports have an added level of coordination complexity, as they often must coordinate with both the utility and their tenants. Though in many cases it is possible (and often preferrable) for a tenant to work directly with the utility to plan for and implement specific projects in close coordination with the port, port authorities benefit from coordinating with and across tenants to understand and plan for how electrification may impact the overall infrastructure and electrical capacity at the port. Port-wide coordination can also highlight opportunities for efficiencies and cost savings across multiple projects. However, facilitating port-wide coordination can be challenging, as ports sometimes lack visibility into their tenant's electrical loads and future electrification plans, which may be considered business sensitive.

Utility coordination could address the following topics.

Electric infrastructure assessments:

- **Electric Capacity**: Establish a current understanding of the relevant electrical infrastructure serving the port, including the total electrical service available. If increased capacity is required, discuss associated costs and timelines. It may be useful to address the following topics in electric infrastructure assessments:
    - **Grid Capacity Expansion –** Explore the strategies and challenges involved in expanding the grid's capacity to accommodate increased electrical demand from port electrification initiatives.
    - **Voltage Regulation –** Discuss the importance of voltage regulation in maintaining the stability and reliability of the electrical infrastructure within port facilities.
    - **Distribution System Upgrades –** Examine the necessary upgrades to distribution circuits, transformers, and other components of the electrical distribution system to support port electrification efforts.
    - **Smart Grid Technologies –** Investigate the incorporation of smart grid technologies, such as advanced metering infrastructure, demand response, and scheduling optimization, to maximize the performance and efficiency of the upgraded electrical infrastructure.

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[47] Seattle City Light, Port of Seattle, and Northwest Seaport Alliance. 2021. *Partnering Agreement Between the Port of Seattle, Northwest Seaport Alliance, and Seattle City Light for the Seattle Waterfront Clean Energy Strategy*. https://www.portseattle.org/sites/default/files/2021-10/Final_Seattle_Waterfront_Clean_Energy_Strategy_Partnering_Agreement.pdf.

- **Critical Infrastructure Identification** – Work with the utility to determine how the port's critical infrastructure currently is connected to the grid and any potential vulnerabilities in the system.
- **Resiliency Enhancements** – Explore measures to enhance the resiliency of the electrical infrastructure, including strategies to mitigate the impact of extreme weather events and natural disasters.

Electrification Planning Coordination:

- **Load Forecast Planning** – Consider potential new electrification technologies and associated electric loads and/or generation profiles. Discuss pathways to meet these potential loads and anticipated challenges, including timelines and stages of deployment.
- **Planning and Permitting Processes** – Gain an understanding of the processes and associated timelines for large electrification projects with the utility. What are the necessary steps and approvals? Identify where utility permits will be necessary, associated permitting timelines, and what qualifications are necessary to be issued the permits.
- **DER Interconnection and Operations** – Work with the utilities to determine what their interconnection and integration processes are for DER, especially PV and BESS devices. The utility may require specific equipment or operating procedures, especially if they can operate as a microgrid. Utilities may be new to those technologies and work with the port to improve their understanding and processes.
- **Regional Coordination Efforts** – Invite utilities to participate in regional planning efforts related to port electrification. For example, in the Pacific Northwest region, utilities were engaged in the development of the Northwest Ports Clean Air Strategy, a collaboration between the Port of Seattle, Port of Tacoma, Northwest Seaport Alliance, and Port of Vancouver (British Columbia) to reduce seaport-related emissions.

Collaboration Opportunities:

- **Grant Opportunities** – Discuss current or anticipated grant and other funding opportunities. The utility may be interested in co-developing a grant application or may be willing to provide a letter of support.
- **Legislative Coordination** – Identify opportunities for utilities and ports to work together to understand and influence current and future legislation that meets mutual strategic goals.
- **Economic Development** – Utilities and ports may share ambitions related to economic development that can be advanced through ongoing coordination. For example, potential port customers or tenants might select a port location partially based on the reliability of affordable, clean electricity.

Supportive Utility Policies and Programs:

- **Rate Structures Supporting Port Electrification** – Evaluate potential rate structures that may support the port's business case for electrification. This may include rates specific to shore power, EV charging, and e-fuel production. In the case of shore power rates, utilities may use adjusted cost recovery to eliminate demand charges that are difficult to account for across multiple berthing vessels.

- **Utility Programs and Incentives** – Utilities may have the ability to help cover some costs of electrification projects. These could include formal programs, such as EV charging infrastructure programs, or could be unique opportunities developed through collaboration with the utility.
- **Clean Fuel Programs** – Programs in California, Oregon, and Washington offer financial incentives for providing clean fuel alternatives in the transportation industry, and other states are considering future programs. Depending on a program's structure, it may be beneficial to coordinate with the utility to take advantage of clean fuel programs.

STAKEHOLDER AND PARTNER ENGAGEMENT

Each port will have a unique group of stakeholders and partners to engage in their electrification efforts depending on the port type, operational structure, and regional characteristics. For example, operating ports may need to engage labor unions and communicate directly with their customers on electrification goals, while landlord ports might instead communicate with tenants who manage relationships with their own labor and customers. Regardless of these variables, successful port electrification projects require multi-stakeholder coordination and benefit from broader engagement with a wide variety of partners. For example, many ports occupy Tribal lands or waters with Tribal treaty rights and must coordinate with these partners to ensure any potential changes do not interfere with the rights of these sovereign nations. **Table 3** includes a map of potential stakeholders and partners to consider engaging. There are many ways ports may choose to organize stakeholder and partner engagement activities. For example, the Port of San Diego has established an Environmental Advisory Committee that meets regularly to discuss ongoing projects and encourage input from stakeholders, including its tenant association, environmental groups, relevant federal agencies, and local universities.

Table 3. Potential port electrification stakeholders, partners, and collaborators.

Category	Examples
Internal Stakeholder	Sustainability, Policy, Legal, Maintenance, Operations, Business Development, Construction, Fleets
Operational Stakeholder	Labor Unions, Customers, Tenants, Fuel Providers, Equipment Providers, Construction Providers, Consultants
Regulatory Body	Electric Utility, Fire Department, Regional/State/Federal Government Agencies (e.g., Energy Commission, Coast Guard, Environmental Reviewers, Clean Air Agencies)
External Partner	Tribal Governments, Community Organizations, Adjacent Residents, Clean Cities Coalitions, Regional/State/Federal Government Agencies (e.g., Environmental Agencies, Economic Development Offices, Security Departments), Training Providers, Academic Institutions, National Laboratory Partners

COMMUNITY ENGAGEMENT

Near-port communities experience disproportionate impacts from port activities and are critical stakeholders in port energy transition planning. Communities have catalyzed electrification projects by advocating for their priorities to council members. Alternatively, communities have delayed and sometimes ended clean energy projects that generate concern due to potential negative impacts. In summary, communities hold power and influence, and ports should work with them to develop port energy transition plans that can help provide desired benefits to community members. A few best practices for community engagement are listed below. More guidance on identifying and engaging stakeholders in energy projects can be found in DOE's Office of Fossil Energy & Carbon Management's Creating a Community and Stakeholder Engagement Plan.

- Relationships take time to develop. Find ways to begin understanding community members and building trust. One way to do this could be by supporting community events or hosting listening sessions open to community members.
- Develop relationships and partner with trusted community-based organizations for community outreach and engagement efforts.
- Coordinate community engagement efforts across port projects and potentially with other clean energy stakeholders to avoid duplicating efforts and exhausting community members. Review available meeting summaries to understand and integrate what already may have been discussed.
- When seeking community feedback, compensate participants for their contributions, as feasible, and consider ways to enhance accessibility (e.g., providing translation services, remote engagement opportunities, or scheduling meetings after typical business hours).
- Clearly communicate the goal of any community engagement activities. How will feedback be recorded and used and what could it influence? See **Table 4** for examples.

Table 4. Potential participation goals for community engagement.[48]

Participation Goal	INFORM	CONSULT	INVOLVE	COLLABORATE	SUPPORT
Example	The port will be installing EV charging infrastructure.	The port will be installing EV charging infrastructure and is asking community members for locations of interest.	The port will be installing EV charging infrastructure and would like to discuss how plans could be adjusted to better reflect community EV charging needs.	The port has funding for supporting EV charging infrastructure and would like to engage community members in developing and executing project plan.	The port would like to support a community-based EV charging project by providing funding and lessons learned to community members who are leading the project.

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[48] Categories for **Table 4** derived from the following source: NRPA. n.d. *Community Engagement Resource Guide: Creating Equitable Access to High-Performing Parks*. National Recreation and Park Association. https://www.nrpa.org/contentassets/19b3cbe05a634d5e8d3b712dbc8aa9d0/community-engagement-guide-nrpa.pdf.

PORT LEVERS TO SUPPORT ELECTRIFICATION

Ports have varying degrees of operational authority depending on whether the port is an operational port, a landlord port, or if it falls under another business structure. While operational ports generally maintain ownership of port equipment and manage port activities, landlord ports rent or lease space to terminal operators who invest in their own equipment and manage their own day-to-day activities within the bounds of their contractual agreements. It may be more straightforward for operational ports to electrify operations because they have greater control over activities and investments impacting their port. However, all ports, and particularly landlord ports, have a variety of creative levers available to them to help achieve their electrification and decarbonization objectives. These are outlined in **Figure 15** across five categories: Funding Support, Education and Coordination, Implementation, Guiding Policies, and Stakeholder Engagement.

Funding Support

- ✓ Provide funding for tenant projects or other incentives
- ✓ Sponsor grant applications
- ✓ Advocate for funding support from state and federal sources
- ✓ Seek support from the electric utility (e.g., maritime tariffs)

Education & Coordination

- ✓ Lead and/or support coordination and negotiation with the electric utility
- ✓ Provide information to tenants (e.g., grant opportunities, utility programs, incentives)
- ✓ Lead and/or support coordination across tenants
- ✓ Coordinate across ports and stakeholders to articulate demand for greener shipping methods

Implementation

- ✓ Install DERs at tenant-owned facilities
- ✓ Deploy infrastructure to serve tenant-owned facilities and support tenant implementations
- ✓ Demonstration projects

Guiding Policies

- ✓ Integrate environmental requirements in lease or tariff
- ✓ Require energy emissions reporting from tenants
- ✓ Integrate decarbonization policies in new construction and new tariff agreement requirements
- ✓ Advocate for desired regulatory support from state and federal government

Stakeholder & Partner Engagement

- ✓ Provide meaningful opportunities for community engagement and feedback
- ✓ Develop and/or participate in collaboratives advancing port electrification

Figure 15. Mechanisms for port electrification and decarbonization.

RESILIENCY PLANNING

Maritime ports are an essential component of the national and international multimodal transportation system. Cargo activities at U.S. seaports generate over $5 trillion in economic activity, equal to 26 percent of the U.S. economy.[49] They are also gateways to critical supplies, particularly in the case of natural disasters. Climate change is projected to cause storms of increasing severity and sea level rise that will impact ports and near-port communities. Ports should also evaluate non-climate-related threats such as tsunamis, earthquakes, and cyberattacks. Port energy transition planning must consider not only how to integrate cleaner energy options that can begin to mitigate the climate change impacts of traditional port activities, but also how a port's new energy infrastructure and sources will withstand the impacts of climate change.

The United Nations Conference on Trade and Development (UNCTAD) maintains a Guidebook on Resilient Maritime Logistics, including a section (Part 1) on tools and methods for building port resiliency. The Port Resilience Building Process, from the UNCTAD Guidebook, is depicted below in **Figure 16.**[50]

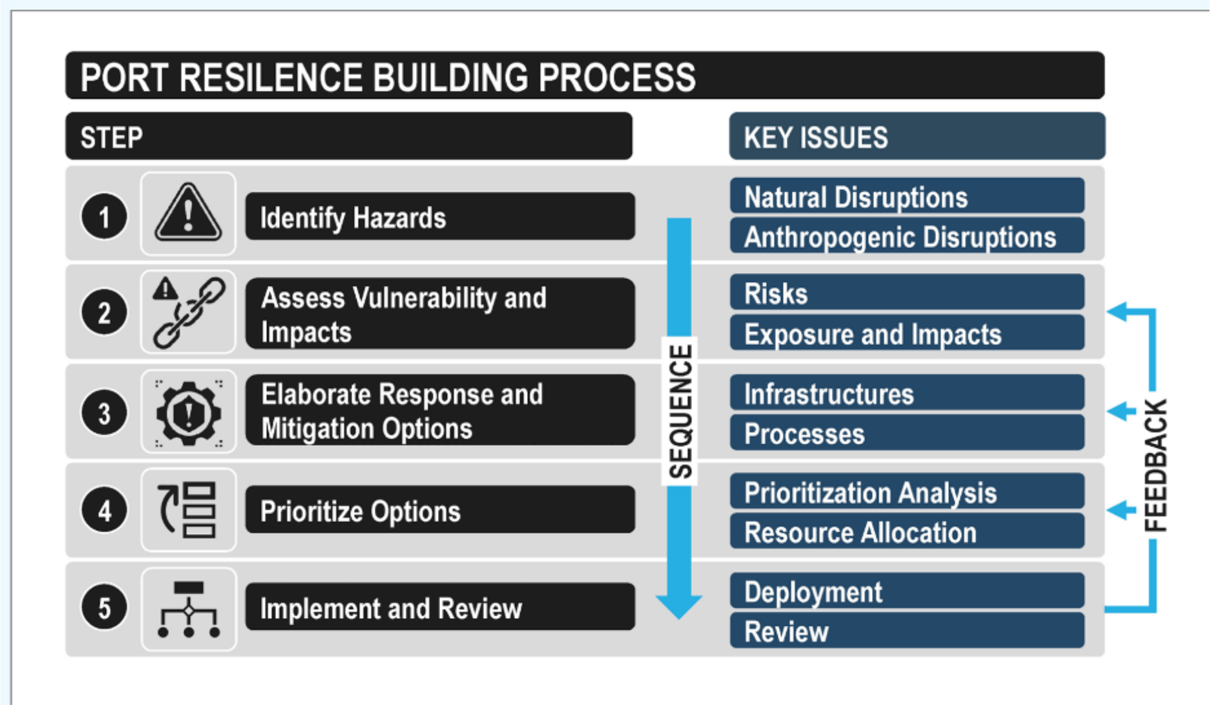

Figure 16. UNCTAD Guidebook's Port Resilience Building Process.

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[49] AAPA. n.d. "Export, Jobs & Economic Growth." American Association of Port Authorities. https://www.aapa-ports.org/advocating/content.aspx?ItemNumber=21150.

[50] UNCTAD. 2022. *Building Capacity to Manage Risks and Enhance Resilience: A Guidebook for Ports*. United Nations Conference on Trade and Development. https://resilientmaritimelogistics.unctad.org.

More specifically, port electrification offers opportunities to address vulnerabilities in a port's existing energy infrastructure by integrating renewable on-site generation and storage (e.g., microgrids), which can provide localized energy to ports and benefit national security. Microgrids can be used to power port operations, particularly during a bulk power system outage. They also can increase the redundancy of power availability, for example, by having multiple DERs integrated into the microgrid (e.g., solar PV, distributed wind, and biodiesel generators). These technologies are described in further detail in the **Port Electrification Technologies** section.

On-site generation and microgrids are an important but relatively expensive clean energy solution. Therefore, port resiliency planning should distinguish critical loads (e.g., communications centers, cranes) and design solutions that prioritize service to those loads during a bulk system outage. This can reduce the overall microgrid size and generation demands, while providing invaluable benefits to port and community resiliency. Sandia National Laboratories (Sandia)'s Microgrid Design Toolkit provides design guidance for microgrids, including identifying system goals and planning for design-based threats.

CYBERSECURITY

With the electrification of maritime ports, advanced technologies are being deployed. Many of these, such as microgrid and DER deployments, may require some form of central control for operations. Others, such as fleet vehicles and CHE, may be transmitting container details and yard position to help overall operations. In both applications, newer and deployed devices will have increased connectivity and data being exchanged with each other and server environments. With such interconnectedness, cybersecurity clearly becomes an issue to consider. Local regulations or, more likely, insurance and bonding agencies will require specific cybersecurity protections in place before operations can begin with this equipment. The Cybersecurity & Infrastructure Security Agency provides a suite of further resources relevant to ports that are evaluating and maintaining their cybersecurity, including advisories, resources, and training tools.

While individual technologies deployed, communication channels and protocols used, and current capabilities of the port's IT department will influence how cybersecurity is approached, some general guidance is available. The National Institute for Standards and Technology (NIST) has their Cybersecurity Framework[51] and various NIST IR documents for specific applications, the Department of Defense has their general Cybersecurity Resource and Reference Guide,[52] and the Cybersecurity and Infrastructure Security Agency (CISA) has their Cybersecurity Best Practices document,[53] along with links to individual area bulletins and security alerts.

Many techniques are outlined in those security guides, but often distill down for a few areas of application. The first is "secure by design"—build security in the system from the ground up, by

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[51] NIST. n.d. "Cybersecurity Framework." National Institute of Standards and Technology. https://www.nist.gov/cyberframework.

[52] DOD. 2022. *Cybersecurity Resource and Reference Guide*. Department of Defense, Chief Information Officer, Cybersecurity Partnerships Division. https://dodcio.defense.gov/Portals/0/Documents/Library/CSResourceReferenceGuide.pdf.

[53] CISA. n.d. "Cybersecurity Best Practices." Cybersecurity & Infrastructure Security Agency. https://www.cisa.gov/topics/cybersecurity-best-practices.

intentionally isolating and segmenting networks that do not need to exchange data. Critical security camera feeds and communications should not run on the same network as the cargo handling vehicle status messages. Appropriate firewalls and intrusion detection systems should be deployed to help prevent and detect any network anomalies. Rule-based access control and principles of zero trust architectures should be deployed to help prevent collateral damage from any successful intrusions.

In addition to the security by design aspect, cybersecurity must also have appropriate operation and contingency procedures documented and should periodically be evaluated/tested. Such practices can help ensure the cybersecurity of the port system remains abreast of an ever-evolving threat space, as well as ensure involved personnel know what to do when an event occurs. Regular exercises specific to cybersecurity events should be conducted or integrated into existing port emergency drills and planning.

If time and resources permit, the cybersecurity approach should consider where the various technologies are heading. More assets are becoming interconnected, but technology used to connect and secure them is rapidly evolving, as well. Concepts like post-quantum cryptography are being evaluated and discussed—any technology deployments should investigate how the industry is moving and ensure hardware deployed may not already be on the trailing edge of best security practices. For example, newer standards in EV charging communications include strong security and cryptography approaches (e.g., IEC 15118-20), which not all vendors offer yet and can sometimes have hardware incompatibilities. Purchasing equipment that may not have the capability to upgrade to a nascent standard or practice may lead to a more costly replacement later.

Photo credit: Port of Seattle.

ASSESSING THE BUSINESS CASE FOR PORT ELECTRIFICATION

Technoeconomic Analysis (TEA) serves as a vital tool for evaluating the economic feasibility and performance of various projects. Specifically, in the context of port electrification, TEA enables stakeholders to assess the costs and benefits associated with transitioning to electric power sources for port operations. By quantifying the initial investment required for infrastructure upgrades, equipment, and ongoing operational costs, TEA provides valuable insight into the financial implications of electrification. Additionally, TEA facilitates the comparison of alternative electrification strategies, such as shore power systems or renewable energy integration, helping decision-makers identify the most cost-effective and sustainable solutions for reducing emissions and improving operational efficiency in port environments.

TECHNOECONOMIC ANALYSIS CONSIDERATIONS

When conducting a TEA for port electrification, it is crucial to comprehensively evaluate all aspects of costs and benefits. The electrification of port operations, whether fully or partially, can introduce significantly higher strain on existing electrical infrastructure, increased electricity bills for various stakeholders, and impact the port's resiliency in the event of a grid outage. Projects that seek to electrify equipment should consider the capital cost of the equipment and any training and infrastructure needed to support that equipment.

TEA can evaluate performance through a variety of different mechanisms. For DER deployment, it may not only be the economic performance of the resources, but also resilience and planning-related improvements, as well as emissions and environmental impacts, that factor into the decision. For DERs and electrification assets deployed to existing facilities, it simultaneously may be addressing structural upgrades and mitigations that would be required in the near future. It may also be prudent to evaluate the marginal cost of related equipment upgrades, such as laying additional conduit or vaults while a trench is open for future and anticipated near-term use. If the concrete or asphalt of a particular section needs to be replaced to run electrical lines for new equipment, new drainage systems or subgrade materials can be deployed at the same time.

Operational aspects of the port electrification (whether via new equipment or changing how existing assets are operated) also play a key role in the TEA evaluation. For example, converting CHE to pure electric may require working a charging cycle into the schedule and ensuring the selected charger can provide enough power or potentially requiring two pieces of equipment so the charging equipment can be slower/cheaper and still meet operational requirements. If a tethered CHE is deployed, the procedure to move that between power sources or its operational range (length of the tether/cord) may also influence how many are needed. Even deploying DERs may have operational considerations if the utility does not allow reverse power through the revenue meter; energy storage may be required to maximize the benefit. Additional staff may be required to do new forms of maintenance and cleaning associated with the electrified assets. This may be offset by changing job duties as electrification increases, but it may also be completely new job positions to fill.

ESTABLISH SCOPE AND GOALS

TEA can encompass an individual piece of equipment or the holistic view of all port operations, including everything from fuel costs to maintenance requirements to community impact. Balancing these various requirements can often be difficult, especially for new and unproven technologies. A key first step is to establish a clear scope and set of goals that prioritize all the requirements, such as economic efficiency, environmental benefits, and resiliency performance. By incorporating these objectives from the outset, stakeholders can ensure that the technologies and assets chosen not only contribute to cost savings and emission reduction, but also enhance the port's ability to withstand and recover from disruptions. Typical goals include the following:

- **Economic Efficiency**: This involves evaluating the initial capital investment, operational costs, and potential benefit streams because of enhanced operation flexibility against varying demand patterns and reduced emissions. Additionally, it should consider factors such as payback period, return on investment, and net present value to assess the long-term financial viability of each option.
- **Environmental Benefits**: This includes emissions targets, such as reduced CO_2 and other greenhouse gases. Particulate matter (PM 2.5, PM 0.5) is often included in here. Improvements in air and water quality need to be quantified, which may be a tonnage reduced, an emissions-related credit value, or even the levelized societal cost of emissions.[54]
- **Resiliency Performance**: This includes assessing their ability to maintain power supply during grid outages or other disturbances to critical loads. The probability of the prospective asset to survive through outages must be modeled and analyzed thoroughly.

In summary, establishing a comprehensive set of goals that incorporate both economic and resiliency performance into the planned project is critical for ensuring the successful implementation of port electrification projects. By explicitly modeling these objectives, stakeholders can identify and deploy the most cost-effective solutions that are able to meet regulatory standards, provide the social benefits, and even withstand and recover from disruptions.

ASSEMBLE DATA INPUTS

Necessary data inputs must be collected to conduct an accurate and comprehensive TEA. This can vary depending on the scope of the TEA, but below are some common datasets needed.

Load Profiles: To accurately assess the benefits and operational costs of DERs to an electrified port, hourly load profiles covering a typical year of main loads are required for a comprehensive analysis that considers diurnal, weekly, and seasonal factors in port operation. This includes traditional loads, such as various buildings and exterior lighting, and new loads that are unique in electrified ports. For some of these loads, like ECHE, ships, or vehicles, port calls and historical usage data may need to be converted into an electric equivalent. An Excel spreadsheet is

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[54] EPA. 2023. "Supplementary Material for the Regulatory Impact Analysis for the Final Rulemaking, 'Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review,'" *EPA Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances*. Environmental Protection Agency. https://www.epa.gov/system/files/documents/2023-12/epa_scghg_2023_report_final.pdf.

available with this handbook to help generate an annual load profile for use in TEA, with the formatting suitable for export into a .CSV file that most TEA programs should be able to ingest.

Renewable Generation Profile: In contrast to traditional generation assets, renewable energy sources, such as solar, wind, and marine energy, often exhibit intermittent and uncontrollable output. As a result, the generation profile of these assets (which often varies with location, technology, and configuration) becomes essential input data for accurately evaluating the expected performance for the microgrid.

- Solar PV is a popular generation resource to consider in port electrification projects. PV power output often can be produced by tools like PVWatts.[55]
- Wind is another promising energy source for ports. Modeled and recorded generation data can be obtained from publicly accessible databases, such as the Plant-Level US multi-model WIND and generation (PLUSWIND) data repository.[56]
- Marine energy is an emerging energy source that could use tides or wave energy to provide power to the port. Predicted values may be obtained using the DOE Water Power Technology Office US Wave dataset.[57]

Expected Maintenance and Operations Costs: Once deployed, any building, piece of equipment, or general port electrification asset will have upkeep costs associated with it and may have normal operating costs. For ECHE or ship shore power, this may be the electricity rate expected for that type of load. For BESSs and other devices, annual safety inspections and certifications may be needed, which might even require training staff to perform those inspections. NREL's Annual Technology Baseline[58] data platform provides annual estimates of the Operation and Maintenance costs for commercial battery storage and other electrification technologies. Periodic maintenance schedules for vehicles and equipment should be available from the vendor/manufacturer to include, even if just as an expected annual cost.

Capital Costs: The capital investment costs to procure, construct, and/or deploy the port electrification technologies is obviously a large input to the TEA. NREL's Annual Technology Baseline[59] data platform provides annual estimates of the Overnight Capital Cost for commercial battery storage and other electrification technologies.

Other Costs: There may be other project-dependent switching costs to account for such as workforce training, environmental reviews, or decommissioning costs for old equipment. Though some of these may be captured in capital costs, depending on accounting policies, they are not always placed within that category and should be accounted for in any case.

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[55] NREL. n.d. NREL's PVWatts® Calculator. Website version 8.2.1 using PVWatts® API version 8.0. Golden, CO: National Renewable Energy Laboratory. https://pvwatts.nrel.gov.

[56] Millstein, D., S. Jeong, A. Ancell, and R. Wiser. 2023. "A Database of Hourly Wind Speed and Modeled Generation for US Wind Plants Based on Three Meteorological Models." *Scientific Data* 10: 883. https://doi.org/10.1038/s41597-023-02804-w.

[57] DOE's Water Power Technology Office's (WPTO) US Wave dataset was accessed on April 8, 2024, from https://registry.opendata.aws/wpto-pds-us-wave.

[58] NREL. n.d. Annual Technology Baseline. Golden, CO: National Renewable Energy Laboratory. https://atb.nrel.gov.

[59] NREL, n.d. (see Footnote 58). https://atb.nrel.gov.

In addition to the data listed above, there are data associated with specific use cases or value streams, which will be covered in the following subsection.

IDENTIFY VALUE STREAMS

Many of the prior items represent pure costs for deploying port electrification technologies. Some of those assets, particularly items that interface with the main power grid, may have the ability to provide other revenue streams during their operation.

Electricity Bill Management

As a utility customer, the port stakeholders are charged for the electricity they use from the grid. This typically includes energy charge and demand charge; both can be reduced by operating DERs deployed as part of the port electrification.

- **Energy charge reduction** – Energy charge is based on the amount of energy consumed and the time when energy is consumed. It reflects the operational cost in electricity generation and delivery. Generation from solar PV and other assets can offset some the energy consumptions. An ESS also can be used for energy shifting to take advantage of time-of-use tariff structures. Some other bill components, such as transmission charge, depend on the energy consumption during specific hours that are given or can be forecasted. Such kinds of charges also can be captured by adding the corresponding rates to the energy charge rate to generate a lumped “energy” charge rate.
- **Demand charge reduction** – Demand charge is based on the highest power consumption during a billing period (typically a month). It mainly is designed to recover the investment in electricity generation and transportation infrastructure. DERs can be used to effectively lower the peak load and, thereby, reduce demand charge.

Demand Response

Electrified assets may have the ability to either disconnect from the main grid (microgrid) or curtail their consumption via extra controls (like charging management controllers). Demand response programs compensate commercial and industrial customers for curtailing their energy when the demand is forecasted to be at its peak. A participating customer would be compensated for the amount of energy curtailed on a pay-for-performance basis. The rules and incentives vary by demand response program. Dispatchable DERs, such as ESSs, can adjust their power output relative to a baseline calculated by the applicable program administrator.

Critical Infrastructure Upgrade Deferral

DERs deployed, especially ESSs, can play an important role by reducing the peak load on a specific portion of the distribution system and, thereby, help defer or postpone specific projects and electrical system upgrades that otherwise would be needed earlier to meet the growing demands. Depending on the circumstances, the benefits can be quite significant, especially if the deferred upgrade is expensive. In most situations, an ESS for this application is used only for a small portion of the year when the load exceeds the existing grid equipment’s capacity. To receive the value from deferring a local infrastructure investment/upgrade, an ESS must exceed a certain power output level during peak hours. The same ESS can be used for numerous other applications in the remaining time. The economic benefits can be estimated based on the upgrade cost and the number of years an upgrade can be deferred.

Emission Reductions

The benefits of emission reductions can be evaluated through various approaches, including considerations of carbon tax, the social cost of carbon, health benefits, and other community advantages. While some benefits may be challenging to quantify, they remain crucial factors to consider.

The EPA provides some resources to estimate the amount of emissions and their associated costs. The Pollution Prevention Tools and Calculators can be used to estimate the on-site emissions of GHG and pollutants, such as SO_2 and NOx, as well as the associated costs. The social cost estimate of GHG can be obtained from Report on the Social Cost of Greenhouse Gases.

The Hourly Energy Emission Factors for Electricity Generation in the United States data published by NREL can be used to estimate the emissions of electricity consumed from the grid on an hourly basis. By comparing the annual emissions based on the hourly net power consumption from the grid with or without the DERs, emission reductions can be calculated and further converted to benefits in dollar values based on the per-metric-ton costs.

Resiliency Enhancement

DERs can be used to strengthen the resiliency of a microgrid and reduce power interruptions of critical facilities. Resiliency is the ability of a system to prepare for and adapt to changing conditions and to withstand and recover rapidly from deliberate attacks, accidents, or naturally occurring threats or incidents. In practice, it may be difficult for a facility manager or end user to quantify the value of resiliency and estimate the cost associated with an outage occurring at different times with different durations and magnitudes. More importantly, resiliency performance and requirements, in general, cannot fully be captured as a monetary value. Therefore, resiliency performance often is considered as a separate metric from economic benefits.

Other Socioeconomic Impacts

Other socioeconomic impacts of port electrification also should be considered. This includes assessing the potential for job creation, workforce benefits, and the attainment of a social license to operate. These aspects contribute to a more holistic understanding of the broader benefits and implications of transitioning to electrified port operations.

TECHNOECONOMIC ANALYSIS TOOLS

TEA commonly is conducted using either spreadsheet software, such as Microsoft Excel, or a simulator platform. Spreadsheets usually are favored for emerging technologies due to their flexibility, accessibility, and transparency. Conversely, simulator-based tools typically are more robust, offering greater accuracy and incorporating built-in cost estimation capabilities.

Microgrid Asset Sizing considering Cost and Resilience (MASCORE) is a publicly accessible web-based application within PNNL's Energy Storage Evaluation Tool (ESET™). MASCORE is a modeling and analysis tool designed for optimal sizing of DERs in the context of microgrids, considering both economic benefits and resiliency performance. It can be used to identify the most cost-effective combination and sizes of DERs for a port electrification project. It is designed to strike a balance between user-friendliness and functional complexity/usefulness. It is based on a chance-constrained, two-stage stochastic approach to jointly determine optimal sizes of various DERs, including renewables, energy storage, microturbines, and diesel generators. MASCORE explicitly models the interaction between DER sizing at the Planning phase and hourly or sub-hourly microgrid dispatch at the operating phase in both grid-connected and islanding modes, considering stochastic grid disturbances, load, and renewable generation.

NREL's Annual Technology Baseline provides consistent data on electricity and transportation technologies, including data regarding DERs, battery storage technologies, and marine fuels. This data can support TEA calculations and other forms of energy analysis.

NREL's System Advisor Model (SAM) is a technoeconomic computer model that calculates performance and financial metrics of renewable energy projects. Graphs and tables of SAM results can be useful in the process of evaluating financial, technology, and incentive options for renewable energy projects. SAM simulates the performance of PV, concentrating solar power, solar water heating, wind, geothermal, and biomass power systems, and includes a basic generic model for comparisons with conventional or other types of systems.

NREL's Renewable Energy Integration & Optimization (REopt®) Lite is a web tool that helps commercial building managers evaluate the economic viability of grid-connected PV, wind, and battery storage at a site; identify system sizes and battery dispatch strategies to minimize energy costs; and estimate how long a system can sustain critical load during a grid outage.

Berkeley Lab's Distributed Energy Resources Customer Adoption Model (DER-CAM) can be used to find the optimal portfolio, sizing, placement, and dispatch of a wide range of DERs, including storage, while co-optimizing multiple stacked value streams that include load shifting, peak shaving, power export agreements, or participation in ancillary service markets.

Several input data are necessary to effectively utilize TEA tools. In addition to the load profile spreadsheet accompanying this handbook, other tools can assist in generating or acquiring these data. For instance, NREL's PVWatts® Calculator can simulate the PV generation profile, while Idaho National Laboratory's Caldera can generate EV charging profiles.

TECHNOECONOMIC ANALYSIS EXAMPLE

In this subsection, a microgrid in a contrived, fully electrified seaport, illustrated in **Figure 17,** is provided as an example of TEA. A more detailed discussion on the types of inputs used in the analysis can be found in the accompanying spreadsheet and support materials. Below is an example of using the MASCORE tool to obtain the optimal sizes of DERs in a prospective microgrid in a maritime port, covering two single-berth container terminals, one double-berth container terminal, one single-berth cruise terminal, and office and warehouse buildings.

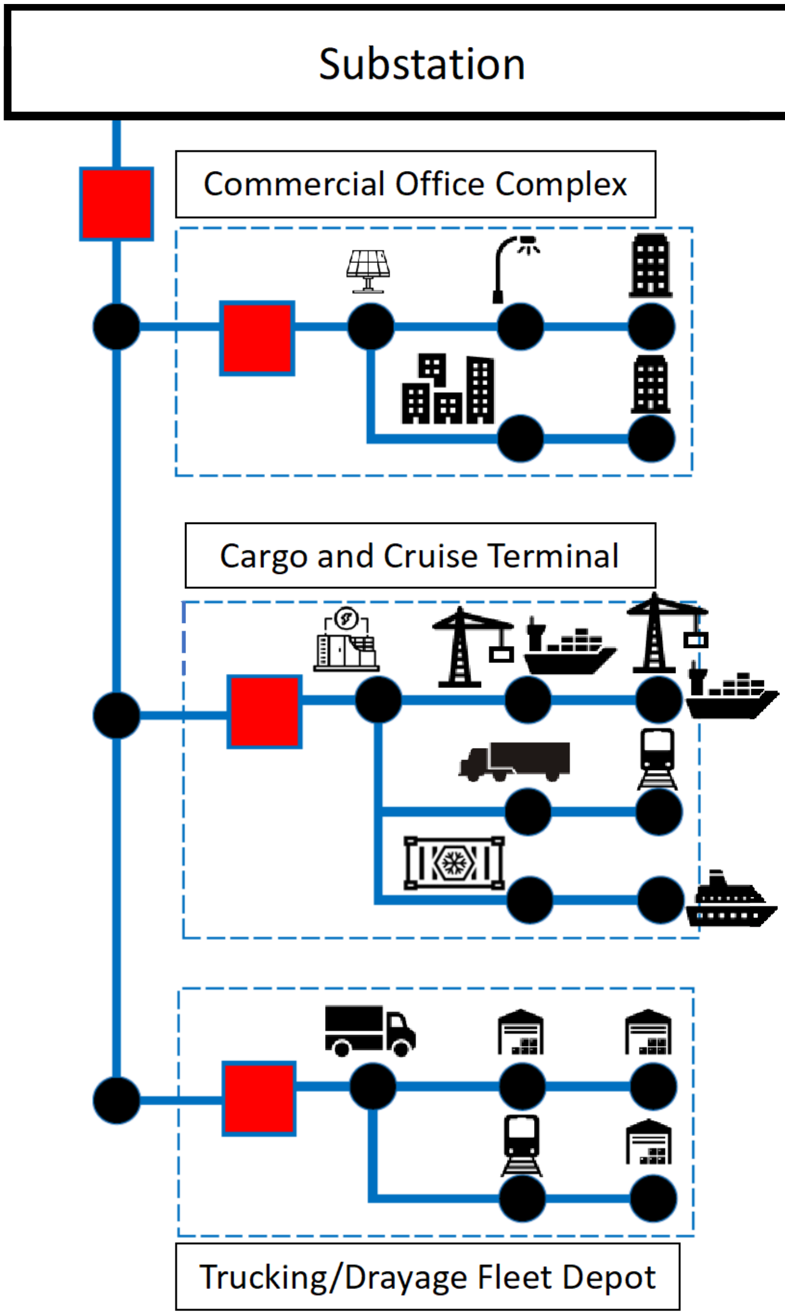

Figure 17. Microgrid diagram in a contrived fully electrified seaport.[60]

The electric loads consist of CHEs, exterior lighting, switch locomotives, MD/HD EV charging, shore power, RCUs, and various building loads, as shown in **Figure 18**. A subset of these loads is considered critical and is required to remain in operation during a grid outage.

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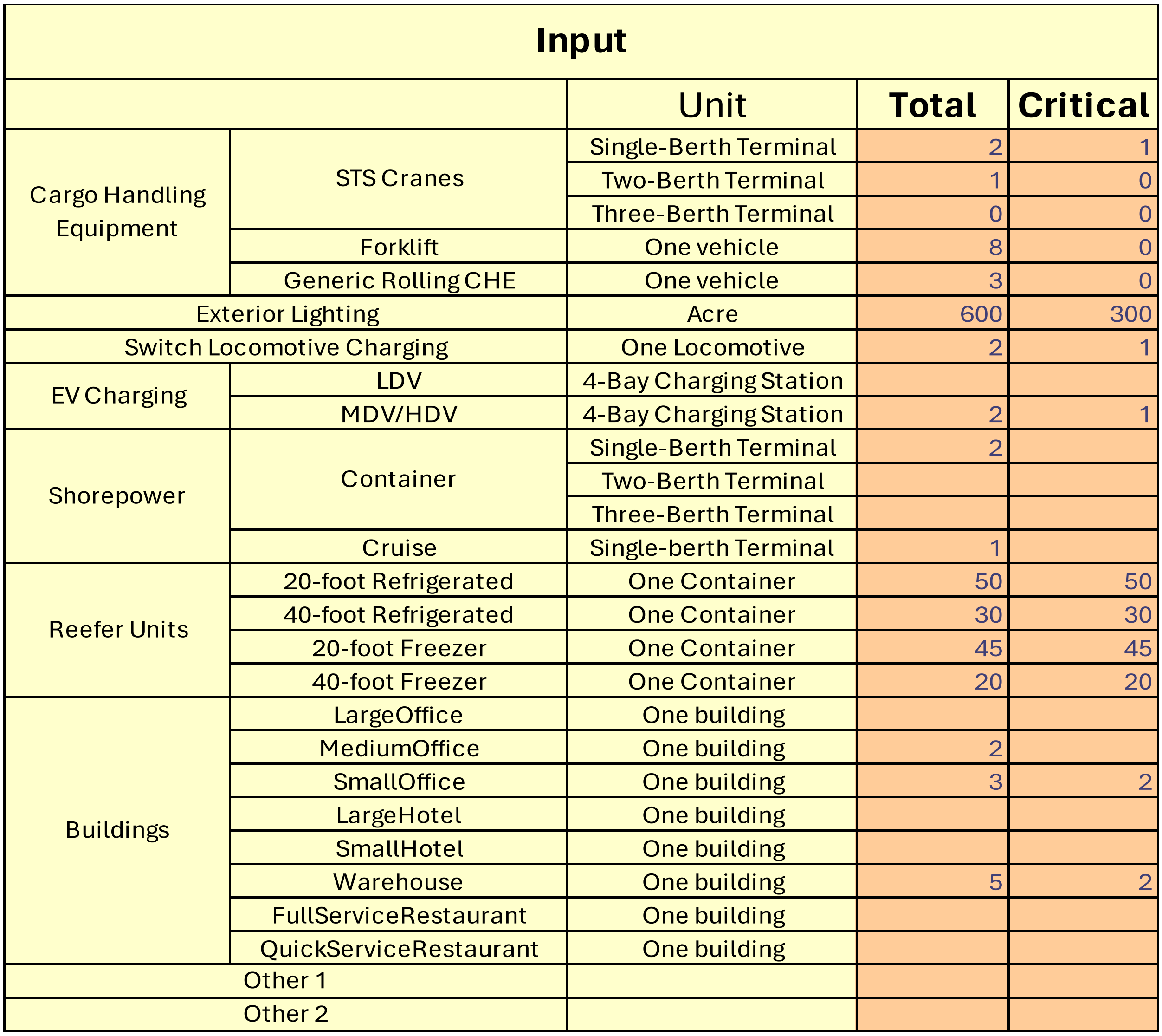
[60] This diagram has been designed using images from Flaticon.com.



Input

		Unit	Total	Critical
Cargo Handling Equipment	STS Cranes	Single-Berth Terminal	2	1
		Two-Berth Terminal	1	0
		Three-Berth Terminal	0	0
	Forklift	One vehicle	8	0
	Generic Rolling CHE	One vehicle	3	0
Exterior Lighting		Acre	600	300
Switch Locomotive Charging		One Locomotive	2	1
EV Charging	LDV	4-Bay Charging Station		
	MDV/HDV	4-Bay Charging Station	2	1
Shorepower	Container	Single-Berth Terminal	2	
		Two-Berth Terminal		
		Three-Berth Terminal		
	Cruise	Single-berth Terminal	1	
Reefer Units	20-foot Refrigerated	One Container	50	50
	40-foot Refrigerated	One Container	30	30
	20-foot Freezer	One Container	45	45
	40-foot Freezer	One Container	20	20
Buildings	LargeOffice	One building		
	MediumOffice	One building	2	
	SmallOffice	One building	3	2
	LargeHotel	One building		
	SmallHotel	One building		
	Warehouse	One building	5	2
	FullServiceRestaurant	One building		
	QuickServiceRestaurant	One building		
Other 1				
Other 2				

Figure 18. Load composition in the example microgrid.

The total and critical load profiles can be obtained using the load profile spreadsheet accompanying this handbook. The PV generation profile can be obtained via the PVWatts® Calculator.

MASCORE can be used to perform the analysis by following the steps outlined in the associated Technoeconomic Analysis – Supplemental Document. The results for this example are visualized in **Figure 19**. The optimally sized ESS is a 3.3 MW battery with a duration of about five hours. The rated power of solar PV is about 2.1 MW. Such a microgrid has a probability of 91 percent to survive a 24-hour outage, above the survivability requirement of 90 percent. The total benefit is equal to $10.7 million (M), which includes savings in energy charges and demand charges, critical infrastructure upgrade deferral (CIUD), investment tax credit (ITC), and the avoided costs of CO_2, SO_2, and NOx emissions.

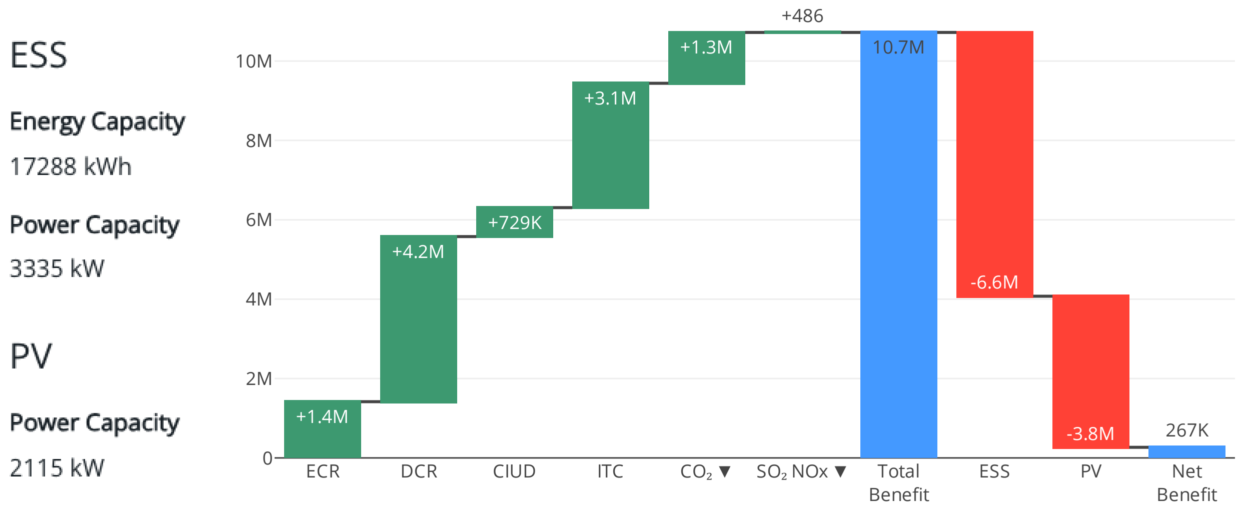


Figure 19. Sizing results and benefit-cost analysis of the example microgrid (note: ECR is energy charge reduction, and DCR is demand charge reduction).

The CIUD benefit is estimated as follows. The distribution line feeding to the proposed microgrid has a capacity of 15 MW. Assuming the total load grows by 2 percent annually, the line upgrade, which costs $5 M, can be deferred by four years (from Year 5 to Year 9) because of the DERs. This yields a benefit of $729 thousand (K), with the discount rate of 5 percent. The $3.1 M ITC benefit is calculated based on provisions in the Inflation Reduction Act that allow solar PV and energy storage projects to claim ITC of up to 30 percent (26 U.S.C. § 48 & 48E). The avoided cost of emissions is estimated by comparing the annual emissions of electricity purchased from the grid with and without DERs, based on the Hourly Energy Emission Factors for Electricity Generation in the U.S. dataset (CAMX region) and the social cost of carbon. The total cost in present value is $10.45 M, which consists of $6.6 M for the ESS and $3.8 M for the solar PV system.

The resulting net benefit in present value is $267 K, with a benefit-cost ratio (BCR) of 1.02.[61] As previously noted, certain benefits, such as resiliency and socioeconomic advantages (in addition to those of emission reduction, which are explicitly considered), are challenging to quantify in monetary terms and, thus, not factored into the BCR. The stakeholders should carefully evaluate the results of these analyses, along with these additional considerations, to make an informed decision on whether to proceed.

FUNDING OPPORTUNITIES & INCENTIVES

There is a growing amount of financial support to advance port electrification and close the cost gap between traditional equipment and their electrified counterparts. This includes a variety of federal programs, which can be divided into two main categories: 1) grants and cooperative agreements and 2) incentives.

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[61] BCR is equal to the calculated total benefit divided by the calculated total cost, both in present value.

FEDERAL GRANTS AND COOPERATIVE AGREEMENTS

Federal funding opportunities are spread across various agencies and offices that can support port decarbonization. These opportunities can be difficult to predict, especially beyond the next year due to federal funding cycles. However, understanding the basic landscape, including key agencies, offices, and programs, and being aware of updates to these programs helps ports become well-positioned to apply for future opportunities. The federal government issues discretionary grants, as well as formula grants, where funding is allocated to a select group (e.g., U.S. states) to achieve the same goals.

- Department of Energy – DOE accelerates transformative science related to the nation's energy and environmental challenges. Grants, Cooperative Agreements, and other funding contracts typically are distributed by individual offices within DOE, depending on funding available to the office and any funding requirements outlined in associated legislation.
    - Office of Electricity (OE): OE advances low-cost clean energy through research addressing grid systems, components, and energy storage. OE is also the sponsor of this Port Electrification Handbook.
    - Office of Energy Efficiency & Renewable Energy (EERE): EERE comprises multiple offices that each release funding in alignment with their focus area. These include the Vehicle Technologies Office, Hydrogen Fuel Cells Technologies Office, and Bioenergy Technologies Office, among others. A full list is available on the EERE website.
    - Grid Deployment Office (GDO): GDO works to maintain grid resiliency and improve and expand the power system to provide reliable, affordable electricity to everyone.
    - Loan Programs Office (LPO): LPO provides attractive debt financing for high-impact, large-scale energy infrastructure projects.
    - Other offices with missions related to port decarbonization and potential associated funding opportunities include the Office of Clean Energy Demonstrations and Office of Fossil Energy and Carbon Management.
    - National Laboratories: DOE also funds 17 national laboratories that address complex research challenges, including energy security, clean energy, and grid resiliency. There may be opportunities to partner with national laboratories to access technical assistance for port electrification. This could be done through co-developing funding proposals, establishing joint cooperative agreements, or engaging in informal collaborative opportunities (e.g., open consortium meetings). A full list of national laboratories is available on the DOE website.
- Environmental Protection Agency – The EPA works to protect human health and the environment and manages multiple programs relevant to port electrification.
    - Clean Ports Program – This program works to reduce harmful air emissions from ports through supporting processes and projects that include meaningful community engagement.
    - Clean Heavy-duty Vehicles – This program supports investments in cleaner vehicles, supportive infrastructure, and associated workforce development.
    - Climate Pollution Reduction Grants – This program funds state/local governments, Tribes, and territories to reduce emissions, including greenhouse gases and other harmful air pollutants.

- Department of Transportation – The DOT advances nationwide transportation priorities, including safety, mobility, and economic growth. It includes multiple administrations, with funding programs related to port electrification.
  - Federal Highways Administration (FHWA) – FHWA stewards and strengthens the national highway system. It administers the Construction of Ferry Boats and Ferry Terminal Facilities Formula Program.
  - Maritime Administration (MARAD) – MARAD manages the U.S. waterborne transportation system and administers funding to ports and associated stakeholders through multiple programs, most notably the Port Infrastructure Development Program and the U.S. Marine Highways Program.

FEDERAL INCENTIVES

Clean energy incentives are designed to accelerate corporate investment in related technologies and can help improve the business case for some projects related to port electrification. These incentives are each unique, and it is important to discuss any potential incentives with a qualified professional to gain a clear understanding of how they could impact a specific project. Similar to grants, incentives fluctuate over the years. In 2022, the landmark Inflation Reduction Act significantly expanded the landscape by creating over 20 federal energy tax credits. Incentives of high relevance to port electrification include the following:

- Energy Investment Tax Credit (26 U.S.C. § 48 & 48E) – Taxpayers can receive a credit based on a percentage of the total investment amount to deploy a qualified energy property, which could include a solar PV, distributed wind, or energy storage facility.
- Qualified Commercial Clean Vehicle Credit (26 U.S.C. § 45W) – Businesses or organizations that purchase qualified commercial clean vehicles are eligible for a tax credit of up to $7,500 for light-duty vehicles and up to $40,000 for MD/HD commercial clean vehicles (weighing over 14,000 lb.).
- Energy Efficient Commercial Buildings Deduction (26 U.S.C. § 179D) – Owners or long-term lease holders of commercial buildings can use this tax deduction to support projects that reduce a building's total annual energy use by at least 25 percent through qualified building improvements.
- Clean Hydrogen Production Credit (26 U.S.C. § 45V) – Qualified clean hydrogen production facilities are eligible for a credit per kg of hydrogen produced. The credit amount is determined by the life-cycle emissions of the hydrogen produced.

Additionally—depending on a port's location—there may be other financial support available at the state, regional, or local level. This support varies but could include state, local, or nonprofit grant programs and specialized loan programs. Electric utilities also may offer grants and rebates for certain electrification projects and equipment. Projects may also qualify for renewable energy certificates, clean fuel credits, or other environmental attributes that can be sold in related markets.


HONG KONG

CASE STUDIES

CASE STUDY: METER STUDY AND MICROGRID OPTIONS EVALUATION

INTRODUCTION

Don Young Port of Alaska (PoA) is the state's primary inbound port. While PoA is small compared to many ports in the lower 48 states, it has an outsized role in Alaska. It handles 80 percent of total vans and containers shipped to Southcentral Alaska ports, which are eventually distributed to every region of the state. It handles 75 percent of all non-petroleum marine cargo shipped into Alaska and 50 percent of freight shipped by all modes, including marine, road, and air. The port serves 90 percent of Alaska's population, and the value of commercial activity totals $14 billion annually.

There is only one road that connects Alaska to the continent and no rail link. Most of the food consumed in Alaska is shipped from outside the state, and at any given time, there is a 6- to 10-day supply. PoA is also Alaska's main fuel distribution and storage center. It handles three-quarters of the jet fuel consumed at the Ted Stevens Anchorage International Airport (ANC), the second busiest air cargo hub in the U.S. and third busiest in the world by landed tonnage.

PoA is adjacent to Joint Base Elmendorf-Richardson (JBER) and plays a major role in the supply of cargo and fuel to the base via secure haul road and pipelines. Therefore, it is evident that the port serves a critical role for both the well-being of the state's population and for national security. Consequently, the Municipality of Anchorage, the owner and operator of PoA, has been evaluating options for increasing PoA resilience to natural and manmade threats. One of the main components of this resilience plan is a set of upgrades to PoA's energy infrastructure that, when fully implemented, will coalesce into a microgrid that is able to support operations of the port itself, along with a subsection of JBER operations.

To date, three studies have been conducted: a pre-feasibility study in 2017 by DeerStone Consulting, considering the installation of a PV array on port premises; a 2020 conceptual study by Electric Power Systems, Inc. for a microgrid, considering the selection and sizing of energy systems; and a technoeconomic analysis by Sandia and Launch Alaska, considering ownership and operations options to understand the economic feasibility of the project. Since the inception of the microgrid concept, some of its components have been procured and are in the process of being commissioned, while support for other components is still being sought.

OVERVIEW OF PORT LAYOUT AND ENERGY INFRASTRUCTURE

An aerial view of the port is shown in **Figure 20**. PoA is a multimodal commercial facility that handles containers, bulk (liquid and solid), and occasional cruise ships. On the land side, cargo enters and exits the port by truck, rail, or pipeline. Cargo handling equipment includes more than 50 yard trucks and 4 top pickers, all diesel-powered, currently. Containers are loaded to/unloaded from ships either via three electric gantry cranes or by roll-on/roll-off yard trucks. Tank farm pumps move fuel to JBER and ANC. Trucks are used to bunker fuel to vessels. A large cement loadout facility uses large electric motors to regularly stir cement powder to prevent it from setting. An electric docksider offloads cement vessels and an electric compressor moves cement from dock, through pipeline, to the storage facility. Container yards use electricity to keep refrigerated containers cold and to heat containers in winter to prevent freezing. PoA also uses heat traces to prevent the dock and water or liquid-handling systems from freezing. Other electric loads include building ventilation and lighting.

Figure 20. Aerial view of Port of Alaska. A dock with three gantry cranes, fuel storage and handling infrastructure, and container stacking areas are visible.

PoA operates as a “landlord” port—it owns, operates, and maintains docks/ship berths and certain common facilities, including main roads and overall PoA-related security systems. Tenants lease their yards and own, operate, and maintain most of their own facilities and equipment in their leased areas (e.g., lighting, buildings, fuel tanks, cement silos, roll-on/roll-off ramps, etc. PoA owns the cranes, but tenants (Matson) operate and maintain them under a lease agreement.

There are seven tenants at the port that deal with individual aspects of operations, including fuels, cement, containers, refrigerated cargo, vehicle transportation, aviation, and shipping. Chugach Electric Association (CEA), the local electricity provider, bills more than 60 meters that serve either PoA or one of the seven tenants or their subtenants. Each tenant uses electricity according to its operational needs, with little or no central coordination.

PoA and its tenants are served by an electrical distribution loop operated at 34.5 kV. The main feeder from a utility substation enters the port area by overhead lines, then transitions to underground and then into a padmount switch. From there, a main feeder loop serves customers via local laterals that connect to service points at 480 V or 208 V. A second underground tie, which is normally open, connects the primary distribution loop to a separate utility feeder.

The 2017 study by DeerStone concluded that the installation of a 2.4 MW peak AC PV array is physically feasible on PoA property but did not provide conclusive evidence to support its economic viability. It should be noted that, due to a variety of reasons, PoA no longer plans or expects to develop significant on-port solar PV generation. However, several PoA users are exploring options to install smaller scale, building-mounted solar PV.

PRELIMINARY CONCEPTS FOR A PORT OF ALASKA MICROGRID

In 2020, Electric Power Systems, with support from Sandia, considered options to improve the resilience of both PoA and JBER operations by installing microgrids with local generation and storage. In the study, the combined peak load of 6,850 MVA was obtained using known historical meter data from some of the tenants, estimated data for JBER, and for the remaining customers who did not have available historical data, an assumed coincidence factor and an assumed power factor. Moreover, a minimum load of 1,680 kVA was obtained using an assumed 1:4 minimum load ratio.

Energy resources for the port microgrid consist of an on-site PV installation, a battery energy storage, and diesel generation.

The minimum size of the on-site diesel generation was chosen to meet the peak combined load of 6,850 kVA, because of the high latitude location entailing long periods with little or no solar PV generation. To prevent wet stacking (operation of diesel generation below the minimum turndown ratio), the recommendation was to install two generators rated at 3,500 kVA, each of which could operate down to 1,050 kW without wet-stacking concerns. Electric Power Systems also ran load flows of the system to verify that no voltage or current violations occurred.

Two microgrid configurations were examined: one suitable for port operations management of the microgrid under islanded conditions (baseline), the other requiring the utility to operate the microgrid even in islanded conditions (alternate). The microgrid baseline configuration is shown in **Figure 21**.

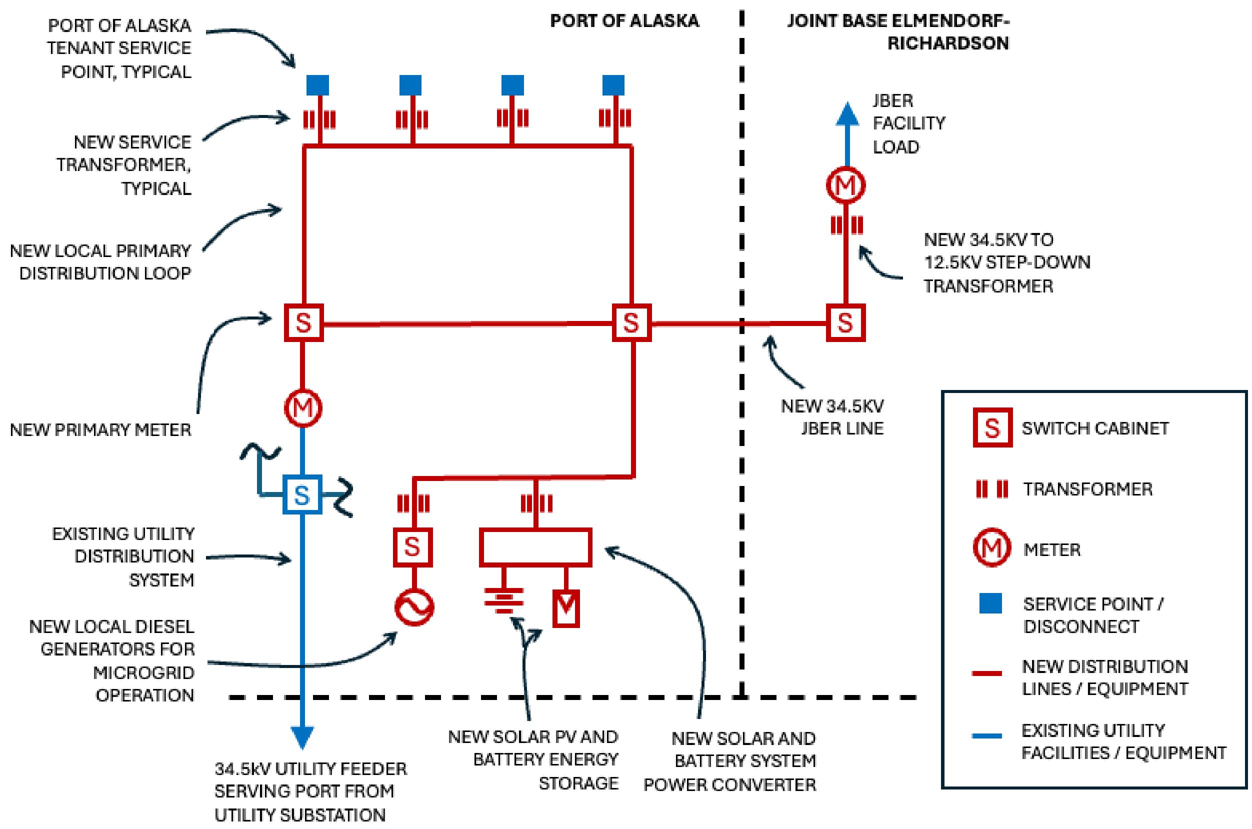

Figure 21. Baseline configuration of the microgrid, allowing the port to manage systems operations in islanded conditions. The existing utility-owned distribution loop (not shown for clarity) would remain in place.

In this configuration, a new primary distribution loop would be constructed. The loop would be owned by the port or some other private entity, and port tenants could choose to connect to this loop. The port and selected tenants would share a primary meter at the point of interconnection of the new loop and come to an agreement concerning payment for power consumed, likely via sub-metering. Tenants could also choose to stay connected to the existing utility-owned distribution loop and pay the utility directly for energy services. A new 34.5 kV tie-in would serve specific JBER loads, after stepping down to 12.5 kV. This tie-in would require approval by the Regulatory Commission of Alaska (RCA).

In the alternative configuration, shown in **Figure 22**, the existing primary distribution loop would continue to serve power to the port and its tenants. In this configuration, the new local energy resources (diesel, solar PV, and battery storage) would tie into the existing primary distribution loop. This configuration would cost less because there would be no need to duplicate the existing distribution loop. This configuration would require full participation by the utility. An agreement between the utility, PoA, and potentially the tenants could be set up to compensate participants for services provided by the DERs, for example, peak shifting, voltage support, or frequency regulation.

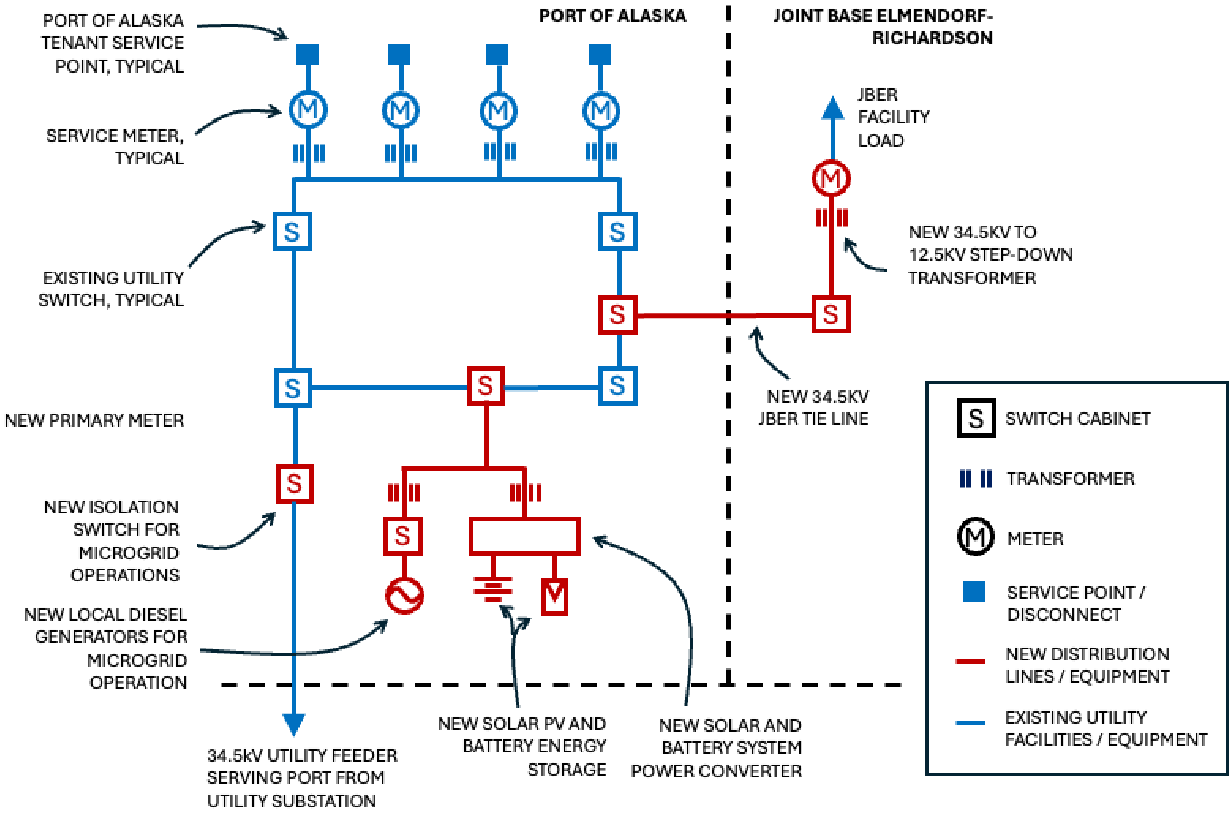

Figure 22. Alternate microgrid configuration, with utility ownership of the primary distribution loop. The utility would be responsible for operating the microgrid and its local energy resources.

As of today, the baseline option has been abandoned in favor of a model that largely resembles the alternative configuration, with new economic and energy management options provided by smart metering but without the PV array. PoA may ultimately own some lines connecting battery storage to the system. CEA will likely operate and maintain most of the equipment, thereby avoiding most RCA approval. CEA intends to develop microgrid rates that will require approval by RCA.

TECHNOECONOMIC ANALYSIS OF VARIOUS MICROGRID MODELS

In 2022, Sandia commissioned Launch Alaska to conduct a technoeconomic analysis for the purpose of evaluating the economics of various options for future microgrid installation. Following the DeerStone report, which determined the maximum size of a PV array on port property, as well as funding by the Department of Defense’s Defense Community Infrastructure Pilot (DCIP) of a 4.5-MW/10-MWh BESS, the focus of the technoeconomic analysis shifted from that of optimal sizing of DERs to that of evaluating the economics of a series of possible ownership options.

The technoeconomic analysis is based on benefits of operating the PV and BESS, in blue sky conditions, to offset energy costs either by reducing energy charges or demand charges, based on the existing rate structure that the port is operating under. Moreover, only the PV and BESS are used to offset energy consumption, based on the assumption that operation of the diesel genset(s) would only occur during black sky conditions.

To improve the quality of the TEA, an accurate representation of the load is a necessary input. For this purpose, meters were deployed at strategic locations on the distribution system and at end uses. One meter was located at the head of one of the two feeders that supply power to the distribution loop. The distribution loop was configured in such a way that all loads were powered by the one instrumented feeder. Additional meters were sited to meter each of the three gantry cranes, the largest individual loads on the system. Data were collected by Sandia staff for the period from May 25, 2022, to July 8, 2022, using a three-second sampling rate. The data were down-sampled to one-minute resolution for compatibility with the TEA software (HOMER Pro). A subset of the data is shown in **Figure 23**.

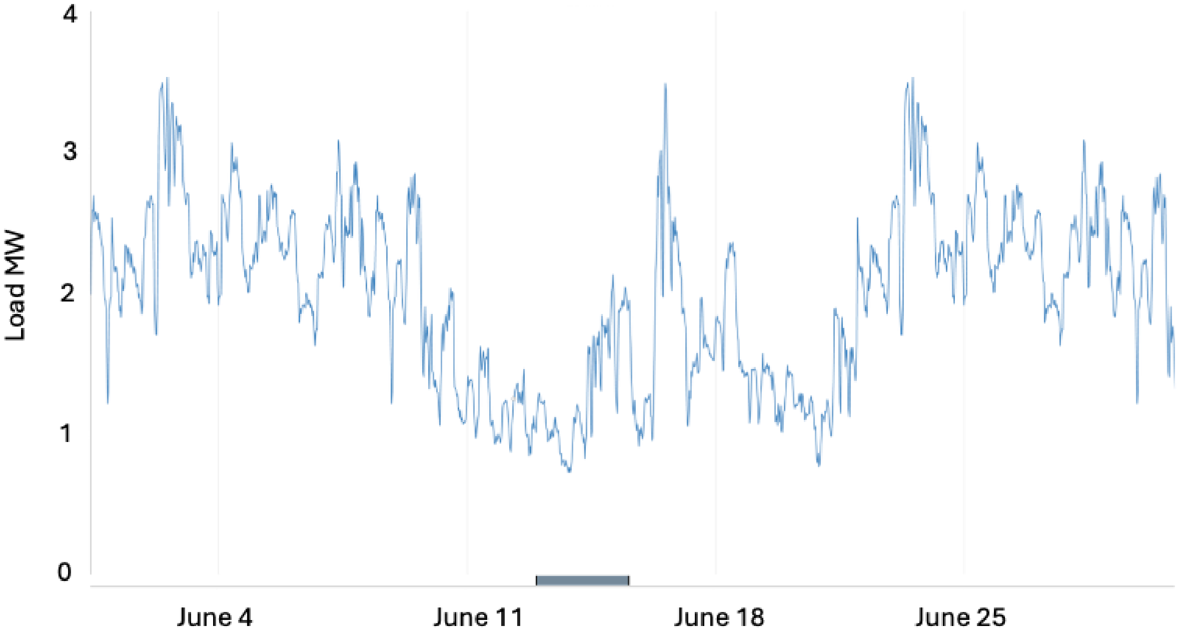

Figure 23. Month-long sample of data at one-minute resolution. The data sample was repeated to span an entire year.

The PV system was modeled as a 2.4 MW system with 30-degree panel tilt. Solar data from the NREL solar energy database were used as a resource, and the system was derated to match the overall yearly power production determined in the DeerStone study. Utility outages lasting four hours, with a 10 percent standard deviation, occurring six times per year, were determined to be an accurate representation of the outages observed in recent years.

The cost of utility power was based on the CEA North District Large General Secondary Service Rates 1. The energy charge is $0.0247/kWh and the demand charge is $44.53/kW. The value of renewable energy sold back to the CEA grid was modeled at $0.055/kWh. The cost of the PV array is estimated as $1.75/W and the cost of the BESS is $7.6 M, with $5.3 M provided by the

DCIP grant. Total Operations and Maintenance cost for year 1 is $25,000, with a 2 percent yearly escalation. It should be noted that these rates may change because of a pending CEA rate case.

Four scenarios were investigated, each representing feasible combination of ownership and operation of the energy resources. These are summarized in **Table 5**.

Table 5. Summary of ownership and operation scenarios considered.

Scenario	BESS Owner	PV Owner	BESS Operator	PV Operator	Use Case 1	Use Case 2
Scenario 1	PoA	PoA	CEA	CEA	Reliability	
Scenario 2	PoA	PoA	CEA	CEA	Reliability	Peak Shaving
Scenario 3	PoA	3rd Party	CEA	3rd Party	Reliability	
Scenario 4	PoA	3rd Party	CEA	3rd Party	Reliability	Peak Shaving

In all cases, PoA owns the BESS and CEA operates it. In scenarios 1 and 2, PoA also owns the PV array, which is operated by CEA, as is the case for the BESS. In scenarios 3 and 4, a third party owns and operates the PV. For each of the two energy asset ownership and operation combinations, two use cases are considered:

1. Reliability only, in which the battery is always kept at maximum state of charge, so that it is always ready to provide power in case of a grid outage.
2. Combined reliability and peak shifting, in which the battery is dispatched to reduce demand charges by reducing peak demand.

In the combined reliability and peak shaving use case, the amount of peak shaving is adjusted so that reliability is not degraded substantially compared to the reliability-only use case.

For each of the four scenarios, several simulations were performed, each representing different statistical realizations of the grid outages. The net present cost of the system was compared to the net present cost of the baseline system (i.e., the status quo, with no solar PV or BESS). The total "resilience fee" that tenants would have to pay was then calculated by subtracting the net present cost of the baseline option from the net present cost of the option in question. The resilience fee represents the minimum cost that the tenants would pay to the port in exchange for the added resilience. The results are summarized in **Table 6**.

Table 6. Summary of resilience (in terms of hours of load loss per year) and cost (in terms of tenant resilience fee).

Scenario	Average Outage (hours per year)	Annual Resilience Fee ($K)
Baseline	24.0	0
Scenario 1	2.47	411
Scenario 2	2.51	212
Scenario 3	2.4	198
Scenario 4	2.93	0

The results are illuminating from several perspectives. First, using the BESS for peak shifting (scenarios 2 and 4) provides more value, through demand cost reduction, than simply using the solar PV for energy cost reduction (scenarios 1 and 3). Second, third-party ownership of the PV (scenarios 3 and 4) provides better value to PoA than direct ownership, since it allows PoA to benefit from the resilience without the upfront investment. In turn, the third party could access investment tax credits and other grants not accessible to PoA.

This analysis provided an overview of several scenarios and highlighted how they may differ for Port of Alaska. Once one has been selected as the preferred ownership and operation model, a more detailed financial evaluation will be required that more closely aligns to the methods and procedures used by the Municipality of Anchorage to make financial decisions and that validates the assumptions made in this analysis. In addition, a model to distribute any monetary benefits to the tenants that result from the project, such as potential lower energy costs, needs to be developed.

LESSONS LEARNED

The process undertaken by PoA to improve the resilience of the port has already lasted several years. As noted in the **Planning Considerations** section, the Pre-planning, Planning, and Implementation phases can blend into one another. Furthermore, financial resources for the various stages of the process can be obtained sequentially and from various sources.

Circumstances change as the process evolves, due to changes in internal requirements and the external environment. For example, only changes to the electricity infrastructure were considered initially, while recent developments point to the need to also consider hydrogen and associated e-fuels as part of the overall decarbonization and resilience picture.

The process of Pre-planning and Planning for PoA, a relatively small port, has many complexities, resulting from the needs of multiple tenants, regulations, local climate conditions, and the evolution of the energy economy of the state. Despite the several years of Pre-planning and Planning, and the installation of a component of the distributed energy system (the BESS), the Planning process is not over. PoA has and continues to modify an overall Port Power strategy that consists of smaller, more easily developed projects that have independent utility, and that also combine into an overarching power system with greater combined utility (e.g., system reliability, resilience, better economics, lower emissions, etc.). The resilience analysis carried out so far is limited to the assumption of a long disruption to grid power. The individual threats that could cause long grid outages—such as tsunami (a new planning factor that emerged from a recent USGS/University of Alaska Fairbanks study), earthquake, sea level rise, severe storms—could also cause damage to local distributed energy systems. Further analysis using appropriate tools would provide better insight into how local resources would withstand hazards associated with these threats and better insight into the resilience of the microgrid as a whole.

PROJECT CONSIDERATIONS

Potential Planning Steps:

- Obtain loads for individual tenants
- Perform a meter study to obtain an accurate description of the distribution circuits
- Catalog emissions from port equipment
- Consider technology options to reduce and eventually eliminate emissions
- Perform analysis to determine optimal microgrid configuration and system sizing
- Determine optimal options for ownership and operation
- Assess equipment availability and consider impact on implementation schedule
- Perform study to evaluate safety of first-of-a-kind components and systems
- Engage with stakeholders to choose among the options
- Engage with the local community and workforce to ensure that changes do not produce adverse effects and, indeed, seek to produce beneficial effects
- Consider opportunities to fund individual components of the microgrid

Potential Implementation Steps:

- Obtain funding for one or more system components
- Gradually install components, if possible, ensuring that they are compatible with future microgrid operation and that they align with the evolving energy environment
- If needed, procure and deploy new distribution infrastructure (e.g., lines, switches, meters)
- Test operation of the components, individually and as part of a system
- Discuss equipment operation flexibility with tenants/operators
- Train system operators as new technology is deployed
- Evaluate options for energy management protocols
- Deploy energy management system
- Commission the microgrid in various modes of operation

Potential Iteration Steps:

- Continue to monitor the performance of system and its components
- Continue to monitor technology advancement to find opportunities for incremental improvement
- Continue to keep community informed about system performance
- Engage with operations personnel to gauge opportunities for improvement
- Communicate successes and failures with the ports community at large

Photo credit: Port of Long Beach.

CASE STUDY: PORT MICROGRID DEPLOYMENT

INTRODUCTION

With the electrification of more port operations and assets, as well as increasing demands on the utility grids from public, commercial, and industrial users, methods to ensure provision of power to these assets should be analyzed against the risk of grid failure. Using DERs like solar PV generation, battery energy storage, and other distributed generation (e.g., biodiesel), a microgrid can be formed to provide backup power during outages and ensure a continuity of operations. This case study will examine what goes into defining and operating a microgrid, with some loose ties and lessons learned derived from the Port of Long Beach microgrid deployment. The Port of Long Beach has recently deployed a microgrid to provide backup power to the port's Joint Command and Control Center. The $18 M microgrid, which received a $5 M grant from the California Energy Commission, includes a solar PV array, a stationary BESS, and a microgrid-extending mobile battery energy storage system (mBESS).[62] The mBESS is typically connected to the port's microgrid system but can be separately deployed to power other buildings, stranded RCUs, small pump stations, and other assets that might be experiencing an outage. Additionally, the port worked with its utility, Southern California Edison (SCE), to acquire permission to power the adjacent port pilot facility during unplanned outages; this facility is crucial to emergency and recovery operations.

OVERVIEW

A microgrid is defined by DOE as "a group of interconnected loads and DERs within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or islanded-mode."[63] The load side of a microgrid may often be an asset that requires power be maintained through outages, such as port operations centers. For the Port of Long Beach, this translated to maintaining power to the Joint Command and Control Center, which manages security operations like the Port of Long Beach Harbor Patrol and Port Police. Microgrids often are deployed to maintain power to environmentally controlled devices (e.g., a device requiring a specific temperature or humidity range be maintained, such as RCUs) or even standard equipment (e.g., STS cranes). Power and energy for a microgrid can be from renewable sources like rooftop solar PV or microturbines (wind), discharged from battery energy storage devices, produced from hydrogen fuel cells, or from traditional diesel, biodiesel, and natural gas generators. Additional power system switch gear and protective devices are needed to connect and disconnect these devices from each other and the main power system, and some form of management (e.g., microgrid controller) is needed to coordinate the devices and switching sequences. These different communication connections can require varying levels of cybersecurity evaluation, depending on the nature of the connected load and the extent to which

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[62] Port of Long Beach. 2022. "Port Starts Construction on Microgrid Project." March 8, 2022. https://polb.com/port-info/news-and-press/port-starts-construction-on-microgrid-project-03-08-2022.

[63] Ton, D., and M. Smith. 2012. "The U.S. Department of Energy's Microgrid Initiative." *The Electricity Journal* 25 (8): 84–94. https://dx.doi.org/10.1016/j.tej.2012.09.013 or https://www.energy.gov/sites/prod/files/2016/06/f32/The%20US%20Department%20of%20Energy%27s%20Microgrid%20Initiative.pdf.

the microgrid owner wishes to isolate the microgrid system from other networks. In the case of the Port of Long Beach, a decision was made to completely isolate the microgrid and not rely on the vendor's cloud-based interfaces.

Microgrid consideration and deployment begins with an assessment of what loads need to be on the microgrid and how much power they require over time. This may be as simple as nameplates on the equipment or information from the manufacturer. Meter data in a building management system or from a utility bill may also be sufficient if loads are constant and no connected equipment has a large inrush current (such as a large motor load). If the load does exhibit a large inrush current (where it may consume up to 4x the current for a couple seconds),[64] that characteristic will need to be noted to make sure the generators deployed can support that power level or if additional equipment is needed (e.g., motor soft start or variable frequency drive). Detailed evaluation may require deploying metering devices to the desired loads, which can range from simple "plug-and-play" type meters all the way up to things requiring facility crews/electricians to permit and install. Knowing the size and criticality of the loads will help determine how much generation or energy storage is needed. However, in some cases, space and economic constraints may limit a microgrid's ability to serve all loads for an extended period of time. Therefore, it may be useful to design load tiers; that is, designating which loads may be less important and can be shut down during a prolonged outage. For example, a microgrid may support all buildings and equipment for 10 minutes but then shed non-critical loads to maximize the runtime for the fuel or energy on-site.

Figure 24. Left to right (1) main incoming board for the microgrid, (2) wiring for solar PV panel array, (3) microgrid-extending mobile BESS, and (4) 306 kW DC solar PV array on warehouse roof. Photo Credit: Port of Long Beach.

With the desired loads for the microgrid identified and sized, engaging with the utility and relevant authorities having/holding jurisdiction (AHJ) is often the next step. The utility will have safety and relay setting requirements, which also may be enacted to ensure a minimal backflow of power to the grid. These will be identified in interconnection permit applications. Many utilities have been granted monopolies on the provision of power and prohibit distribution of power from one metered customer, beyond "fencelines," to another customer. The Port of Long Beach microgrid crosses a fenceline from the Joint Command and Control Center to the separately metered port pilot facility, so the port worked with SCE to obtain an exception from the California Public Utilities Commission.

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[64] Robles 2015 (see Footnote 45). https://certs.lbl.gov/publications/commercial-3-phase-rooftop-air.html.

With both “traditional fuel” generators and batteries, safety agencies may impose unique constraints, as well. For the Port of Long Beach microgrid, an existing building wall needed to be upgraded to have a two-hour fire rating due to its proximity (less than 10 feet away) to the mBESS. Additional setbacks, such as distance from parked cars, were required and dependent on the size of the installed battery system. Certain physical installations associated with a new microgrid may also trigger building code updates, such as seismic requirements or hazardous materials removal. The solar PV system installed by the Port of Long Beach was located on a 1960s warehouse roof; the local air control agency required a complete abatement of non-friable asbestos and would not allow enclosure or encapsulation. Some of these elements may not become apparent until construction begins, even with building permits in place, and may result in large unplanned cost increases.

Other limitations may be associated with the size of the microgrid or equipment (both in physical size and the power draw). For example, there may be additional fire suppression requirements for a larger, single battery installation than two separate, smaller battery installations. Utility regulations may have a power threshold where different interconnection and operational rules come into play, so splitting a microgrid into two separate entities may work around those problems. Operating a microgrid that is completely isolated (no grid connection) may also allow some utility regulations to be avoided. However, many regulatory bodies have more generic terminology like “power producer” that encompass their regulatory authority, so an exception may still need to be filed.

Complementary to electrical and physical operations and constraints, cybersecurity aspects of the information and operational technology portions of the project should be considered. Remote access to the microgrid controls and data will need to be evaluated, especially if the microgrid is operating critical assets for the port. Even with a localized microgrid, additional controls like specific login credentials or access controls may be required by the microgrid owner or operator, as well as other authorities (e.g., port authority, the insurance company for the port or tenant, or even the asset owner themselves). Additionally, utilities will have cybersecurity requirements for grid-connected microgrids. Knowing these limitations will aid in the equipment selection and what design/certification processes must occur.

With the equipment and operational constraints in mind, selection of the generation sources and control equipment can be evaluated. Per the prior discussions, different types of generation may require additional equipment, permits, certifications, or IT considerations, which will factor into the overall cost-benefit analysis. Fundamentally, the location of the microgrid or goals of the port authority may influence the generation selection, as well. If the microgrid is located in an environmentally sensitive area, or if a port is working to lower greenhouse gas emissions and criteria pollutants, fuel-spill mitigation or generator emissions categories may drive costs and feasibility. The Port of Long Beach microgrid uses its existing diesel generator as its anchor asset because large motors must be started that the inverter cannot power (due to inrush and starting currents mentioned earlier). However, inverter technologies are improving, and it may be possible to use a BESS to anchor the microgrid in the future.

If solar power generation is desired, available space must be considered (e.g., rough metrics for solar PV are 1 kW per 100 square feet of roof or 1 MW per 5 acres of land). Batteries also take up space and fuel cells rely on hydrogen or other fuels that may not be readily available. The use case for the generation sources is also important—will they be purely for backup power or are they able to run and provide a potential grid service (or revenue source) during "blue sky" operations? For "blue sky" operations, additional metering gear, emissions licenses, and cybersecurity requirements may be relevant, which will influence the cost-benefit analysis. Maintenance schedules, training requirements, and parts required will need evaluation. If fuel-based generation is present, storage facilities or refueling contracts will need to be explored and included in the cost-benefit analysis.

Once all regulatory and high-level generation/load selection decisions have been resolved, the microgrid design can be finalized and permits from local AHJs and utilities (for interconnection) can be obtained. This is likely to be an iterative process; microgrids can be complex and usually are built to suit. Furthermore, many permitting agencies have limited experience with this technology. This is further complicated by switchgear, batteries, and renewable generation that are in high demand, and equipment lead times could be months, if not years, for some equipment. Some microgrids can be installed very close to the main feed of buildings they will service, while others will require extensive trenching for conduits to connect energy resources.

Upon completion of construction and deployment of the microgrid, commissioning of the system will be needed. Prior to commissioning, battery health for any uninterruptible power supplies supporting critical equipment during commissioning tests should be checked. Depending on the complexity of the microgrid and how many approvals need to occur, the commissioning process may take a few days to a few months. For a microgrid providing power to critical port resources or buildings that are occupied, commissioning tests may need to be scheduled during off-peak hours, such as weekends, which may extend the timelines and add costs. Initially, commissioning will ensure individual devices in the system behave as expected, from DERs producing the proper amount of power to switchgear operating correctly. Commissioning might be phased, starting with battery charging and discharging, solar PV generation production, and communication testing. Transfer switches and other relays may need to be reset during the tests. If load changes were made to the facility between the microgrid design and commissioning, additional power studies may be required prior to commissioning. Overarching operations (the microgrid controller) and scenarios should be tested according to written methodologies that are understood by the designers and microgrid owners, especially the owner's building engineers and electricians. Utility and other AHJ representatives may have specific commissioning and testing before their approval is met, which need to occur, as well. Commissioning tests for the Port of Long Beach required several building outages and were held on weekends. The port was required to reimburse overtime labor for utility and city permitting staff who witnessed the commissioning tests.

After the microgrid owner has identified in-house operators and maintenance staff, the microgrid designer should provide thorough operational and maintenance training and provide concise manuals that are reviewed during the training. Since many microgrids provide emissions-reduction benefits, a user interface that logs and shows performance data, such as solar power generation, might be desired. An interface could be added to an existing website for public access and education. Service contracts from the microgrid contractor should extend a year or more to cover unexpected problems. And, finally, the addition of significant electrical loads or DERs to any existing microgrid system needs to be evaluated prior to installation to ensure that the switchgear and other attributes of the microgrid will continue to function as designed.

LESSONS LEARNED

- ✓ Microgrids can provide a key capability toward resilient operations of critical port functions and assets.
- ✓ Microgrids may not be cost-effective from a power backup capability. Additional revenue streams from grid services or other metrics, such as resiliency and energy independence, may provide the additional benefits to justify the deployment.
- ✓ Loads on the system may have significant inrush or startup current needs. Generation sources in the microgrid must be able to support the momentary large current or additional equipment at the load side may need to be deployed to mitigate the spike in current (e.g., motor soft start).
- ✓ Deployment of microgrids as part of new construction (greenfield) can help avoid any unexpected hurdles of retrofitting an existing system, such as triggering building code updates and abatement of hazardous materials in the older construction.
- ✓ Networking microgrids or connecting more assets can provide greater operational flexibility but may incur additional regulation and exceptions to be acquired.
- ✓ Renewable generation sources can often meet other goals of port electrification (emissions reduction, energy independence) but may require more physical space than the port has available to be of sufficient size.
- ✓ Engaging the utility, fire and building inspectors, and other AHJs early is recommended, since they may have additional requirements.
- ✓ Maintenance, training, and periodic testing should be included in the cost-benefit analysis, as well as any operational guidelines, to ensure a full picture of the microgrid is considered at all stages of the deployment.

PROJECT CONSIDERATIONS

Potential Planning Steps:

- Catalog the loads and operations that require backup power to maintain port operations.
- Assess and promote the benefits the port microgrid can provide during “blue sky” operations such as additional renewable power availability and potential cost savings.
- Examine if any initiatives, environmental grants, or legislative mandates exist for microgrids or different types of generation sources to determine additional restrictions and potential funding sources.
- Engage the local utility to determine what restrictions may be present on interconnecting the microgrid assets, operating them, and how power transfers may be restricted.
- Engage other stakeholders (e.g., local fire code, utility commissions or municipal boards, port tenants) to determine any restrictions or considerations there may be for deploying a microgrid at the desired site.
- Evaluate what generation sources make sense for the power and energy requirements, as well as the space constraints, other goals of the port, and different operating scenarios of the equipment.
- Evaluate where control will reside and any cybersecurity aspects required by various stakeholders.

Potential Implementation Steps:

- Assemble the project team, likely to include sustainability, maintenance, operations, legal staff, and external collaborators like a utility representative, fire inspection, and environmental assessment office.
- Develop scope, schedule, budget accounting for funding requirements, equipment availability, utility timelines, and required stakeholder coordination.
- Determine any fuel requirements (e.g., diesel, biodiesel, hydrogen), including storage and resupply contracts during outages.
- Evaluate if other electrical upgrades can benefit from the process, such as leveraging forced outages.
- Work with provider(s) to order and deliver equipment and associated charging infrastructure.
- Plan for equipment commissioning to minimize disruptions and establish a backup plan.
- Work with relevant labor organization or operations management to ensure workers are prepared to operate new equipment, if necessary.

Potential Iteration Steps:

- Evaluate performance of equipment, including improved uptime for operations, emissions impacts, outage or large infrastructure costs deferred, efficiency impacts, and other lessons learned.
- Solicit feedback from stakeholders, which may include internal colleagues, electric utility, or labor organizations.
- Communicate outcomes, especially related to ability to maintain operations during outages.
- Evaluate feasibility of extending the “fenceline” of the microgrid, or networking with adjacent microgrids, for increased operational flexibility and resiliency.

CASE STUDY: ELECTRIC CARGO HANDLING EQUIPMENT

INTRODUCTION

Ports nationwide are electrifying various types of CHE to reduce the environmental impact of their ongoing activities. A single port may maintain several hundred pieces of CHE with varying operational demands and shift schedules, so there is no one-size-fits-all approach to guide ports in this transition. This case study examines the deployment of one type of ECHE, electric/electrified ERTG cranes, to handle international container cargo. This is because the use cases, operational demands, and load profiles can vary greatly across different ECHE types. This case study is based loosely on the experience of the Georgia Ports Authority (GPA), an operational port and early adopter of electric CHE. GPA has 40 ERTGs in their current fleet spread across multiple locations, including the Northwest Georgia Regional Port and Port of Savannah.

Figure 25. One of GPA's ERTGs in operation. Photo credit: Georgia Ports Authority.

OVERVIEW

Rubber-tired gantry (RTG) cranes move and stack cargo containers on a port terminal. They are traditionally diesel-powered, but electric and hybrid technologies are now also available, and hydrogen options are coming to market. Ports may require a mixture of electric and hybrid (and potentially in the future hydrogen) RTGs to decarbonize operations. The electric options can be powered by direct connection to the grid via a cable reel or through a bus bar, which powers the equipment when in contact with the bus bar. The cable reel ERTG strengths include its simplicity and reliability in power supply. The bus bar ERTGs introduce a higher level of complexity and opportunity for human and equipment error related to establishing and/or reestablishing a charging connection.

Today's ERTGs are best suited for operations in a limited area to maintain connection with their electric power supply. Early-stage planning should catalogue the existing RTG fleet operations and identify where ERTGs could be implemented, which may include only a portion of sites. Where ERTGs are not operationally feasible due to traveling requirements, ports may elect hybrid alternatives that provide emissions and fuel savings benefits. Early-stage planning should also integrate load forecasting information and an electrical service assessment to identify necessary electrical upgrades to support desired equipment. Utility coordination in this process is critical, as electrical service availability, costs, and utility construction timelines can create significant, and sometimes insurmountable, barriers to desired deployments. Additionally, ongoing utility coordination can lead to opportunities for increased efficiencies and cost savings, particularly by combing upgrades needed for multiple projects into one utility coordination effort.

Once the desired number and type of ERTGs are identified, equipment providers can give estimates for use in capital planning and grant applications. Some ports may be able to pay for their own equipment, justifying the investment with cost-benefit analysis. Though ERTGs are more expensive upfront than their diesel counterparts, cost savings may be generated due to increased reliability (primarily with the cable reel option), regenerative energy technology, and reduced maintenance and energy costs. Though more difficult to calculate, there is also potential savings from avoided future fuel spills. Ports may also cover project costs through cost share with tenants and/or applying for grant funding. Funding opportunities have varying requirements related to equipment scrappage, ownership, and manufacturing (e.g., Build America, Buy America Act) that are important to account for during project planning and when reviewing equipment options.

After equipment is ordered and delivered, the commissioning process begins. It is beneficial to have a clear checklist and backup plan during this phase, which may last from a few days to a few months. Ideally, commissioning can coincide with off-peak operations to minimize disruptions. Equipment providers should include clear handoff documentation that, among other things, highlights any training requirements for equipment operators, maintenance procedures, and warranty information.

LESSONS LEARNED

- ✓ Today's ERTGs are best suited for operating in a limited area where they can maintain connection with their power supply. The bus bar charging configuration introduces increased equipment complexity and opportunity for error compared to the cable reel configuration.
- ✓ Invest in the planning phase to set a strong foundation and direction for the project.
- ✓ Coordinate with the electric utility closely and as early as possible. Utility upgrades to support electrification can quickly become the largest project cost and create delays.
- ✓ Work with the utility and equipment provider to understand and prepare to support the unique ERTG load profile, including energy generated from lowering loads.

- ✓ The business case for ECHE is strongest when replacing equipment at the end of its lifespan. Therefore, it is helpful to have an accurate inventory of existing equipment and to plan for electric alternatives when existing equipment reaches end-of-life.
- ✓ ERTGs, when deployed in the correct operational environment, offer strong benefits including emissions reductions, increased reliability, and operational cost savings.

PROJECT CONSIDERATIONS

Potential Planning Steps:

- Catalogue existing infrastructure and available alternatives. Consider cost, availability, charging requirements, operational requirements, and emissions impacts.
- Discuss options and coordinate with stakeholders, which may include tenants, the electric utility, and labor organizations.
- Identify and plan for upcoming equipment replacement needs.
- Develop a load forecast for desired new equipment.
- Assess electrical availability and determine need for additional service or infrastructure.
- Work with utility to estimate timeline and costs for any required upgrades.

Potential Implementation Steps:

- Assemble project team, likely to include sustainability, maintenance, operations, legal staff, and external collaborators (e.g., electric utility contact).
- Develop scope, schedule, budget accounting for funding requirements, equipment availability, utility timelines, and required stakeholder coordination.
- Coordinate with and leverage other related projects underway.
- Work with provider(s) to order and deliver equipment and associated charging infrastructure.
- Plan for equipment commissioning to minimize disruptions and establish a backup plan.
- Work with labor organization to ensure workers are prepared to operate new equipment, if necessary.

Potential Iteration Steps:

- Evaluate performance of equipment, including emissions benefits, cost savings, efficiency impacts, and other lessons learned.
- Solicit feedback from stakeholders, which may include internal colleagues, electric utility, or labor organizations.
- Communicate outcomes.
- Coordinate with tenants on future tenant adoption planning (if a landlord port).
- Select next steps and identify potential future projects.

CONCLUSION

U.S. ports are essential national infrastructure and ensuring their sustainable operations is of the upmost importance to global trade and national security. Electrifying port operations is a leading solution to reduce the harmful environmental and human health impacts of fossil-fueled port operations; many electrification technologies are commercially available today. Furthermore, when integrating energy storage, such as with a port microgrid, electrification can offer added benefits, including energy independence and increased resiliency of critical port operations. This handbook was developed as a guide and reference to aid ports and other stakeholders in their electrification journeys. It is available as a stand-alone document and also will be included as a resource in the online Port Decarbonization and Electrification Toolkit, an effort led by Sandia (expected in the fall of 2025).

Port electrification is a complex multi-stakeholder effort that requires significant planning and coordination. Arguably the most notable stakeholder is the electric utility, which can provide power to new electric loads pending electrical availability and project timelines. Other important stakeholders include tenants, customers, employees and contractors, community organizations, labor representatives, and equipment providers. Ports can also benefit from regional collaboration on electrification planning as ports within a region often have similar needs and can join forces to more effectively advance common goals.

The maritime sector is experiencing an unprecedented demand from international, national, and sometimes regional forces to transition toward cleaner energy sources, including electricity. This demand is coupled with an influx of funding, largely from federal sources, that will support port energy transition activities and infrastructure buildout. Though the road ahead is largely unpaved, there is an increasing library of lessons learned from the implementation efforts of industry leaders and resources, such as this handbook, that help guide port efforts. Port electrification, when planned carefully with relevant stakeholders, can facilitate port energy transitions and strengthen the resiliency of the nation’s critical infrastructure while advancing environmental justice.

Photo credit: Port of Anacortes.

APPENDIX A – PORT ELECTRIFICATION RESOURCES

Name	Link	Author	Topic Area	Type
Cargo Handling Equipment at Ports	https://www.anl.gov/sites/www/files/2022-03/Cargo%20Handling%20Equipment%20At%20Ports%20FINAL%203-23-22b%5B75%5D.pdf	ANL	CHE	Report
Cyber Framework	https://www.nist.gov/cyberframework	NIST	Cybersecurity	Website
Cybersecurity Resource and Reference Guide	https://dodcio.defense.gov/Portals/0/Documents/Library/CSResourceReferenceGuide.pdf	DOD	Cybersecurity	Report
Cybersecurity Best Practices	https://www.cisa.gov/topics/cybersecurity-best-practices	CISA	Cybersecurity	Website
PVWatts® Calculator	https://pvwatts.nrel.gov/	NREL	DERs	Online Tool
Marine Energy Atlas	https://maps.nrel.gov/marine-energy-atlas/	NREL	DERs	Online Tool
Portal and Repository for Information on Marine Renewable Energy	https://openei.org/wiki/PRIMRE/About	DOE-WPTO, PNNL, NREL, Sandia	DERs	Website
Asset Score	https://buildingenergyscore.energy.gov/	PNNL	Energy Efficiency	Online Tool
Vehicle Cost Calculator	https://afdc.energy.gov/calc/	DOE – AFDC	EVs & Charging	Online Tool
Vehicle Search	https://afdc.energy.gov/vehicles/search	DOE – AFDC	EVs & Charging	Online Tool
Alternative Fuels Data Center	https://afdc.energy.gov/	DOE – AFDC	EVs & Charging	Website
Sustainable Fleet Plan	https://www.portseattle.org/sites/default/files/2021-10/Port_SustainbleFleet_2021_3.pdf	Port of Seattle	EVs & Charging	Report
Caldera	https://inl.gov/document/electric-vehicle-charging-simulation-platform/	INL	EVs & Charging	Downloadable Tool
Microgrid Design Toolkit	https://energy.sandia.gov/news/download-sandias-microgrid-design-toolkit-mdt/	Sandia	Microgrids	Report
The U.S. Department of Energy's Microgrid Initiative	http://dx.doi.org/10.1016/j.tej.2012.09.013 or https://www.energy.gov/sites/prod/files/2016/06/f32/The%20US%20Department%20of%20Energy%27s%20Microgrid%20Initiative.pdf	DOE	Microgrids	Publication
Sea Level Rise Viewer	https://coast.noaa.gov/digitalcoast/tools/slr.html	NOAA	Planning	Online Tool
Pathways to Net-Zero 2050 in the North American Marine Shipping Industry: Fuel and Propulsion Systems	https://www.bluesky-maritime.org/pathways-to-net-zero-2050-in-the-north-american-marine-shipping-industry	Blue Sky Maritime Center	Planning	Report
Greenhouse Gas Equivalencies Calculator	https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator	EPA	Planning	Online Tool
Creating a Community and Stakeholder Engagement Plan	https://www.energy.gov/sites/default/files/2022-08/Creating%20a%20Community%20and%20Stakeholder%20Engagement%20Plan_8.2.22.pdf	DOE – FECM	Planning	Report

Name	Link	Author	Topic Area	Type
Guidebook on Resilient Maritime Logistics	https://www.google.com/search?q=Guidebook+on+Resilient+Maritime+Logistics&rlz=1C5CHFA_enUS1067US1067&oq=Guidebook+on+Resilient+Maritime+Logistics+&gs_lcrp=EgZjaHJvbWUyBggAEEUYOTIHCAEQIRigAdIBCDMxMzNqMGo0qAIAsAIA&sourceid=chrome&ie=UTF-8	UNCTAD	Planning	Report
U.S. National Blueprint for Transportation Decarbonization	https://www.energy.gov/eere/us-national-blueprint-transportation-decarbonization-joint-strategy-transform-transportation	DOE	Planning	Report
Practical Pathways for Port Decarbonization and Environmental Justice	https://www.edf.org/sites/default/files/documents/2024-EDF_Port_Decarb_EJ_Report_0.pdf	Environmental Defense Fund	Planning	Report
Port Emissions Inventory Guidance	https://www.epa.gov/state-and-local-transportation/port-emissions-inventory-guidance#:~:text=The%20Port%20Emissions%20Inventory%20Guidance,to%20prepare%20mobile%20source%20emission	EPA	Planning	Multiple
Energy Storage Evaluation Tool	https://eset.pnnl.gov/	PNNL	TEA	Online Tool
System Advisor Model	https://sam.nrel.gov/	NREL	TEA	Downloadable Tool
Renewable Energy Integration & Optimization (REopt®) Lite	https://reopt.nrel.gov/tool	NREL	TEA	Online Tool
Distributed Energy Resources Customer Adoption Model	https://gridintegration.lbl.gov/der-cam	Berkeley Lab	TEA	Downloadable Tool
Shore Power Technology Assessment at U.S. Ports	https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1016C86.pdf	EPA	Vessel Shore Power	Report
Shore Power Emissions Calculator	https://www.epa.gov/ports-initiative/shore-power-technology-assessment-us-ports#:~:text=Shore%20Power%20Emissions%20Calculator%20(SPEC)%20Ver.2023%20(xlsx)	EPA	Vessel Shore Power	Downloadable Tool

Photo credit: Port of Seattle.

APPENDIX B – WORKSHOP SUMMARY

BACKGROUND

The Port Electrification Handbook (PEH) Workshop was hosted on February 1, 2024, in Seattle, Washington. The goal of the workshop was to create a vibrant dialogue that captures opportunities and challenges facing ports nationwide related to port electrification, as well as to get feedback from participants on the value of integrating certain topics and toolsets within a PEH, a project led by Pacific Northwest National Laboratory (PNNL) and sponsored by the United States (U.S.) Department of Energy (DOE)'s Office of Electricity. The day included a combination of presentations and breakout sessions to foster dialogue, help build connections across related projects, and discuss lessons learned from port experts.

Washington Maritime Blue hosted the PEH Workshop at their headquarters in Fisherman's Terminal. Green Marine and Sandia National Laboratories (Sandia) provided facilitation support as collaborators on the PEH. Port participants were selected to represent a diversity of perspectives, including different regions, sizes, and operational focuses. Representative from eight ports attended the workshop.

WORKSHOP ATTENDEES

PNNL (Project Leader), Washington Maritime Blue (Workshop Lead & Facilitator), Green Marine, Sandia, Northwest Seaport Alliance, Port of Anacortes, Port of Bellingham, Port of Detroit, Port of Long Beach, Port of Los Angeles, Port of Olympia, and Port of Seattle.

AGENDA

9:00–9:30	Welcome, Opening Remarks, and Introductions
9:30–10:30	Port Electrification Handbook Overview & Current Draft
10:40–12:00	Breakout Session 1, Port Electrification Challenges & Opportunities
12:10–12:40	Working Lunch/Technoeconomic Analysis Overview
12:40–1:25	Port Electrification Case Studies
1:35–2:50	Breakout Session 2, Port Electrification Step by Step
2:50–3:00	Next Steps, Closing Thoughts
3:00–5:00	OPTIONAL Port of Seattle/NWSA/SSA Marine Terminal Tour

BREAKOUT SESSION 1 – KEY TAKEAWAYS

In Breakout Session 1, attendees divided into three groups and discussed opportunities and challenges related to implementing Electric Vehicles, Cargo Handling Equipment, and Vessel Shore Power at ports via rotating breakout rooms.

Electric Vehicles: All ports were considering vehicle electrification, most focusing on internal fleets first, such as security and personnel vehicles. This is because light-duty electric vehicles (EVs) are more ubiquitous and cost-effective than medium- and heavy-duty EVs in today's market. Additionally, ports typically own and manage their light-duty fleets, which makes them easier to electrify compared to drayage trucks, for example, which are owned by independent trucking companies. Some ports were considering electrified rail (e.g., switch locomotives), ground transportation between port facilities (e.g., shuttles), supporting electric rideshare providers, supporting vehicle electrification for port tenants, and electric harbor craft. There was some concern with the performance of EVs, particularly in colder weather, with discussions on consideration for hydrogen fuel cells as an alternative with superior cold weather performance. To plan for electrification, ports were considering where and how to charge electric fleets, most preferring to charge at night and between shifts to minimize impacts on port operations. Many ports had installed charging infrastructure and preferred to install Level 2 (AC) chargers for light-duty fleet vehicles, provided charging speeds would meet operational requirements. Some were looking into mobile charging and managed charging solutions, including software solutions and battery-to-battery charging. Many expressed interest in vehicle-to-grid solutions that could provide backup power supply during an unexpected outage or help with demand charge mitigation.

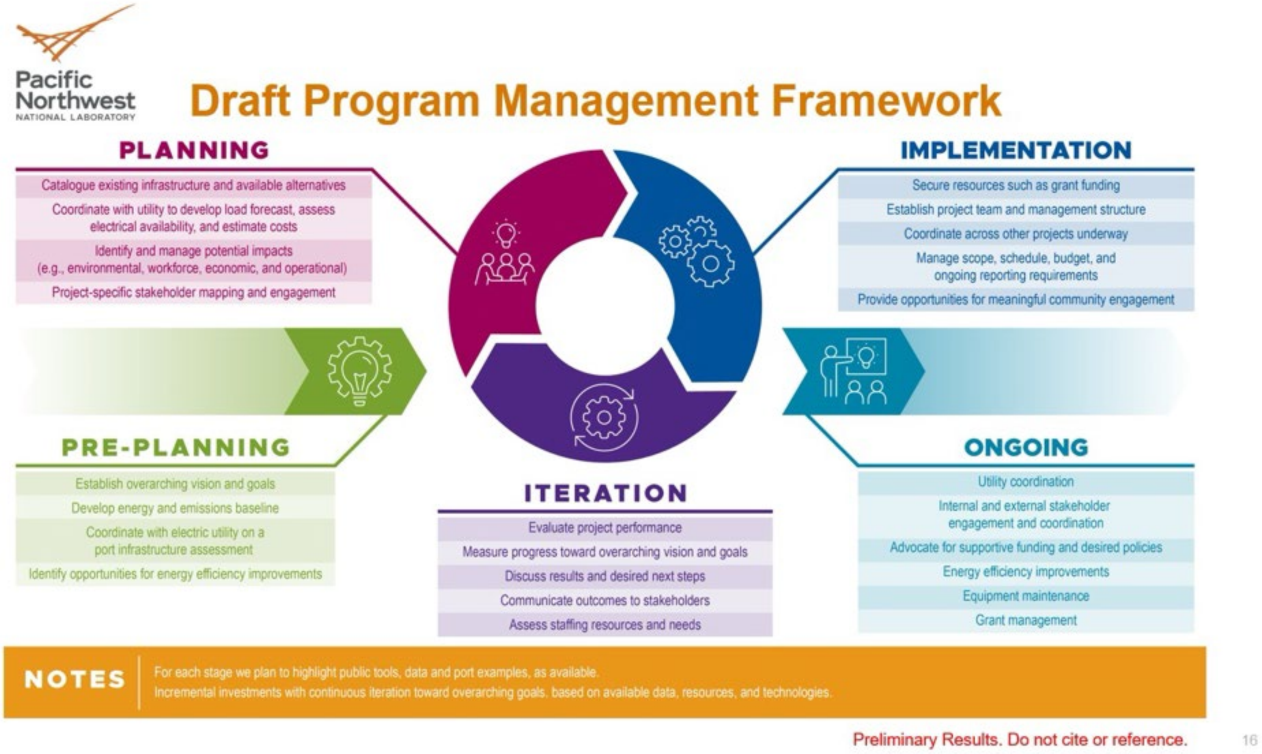
Cargo Handling Equipment: Each port has unique operations and associated equipment needs, and the process and technologies for electrifying cargo handling equipment (CHE) vary widely across ports. Electric CHE (ECHE) could include berth cranes, rubber-tired gantry cranes, forklifts, top handlers, reach stackers, and terminal tractors with smaller equipment generally being easier to electrify. Larger equipment with higher operational demands may be more effectively powered by hydrogen fuel cells compared to batteries. In some cases, ECHE can be connected directly to the electrical grid. Ports noted challenges related to equipment availability, cost, and reliability. Because the cost of ECHE is much higher compared to traditional fossil-fueled equipment, ports noted that regulation and/or incentives may be necessary to accelerate desired equipment switching, particularly by port tenants. Another challenge is that electrification of CHE can be linked to automation, and some stakeholders, including labor unions, are concerned about implementing new technologies that could have workforce impacts. CHE may be owned by ports, individual tenants, or shared between the port and its tenants, adding additional challenges to financing CHE electrification, as well as ownership of the emissions from fossil-fueled equipment. The business case for electrification is strongest when replacing equipment at the end of its lifespan. Therefore, ports discussed the value in inventorying existing equipment regularly and planning for electric alternatives when existing equipment reaches end-of-life.

Vessel Shore Power: Ports are deploying vessel shore power projects of different scales to serve harbor craft, cruise, and cargo vessels. Multiple participants emphasized that regulation and/or incentives help make the business case for shore power and are necessary to accelerate its adoption. A key challenge with shore power is standardization. There are electrical standards for some container and cruise vessels but not all vessel types. Furthermore, plug-in port locations vary across vessels, which makes it challenging to accommodate multiple vessels at one shore power location. There are some mobile shore power solutions that begin to address this challenge. It is easier for ports who frequently accommodate the same vessels to coordinate with their customers and invest in shore power installations. Shore power installations often cost multiple millions of dollars and there is some concern about future stranded assets, particularly if vessels are eventually powered by cleaner alternative fuels and no longer need shore power to reduce their emissions while at berth. Shore power installations are dependent on electrical service availability and require ongoing coordination with the utility. Ports noted that it can be helpful to “think outside the box” when designing shore power solutions, particularly when facing electric infrastructure or geographical constraints and when planning how to accommodate shore power loads.

Note: <u>Electrification of rail infrastructure</u> was highlighted as a gap that should be further addressed in the PEH. Some ports are beginning to pilot electric switcher locomotives, but overall electric rail technologies are not well-demonstrated or widely commercially available in the U.S. Hydrogen and other clean alternative fuels may be better suited to decarbonize some rail applications. Decarbonizing rail activities at ports must be done in coordination with railroad companies.

BREAKOUT SESSION 2 – KEY TAKEAWAYS

In Breakout Session 2, attendees divided into three groups and discussed a draft port electrification process diagram. Participants were encouraged to think through an example port electrification project to provide feedback on where the diagram was helpful and where it could benefit from adjustment. An updated draft version of the diagram, integrating some feedback from participants but not the final version, is included below (**Figure B.1**). A final updated version will be released in the PEH.



Pacific Northwest
NATIONAL LABORATORY

Draft Program Management Framework

PLANNING
- Catalogue existing infrastructure and available alternatives
- Coordinate with utility to develop load forecast, assess electrical availability, and estimate costs
- Identify and manage potential impacts (e.g., environmental, workforce, economic, and operational)
- Project-specific stakeholder mapping and engagement

IMPLEMENTATION
- Secure resources such as grant funding
- Establish project team and management structure
- Coordinate across other projects underway
- Manage scope, schedule, budget, and ongoing reporting requirements
- Provide opportunities for meaningful community engagement

PRE-PLANNING
- Establish overarching vision and goals
- Develop energy and emissions baseline
- Coordinate with electric utility on a port infrastructure assessment
- Identify opportunities for energy efficiency improvements

ITERATION
- Evaluate project performance
- Measure progress toward overarching vision and goals
- Discuss results and desired next steps
- Communicate outcomes to stakeholders
- Assess staffing resources and needs

ONGOING
- Utility coordination
- Internal and external stakeholder engagement and coordination
- Advocate for supportive funding and desired policies
- Energy efficiency improvements
- Equipment maintenance
- Grant management

NOTES For each stage we plan to highlight public tools, data and port examples, as available.
Incremental investments with continuous iteration toward overarching goals, based on available data, resources, and technologies.

Preliminary Results. Do not cite or reference. 16

Figure B.1. Draft Program Management Framework for port electrification. This example was provided to workshop participants to prompt discussion and feedback during Breakout Session 2.

We heard the following from participants during Breakout Session 2:

- The Framework is likely most useful to ports in earlier stages of electrification program design. Ports who are further along have thought through many of these elements and may require a higher level of detail. This framework may not be as useful to them.
- Securing funding to support electrification projects happens at every stage of the process. Identifying, applying for, managing, and reporting on grants requires significant staff time.
- Port electrification is not a one-way process flow. Though logically certain items would happen in sequence, the process is often adjusted to account for grant requirements, council member requests, technology availability, etc. It may be more helpful to frame the process as a checklist that walks ports through key topic areas for program or project planning.
- Utility coordination is critical at all parts of the electrification process. Ports recommended including guidance on establishing a relationship with the electric utility company, which can help define electrification timelines, identify opportunities for cost sharing, and compare costs of traditional infrastructure to non-traditional infrastructure (e.g., port microgrid).
- Staffing requirements must be accounted for in electrification planning and are significant. Ports may train existing staff to take on new responsibilities though large projects will likely require onboarding new staff. This could include grant staff, management staff, and maintenance staff.

ADDITIONAL KEY TAKEAWAYS

- **Define terminology.** Some terms have different meanings to different audiences and should be defined in the context of the PEH. An example was provided around the term “resilience,” which could define the electrical grid’s ability to withstand disruptions, but also could describe a port’s ability to withstand to climate change impacts, such as sea level rise.
- **Provide port tool(s).** Ports were interested in analysis tools, from reputable government sources such as a national laboratory, that they could use to support their investments and better communicate potential impacts.
  - Specifically, ports requested a Life-Cycle Analysis tool and Cost-Benefit Analysis tool related to port electrification.
  - When given an option between a website tool, Excel tool, or command line programming tool, most ports preferred an Excel tool containing a simplified user interface and supportive data in the spreadsheet.
  - Ports suggested designing tool calculations and outputs to align with inputs requested by the Environmental Protection Agency (EPA) and Maritime Administration (MARAD) in grant applications (e.g., estimated greenhouse has reduction potential).
- **Address a challenging port electrification landscape.** Despite growing interest and funding support, electrifying port operations remains challenging for a variety of reasons.
  - **Equipment availability.** Not all equipment has an electric alternative in today’s market. Even if a piece of equipment is available, it may not meet grant requirements, such as Build America Buy America, or be UL listed.
  - **Equipment costs.** Electric equipment can be over twice as expensive as traditional fossil-fueled equipment. One example was given of a Top Pick, which is typically about $800 K. An electric Top Pick with charging would be about $1.7 M and a hydrogen Top Pick could

be over $2 M. It is difficult to impossible to make the business case for added cost of this magnitude and costs must decline for electric equipment adoption to accelerate.

  - **Operational requirements.** Even if electric equipment is available, it is not always a one-to-one replacement for fossil-fueled equipment. This could be due to charging requirements, battery lifespan, or operational power demands. Having reliable equipment is of upmost importance to ports in order to avoid operational interruptions and associated costs.

  - **Electrical infrastructure requirements.** Port electrification generates new electric loads that often require utility infrastructure upgrades and associated permitting. While the equipment is expensive, the electrical infrastructure to support it can be the most expensive and unpredictable project cost. Permitting processes can also be unclear and cause unexpected delays. Furthermore, some grants will not cover electrical infrastructure upgrade costs. Some funders score grant applications on emissions reduction potentials, which incentivizes applications with more equipment costs and fewer infrastructure costs.

- **Coordinate with other agencies.** There are multiple coordinating organizations (e.g., public port authority associations) and federal agencies (e.g., EPA, MARAD) working to advance port electrification. Coordinating with them will help ensure the PEH provides the most relevant information and that it can be shared via channels that ports typically follow. Ideally, the PEH can be a tool to inform future anticipated grant applications, such as applications for the EPA Clean Ports Program.

- **Describe how electrification fits within the broader decarbonization landscape.** Ports described electrification as a leading decarbonization solution, but they also reported considering hydrogen, biofuels, renewable fuels, and e-fuels. Multiple factors, including electricity availability, electricity cost, and equipment operational requirements, will influence which decarbonization technology is best suited for a port's needs. Furthermore, the carbon intensity of electricity varies nationwide, and ports with cleaner electrical grids will capture a higher environmental benefit from electrification.

- **Emphasize the importance of community engagement.** Community engagement was highlighted throughout the workshop as an important early step in port decarbonization planning and in project implementation. Community stakeholders can influence and sometimes halt projects they do not support, or, alternatively, they can be a catalyst to push projects toward completion that they do support. Port decarbonization activity will have an impact on nearby port communities and port workers. Activities must be coordinated with these stakeholders to maximize potential benefits and help address historically inequitable impacts of port activities.

APPENDIX C – PORT ELECTRIFICATION SURVEY SUMMARY

Pacific Northwest National Laboratory (PNNL) conducted a brief, online Port Electrification Survey from October 2023 to January 2024 to collect perspectives on electrification from ports nationwide. Survey results were used to inform the overall Port Electrification Handbook (PEH), which was scheduled for release in later 2024. The survey included seven content questions that are listed for reference in the **Survey Questions** section, and the results are summarized and discussed below. Twenty respondents completed the survey, and this analysis assumes respondents represent distinct ports across the United States. However, there is no way to validate this assumption because the survey was completed anonymously.

SURVEY RESPONSES & ANALYSIS

QUESTION 1: ANNUAL CARGO VOLUME

Figure C.1 depicts the distribution of Annual Cargo Volume among survey respondents provided in survey Question 1. Respondents represent a diverse distribution of cargo volume activity, though most (40%) represent large ports that handle over one million Twenty-foot Equivalent Units (TEUs) annually. Additionally, 40% of respondents said this question was not applicable to their port, which most likely means they do not handle container cargo since the TEU metric is used to measure cargo volume at container ports.

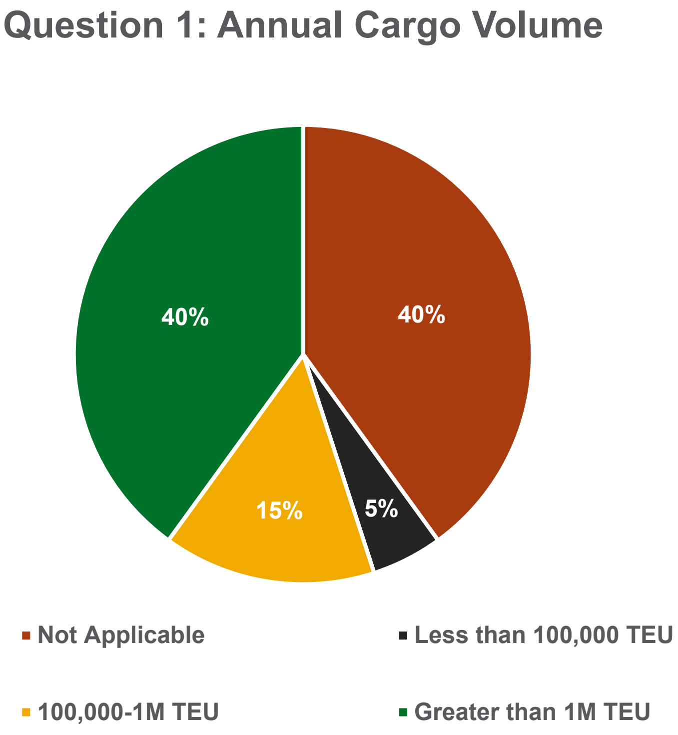


Figure C.1. Distribution of Annual Cargo Volume among survey respondents.

QUESTION 2: PRIMARY PORT ACTIVITIES

Table C.1 summarizes respondents' primary port activities provided in survey Question 2. Respondents could select multiple primary activities for their port. The most common answer was international commercial activity (85%), which could include a diverse group of imports/exports such as container cargo, bulk cargo, and roll-on/roll-off cargo. However, the survey did not evaluate the further breakdown of international commercial activity. The second most reported activity was on/near-dock railyard (60%), followed by drayage trucking (55%), domestic commercial (50%), and recreational boating (50%) activities. Cruise and bulk cargo were the least commonly reported activities at 25% and 20%, respectively. However, neither cruise or bulk cargo were originally listed as an activity option in Question 2 and were added after the fact because multiple respondents listed them through the "Other – free fill" option. This could have potentially caused these activities to be misrepresented, likely underrepresented, in the final data.

Table C.1. Primary port activities provided by respondents. Question 2 allowed respondents to select multiple primary activities for their port.

Primary Activity	Count of Responses	% of Total Respondents
Recreational boating	10	50%
Domestic commercial (e.g., fishing)	10	50%
International commercial (e.g., international cargo)	17	85%
On/near-dock railyard	12	60%
Drayage terminal	11	55%
Cruise	5	25%
Bulk cargo	4	20%

QUESTION 3: PORT ELECTRIFICATION STATUS

Figure C.2 depicts the distribution of responding ports' electrification status, ranging from early-stage information gathering to later-stage large-scale implementation. Though the options listed are not always distinct activities (e.g., ports could be information gathering while simultaneously developing an electrification strategy), they generally represent the progression of electrification activity at ports. The percentage of respondents in each category declines along the progression of activities, with the most respondents reporting to be in the "Information gathering and educational phase" (35%) and the least reporting that "Large-scale implementation is underway" (15%).

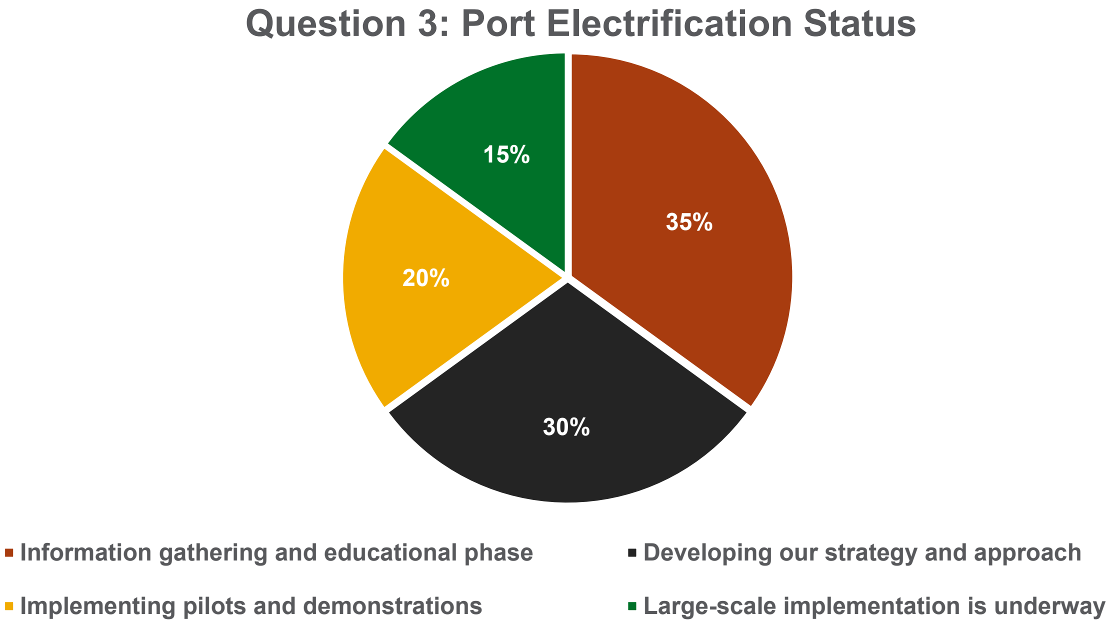


Figure C.2. Port electrification status provided by ports in survey Question 3.

QUESTION 4: INTEREST IN SELECT ELECTRIFICATION TECHNOLOGIES

The fourth survey question asked respondents to rate their interest in select electrification technologies. Options were Low, Medium, High, and No Response. Responses to survey Question 4 are depicted in **Figure C.3**.The highest reported interest was in electric vehicles (EVs) with Grid Connection (45% reported high interest), followed by Battery Energy Storage Systems and Hydrogen Generation and Storage (both with 35% reported high interested). Interest in On-site Renewables and Fossil Fuel/Biodiesel Generators was also strong, though slightly lower, with 25% reporting high interest in these technologies. Flywheel and Small Module Reactor technologies were of notably lower interest than the rest of the options, with 75% reporting low interest in both these technologies.

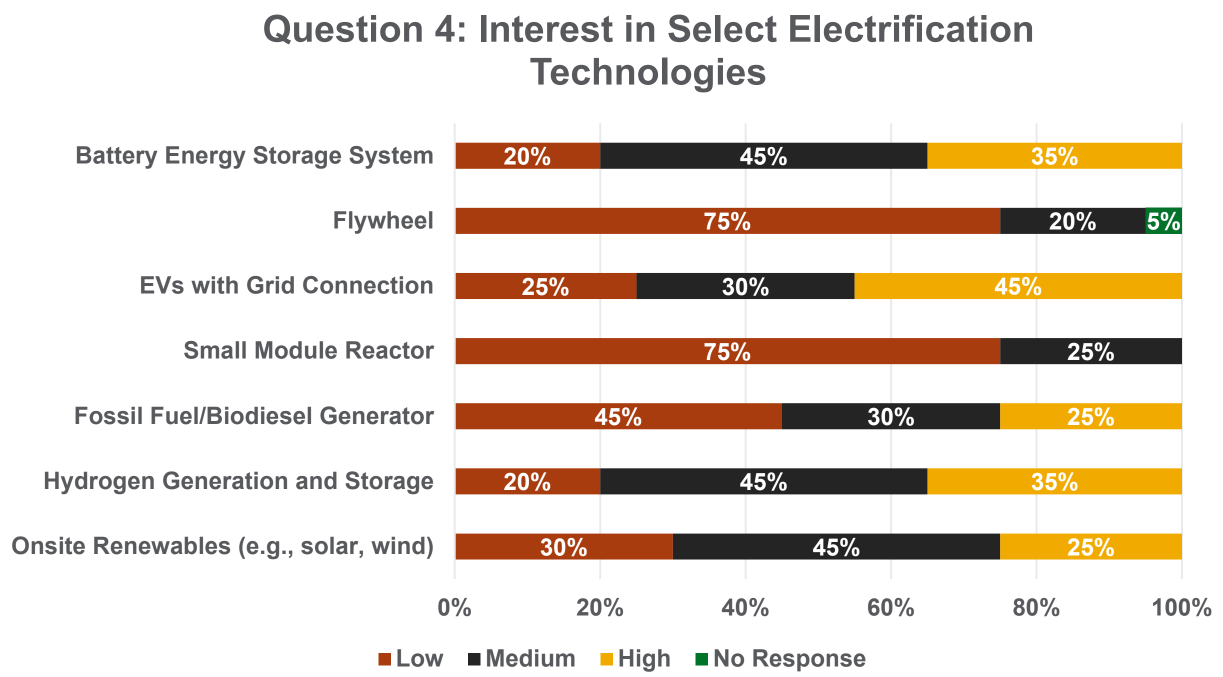


Figure C.3. Distribution of interest in select electrification technologies (ranging from Low to High) reported by respondents in survey Question 4.

Question 4 also offered an opportunity for respondents to provide other technologies of interest. Seven out of 20 respondents mentioned additional technologies or topics relevant to port electrification in this field, including the following:

- Hydrokinetic energy
- Off-site renewable electricity offsets
- Utility planning and distribution system upgrades
- Carbon capture and storage
- Thermal storage
- Load controls
- Hydrogen fuel cell equipment
- Energy efficiency
- High-efficiency heat pumps
- Smart EV charging.

QUESTION 5: ELECTRIFICATION STATUS BY POTENTIAL LOAD

Survey Question 5, depicted in **Figure C.4**, asked respondents to report their electrification status by potential load, including loads such as EV charging, vessel shore power, and cargo handling equipment. The most progress has been made in electrifying refrigerated container units (25% fully electrified), followed closely by vessel shore power and buildings (both 20% fully electrified). This progress may be driven by California’s requirements for refrigerated container units and vessel shore power that are aimed at reducing emissions. However, because the survey was completed anonymously, it is impossible to know with certainty the driving factor(s) behind the progress. Light-duty fleet electrification is currently the focus of multiple port pilots, with 55% reporting pilots underway. On the other hand, electrifying heavy-duty fleets and cargo handling equipment are under consideration for multiple ports; respondents reported 50% are strategizing around heavy-duty fleet charging and 65% are strategizing around electrifying cargo handling equipment. These responses align with what is expected given the current availability of different EV technologies. Light-duty EVs are generally widely available, while medium-/heavy-duty EVs and electric cargo handling equipment have more limited availability and much higher cost compared to their traditional fossil-fuel counterparts.

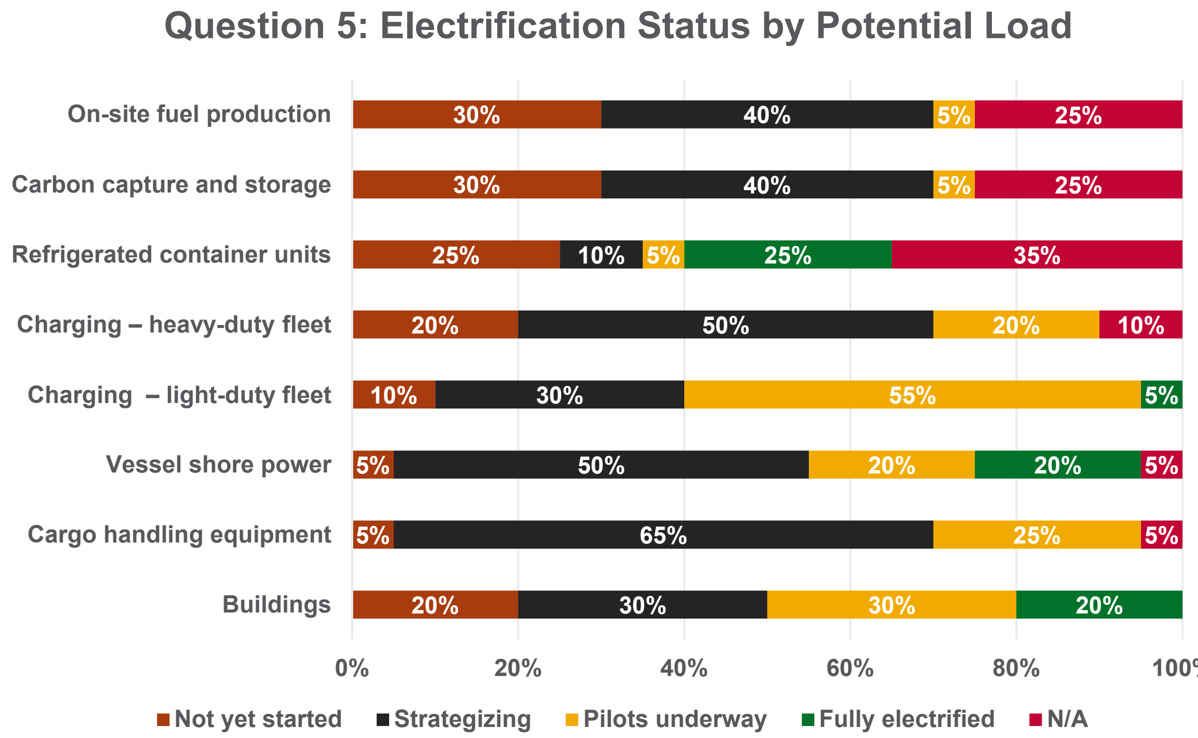


Figure C.4. Distribution of electrification status by potential electrification load for respondents.

QUESTION 6: IMPORTANCE OF ADDRESSING SELECT TOPICS IN THE PORT ELECTRIFICATION HANDBOOK

Survey Question 6 aimed to assess which broad topics related to port electrification would be most relevant to PEH readers and included options like case studies, funding opportunities, and climate benefits. Results of survey Question 6 are depicted in **Figure C.5**. Every potential topic was of high interest to 50% or more of respondents, so the PEH integrated information about all of them. Respondents reported the highest interest in funding opportunities (85% reported high interest), followed closely by utility coordination (75% reported high interest). Both **Funding Opportunities & Incentives** and **Electric Utility Coordination** are discussed thoroughly, with their own sections in the PEH.

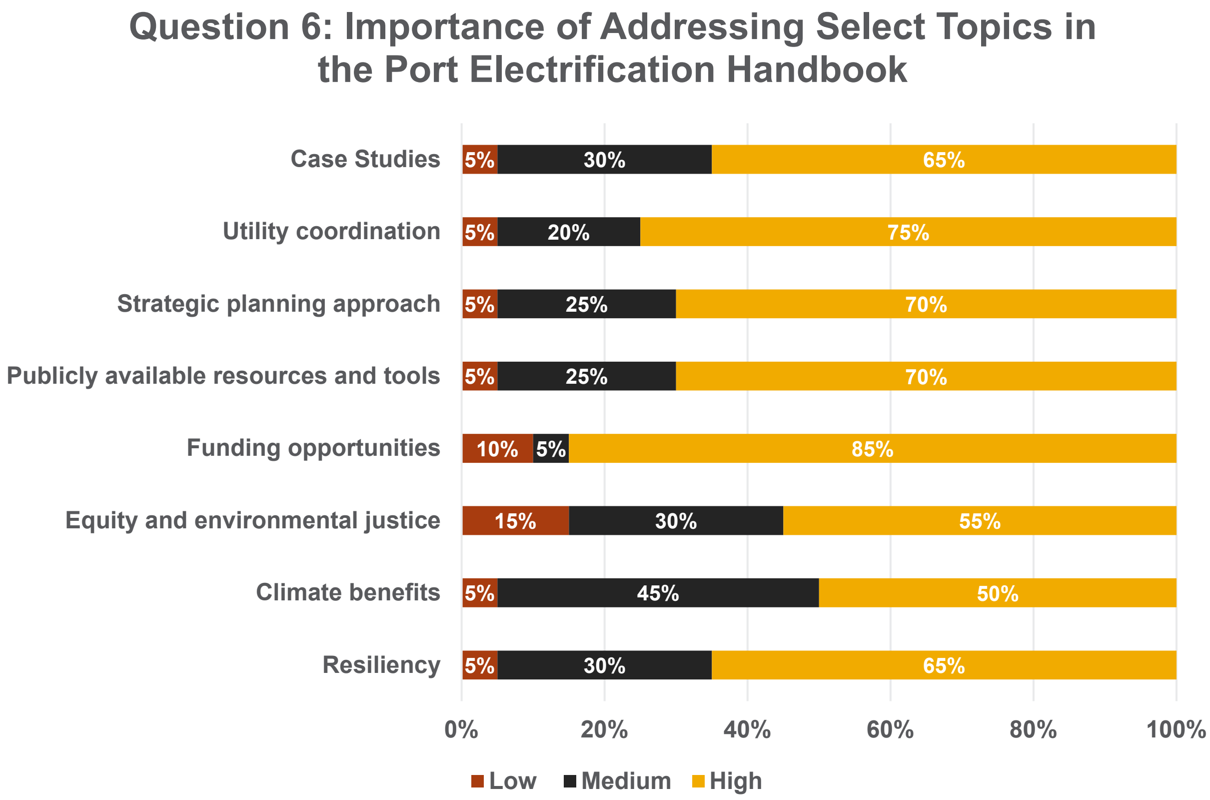


Figure C.5. Distribution of respondents' interest in select topics related to port electrification.

QUESTION 7: OTHER TOPICS FOR CONSIDERATION IN THE PEH

The final question, survey Question 7, was an open-ended opportunity for respondents to highlight other topics for consideration in the PEH. Six out of the 20 respondents provided additional suggestions, including the following topics:

- Cost-benefit analysis
- Tax credit availability
- Life cycle emissions estimates
- Tax credit availability
- Making the business case for zero emissions technologies
- Encouraging private sector participation in electrification (e.g., drayage fleets, terminal operators, tug operators, railroads)
- Adaptive management
- Avoiding stranded assets
- Information relevant for dry bulk and break-bulk cargo ports
- Footprint and space limitation for EV charging infrastructure
- Hybrid-electric equipment.

RESULTS

The survey results were useful in guiding which content to include in the handbook and where to focus limited project resources to best address port interests. Results were referenced regularly, along with outcomes of other outreach activities, including the one-on-one port and stakeholder meetings and workshop findings (see **Appendix B – Workshop Summary**). Though the survey only captures insights from 20 out of the 300+ U.S. maritime ports, the limited respondents represented diverse ports, particularly regarding port activities (Question 2) and electrification status (Question 3). Topics and technologies of high interest are thoroughly discussed within the handbook, including EVs, electric cargo handling equipment, and Battery Energy Storage Systems, among many others. The handbook also discusses how all these priority components and more can be designed into a port microgrid. The brief online survey provided valuable guidance that helps ensure the PEH is designed to address the electrification topics and challenges top-of-mind for today's ports.

SURVEY QUESTIONS

#1 – What is your organization's annual cargo volume handled?

- Less than 100,000 TEU
- 100,000–1 M TEU
- Greater than 1 M TEU
- Not Applicable

#2 – Which best describes the primary activities at your port? (check all that apply)

- Recreational boating
- Domestic commercial (e.g., fishing)
- International commercial (e.g., international cargo)
- On/near-dock railyard
- Drayage terminal
- Other – Free fill

Note: Multiple respondents added cruise activity and bulk cargo through the "Other – Free fill" option. These responses were aggregated into new categories—"Cruise" and "Bulk cargo"—for data display.

#3 – Which thought(s) best describe your organization's status related to electrification?

- Information gathering and educational phase.
- Developing our strategy and approach.
- Implementing pilots and demonstrations.
- Large-scale implementation is underway.

#4 – What is your organization's level of interest in the following technologies? (Low/Medium/High)

- On-site renewables (e.g., solar, wind)
- Hydrogen generation and storage
- Fossil fuel/biodiesel generator
- Small module reactor
- EVs with grid connection
- Flywheel
- Battery Energy Storage System

Are there additional resources your organization is planning for that are not on the above list?

#5 – Where is your organization in terms of electrifying these potential loads?

- Buildings
- Cargo handling equipment
- Vessel shore power
- Charging infrastructure – light-duty fleet
- Charging infrastructure – heavy-duty fleet (e.g., drayage)
- Refrigerated container units
- Carbon capture and storage
- On-site fuel production (e.g., hydrogen)

Are there additional loads you are planning for that are not on the above list? Free answer.

#6 – How important is it that the Port Electrification Handbook address the following topics? (Low/Medium/High)

- Resiliency
- Climate benefits
- Equity and environmental justice benefits
- Funding opportunities
- Publicly available resources and tools
- Strategic planning approach
- Utility coordination
- Case studies

#7 – Are there additional topics your organization is interested in that are not on the above list?

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