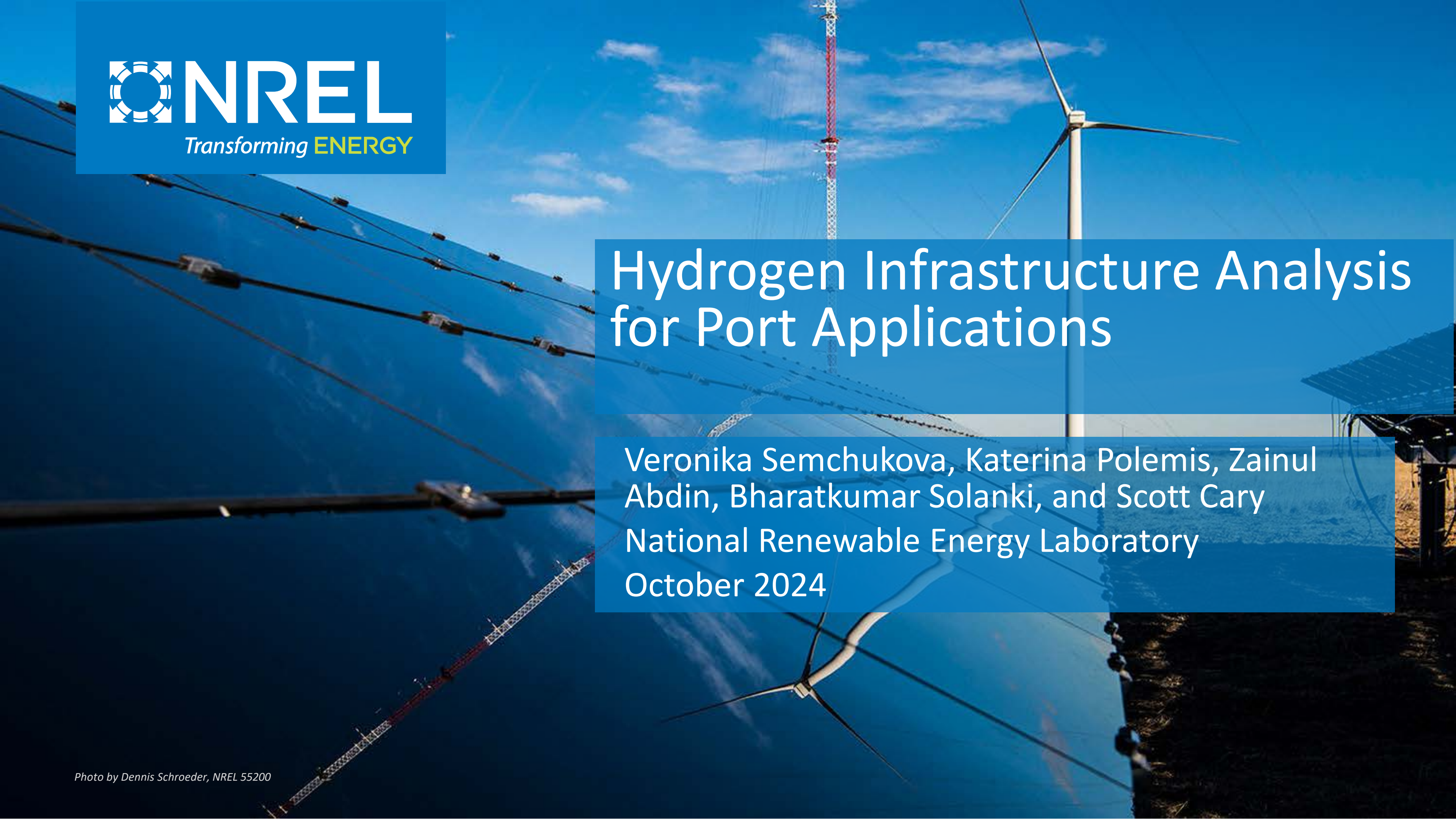

# Hydrogen Infrastructure Analysis for Port Applications


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National Renewable Energy Laboratory


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*Photo by Dennis Schroeder, NREL 55200*

# Notice

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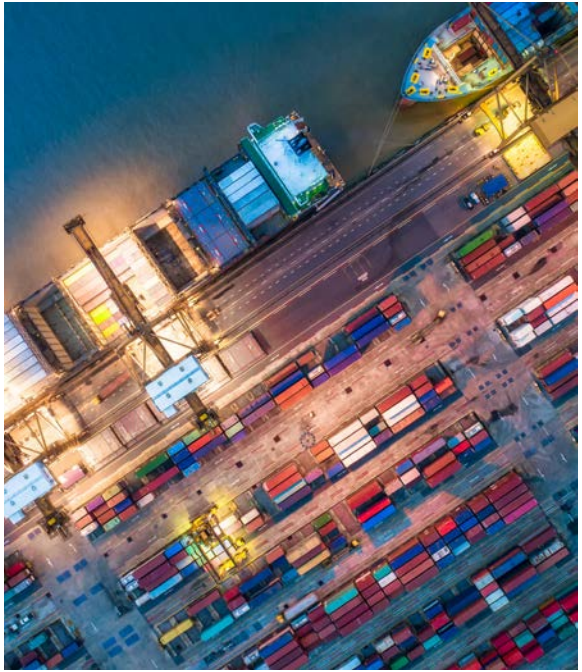
# Content

# Introduction

# Objectives

- To perform an energy analysis on the port system
- To take a holistic approach and view the port as an entire ecosystem that functions as a transportation and energy node
- To address existing data gaps by evaluating five representative port types, determining the potential for using hydrogen in each of them, and developing a comprehensive view for future analysis efforts
- To classify the ports into reference cases with scaling factors for the relative size of port operations and applications
- To provide reference port data to the U.S. Department of Energy for future use, potentially as baselines for analysis and the development of demonstration programs



*Microsoft images*

# Tasks

| Task 1: Reference ports and technology readiness of equipment | Task 2: Energy and infrastructure analysis | Task 3: Model development and validation linking equipment inventory with energy demand and capacity metrics | Task 4: Zero and near-zero emission fuel supply at ports |
|---|---|---|---|
| • Identify reference ports<br>• Access technology and commercial readiness levels of each piece of equipment for conversion to hydrogen-battery hybrids or battery electric equipment | • Expand inventory of equipment at ports to apply to reference ports<br>• Advance hydrogen integration and electrification strategies | • Develop and validate an adaptive model linking equipment inventory with energy demand and capacity metrics | • Evaluate zero and near-zero emission fuel production and bunkering (refueling of cargo vessels) at ports |

# Task 1: Reference Ports and Technology Readiness of Equipment

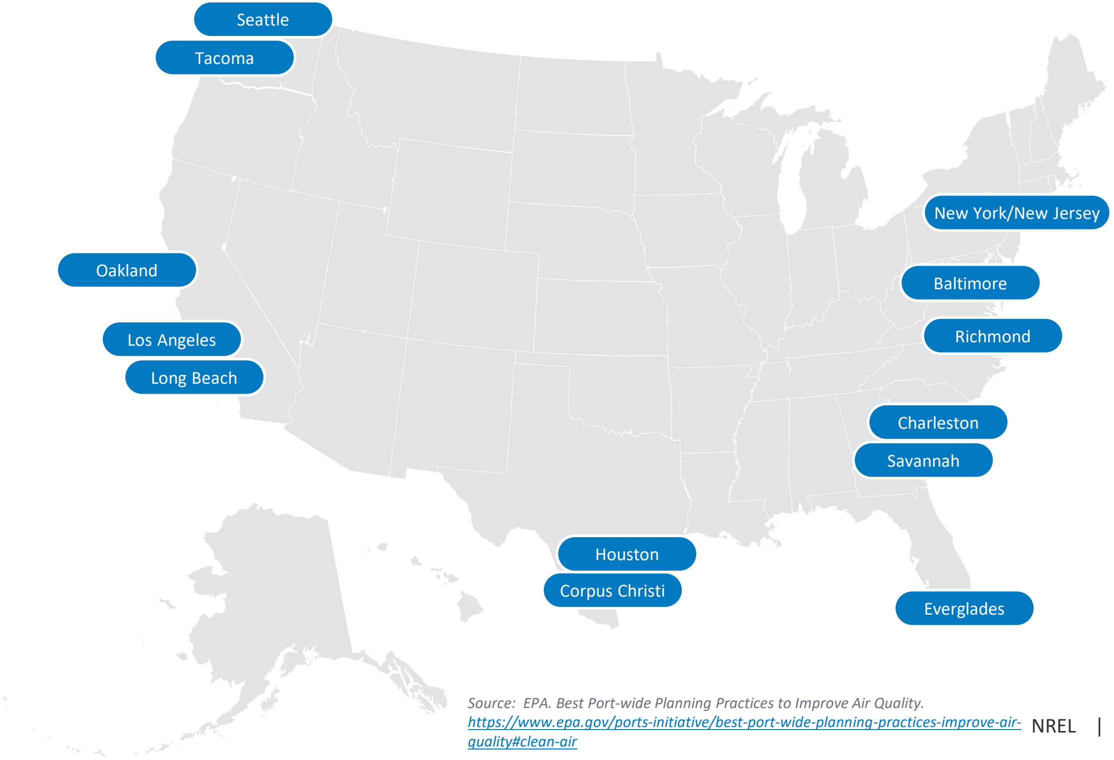
- Identify reference ports
- Access technology and commercial readiness levels of each piece of equipment for conversion to hydrogen-battery hybrids or battery electric equipment

# Selection Process

Screening criteria for identifying the reference ports:

- Recently published emissions inventory reports
- Cargo handling inventory
- Inventory of ocean-going vessels visiting the port (shore power)
- Data on cargo throughput by type

## U.S. ports with published emissions inventories




*Source: EPA. Best Port-wide Planning Practices to Improve Air Quality. https://www.epa.gov/ports-initiative/best-port-wide-planning-practices-improve-air-quality#clean-air*

# Bulk Handling Terminals

A bulk handling port specializes in efficiently managing large quantities of unpackaged, homogeneous cargo like grains and ores. These ports are equipped with specialized machinery, such as conveyor systems and bulk cargo cranes, along with streamlined processes to facilitate the rapid loading and unloading of bulk materials.

**Dry bulk**

Cargo types handled

- Major: Iron ore, coal, grain
- Other: Alumina, phosphate, fertilizers, cement, sand

Equipment used for bulk handling

- Ship loaders/unloaders
- Stacker reclaimers
- Conveyor systems
- Grain elevators
- Yard and warehouse vehicles (tractors, forklifts)
- Auxiliary services: washing, screening, blending, dust control

**Liquid bulk**

Cargo types handled

- Crude oil, oil products, liquefied natural gas, liquefied petroleum gas

Equipment used for bulk handling

- Moved mainly by pipeline connected to storage tanks or directly to petrochemical or chemical sites

Bulk handling terminal at the Port of Houston
Figure: Google Earth

*Sources: Notteboom, T., Pallis, A. and Rodrigue, J.P., 2022. Port economics, management and policy. Routledge., https://www.pfri.uniri.hr/bopri/documents/16-ME-tal_001.pdf*

# Bulk Handling Examples

| Port | Twenty-foot equivalent unit, 2022 | Cargo, metric tons, 2022 | Numbers of terminals | Terminals by cargo type | Key commodities (public and private terminals) | Percentage of CHE* emissions | Percentage of OGV* calls by type |
|---|---|---|---|---|---|---|---|
| Port Houston | 3.3 million | 47.7 million | 8 (public)<br>200 (private) | Public<br>• General cargo—3<br>• Container—2<br>• Bulk—2<br>• Multi-modal—1 | • Petrochemical exports<br>• Agricultural exports<br>• Steel products<br>• Petcoke, coal, aggregate | 11% | Public<br>29%—tanker<br>15%—bulk<br><br>Private<br>80%—tanker<br>7%—bulk |
| Port Corpus Christi | n/a | 170.5 million | 38<br>(public and private) | Public and private<br>• Liquid cargo—18<br>• Dry cargo—9<br>• Bulk materials—5 | • Crude oil, petroleum<br>• Bulk grain (Sorghum)<br>• Iron ore pellets, pet coke, hot briquetted iron, aggregate)<br>• Project cargo, steel pipe, wind turbines | 0.5% | 81%—tanker<br>10%—bulk |

*Five mobile source sectors are responsible for the total emissions at a port: cargo-handling equipment (CHE), heavy-duty vehicles, ocean-going vessels (OGV), harbor craft, and locomotives.

*Sources: Martin Associates. 2023. Economic Impact of Houston Ship Channel Activity. Starcrest Consulting Group & Kristiansson. 2021. 2019 Goods Movement Emissions Inventory, Starcrest Consulting Group. 2021. Port of Corpus Christi Authority 2020 Air Emissions Inventory. , Cargo Report by Commodity. 2022. Port of Corpus Christi.*

# Breakbulk Handling Terminals

A breakbulk handling port specializes in managing diverse cargo with varying shapes and sizes, using versatile equipment like forklifts and cranes. This ensures the effective handling and transfer of individually packed shipments.

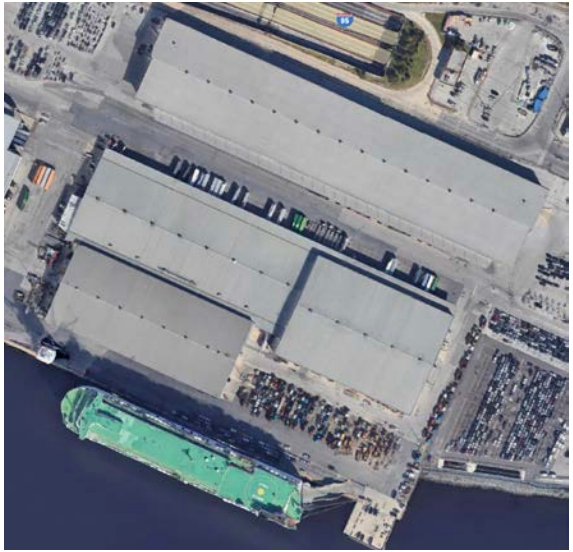
Cargo types handled

- Project cargo, heavy machinery and equipment, steel, and forest products

Equipment used for bulk handling

- Cranes: Quay, floating, level-luffing, mobile cranes, ship's cargo gear
- Forklifts
- Pallet jacks
- Top loaders

Breakbulk terminals are often configured to handle multiple categories of cargo, such as roll-on/roll-off and containers.



Breakbulk terminal at the Port of Baltimore specializing in forest products
Figure: Google Earth

*Sources: Notteboom, T., Pallis, A. and Rodrigue, J.P., 2022. Port economics, management and policy. Routledge., https://www.pfri.uniri.hr/bopri/documents/16-ME-tal_001.pdf*

# Breakbulk Handling Examples

| Port | Twenty-foot equivalent unit, 2022 | Cargo, metric tons, 2022 | Numbers of terminals | Terminals by cargo type | Key cargo | Percentage of ocean-going vessel calls by type |
|---|---|---|---|---|---|---|
| Port Charleston | 2.8 million | n/a | 6 (public)<br>14 (private) | Public<br>• Container—3<br>• Breakbulk, Ro/Ro—1<br>• Breakbulk, cruise—1<br>• General cargo—1 | • Equipment (brewery tanks, military tanks, wind turbines)<br>• Containerized (furniture sporting, machinery parts, fibers, textiles) | Public<br>75%—container<br>13%—auto carrier<br>3%—breakbulk |
| Port of Baltimore | 1.1 million | 10.9 million | 5 (public)<br>6 (private) | Public<br>• General cargo—2<br>• Container—1<br>• Ro/Ro—1<br>• Forest products—1 | • Autos, roll-on/roll-off<br>• Containers<br>• Forest products<br>• Project cargo | n/a* |

*This information is not included in the emissions report. As of 2015, general cargo calls accounted for 52% of total port calls at the Port of Baltimore.

Greenhouse gas emissions are excluded from the scope of emissions reports for both ports.

*Sources: Maryland Port Administration. 2023. General Cargo Monthly Data for the MPA's public terminals., South Carolina Ports Authority. 2023. TEU History. https://scspa.com/wp-content/uploads/teu-history.pdf, , AECOM. 2018. South Carolina Ports Authority 2017 Air Emissions Inventory, Bureau of Transportation Statistics. 2015. Top 50 U.S. Ports by Port Calls and Vessel Type.*

# Container Handling Terminals

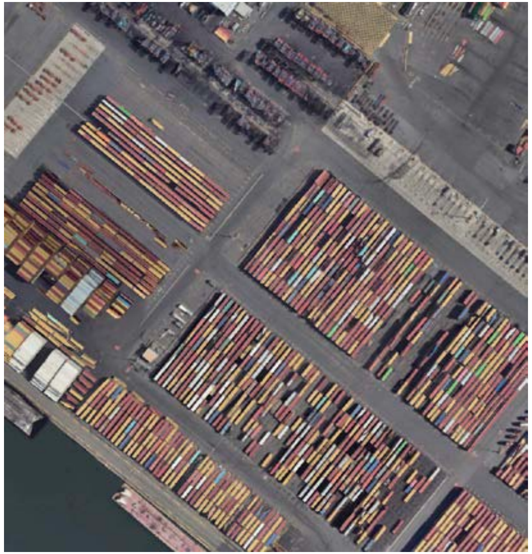
Container handling ports feature well-organized logistics systems for the seamless loading and unloading of shipping containers, using dedicated equipment such as container cranes, reach stackers, and straddle carriers. Standardized containers further enable easy integration with various transportation modes.

Types of containers

- Dry containers (20-foot, 40-foot, 40 high cube)
- Refrigerated containers
- Special dimensioned containers (open top, flat rack)

Equipment used for container handling

- Rubber-tired gantry cranes
- Yard tractors
- Straddle carriers
- Reach stackers
- Top handlers
- Forklifts



Container storage and cargo handling equipment area at the Port Newark Container Terminal within the Port of New York/New Jersey
Figure: Google Earth

*Source: Notteboom, T., Pallis, A. and Rodrigue, J.P., 2022. Port economics, management and policy. Routledge., MAERSK, A guide to shipping container sizes and types.https://www.maersk.com/logistics-explained/transportation-and-freight/2023/08/28/freight-container*

# Container Handling Examples

| Port | Twenty-foot equivalent unit, 2022 | Numbers of terminals | Terminals by cargo type | Numbers of pieces of cargo-handling equipment | Major equipment types | Percentage of cargo-handling equipment emissions | Percentage of ocean-going vessel calls by type |
|---|---|---|---|---|---|---|---|
| Port of Los Angeles | 9.9 million | 25 | • Container—7<br>• Liquid bulk—7<br>• Break bulk—4<br>• Dry bulk—3<br>• Passenger—2<br>• Auto—1<br>• Multi-use—1 | 1,915 | Yard tractors (48%) | 15% | 54%—container<br>17%—cruise<br>13%—tanker |
| Port of Long Beach | 9.1 million | 22 | • Break bulk—5<br>• Container—6<br>• Dry bulk—6<br>• Liquid bulk—5 | 1,221 | Yard tractors (44%) | 12% | 43%—container<br>21%—tanker |
| Port of New York/New Jersey | 9.5 million | 6 | All 6 are container terminals with capabilities to handle dimensional cargo, breakbulk, in some cases roll-on/roll-off | 1,498 | Yard tractors (28%), straddle carriers (26%) | 20% | 75%—container<br>13%—auto |

- Port of Los Angeles—90% of cargo-handling equipment emissions from container terminals
- Port of Long Beach—96% of cargo-handling equipment emissions from container terminals
- Port of New York/New Jersey's inventory excludes bulk cargo-handling equipment

*Sources: Port of Long Beach. 2023. Port of Long Beach Closes 2022 with Second-Busiest Year., Port of Los Angeles. N.d. Interactive Map of Port of Los Angeles Cargo Facilities., Stacrest Consulting Group. 2022. The Port of New York and New Jersey Port Department 2021 Multi-Facility Emissions Inventory, Starcrest Consulting Group. 2023. Port of Los Angeles 2022 Air Emissions Inventory., Starcrest Consulting Group. 2023. Port of Los Beach 2022 Air Emissions Inventory.*

# Inland Waterway Terminals

Inland waterway ports, which typically receive cargo via barges, feature streamlined logistics systems designed for the efficient transfer of goods along water routes. With specialized infrastructure like lock systems and handling equipment, these ports play a crucial role in connecting coastal ports with inland markets.

Commodities transported domestically via inland waterways

- 14% of crude oil, 3% of coal, 16% of other fuel oils (coal corridor—Ohio River, petrochemical corridor—Mississippi River)
- 60% of grain exports are connected to coastal ports by inland waterways (key routes—Mississippi, Columbia rivers)

Characteristics of an inland port:

- Intermodal terminal
- Connection with a coastal terminal
- Logistical activities


Inland and intracoastal waterways system

*Figure: EBP U.S. 2021. Ports and Inland Waterways– Anchoring the U.S. Economy., Notteboom, T., Pallis, A. and Rodrigue, J.P., 2022. Port economics, management and policy. Routledge*

# Inland Waterway Example

| Port | Twenty-foot equivalent unit, 2022 | Cargo, metric tons, 2022 | Numbers of terminals | Facilities by cargo type | Key cargo handled |
|---|---|---|---|---|---|
| Richmond Marine Terminal | 73,138 | 559,912 | Satellite port, part of the six terminals within the Port of Virginia | General cargo | • Containers (consumer goods)<br>• Reefers (frozen seafood)<br>• Breakbulk (forest products, machinery, project cargo)<br>• Bulk (agriculture) |

*Sources: The Virginia Port Authority. 2023. The Fiscal Year 2022 Virginia Economic Impacts of the Port of Virginia., The City of Richmond. Nd. Richmond Marine Terminal. https://www.portofvirginia.com/wp-content/uploads/2023/09/FY-2022-VIRGINIA-ECONOMIC-IMPACTS-042823-2.pdf, Port of Virginia. 2021. 2065 Master Plan.*

# Representative inventory of equipment

Representative inventory for each port category (container, bulk, breakbulk handling, inland waterway port) has been developed based on communication with the port authorities, published emissions reports, and mapping programs.

# Reference Ports and Respective Mobile Equipment Inventory

Legend

| | Container handling | Inland waterway port | Bulk handling port | Breakbulk handling |
|---|---|---|---|---|
| **Representative port** | **Port of Tacoma** | **Port of Virginia** | **Port of Corpus Christi** | **Port of Charleston** |
| Terminal tractor | ✓ | ✓ | ✓ | |
| Top handler | ✓ | ✓ | | |
| Side handler | ✓ | | | |
| Rubber-tired gantry crane | ✓ | | | |
| Mobile harbor crane | | ✓ | ✓ | |
| Heavy-duty forklift | ✓ | ✓ | ✓ | ✓ |
| Medium/light-duty forklift | | ✓ | ✓ | |
| Reach stacker | ✓ | | | |
| Straddle carrier | ✓ | | | |
| Wheel/skid steer loader | | | ✓ | |
| Backhoe, sweeper | | | ✓ | |
| Crane truck | | | | ✓ |

*Sources: Starcrest Consulting Group. 2016 Puget Sound Maritime Air Emissions Inventory. 2018.*
*AECOM. South Carolina Ports Authority 2017 Air Emissions Inventory. 2018*

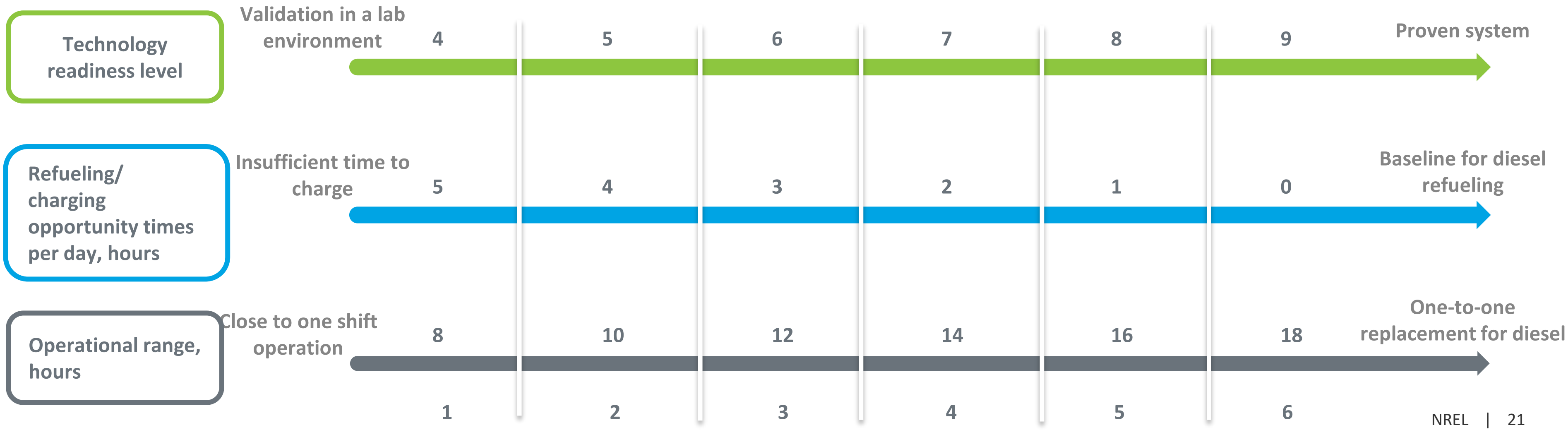
# Framework for powertrain comparison

The following section provides a framework for comparing the fuel cell and battery electric vehicle alternatives based on five characteristics: technology readiness level, refueling time, continuous operational range, energy savings, and energy cost savings compared to baseline diesel equipment.

# Framework for Powertrain Comparison

The following characteristics and their value ranges are used to compare the technology status, refueling time, and operational ranges of fuel cell electric (FCE), battery electric, and diesel cargo handling equipment, where:

- Technology readiness level (TRL) (as defined by Department of Energy office) is based on a literature review
- Refueling/charging for fuel cell/battery electric is based on values reported by original equipment manufacturers (OEMs)
- Refueling for diesel is based on fuel tank capacity and average fuel flow rate (gallons per minute)
- Operational range is based on values reported by OEMs or based on battery/storage tank capacity and hourly energy consumption



# Powertrain Efficiency and Cost Assumptions

| Assumption | Value | Comment |
| --- | --- | --- |
| Battery electric powertrain efficiency | 94% | Reported peak system efficiency by manufacturers of electric powertrain systems, such as Dana TM4 [1] |
| Fuel cell powertrain efficiency | 60% | Peak proton-exchange membrane fuel cell efficiency, lower heating value [2] |
| Diesel powertrain efficiency | 42% | Brake efficiency of the internal combustion engine used in heavy-duty transportation [3] |
| Daily operational hours | 8 | Reference ports' daily operational hours vary from 8 hours to 18 hours; lower bound of 8 hours is used in equipment comparison [4] |
| Electricity price, $/kWh | $0.15, $0.25, $0.35* | Low, medium, and high electricity prices, respectively [8] |
| Hydrogen fuel price, $/kg | $4, $7, $10 | Low, medium, and high hydrogen prices, respectively [5] |
| Diesel fuel price, $/gallon ($/kWh) | $3.72 | Average U.S. ultra low sulfur diesel price in 2024 with subtracted on-road taxes [6] |
| Refueling time and operational range | n/a | For fuel cell electric and battery electric, we used values reported by original equipment manufacturers. For diesel units, we calculated values based on tank capacity and an assumed refueling rate of 10 gallons per minute |


*Sources:*

*[1] Dana TM4, n.d. TM4 Sumo direct-drive electric powertrain systems.*

*[2]Fuel Cell Technologies Office, 2015. Fuel Cells.*

*[3] Edwards KD, Wagner R, Briggs Jr. T, Theiss T. Defining engine efficiency limits 2011.*

*[4] San Pedro Bay Ports, 2022. 2021 Cargo Handling Equipment Feasibility Assessment Report.*

*[5] Hunter, C., Penev, M., Reznicek, E., Lustbader, J., Birky, A., & Zhang, C. (2021). Spatial and temporal analysis of the total cost of ownership for class 8 tractors and class 4 parcel delivery trucks (No. NREL/TP-5400-71796).*

*[7] U.S. Energy Information Administration, 2024. Weekly U.S. No 2 Diesel Ultra Low Sulfur (0-15 ppm) Retail Prices (Dollars per Gallon).*

*[8] Consistent with NL TEA analysis*


**as per DOE Hydrogen and Fuel Cell Technologies Office request*

# Framework for Powertrain Comparison cont'd

The following steps are used to estimate and compare the energy and fuel cost savings per shift for fuel cell electric, battery electric, and diesel cargo handling equipment.

**Step 1**

Identify baseline diesel equipment model

→

**Step 2**

Calculate required mechanical power through horsepower and load factor

→

**Step 3**

Calculate energy savings (kWh) based on battery electric and fuel cell electric powertrain efficiencies

→

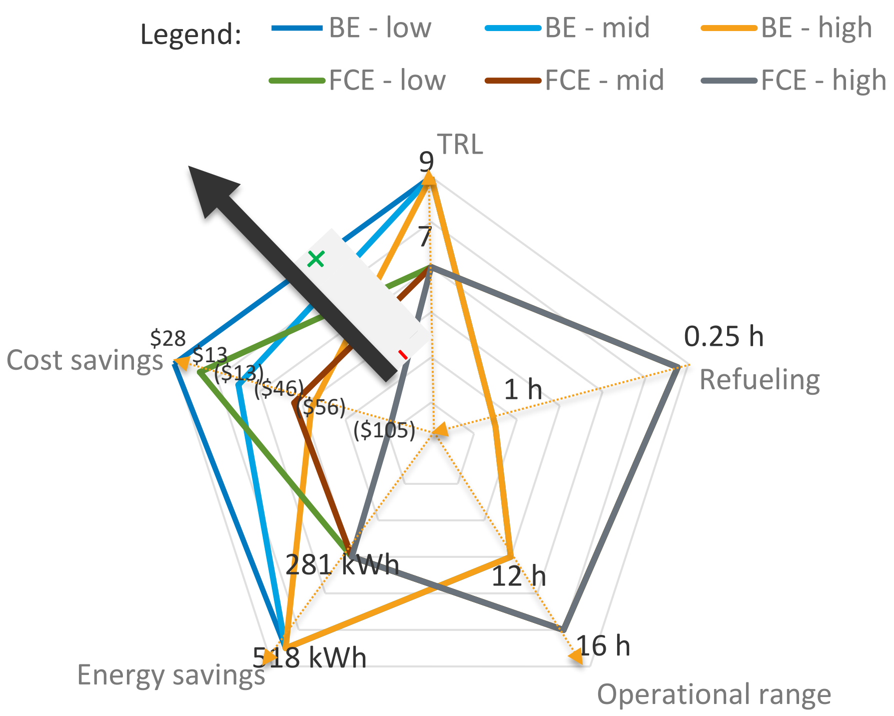
**Step 4**

Apply energy cost ($/kWh) to calculate savings compared to diesel equipment

# Interpreting Powertrain Trade-Off Graphic

- Strengths and weaknesses of each powertrain technology are represented on a radar chart
- The graph reflects the sensitivity of cost savings based on low, mid, and high scenarios for both battery electric (BE) and fuel cell electric (FCE) relative to diesel, as shown in legend. Please refer to low, medium and high energy and hydrogen associated costs in slide 22. Note that upfront cost differences are not considered.
- **The further away from the center the variable is, the more competitive it is with diesel**.

| Interpretation of sample graphic: FCE has a competitive refueling and operational range, while BE technology is commercialized and provides significant cost savings. |
|---|




Sample Graphic

| | Container handling | Inland waterway port | Bulk handling port | Breakbulk handling |
|---|---|---|---|---|
| Legend |  |  |  |  |

# Technology and commercial readiness of equipment types

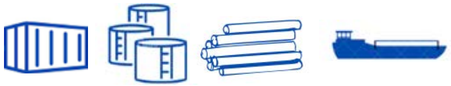
The following section provides the summary of operational characteristics for each powertrain, as well as an overview of equipment functions and relevant hydrogen projects. The section concludes with an overview of the hydrogen refueling infrastructure required to support equipment operations.

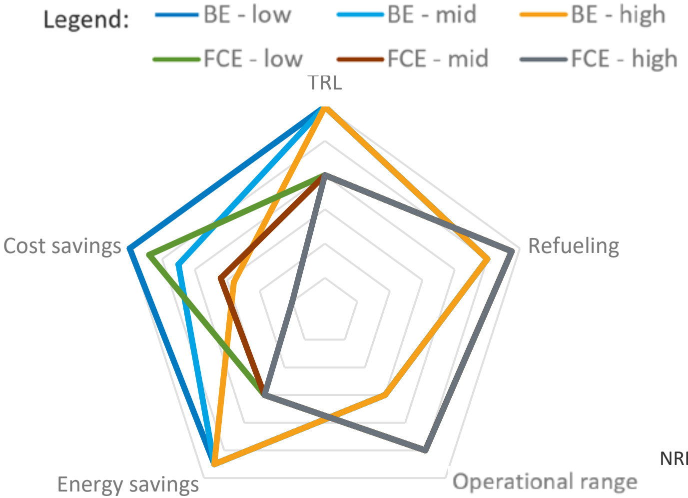
# Terminal Tractor

*Figure: https://commons.wikimedia.org/wiki/File:RM255.jpg*

| Powertrain | Technology readiness level | Charging/ refueling time, hours | Operational range, hours | Approximate energy consumption, kWh/shift | Approximate energy cost—low, $/shift | Approximate energy cost—mid, $/shift | Approximate energy cost—high, $/shift |
|---|---|---|---|---|---|---|---|
| Diesel | 9 | 0.08 | 20 | 936 | $92 | | |
| BE | 9 | 1 | 12 | 418 | $64 | $105 | $147 |
| FCE | 7 | 0.25 | 17 | 655 | $79 | $138 | $197 |

- Port-side terminal tractors are used to move containers and semitrailers within the cargo yard.*
- Hydrogen demonstrations at the Port of Los Angeles (GTI Energy, two units, 2019–2022), ongoing project at the Port of Valencia (ATENA, one unit, 2023–2024) and future demonstration at the Port of Hamburg (Hyster-Yale, 2024)
  - Units are typically battery-dominant where fuel cells act as "range extenders," hydrogen storage onboard <16 kg
- Port category applicability





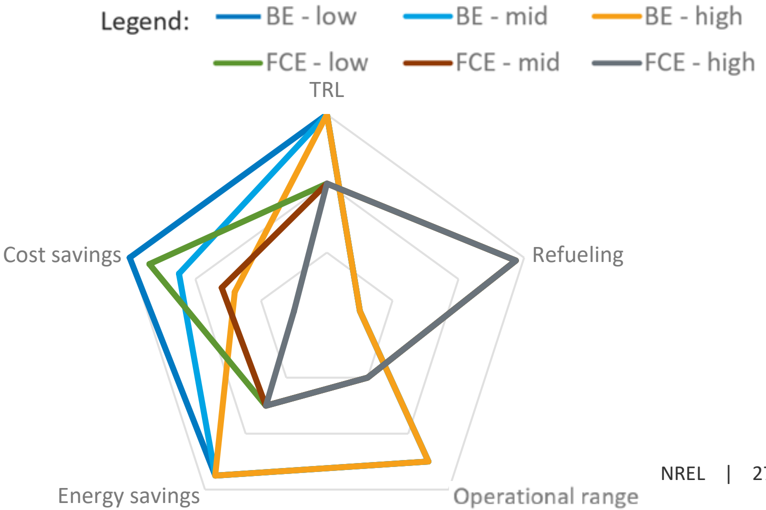

*Sources:*
*GTI Energy. Zero- and Near Zero-Emission Freight Facilities Project: Zero Emissions for California Ports (ZECAP). 2023.*
*H2Ports, n.d. Pilots: Yard Tractor. Access: https://h2ports.eu/pilots/#1560789545801-79c951e9-09b7*
**Argonne National Laboratory, n.d. Cargo Handling Equipment at Ports*

# Loaded container handler

*Figure: https://commons.wikimedia.org/wiki/File:Terex_container_handler_lifting_Vuosaari.jpg*

| Powertrain | Technical readiness level | Charging/ refueling time, hours | Operational range, hours | Approximate energy consumption, kWh/shift | Approximate energy cost—low, $/shift | Approximate energy cost—mid, $/shift | Approximate energy cost—high, $/shift |
|---|---|---|---|---|---|---|---|
| Diesel | 9 | 0.3 | 42 | 2,168 | $214 | | |
| Battery electric | 9 | 5 | 8** | 969 | $145 | $242 | $339 |
| Fuel cell electric | 7 | 0.25 | 8-10 | 1,518 | $182 | $319 | $455 |

- Loaded container handlers use an overhead attachment on a straight mast to move and stack heavy containers within a terminal.*
- Hydrogen demonstration includes a 52-ton top-pick delivered by Hyster-Yale to the Port of Los Angeles (one unit, 2018–2022)
  - Powered by two 45 kW fuel cells and a 130 kWh Li-ion battery, 28 kg of onboard storage @350 bar
  - Performed successfully in lighter applications
- Port category applicability 



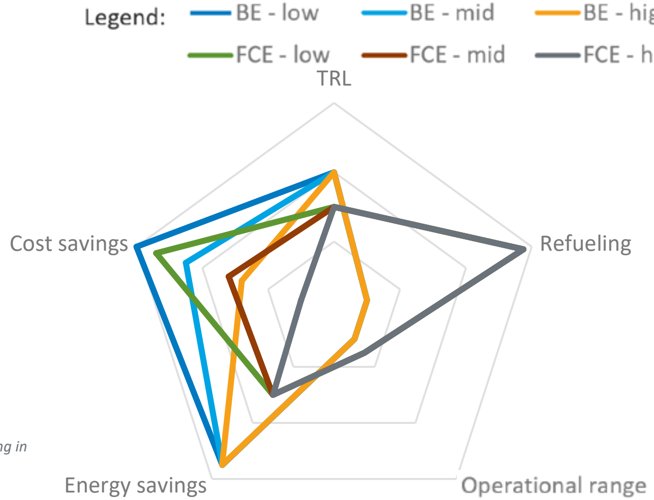

*Sources:*
*Hyster-Yale Materials Handling. Transforming the way the world moves materials from Port to Home. 2022 Annual Report. 2023.*
**Argonne National Laboratory, n.d. Cargo Handling Equipment at Ports*
***OEM defines the range as two-full shift run time (under normal work cycles). One full shift given.*

# Empty Container Handler

*Figure: https://commons.wikimedia.org/wiki/File:Container_handling_6281_%E3%80%90_Pictures_taken_in_Japan_%E3%80%91.jpg*

| Powertrain | Technical readiness level | Charging/ refueling time, hours | Operational range, hours | Approximate energy consumption, kWh/shift | Approximate energy cost—low, $/shift | Approximate energy cost—mid, $/shift | Approximate energy cost—high, $/shift |
|---|---|---|---|---|---|---|---|
| Diesel | 9 | 0.17 | 41 | 1,392 | $137 | | |
| Battery electric | 7 | 8 | 5–6 | 622 | $93 | $156 | $218 |
| Fuel cell electric | 6 | 0.16 - 0.25 | >9 | 975 | $117 | $205 | $292 |

- Empty container handlers use an overhead telescopic boom to lift and move cargo containers sideways by “grabbing” the sides or top and bottom of the longest side of a container.*
- Future hydrogen demonstration includes one unit delivered by Hyster-Yale at the Port of Hamburg
  - Powered by a 60 kW fuel cell and 130 kWh Li-ion battery, 16 kg of onboard storage @350 bar
  - Average expected energy consumption 2.2 kg/h (34 kWh/h)
  - Refueling station on-site is completed, unit delivery expected in 2024
- Port applicability 




*Sources:*


*Hyster, 2022. Hyster to provide Hamburger Hafen und Logistik AG with hydrogen fuel. Access: https://www.hyster.com/en-us/north-america/why-hyster/press-releases/2022/hyster-to-provide-hamburger-hafen-und-logistik-ag-with-hydrogen-fuel/ HHLA, 2023. Clean Port & Logistics presents first milestones at cluster meeting in Hamburg. Access: https://hhla.de/en/media/news/detail-view/clean-port-logistics-presents-first-milestones-at-cluster-meeting-in-hamburg*

**Argonne National Laboratory, n.d. Cargo Handling Equipment at Ports*

# Straddle Carrier

| Powertrain | Technical readiness level | Charging/ refueling time, hours | Operational range, hours | Approximate energy consumption, kWh/shift | Approximate energy cost—low, $/shift | Approximate energy cost—mid, $/shift | Approximate energy cost—high, $/shift |
|---|---|---|---|---|---|---|---|
| Diesel-electric | 9 | 0.6 | 71 | 2,334 | $230 | | |
| Battery electric | 8 | 0.75 | 4 | 1,043 | $256 | $261 | $365 |
| Fuel cell electric | 5 | - | - | 1,634 | $196 | $343 | $490 |

- Straddle carriers move a container by straddling it and lifting from the top. They can stack up to four containers.*
- Fuel cell demonstrations planned at the Port of Hamburg
- Ongoing testing is limited to the dual fuel unit at the Port of Antwerp, with hydrogen replacing diesel up to 70%
  - Part of the Green Straddle Carrier Program, which evaluated four straddle carrier technologies
- Port applicability 


*Figure: https://commons.wikimedia.org/wiki/File:Straddle_carrier_from_Port_of_Chittagong_(05).JPG*

*Sources:*
*Port of Hamburg Magazine 4/23. Energy Hub. Access: https://www.hafen-hamburg.de/assets/files/magazin/poh42023_en/index.html#p=18*
*CMB.TECH. Antwerp Terminal Services (ATS) and CMB.TECH launch World's First Hydrogen Dual Fuel Straddle Carrier 2023.*
**Argonne National Laboratory, n.d. Cargo Handling Equipment at Ports*

# Rubber-Tired Gantry Crane

| Powertrain | Technical readiness levels | Charging/ refueling time, hours | Operational range, hours | Approximate energy consumption, kWh/shift | Approximate energy cost—low, $/shift | Approximate energy cost—mid, $/shift | Approximate energy cost—high, $/shift |
|---|---|---|---|---|---|---|---|
| Diesel | 9 | 0.13 | 72 | 2,006 | $198 | | |
| Grid-connected | 9 | n/a | n/a | 896 | $134 | $224 | $314 |
| Fuel cell electric | 6 | - | 16 | 1,404 | $169 | $295 | $421 |

- Rubber-tired gantry cranes use a cross beam supported on vertical legs that move on rubber tires to move and stack loaded containers.*
- Future hydrogen demonstration by PACECO at the Port of Los Angeles (one unit, 2024–2028)
  - Started in May 2024, scheduled for 4 years
  - 60 kW FC, 64 kg usable hydrogen tank capacity @700 bar
  - Technology can be applied to new cranes or retrofits, helps to maintain yard flexibility
- Port applicability


*Figure: https://commons.wikimedia.org/wiki/File:Rubber_tyred_gantry_crane_(RTG)_pic3.JPG*

*Sources:*

*Mitsui E&S, 2022. Hydrogen Fuel Cell Power Pack Ready for Transtainer®. Access: https://www.mes.co.jp/english/press/2022/0920_001887.html*

*PACECO, n.d. Project to demonstrate a local production and consumption hydrogen model at the PORT OF LA, U.S.A. aiming for the transition to Fuel Cell of port cargo handling machinery and drayage trucks. Access: https://pacecocorp.com/nedo-la-project/*

*Hedrick J., 2021. BNSF Zero-and near Zero-emission Freight Facilities Project (ZANZEFF) data acquisition support*

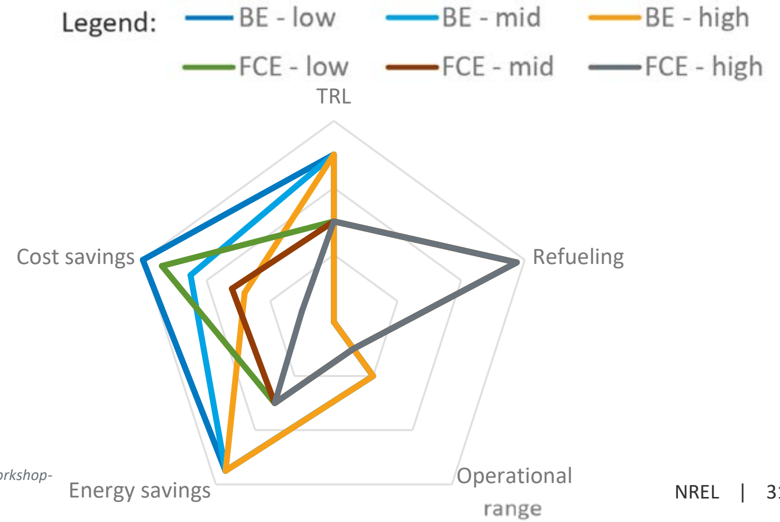
**Argonne National Laboratory, n.d. Cargo Handling Equipment at Ports*

# Reach Stacker

*Source: https://commons.wikimedia.org/wiki/File:PPM_10_GMI_stacker.jpg*

| Powertrain | Technical readiness level | Charging/ refueling time, hours | Operational range, hours[1] | Approximate energy consumption, kWh/shift | Approximate energy cost—low, $/shift | Approximate energy cost—mid, $/shift | Approximate energy cost—high, $/shift |
|---|---|---|---|---|---|---|---|
| Diesel | 9 | 0.25 | 39 | 2,269 | $224 | | |
| Battery electric | 8 | - | 4–10 | 1,014 | $152 | $253 | $355 |
| Fuel cell electric | 6 | 0.16–0.25 | 8–10 | 1,588 | $191 | $334 | $476 |

- Reach stackers use an overhead attachment on a telescopic boom to move and stack loaded containers. They can reach over multiple rows to load containers.*
- Ongoing hydrogen demonstration of a unit by Hyster-Yale (1 unit, 2023–2024) at the Port of Valencia
  - Powered by two 45 kW fuel cells and a 130 kWh Li-ion battery, 32 kg of onboard storage @350 bar
  - Average expected energy consumption 3.2 kg/h (55 kWh//h)
  - Planned testing for 5,000 hours
- Port applicability:




*Sources:*

*Fuel Cell and Hydrogen Joint Undertaking, 2019. EU support to maritime activities. Access: https://www.energy.gov/sites/prod/files/2019/10/f68/fcto-h2-at-ports-workshop-2019-ii2-atanasiu.pdf*

**Argonne National Laboratory, n.d. Cargo Handling Equipment at Ports*

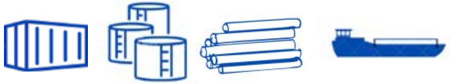
# Other Equipment Types

| Equipment type | Powertrain | Technical readiness level | Charging/ refueling time, hours | Operational range, hours | Approximate energy consumption, kWh/shift | Approximate energy cost—low, $/shift | Approximate energy cost—mid, $/shift | Approximate energy cost—high, $/shift |
|---|---|---|---|---|---|---|---|---|
| Heavy-duty forklift (>10 tons lifting capacity) | Diesel | 9 | 0.18 | 24 | 2,978 | $294 | | |
| | Battery electric | 8 | 3 | 28.5 | 1,331 | $200 | $333 | $466 |
| | Fuel cell electric | - | - | - | - | - | - | - |

We have not found any demonstrations of hydrogen-powered heavy-duty forklifts at ports.

*Figure: https://commons.wikimedia.org/wiki/File:US_Air_Force_(USAF)_49th_Civil_Engineer_Squadron_(CES)_Heavy_Maintenance_Shop_member_AIRMAN_First_Class_(A1C)_George_Moore,_maneuvers_his_forklift_into_position_to_load_a_pallet_of_-_DPLA_-_245323d7deb59e0f56c0a7458ccb30e2.jpeg*

- Heavy-duty forklift port applicability



# Other Equipment Types cont'd

| Equipment type | Powertrain | Technical readiness level | Charging/ refueling time, hours | Operational range, hours | Approximate energy consumption, kWh/shift | Approximate energy cost—low, $/shift | Approximate energy cost—mid, $/shift | Approximate energy cost—high, $/shift |
|---|---|---|---|---|---|---|---|---|
| Mobile harbor crane | Diesel electric | 9 | 1 | 220 | 7,330 | $723 | | |
| | Grid connected | 8 | n/a | n/a | 3,275 | $491 | $819 | $1,146 |
| | Fuel cell electric | - | - | - | - | - | - | - |

We have not found any demonstrations of hydrogen-powered mobile harbor.

*Figure: https://commons.wikimedia.org/wiki/File:Alternate_Port_Concept_150605-Z-UM297-037.jpg*

- Mobile harbor crane port applicability

# Other Equipment Types cont'd

*Figure: https://pixabay.com/photos/forklift-industry-vehicle-shipment-2660508/*

*Figure: https://pixabay.com/photos/machine-forklift-logistics-3184176/*

| Equipment type | Powertrain | Technology readiness level | Charging/ refueling time, hours | Operational range, hours | Approximate energy consumption, kWh/shift | Approximate energy cost—low, $/shift | Approximate energy cost—mid, $/shift | Approximate energy cost—high, $/shift |
|---|---|---|---|---|---|---|---|---|
| Medium-duty forklift (5–10 tons lifting capacity) | Diesel | 9 | 0.03 | 16 | 765 | | $75 | |
| | Battery electric | 9 | 2 | 4–6* | 341 | $51 | $85 | $120 |
| | Fuel cell electric | 5 | 0.08 | 5 | 535 | $64 | $112 | $160 |
| Light-duty forklift (<5 tons lifting capacity) | Diesel | 9 | 0.03 | 26 | 371 | | $37 | |
| | Battery electric | 9 | 1 | 3.3–-13.45* | 166 | $25 | $41 | $58 |
| | Fuel cell electric | 9 | 0.03 | 8 | 260 | $31 | $55 | $78 |

* Range varies based on the battery size and application

- We have not found any hydrogen demonstrations at ports for medium-duty forklifts; Hyundai plans to demonstrate a prototype in various environments until 2026.
- Light-duty hydrogen forklifts are commercially available and typically used in material handling applications in indoor settings. Doosan Bobcat is demonstrating a 3-ton fuel cell forklift (20 kW) in a Korean refinery.
- Port applicability

# Bulk Handling Equipment Types

*Figure: https://pixabay.com/photos/isolated-wheel-loader-gravel-pits-2503788/*

*Figure: https://pixabay.com/photos/vehicle-equipment-isolated-machine-4783285/*

| Equipment type | Hydrogen technical readiness level | Battery electric technical readiness level | Fuel cell electric status |
|---|---|---|---|
| Wheel loader | 5 | 9 | Nuvera demonstration unit (2023), which is now operational in China. The unit is equipped with E-Series Fuel Cell Engines with a rated peak engine efficiency of 58%.<br>Develon DL250 fuel cell electric vehicle 15-ton prototype (2024) with up to 8 hours of operation. The unit is capable of switching between fuel cell pack and battery pack powertrains. |
| Skid steer loader | - | 6 | No hydrogen fuel cell pre-commercial demonstrations were identified. Model development is underway by Doosan Bobcat. |

# Bulk Handling Equipment Types cont’d

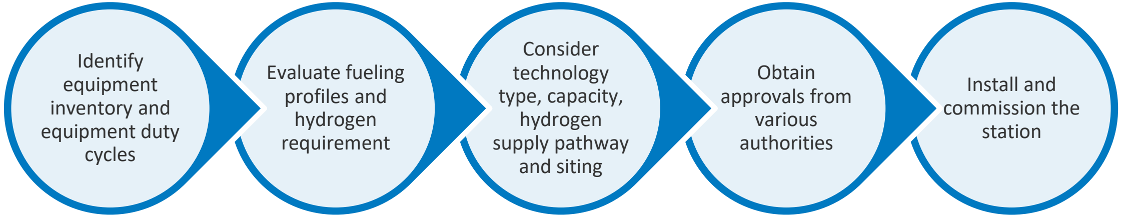
*Figure: https://pixabay.com/photos/backhoe-mixed-work-machine-2449020/*

*Figure: https://pixabay.com/photos/sweeper-street-cleaning-cleanliness-7218811/*

| Equipment type | Hydrogen technical readiness level | Battery electric technical readiness level | Fuel cell electric status |
|---|---|---|---|
| Backhoe | 5 | 9 | JCB developed a new hydrogen internal combustion engine in 2023 and incorporated it into the backhoe unit. The unit has the same shape and form as the diesel-powered version but incorporates five carbon-fiber storage tanks @ 350 bar, including one auxiliary tank for extending the range. Depending on range and size, the machine would consume between 6–10 kg of hydrogen daily. Low-temperature, low-pressure combustion limits nitrogen oxide, and the combustion output is dry steam. JCB designed a mobile hydrogen bowser to refuel vehicles with ~100 kg @500 bar. |
| Sweeper | 7 | 8 | Global M4 ZE-Series 11-ton Street Sweeper with 80 kW fuel cell, 20 kg onboard storage, and up to 10 hours of continuous operation (2018), the unit has been deployed by Caltrans in urban settings.<br>Other light-duty sweepers are available. |

# Hydrogen fueling infrastructure

# Hydrogen Fueling Infrastructure for Medium- and Heavy-Duty equipment




## Refueling station configuration

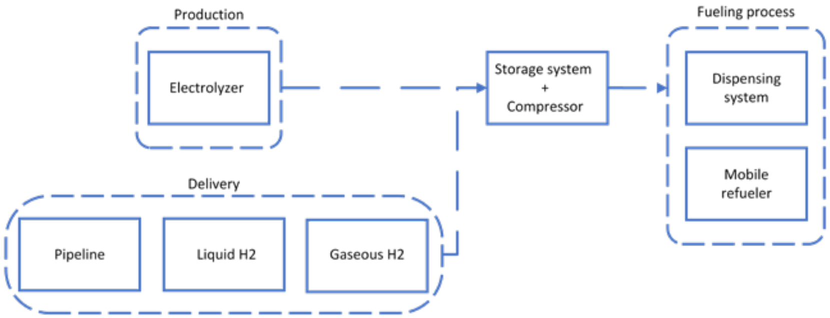



*Figure adapted from hydrogen (H2) station capacity (HyCap) model configuration. NREL, 2023.*

## Challenges and opportunities

- High capital costs
  - Specific costs may decrease with economies of scale and high use rates
- Price of fuel is highly variable by location
- Large footprint required for heavy-duty/medium-duty station and fuel storage
- Siting limitations (e.g., setback requirements) and potentially lengthy permitting process
- Station reliability; unscheduled maintenance of compressors and dispensers
- On-site electrolysis could be limited by the power that ports can bring in
- Port can expand into neighboring real estate for industrial-scale hydrogen production and staging (e.g., hydrogen export)

*Sources:*

*Kurtz, Jennifer, Sam Sprik, and Thomas H. Bradley. "Review of transportation hydrogen infrastructure performance and reliability." International Journal of Hydrogen Energy 44, no. 23 (2019): 12010-12023.*

*Greene, David L., Joan M. Ogden, and Zhenhong Lin. "Challenges in the designing, planning and deployment of hydrogen refueling infrastructure for fuel cell electric vehicles." ETransportation 6 (2020): 100086.*

# Demonstrations at Ports

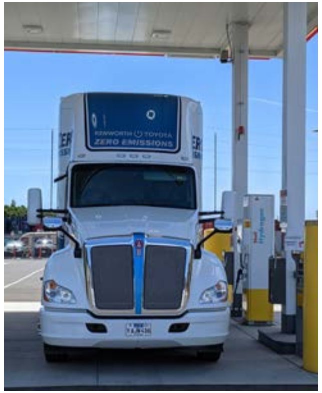
- Refueling operations at ports use tanker trucks providing mobile refueling services directly to parked equipment at the terminal (wet hosing)
- Existing hydrogen cargo handling equipment demonstrations at ports have used:
  - Cascade fill mobile fueling system at the Port of Los Angeles (2019–2022)
    - Cost-effective standalone unit that requires no permanent infrastructure
    - System characteristics: 180 kg capacity @450 bar—sequential refueling—2 vehicles/day
    - Terminal feedback indicates logistic issues and delays attributed to the static nature of fueling stations and manual switching of banks
  - Hydrogen refueling station at the Port of Valencia (2023–2024)
    - Hydrogen refueling station with a fixed part dedicated to the reception, storage, and compression of hydrogen up to delivery pressure and a mobile part that travels to the terminals to refuel hydrogen units
    - System characteristics: up to 60 kg of gaseous hydrogen/day @350 bar, max flow rate 3.6 kg/min
  - Hydrogen refueling station at the Port of Hamburg (2023–2025)
    - High pressure ionic compressor with hydrogen up to 450 bar, cascade storage system
    - Incorporates options for expansion

Companies offer mobile refueling stations with fully automated cascade fills designed to support 1–5 units @350 bar.

*Sources: GTI Energy. Zero- and Near Zero-Emission Freight Facilities Project: Zero Emissions for California Ports (ZECAP). 2023.*
*H2Ports, 2021. Implementing Fuel Cells and Hydrogen Technologies in Ports. Access: https://h2ports.eu/wp-content/uploads/2021/05/2-UPDA1.pdf*
*HHLA, 2023. HHLA and Linde Engineering build hydrogen filling station in the Port of Hamburg. Access: https://www.hafen-hamburg.de/en/press/news/hhla-and-linde-engineering-build-hydrogen-filling-station-in-the-port-of-hamburg/*

# Shell Heavy-Duty Fueling Serving Port of Los Angeles





- The demonstration station served 10 fuel cell electric Class 8 drayage trucks at the Port of Los Angeles
- Design throughput: four trucks per hour
- Estimated electrical maximum power need: ~290 kW
- On-site hydrogen storage capacity of 1,500 kg @450 bar
- Storage vessels and station modules have a footprint of ~750 ft$^2$
- Additional Shell heavy-duty station based at Toyota Logistics Services Terminal, Port of Long Beach


Fueling station in Wilmington, California
Photos: Andrew Kotz/NREL

*Source: Port of Los Angeles, 2019. Zero-Emission Freight "Shore-to-Store" Project, Attachment 2: Project Narrative and Work Plan. https://kentico.portoflosangeles.org/getmedia/b86f16f7-c10c-4e3b-b7c9-ac4020a9348f/Item-11_T1*

*CARB, 2023. The Port of Los Angeles Zero- and Near-Zero-Emission Freight Facilities "Shore to Store" Project. https://www.osti.gov/servlets/purl/2203905*

# Electric vehicle charging infrastructure

# Charging Infrastructure—Electric Vehicle Supply Equipment and Grid Integration

- Identify equipment inventory and equipment duty cycles
- Evaluate charging power requirements
- Identify electric vehicle supply equipment to battery electric equipment (vehicle) ratio
- Leverage managed charging to mitigate high peak power loads
- Identify any backup energy storage requirements for resiliency planning

## Grid integration

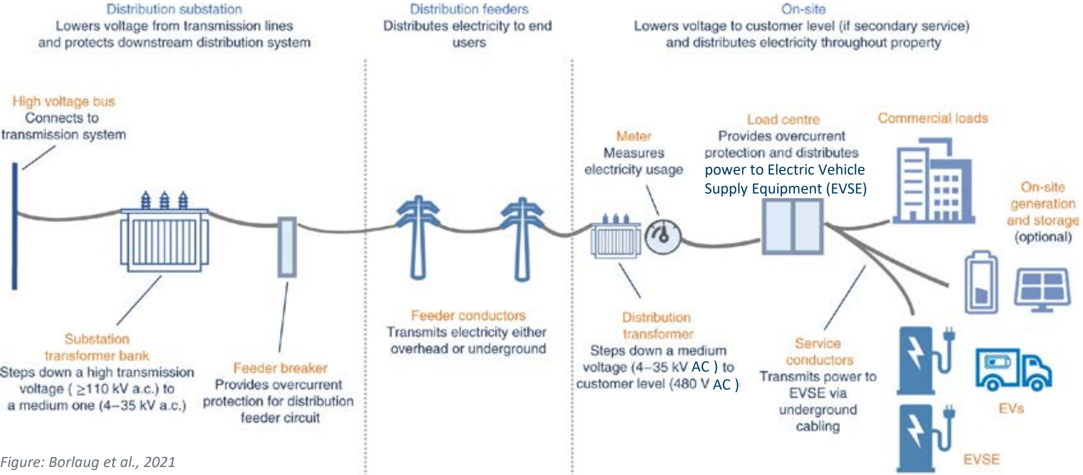



*Figure: Borlaug et al., 2021*

## Challenges of charging infrastructure

- Availability of energy at the site
- Initial capital cost required
- Length of vehicle charging time
  - APM Terminal servicing New York/New Jersey has 3-shift operation, with yard tractor engine run times up to 24 hours.
  - Great opportunity for hydrogen-fueled tractors due to minimal down time during duty cycle

# High-Power Medium- and Heavy-Duty Electric Vehicle Charging

Graphic shows an example of a grid-connected direct current electric vehicle charging infrastructure, including chargers providing varying power levels for different equipment types. Annotations include comparable applications for port electric vehicle supply equipment.

- Electric vehicle supply equipment for light-/medium-duty equipment
- kW fast charger, technology readiness level 8/9 (e.g., light duty forklifts)

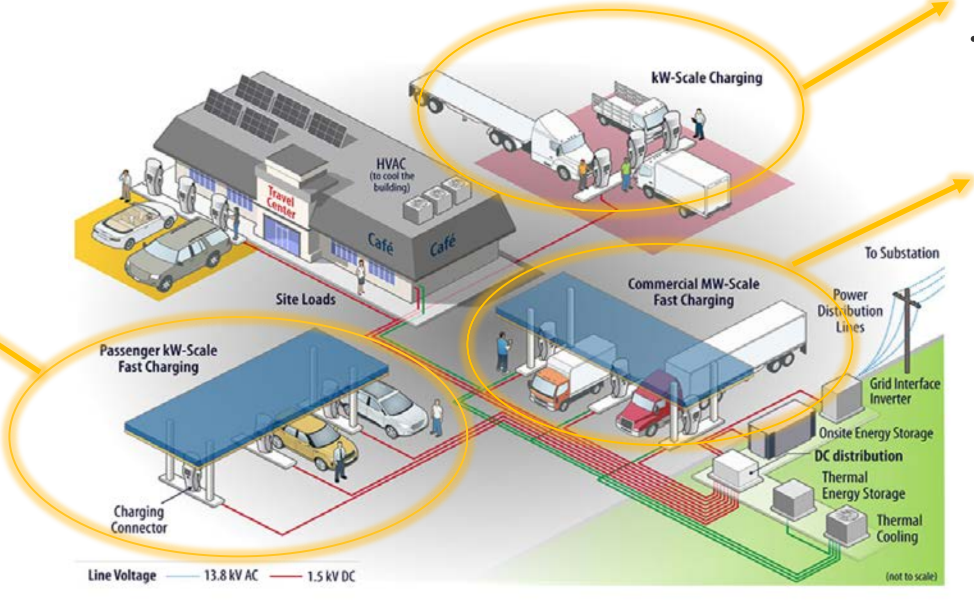



Illustration by Al Hicks, NREL

*Figure: https://www.nrel.gov/transportation/medium-heavy-duty-vehicle-charging.html*

- Electric vehicle supply equipment for medium-/heavy-duty equipment
- kW charging, technology readiness level 8/9 (e.g., medium-/heavy-duty forklifts)

- Electric vehicle supply equipment for heavy-duty equipment
- MW charging, technology readiness level 3 (e.g. top handlers / reach stackers / straddle carriers)

# Task 1 Takeaways

- Trade-offs
  - Battery electric technology readiness level higher than fuel cell electric for all equipment
  - Fuel cell electric equipment currently favored for high persistence operations (24-hour operations, for example) where operational range/charging downtime is a concern
  - Need for onboard energy (fuel cell electric has faster fuel times with less need for onboard energy storage and long ranges; battery electric has longer charge times with more need for onboard storage and longer ranges
- Synergies
  - With full equipment electrification, both battery electric and fuel cell electric technologies will likely coexist. Fuel cell electric may be prioritized for multi-shift operations and in areas with limited grid capacity. Battery electric could be initially prioritized due to higher technology readiness levels and is suitable for equipment that can accommodate charging downtime. For stationary equipment, a direct grid connection is preferred.
- Fuel operating expense analysis
  - Theoretical power train analysis—fuel operating expense for hydrogen cargo handling equipment 2.5 times more than diesel
  - Real-world demonstrations—hydrogen/electric powertrain performing better than theory
- Most fuel cell electric cargo handling equipment demonstrations target assets with the highest use hours at ports with the largest impact on emissions.
- As of Spring 2024—hydrogen refueling solutions at ports cater to the small-scale gaseous demonstrations(1–2 units).
- Insight: Scaling options for fueling infrastructure is crucial for future deployment.

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# Task 2: Energy and Infrastructure Analysis

- Expand inventory of equipment at ports to apply to reference ports
- Advance hydrogen integration and electrification strategies

# Task 2: Methodology Block Diagram

## Task 1

Data collected for each port:

- Equipment count
- Average use hours
- Fuel type
- Horsepower rating
- Load factor

## Task 2

**Step 1: Identifying the use rates for the equipment**

- Using the data received from the ports

**Step 2: Identifying use cases (average and high use)**

- Step 1 provides average use
- For high use, scale the hours to the maximum potential cargo throughput or vessel calls by terminal

**Step 3: Estimating energy demand**

- Mapping the equipment with the respective fuel cell electric or battery electric equipment
- Estimate for a year for both use cases:
  - Volumes of hydrogen required to replace petroleum fuels in equipment likely to use fuel cell
  - Electricity demand for equipment likely to use battery electric equipment

**Step 4: Estimating hydrogen infrastructure cost**

- Outline potential refueling solutions
- Estimate costs for the capital investment

**Step 5: Analyzing grid readiness**

- Estimate the electrical power and energy consumption considering the charging station and hydrogen refueling station
- Analyze utility infrastructure and respective scenarios of infrastructure upgrade
- Analyze on-site generation and storage scenario at a very high level

# Steps 1 and 2: Equipment use hours

This section compares the average annual use hours of cargo-handling equipment and the shift patterns reported by the ports. Additionally, it estimates the maximum annual use hours for each port.

# Average Equipment Use Hours

## Approach

- Extract annual use hours mainly from published air emissions inventories by ports
- Ports of Tacoma, Charleston, and Virginia (by terminal)
- Port of Corpus Christi (port-wide)

**Summary of operational characteristics by port**

| | Port of Virginia (Inland Waterway) | Port of Corpus Christi (Bulk) | Port of Tacoma (Container) | Port of Charleston (Breakbulk) |
|---|---|---|---|---|
| Terminal | Richmond Marine Terminal | Bulk Terminal | Pierce County Terminal | Columbus Street Terminal |
| Cargo | Container, bulk, breakbulk | Dry, liquid bulk | Container | Breakbulk, roll-on/roll-off |
| Daily operating hours | Variable | 24 | 18 | 8 |
| Shift patterns | Limited from 9 a.m. until sunset | 3 shifts x 8 hours | 1 shift x 10 hours, 1 shift x 8 hours | 1 shift x 8 hours |
| Use hours data source | Communication with Virginia Port Authority | Port of Corpus Christi Authority 2020 Air Emissions Inventory | 2021 Puget Sound Air Emissions Inventory | 2021 Air Emissions Inventory |

# Data Limitations and Mitigation

Ports generally do not report use hours for stationary equipment and cranes such as ship-to-shore cranes, mobile harbor cranes, and ship loaders.

**Use hours estimation**

| Port | Equipment | Available data | Assumptions | Calculation |
|---|---|---|---|---|
| Virginia | Mobile harbor crane | Barge trips per year: 158 | Use: 10 hours/day | 158 x 10 = **1,580 hours/year**[1] |
| Corpus Christi[2] | Mobile harbor crane | Cargo throughput at Dock 1 in 2021: 745,109 tons<br>Rated capacity: 1,500 tons/hour | Average capacity: 60% | 745,109 /(1500 x 60%) = **827 hours/year** |
| | Ship loader[2] | Cargo throughput at Dock 2 in 2021: 796,816 tons<br>Rated capacity: 1,500 tons/hour | Average capacity: 60% | 796,816 /(1500 x 60%) = **885 hours/year** |
| Tacoma | Ship-to-shore cranes | Max operating hours: 18 hours/day | Working days: 250 days/year<br>Sustainable capacity: 80%<br>Adjustment for actual use: 60% | (18*250*80%)* 0.6 = **2,160 hours/year** |

[1] Rounded to 1,600 as port indicates crane has the highest use among cargo handling equipment.

[2] Conveyor system connecting the ship loader with the stockpiles not in-scope for Task 2.

# Average Annual Use Hours per Unit by Equipment Type

| Equipment type | Port of Virginia (Inland Waterway) | Port of Corpus Christi (Bulk) | Port of Tacoma (Container) | Port of Charleston (Breakbulk) |
|---|---|---|---|---|
| Terminal tractor | Not publicly available | | 249 | |
| Loaded container handler | | | 254 | |
| Pickup truck | | | | |
| Mobile harbor crane | | 827 | | |
| Light-duty forklift | | | | |
| Medium-duty forklift | | 621 | | |
| Heavy-duty forklift | | | 198 | 303 |
| Backhoe | | 100 | | |
| Ship loader | | 885 | | |
| Wheel loader | | 472 | | |
| Skid steer loader | | 65 | | |
| Sweeper | | 472 | | |
| Tractor | | 57 | | |
| Crane | | | 2,160 | |
| Empty container handler | | | 562 | |
| Straddle carrier | | | 1,244 | |
| Truck crane | | | | 1,454 |

# High Usage Hours: Port of Richmond, Virginia
## Inland Waterway

**Approach**

Scaled annual cargo throughput (based on normal operation) to maximum possible throughput to calculate high use hours

| | |
|---|---|
| Normal operation of port: | Barge service 3 times a week, combined capacity 500 forty-foot equivalent unit |
| Normal operation annual throughput: | 73,138 ten-foot equivalent unit (36,569 forty-foot equivalent unit) |
| High use operation: | Barge service 6 times a week (1,000 forty-foot equivalent unit) |
| Average annual usage hours scaling factor: (to scale to high use hours) | [1,000 forty-foot equivalent unit per week x 52 weeks ] ÷ [36,569 annual forty-foot equivalent unit] |

**Results**

| Equipment type | AVERAGE<br>Usage, hours/year | **HIGH**<br>**Scaled based on increase to 6 days/ week service forty-foot equivalent unit** |
|---|---|---|
| Terminal tractor | 1,400 | 1991 |
| Heavy forklift | 120 | 171 |

**Notes**

All hours calculated on annual basis; if looking at hours on a daily basis, ensure that the caps for maximum daily use are as follows: ~12 hours in summer, ~8 hours in winter

Also estimated average and high usage hours for other equipment such as loaded container handler, pickup truck, mobile harbor crane, light and medium forklifts.

# High Usage Hours: Port of Corpus Christi, Texas
## Bulk (Docks 1 and 2)

**Approach**

- Scaled 3-year average annual dry bulk throughput to 3-year maximum for high usage hours
- Crane hours: only scaled based on cargo throughput at Dock 1, because crane sits at Dock 1
- Ship loader hours: only scaled based on cargo throughput at Dock 2, because ship loader sits at Dock 2
- All other equipment: scaled on cargo throughput at Dock 1 and Dock 2 because they are mobile and operate at both docks

Baseline annual throughput (3-year average):
All docks: 1,828,612 tons
Dock 1: 1,031,796 tons
Dock 2: 796,816 tons

High use throughput (3-year maximum):
All docks: 2,464,910 tons
Dock 1: 1,534,146 tons
Dock 2: 930,764 tons

Scaling Factors:
Crane: 1.49 *(1,534,146 ÷ 1,031,796)*
Ship loader: 1.17 *(930,764 ÷ 796,816)*
All other equipment: 1.35 *(2,464,910 ÷ 1,828,612)*

**Results**

| Equipment type | AVERAGE Usage, hours/year | HIGH Usage, hours/year |
|---|---|---|
| Backhoe | 100 | **135** |
| Crane | 828 | **1,231** |
| Ship loader | 885 | **1,034** |
| Forklift | 621 | **837** |
| Wheel loader | 472 | **636** |
| Skid steer loader | 65 | **88** |
| Sweeper | 472 | **636** |
| Tractor | 57 | **77** |

**Notes**

Cargo handling equipment will be predominantly used for dry bulk (refined liquid petroleum products normally loaded through hydraulic loading arm at dock)

# High Usage Hours: Port of Tacoma
## Container (Pierce County Terminal)

**Approach**

Scaled current vessel during normal operation to maximum possible vessel capacity at terminal

| | |
|---|---|
| Vessel calls | Ever Smile/Ever Superb 6,944 twenty-foot equivalent unit (TEU) capacity |
| Average time in port per vessel call | 40 Shift hours (10-hour day shift, 8-hour night shift) |
| Pierce county terminal max capacity | 14,000 TEU |
| Average annual usage hours scaling factor from current vessel capacity to maximum capacity | 14,000 TEU ÷ 6,944 TEU = ~ 2 |

**Results**

| Equipment type | AVERAGE Usage, hours/year | **HIGH Usage, hours/year** |
|---|---|---|
| Crane | 2,160 | **4,355** |
| Forklift | 186 | **375** |
| Forklift | 211 | **425** |
| Side handler | 562 | **1,133** |
| Straddle carrier | 1,244 | **2,508** |
| Yard tractor | 249 | **502** |
| Top handler | 254 | **512** |

**Notes**

- Assumed that while vessels are at berth, the cargo-handling equipment is being used (during shift hours). Otherwise, vessel will go to anchorage to wait for crew changes/schedule delays.
- Only scaling on increase in vessel capacity and not the number of vessel calls, because increase in cargo throughput also increases time in port by double. Port would not have space for more vessel calling.

# High Usage Hours: Port of Charleston
## Breakbulk (Columbus Street Terminal)

**Approach** Scaled current vessel during normal operation to maximum possible vessel calls

| | |
|---|---|
| Vessel calls, normal operation: | 2/3 berths used at a time |
| Average time in port per vessel call: | 8 shift hours (1 day shift) |
| Number of available berths: | 5 |
| Average annual usage hours scaling factor from current number of berths used simultaneously to maximum available berths | 5 Berths ÷ 3 Berths |

**Results**

| Equipment type | AVERAGE Usage, hours/year | **HIGH Usage, hours/year** |
|---|---|---|
| Forklift 55 K | 303 | **505** |
| Crane truck | 1,454 | **2,423** |

**Notes**

- Assumed that while vessels are at berth, the cargo-handling equipment is being used (during shift hours). Otherwise, vessel will go to anchorage to wait for crew changes/schedule delays.
- High use hours assumed that all berths are in use.
- Cargo type not taken into consideration as it is too variable. Note that vehicle carriers would probably have lower cargo-handling equipment usage.

# Step 3: Energy demand estimation

This section provides estimates of current fuel and energy consumption and estimates future hydrogen and electricity demand for a reference year, assuming full conversion to zero-emission cargo handling equipment.

# Cargo Handling Equipment Energy Demand Estimation

## Approach

Assign cargo-handling equipment types at each terminal to the respective battery electric or fuel cell electric powertrain.

- Conversion to fuel cells is prioritized for:
  - Untethered equipment
  - Higher use hours
  - Larger fleets
  - Moderate to high fuel cell electric system technology readiness level

## Equipment conversion calculation

**Step 1: Inputs**

Equipment inventory data:

- Equipment count
- Use hours (average and high)
- Fuel type
- Horsepower rating or kW
- Load factor

**Step 2: Calculations**

- Calculate diesel, gasoline, liquid petroleum gas consumption (gal) based on powertrain efficiencies
- Calculate electricity (kWh) and hydrogen (kg) demand based on powertrain efficiencies

**Step 3: Results**

Baseline fuel and electricity consumption for average and high use

Projected electricity and hydrogen demand for average and high use

# Powertrain Conversion Spreadsheet

- Spreadsheet has four tabs with the analysis of each port
- Each tab is divided into three sections:
  - Equipment inventory inputs
  - Powertrain conversion inputs
  - Fuel/energy baseline consumption and future demand
- By assigning checkmarks for each type of equipment to indicate its powertrain (fuel cell electric or battery electric), the spreadsheet allows for sensitivity analysis

Note: "Port of Tacoma" tab includes data for two terminals for comprehensive analysis

**Equipment inventory**

| Equipment type | Count | Make/Model (provided by port) | Utilization, hours/year | Fuel | Power (kW) | Assumed make/model | Load factor |
|---|---|---|---|---|---|---|---|
| Terminal tractor | 10 | TICO | 1400 | Diesel | 118 | | 0.39 |
| Loaded container handler | 6 | HOIST/Kalmar | 1600 | Diesel | 265 | | 0.43 |
| Pickup truck | 9 | Various mode | 365 | LPG | | | |
| Mobile harbor crane | 1 | Liebherr (in us | 1600 | Diesel | 400 | | 0.43 |
| Mobile harbor crane | 1 | Manitowoc (b | 0 | Diesel | 325 | | 0.43 |
| Light forklift | 5 | 6 or 8k hyster | 356 | Diesel or LPG | 44 | 6k: 44 kW Diesel | 0.59 |
| Medium forklift | 2 | 15k hyster rer | 365 | Diesel or LPG | 82 | 15.5k: 82 kW Diesel | 0.59 |
| Heavy forklift | 1 | HOIST 52k | 120 | Diesel | 279 | | 0.59 |

**Powertrain conversion**

| Equipment Type | Count | Utilization | FCE system TRL | BE system TRL | Likely conversion to FCE | Likely conversion to BE |
|---|---|---|---|---|---|---|
| Terminal tractor | High | High | 7 | 9 | ✓ | |
| Loaded container handler | Medium | High | 7 | 9 | ✓ | |
| Pickup truck | High | Low | - | - | | ✓ |
| Mobile harbor crane | Low | High | - | 8 | | ✓ |
| Light-duty forklift | Medium | Low | 9 | 9 | | ✓ |
| Medium-duty forklift | Low | Low | 5 | 9 | | ✓ |
| Heavy-duty forklift | Low | Low | - | 8 | | ✓ |

**Outputs**

| Equipment type | Fuel consumption, gal/year | | Electricity demand at port, MWh/year | | Hydrogen demand at port, tons/year | |
|---|---|---|---|---|---|---|
| | *Average hours* | *High hours* | *Average hours* | *High hours* | *Average hours* | *High hours* |
| Terminal tractor | 40,737 | 57,927 | - | - | 32 | 46 |
| Loaded container handler | 69,167 | 98,354 | - | - | 55 | 78 |
| Pickup truck | 5,866 | 8,341 | 3 | 4 | - | - |
| Mobile harbor crane | 16,241 | 23,094 | 293 | 416 | - | - |
| Light forklift | 2,922 | 4,155 | 49 | 70 | - | - |
| Medium forklift | 2,233 | 3,175 | 38 | 53 | - | - |
| Heavy forklift | 1,249 | 1,776 | 21 | 30 | - | - |

# Energy Demand Estimation: Formulas and Assumptions

## Assumptions

| | | |
|---|---|---|
| Battery electric powertrain efficiency | 94% | Reported peak system efficiency by manufacturers of electric powertrain systems, such as Dana TM4 [1] |
| Fuel cell powertrain efficiency | 60% | Peak proton-exchange membrane fuel cell efficiency @ lower heating value [2] |
| Diesel powertrain efficiency | 42%, 45% | Brake efficiency of the internal combustion engine used in heavy-duty transportation, brake efficiency of the internal combustion engine used for in large gensets [3] |
| Diesel energy content | 128,488 Btu-low heating value (LHV)/gal | Energy content of low sulfur diesel [4] |
| Hydrogen energy content | 33.3 kWh-LHV/kg | Energy content of hydrogen |

Note: The calculations assume peak powertrain efficiency. In real-world settings, efficiency should be informed by specific duty cycles. For example, diesel engines have high efficiency at peak load but low efficiency at part load operations.

*Sources:*

*[1] Dana TM4, n.d. TM4 Sumo direct-drive electric powertrain systems.; [2]Fuel Cell Technologies Office, 2015. Fuel Cells.; [3] Edwards KD, Wagner R, Briggs Jr. T, Theiss T. Defining engine efficiency limits 2011.; [4] ANL. Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, version 1. 2013. Input Fuel Specifications. 2013.*

# Energy Demand Estimation: Formulas and Assumptions

## Formulas

| | Formula | Description |
|---|---|---|
| 1 | $P_r = \left(\frac{HP}{1.34}\right) \times LF$ | Where $P_r$ is the average required mechanical power (kW), $HP$ is the average rated engine power, $LF$ is the engine load factor, and 1.34 is the conversion factor from HP to kW. Load factor is a portion of available power at which the type of engine typically operates. |
| 2 | $D_D = \frac{P_r \times 3.6 \times 10^6}{\eta_{bth} \times 1055.058 \times D_{LHV}}$ | Where $D_D$ is the diesel demand in gal/hour, $P_r$ is the required mechanical power in kW, $\eta_{bth}$ is the diesel brake engine thermal efficiency, and $D_{LHV}$ is the diesel lower heating value in Btu/gal. |
| 3 | $H_{2_D} = \frac{P_r}{\eta_{FC} \times H_{2_{LHV}}}$ | Where $H_{2_D}$ is the hydrogen demand in kg/hour, $P_r$ is the required mechanical power in kW, $\eta_{FC}$ is the fuel cell powertrain efficiency, and $H_{2_{LHV}}$ is the lower heating value of hydrogen in kWh/kg. |
| 4 | $E_D = \frac{P_r}{\eta_{FC}}$ | Where $E_D$ is the electricity demand in kWh/hour, $P_r$ is the required mechanical power in kilowatts, and $\eta_{FC}$ is the battery electric powertrain efficiency. |

## Illustration

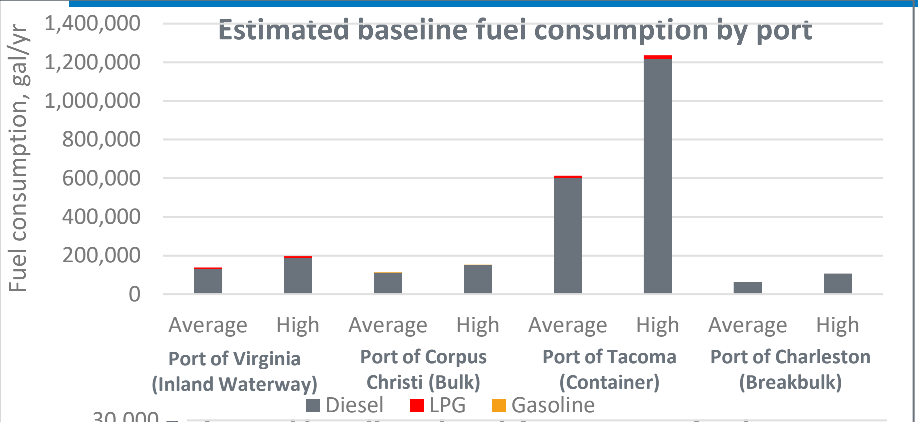
Kalmar loaded container handler: diesel 365 horsepower engine [1], 0.43 load factor [2]

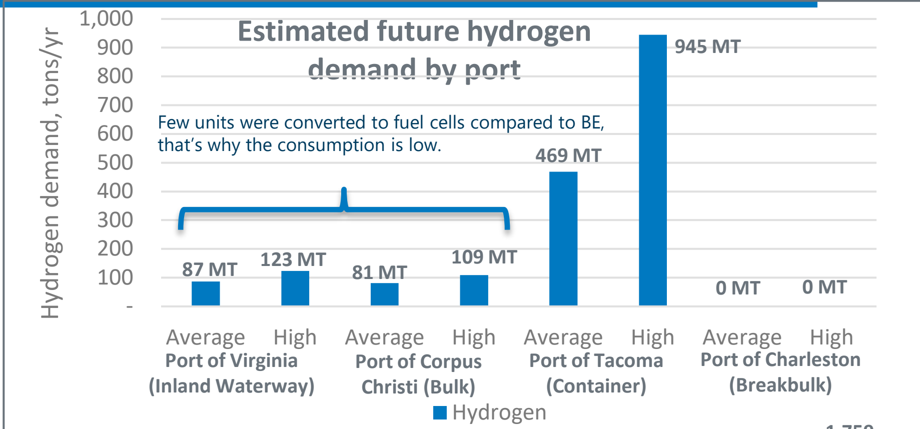
| | | |
|---|---|---|
| 1 | Average required mechanical power | 114 kW |
| 2 | Diesel demand | 7.2 gal/hour |
| 3 | Hydrogen demand | 5.7 kg/hour |
| 4 | Electricity demand | 121 kWh/hour |

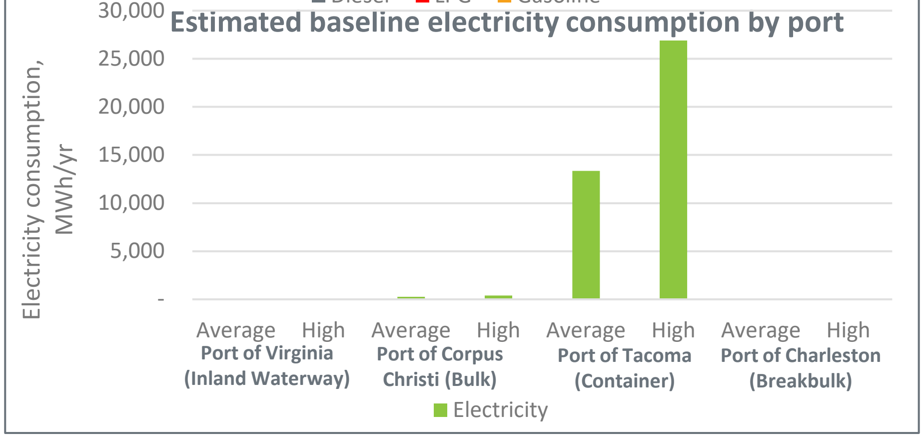
*Sources:*

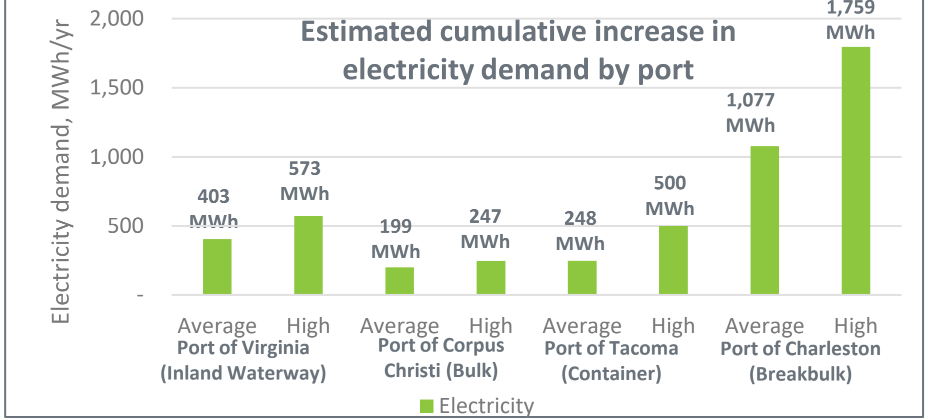
*[1] Kalmar Top Loader DCG400GS-410GS Brochure. [2] EPA, 2022. Port Emissions Inventory Guidance: Methodologies for Estimating Port-Related and Goods Movement Mobile Source Emissions.*

# Cargo-Handling Equipment Energy Demand Estimation



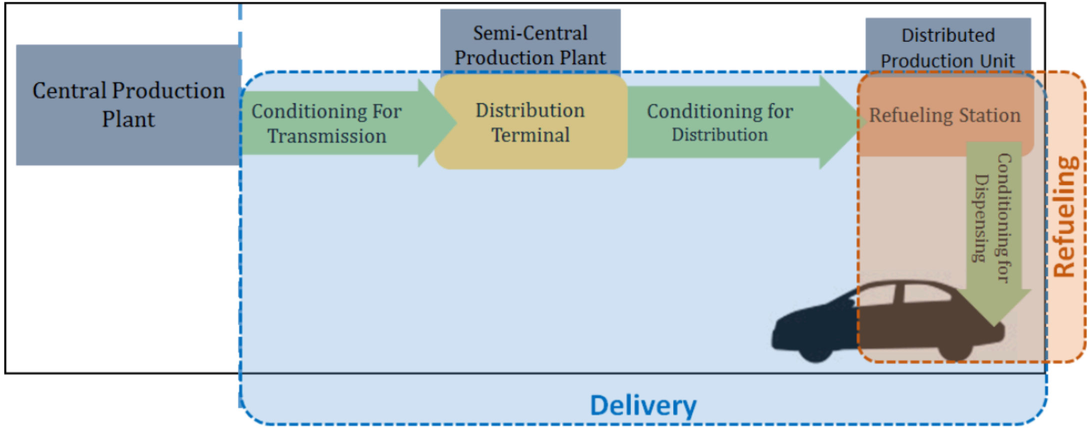

Note: The graphs include energy/fuel consumed by the equipment and exclude any energy used for hydrogen refueling or battery charging. Baseline electricity demand is associated with mainly cranes. At the Port of Virginia, it is a diesel-powered crane. At the Port of Corpus Christi, it is an electrified crane with a relatively low throughput capacity. At the Port of Tacoma, there are 7 cranes, all grid-connected and high usage. At the port of Charleston, there are no cranes. Note the analysis considers only at one terminal at each port to capture the difference between different cargo types.

# Step 4: Hydrogen refueling station installed cost

This section provides preliminary installed cost estimations for each port for stationary and mobile hydrogen refueling infrastructure to support the transition toward decarbonization goals.

# Cost Estimation Overview

- Approach:
  - Use Hydrogen Delivery Scenario Analysis Model (HDSAM) for initial capital costs
  - Base calculations on projected hydrogen demand per port (kg/day)



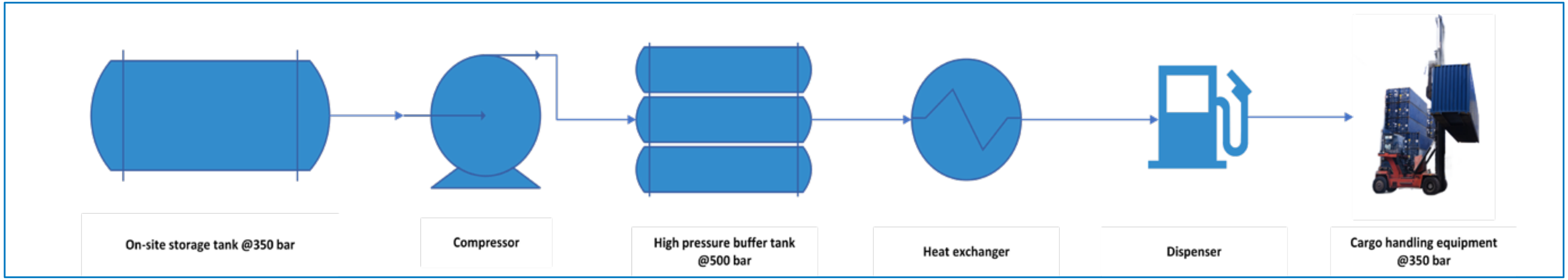

*Source: Argonne National Laboratory. Hydrogen Delivery Infrastructure Analysis. https://hdsam.es.anl.gov/*

- Scope:
  - On-site hydrogen storage and refueling infrastructure

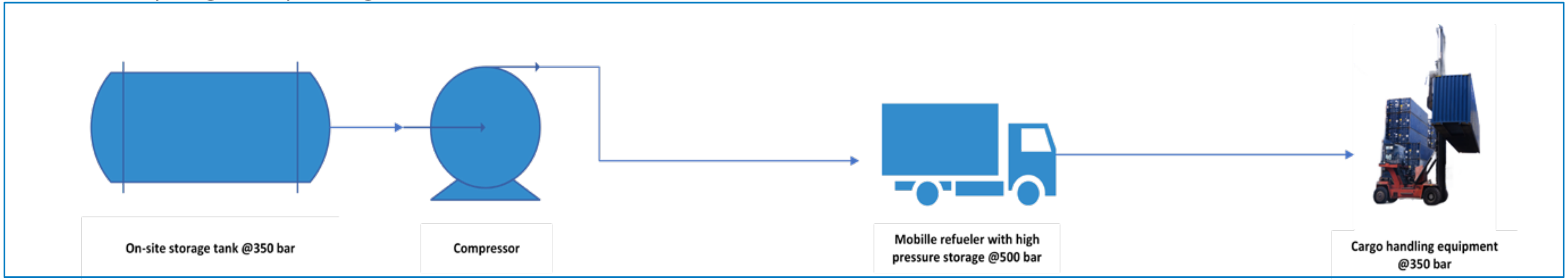
Note: Refer to HDSAM for the rest of operations and maintenance costs and refueling cost per kg

# Refueling Station Major System Components

Stationary hydrogen dispensing




Mobile hydrogen dispensing




Note: The section examines gaseous hydrogen refueling stations. Gaseous stations have limited expansion capabilities as it would lead to multiple tube-tailer deliveries per day (unless hydrogen is delivered via pipeline or produced on-site). Thus, liquid hydrogen stations should also be considered, especially for ports with high expected hydrogen demand.

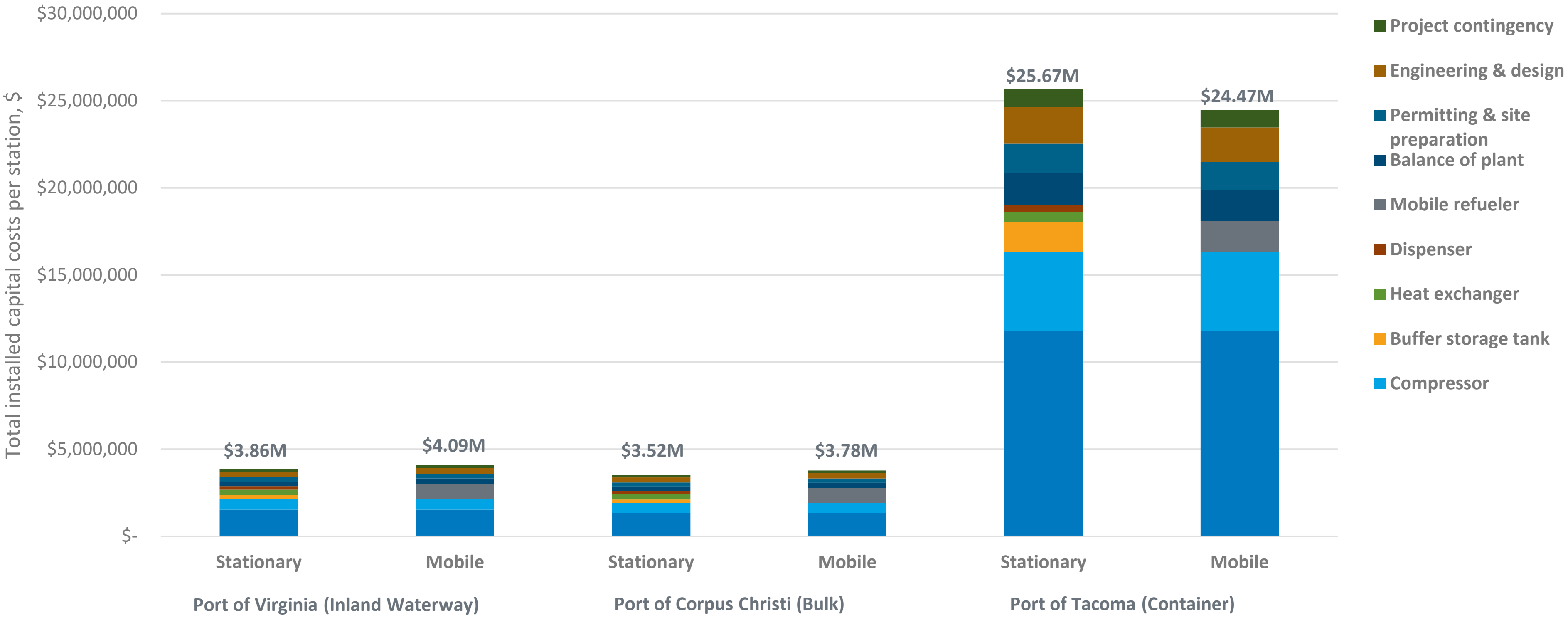
# Refueling Station Installed Capital Costs

| Major system component | Approximate cost [$2022] | Comment | Reference |
|---|---|---|---|
| Storage tank | $1,750/kg | Uninstalled cost of storage @200-350 bar, Type 1 | Hydrogen Delivery Scenario Analysis Model (HDSAM) v4.5 |
| Compressor (50 kg/hour) | $500,871 | Varies based on the number of compressor units and main compressor power. Example here refers to one 90 kW compressor. | HDSAM v4.5 |
| High pressure buffer tank | $1,679/kg | Uninstalled cost of storage @500 bar, Type 1 | HDSAM v4.5 |
| Heat exchanger system | $87,916 | Varies based on the number of heat exchangers (HX) and cooling capacity. Example here refers to 1 HX and 16-ton cooling capacity. | HDSAM v4.5 |
| Dispenser (3.6 kg/min) | $142,089 | Uninstalled cost per one dispenser | HDSAM v4.5 |
| Mobile refueler | $875,432 | Integrated refueler trailer with storage at 500 bar and dispensing with 150 kg onboard storage. Based on the manufacturer’s suggested retail price of a fuel cell electric short-haul truck ($214,000), storage and dispenser costs from above, BOP of 20%, and installation factor of 1.2. | Hunter et al., 2021; Air Products, n.d. |
| Balance of plant (BOP) | 10% | Percent of total uninstalled cost of major system components | |
| Installation cost | Installation factors for compressor, storage tanks, dispenser—1.3. Heat exchanger—2 | | HDSAM v4.5 |
| Permitting and site preparation | 8% | Percent of installed major components and BOP | HDSAM v4.5 |
| Engineering and design | 10% | Percent of installed major components and BOP | HDSAM v4.5 |
| Project contingency | 5% | Percent of installed major components and BOP | HDSAM v4.5 |

# Refueling Station Component Sizing: High Use Hours

| Parameter \ Port | Virginia (Inland Waterway) | Corpus Christi (Bulk) | Tacoma (Container) | Comment | Reference |
|---|---|---|---|---|---|
| Hydrogen demand, kg/day | 339 | 299 | 2,590 | Annual demand divided by the number of days, calculated based on high use | |
| On-site storage tank capacity, kg | 677 | 599 | 5,180 | Storage capacity is twice the daily demand | |
| Compressor capacity, kg/h | 48 | 37 | 235 | To accommodate peak demand and adjacent hour | HDSAM v4.5 |
| Compressor, units | 1 | 1 | 7 | Maximum flowrate of 50 kg/h per unit | HDSAM v4.5 |
| Buffer storage tank capacity, kg | 101 | 89 | 777 | 30% of daily station capacity | |
| Dispensers, units | 1 | 1 | 2 | Based on assumed refueling time for the fleet and refueling station operating hours | HDSAM v4.5 |
| Heat exchanger, units | 1 | 1 | 2 | One heat exchanger per dispenser | HDSAM v4.5 |
| Mobile hydrogen refueler, units | 1 | 1 | 2 | Equal to the amount of dispensers | |

# Installed Capital Cost for Each Port




Note 1: For Ports of Virginia and Corpus Christi, the capital cost of a mobile refueling station is higher due to the onboard storage capacity of a mobile refueler exceeding daily hydrogen demand.

Note 2: With high daily hydrogen demand (i.e., Port of Tacoma), hydrogen storage footprint at maritime terminals may present spatial challenges. Mobile refuelers would offer a solution by enabling hydrogen storage in proximity to the port instead.

# Step 5: Levelized cost of charging and refueling

This section provides the levelized cost of charging and refueling for each reference terminal based on estimated electricity and hydrogen consumption per shift. Dispensed hydrogen cost and electricity utility rates are specific to the California case.

# Levelized Costs of Charging/Refueling, California Case

Cost assumptions

| Charging Types | California (CA) Residential $/kWh | CA Utility $/kWh | CA Private Company $/kWh | Applicability $/kWh |
|---|---|---|---|---|
| AC Level 1 | $0.37 | $0.46 | $0.30 | Light duty vehicles: 120 V, ~1.4 kW peak (plugs in to regular wall outlet) |
| AC Level 2 | $0.43 | $0.47 | $0.32 | Light duty trucks (pickups): 240 V, 80 A, max ~19.6 kW peak power |
| DC Charging | $0.78 | $0.85 | $0.76 | Medium to Heavy Duty Vehicles: 50 kW—350 kW |
| Dispensed hydrogen | $10/kg* | | | Across all equipment types |

Cost of charging and refueling for the reference ports' fleets over an 8-hour shift (all battery electric versus all fuel cell electric scenario)

| Inland | | | Bulk | | | Container | | | Breakbulk | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Level 2 Charge Cost | DC Fast Charging (DCFC) Cost | Hydrogen Cost | Level 2 Charge Cost | DCFC Cost | Hydrogen Cost | Level 2 Charge Cost | DCFC Cost | Hydrogen Cost | Level 2 Charge Cost | DCFC Cost | Hydrogen Cost |
| $4,690 | $12,458 | $7,779 | $ 9,986 | $ 23,718 | $ 14,569 | $ 40,154 | $ 95,365 | $ 58,884 | $ 2,414 | $ 5,733 | $ 3,261 |

*Sources:*

*Electricity price - Argonne National Laboratory, 2023. CHECT.*

*Hydrogen price - Hunter, C., Penev, M., Reznicek, E., Lustbader, J., Birky, A., & Zhang, C. (2021). Spatial and temporal analysis of the total cost of ownership for class 8 tractors and class 4 parcel delivery trucks (No. NREL/TP-5400-71796). National Renewable Energy Lab.(NREL), Golden, CO (United States).*

**As per HFTO request.*

# Charging Cost, California Private Company Electricity Rates

| Equipment | Inland terminal | | | Bulk terminal | | | Container terminal | | | Breakbulk terminal | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Level 2 Charge Cost | DCFC Cost | Hydrogen Cost | Level 2 Charge Cost | DCFC Cost | Hydrogen Cost | Level 2 Charge Cost | DCFC Cost | Hydrogen Cost | Level 2 Charge Cost | DCFC Cost | Hydrogen Cost |
| Terminal tractor | $ 1,254.40 | $ 3,332.00 | $1,841 | | | | $ 573.44 | $ 1,361.92 | $ 837 | | | |
| Top Pick | $ 1,873.92 | $ 4,977.60 | $2,735 | | | | $ 588.80 | $ 1,398.40 | $ 859 | | | |
| Pickup Truck | $ 18.20 | $ 48.35 | $950 | | | | | | | | | |
| Mobile harbor crane | $ 468.48 | $ 1,244.40 | $688 | $ 849.92 | $ 2,018.56 | $1,247 | | | | | | |
| Light Forklift | $ 358.40 | $ 952.00 | $519 | | | | | | | | | |
| Medium Forklift | $ 266.24 | $ 707.20 | $387 | $ 6,809.60 | $ 16,172.80 | $9,955 | $ 1,743.36 | $ 4,140.48 | $ 2,594 | $683.52 | $1,623.36 | $1,003 |
| Heavy forklift | $ 450.56 | $ 1,196.80 | $658 | | | | | | | | | |
| Backhoe | | | | $ 92.16 | $ 218.88 | $131 | | | | | | |
| Shiploader | | | | $ 353.28 | $ 839.04 | $516 | | | | | | |
| Wheel loader | | | | $ 445.44 | $ 1,057.92 | $645 | | | | | | |
| Skid steer loader | | | | $ 243.20 | $ 577.60 | $349 | | | | | | |
| Sweeper | | | | $ 261.12 | $ 620.16 | $381 | | | | | | |
| Tractor | | | | $ 931.84 | $ 2,213.12 | $1,344 | | | | | | |
| STS crane | | | | | | | $ 15,805.44 | $ 37,537.92 | $ 23,215 | | | |
| Side handler | | | | | | | $ 1,474.56 | $ 3,502.08 | $ 2,155 | | | |
| Straddle carrier | | | | | | | $ 19,968.00 | $ 47,424.00 | $ 29,182 | | | |
| Crane truck | | | | | | | | | | $1,730.56 | $4,110.08 | $2,257 |
| **Total** | **$ 4,690** | **$ 12,458** | **$4,397** | **$ 9,986** | **$ 23,718** | **$ 14,569** | **$ 40,153** | **$ 95,364** | **$ 58,844** | **$ 2,414** | **$ 5,733** | **$ 3,261** |

Note 1: Costs shown are for all equipment units, not a per-unit basis; DCFC is DC fast charging

Note 2: Level 2 charging time could be higher and may affect the operation; it is used here for the cost comparison purposes.

# Step 6: Grid readiness and power reliability

# Estimated Electric Peak Demand by Ports From Hydrogen Refueling Station

| | Port of Virginia (Inland) | Port of Corpus Christi (Bulk) | Port of Tacoma (Container) |
|---|---|---|---|
| Hydrogen demand based on high use hours (kg/year) | 123,596 | 152,902 | 945,421 |
| Electricity consumption of the station based on the high use hours (kWh/year) | 128,402 | 158,847 | 982,177 |
| Power demand from refueling station (kW) | 14.65 kW | 18.13 kW | 112.13 kW |
| Order of magnitude peak demand (kW) | 44 kW | 54 kW | 336 kW |

Such order of peak demand magnitude shall not impact the existing electrical infrastructure.

- Specific refueling station electricity consumption for each port: 1.04 kWh/kg of hydrogen, on a low heating value basis.

Main assumptions:

- Max compressor pressure—525 bar
- Max storage tank pressure—350 bar
- Minimum storage tank pressure—50 bar
- Precooling temperature—(-30) °C

# Electrical Peak Demand by Ports From Electric Vehicles

| | Port of Virginia (Inland) | Port of Corpus Christi (Bulk) | Port of Tacoma (Container) | Port of Charleston (Breakbulk) |
|---|---|---|---|---|
| Battery-electric cargo handling equipment (CHE) peak demand (kW)—sum of EVSE | 1,626 | 3,600 | 2,760 | 1,260 |
| Grid-connected CHE peak demand (kW)—sum of kW per hr | 183 | 470 | 6,174 | Not applicable |

This peak demand is considered to check the electrical infrastructure impact analysis. Such increase in electrical demand would require upgradation in electrical infrastructure and explained in following slides. Due to unavailability of data from the reference ports, a general considerations are highlighted.

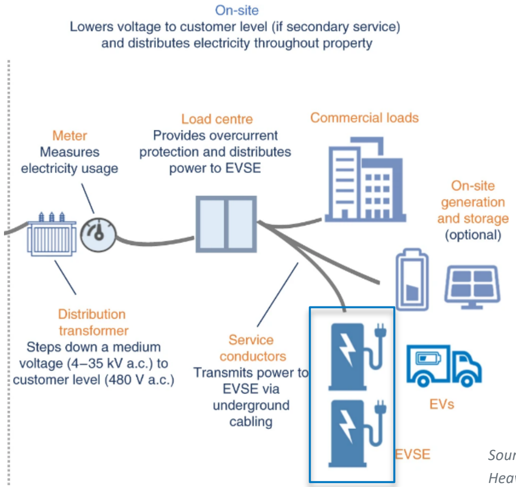
Methodology:

- Use charging and peak demand profile from reference port (Port of Honolulu) to scale estimates of peak demand for each of the following ports
- Categorize each of the equipment into light, medium, and heavy duty-based kWh/hr
- Assign electric vehicle supply equipment (EVSE) requirement to each piece of equipment (light-duty 24 kW, medium-duty 150 kW, heavy-duty 180 kW) (as per https://taylorforklifts.com/products/electric-lift-truck/loaded-container-handler)
- As in reference port data, use most conservative estimate for peak demand: 1:1 equipment to charger ratio, all equipment charging at once

# Cost Range: Electric Vehicle Supply Equipment, Based on Study for Heavy-Duty Truck

| Scenario | EVSE Unit Power (kW) | EVSE Unit Count | EVSE Cost ($/kW) | EVSE Unit Cost ($/unit) | Total EVSE Capacity (MW/site) | Site Total EVSE Cost ($K) |
|---|---|---|---|---|---|---|
| Low range | 150 | 24 | $299.72 | $44,958 | 3.60 | $1,079 |
| High range | 150 | 24 | $415.68 | $62,352 | 3.60 | $1,496 |

The cost of these units as represented in dollars per kilowatt were developed in agreement with the 21CTP infrastructure working group as informed by market analysis performed by the Electric Power Research Institute and a report developed by Gladstein, Neandross & Associates (GNA) for megawatt charging (GNA 2021) and a report by BNEF (Fisher 2020) for kilowatt charging. To account for variability in these costs, ranges were determined for each electric vehicle supply equipment (EVSE) unit's power level—50 kW, 150 kW, and 3 MW—with the **low installation cost scenarios accounting for the lower end of the range and the high installation cost scenario accounting for the higher end of the range**.




| Scenario | EVSE Unit Power (kW) | EVSE Count | EVSE Maintenance ($/year) |
|---|---|---|---|
| Low range | 150 | 24 | $76,800 |
| High range | 150 | 24 | $76,800 |

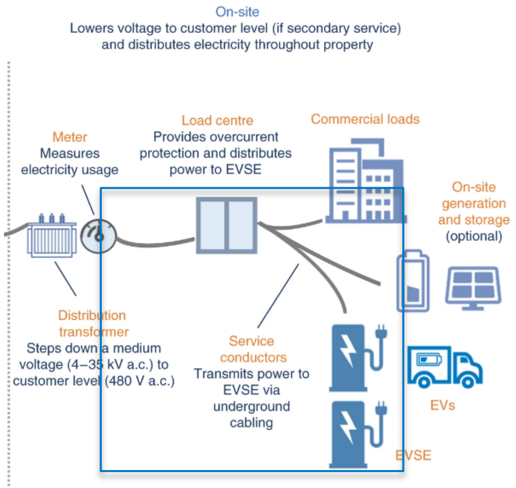
To facilitate the installation of electric vehicle supply equipment (EVSE) units, the site costs must account for the land requirements for site equipment (Black & Veatch, n.d.), parking, and traffic flow, as well as the regular maintenance of EVSE including both **hardware repairs and the network connection costs necessary for transaction processing**.

*Source: Estimating the Breakeven Cost of Delivered Electricity To Charge Class 8 Electric Tractors, https://www.nrel.gov/docs/fy23osti/82092.pdf*
*Heavy-duty truck electrification and the impacts of depot charging on electricity distribution systems, https://www.nature.com/articles/s41560-021-00855-0*

**Note that these costs are very high level, may vary greatly for different projects. Cost numbers are from the published documents and are not site specific.**

# Cost Range: Load Center to Electric Vehicle Supply Equipment, Based on Study of Heavy-Duty Truck

| Scenario | EVSE Unit Power (kW) | Install Cost ($/kW) | EVSE Install ($/unit) | EVSE Capacity (MW/site) | Site Install Cost ($K) |
|---|---|---|---|---|---|
| Low range | 150 | $750.00 | $112,500 | 3.60 | $2,700 |
| High range | 150 | $1,080.00 | $162,000 | 3.60 | $3,888 |




Installation costs for each station configuration, included all **wiring, conduit, protection, and other facility equipment upgrades, as well as construction costs such as trenching that may be required**. Put simply, this metric captures all of the installation and construction costs—**with the exception of the EVSE unit—for everything on the charging station side of the utility meter**.

*Source: Estimating the Breakeven Cost of Delivered Electricity To Charge Class 8 Electric Tractors, https://www.nrel.gov/docs/fy23osti/82092.pdf*

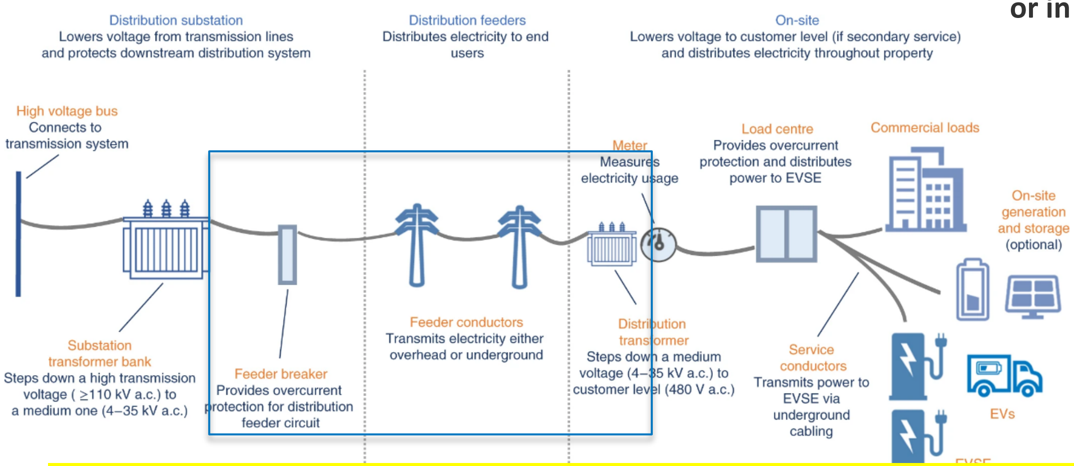
*Heavy-duty truck electrification and the impacts of depot charging on electricity distribution systems, https://www.nature.com/articles/s41560-021-00855-0*

**Note that these costs are very high level, may vary greatly for different projects. Cost numbers are from the published documents and are not site specific.**

# Cost Range: Utility Upgrade Based on Electric Vehicle Supply Equipment Study for Heavy-Duty Truck

| Scenario | EVSE Unit Power (kW) | EVSE Capacity (MW/site) | Site Peak Demand (MW) | Utility Upgrade Costs ($K) |
|---|---|---|---|---|
| Low range | 150 | 3.60 | 4.23 | 945 |
| High range | 150 | 3.60 | 4.23 | 2,445 |

The necessary grid upgrades included **new service drops, distribution transformer upgrades, and, for the larger sites, the costs associated with a reconductoring of the main feeder line**. There is some uncertainty associated with these costs, and therefore a range of upgrade costs was determined with the lower end of the range applying to low installation cost scenarios and the upper end of the range associated with high installation cost scenarios. **Not that these costs are sometimes covered completely or in part by the utility.**




*Source: Estimating the Breakeven Cost of Delivered Electricity To Charge Class 8 Electric Tractors, https://www.nrel.gov/docs/fy23osti/82092.pdf*

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**Note that these costs are very high level, may vary greatly for different projects. Cost numbers are from the published documents and are not site specific.**

# On-Site Generation and Storage Solution Considerations

- On-site generation and storage solutions can help the integration of battery electric cargo handling equipment, electric vehicle supply equipment (EVSE), and the hydrogen refueling station by reducing the peak demand and energy consumption from the utility.
- To determine the optimal distributed energy resource mix and size, a techno-economic analysis can be performed.
- First step is to derive the load profile, considering the EVSE charging demand and hydrogen refueling station electric power consumption for a year with as much granularity as possible.
- Based on the port and area available for solar photovoltaics (PV), PV size constraints can be highlighted.
- For economic consideration, the discount rate, capital expenditures and operating expenditures of distributed energy resources (DERs), and utility tariffs are assumed.
- Operational characteristics for the DERs are considered throughout their life.
- Tools like Renewable Energy Optimization (REopt) can be used to perform the techno-economic analysis.
- The outcome of the analysis will be optimal DER mix, size, dispatch strategy, and potential economic outcomes such as net present value, return on investment, and payback.

# Task 2 Key Takeaways

- Equipment conversion and energy demand analysis
  - Use profiles vary across ports for same equipment types (e.g., forklifts)
  - Modern cranes (e.g., ship-to-shore, mobile harbor) often grid-connected or capable
  - Highest hydrogen demand likely to originate from container terminals, depending on the equipment profiles:
    a. Straddle carriers, container handlers
    b. Rubber tired gantries, container handlers, terminal tractors, reach stackers
    c. Container handlers, terminal tractors
- Refueling station analysis
  - On-site storage: significant capital expenditure impact; potential mitigation via tube trailer delivery and storage
  - Mobile refuelers: cost uncertain, potentially effective for large deployment (e.g., Port of Tacoma)
  - Average station use: ~50% to 75%

# Task 3: Methodology Block Diagram: Development and Validation of an Adaptive Model Linking Equipment Inventory With Energy Demand and Capacity Metrics

## Task 1

Data collected for each port:

- Equipment count
- Average use hours
- Fuel type
- Horsepower rating
- Load factor

## Task 3

**Step 1: Define variables**

- Dependent variable: Energy demand, measured in kWh for storage capacity or kW for power demand
- Independent variables: Cargo type, cargo handling equipment inventory, cargo throughput (twenty-foot equivalent units [TRUs], volume, or weight)

**Step 2: Data collection and preparation**

- Task 1 provides data for four reference ports
- Associating the data with the variables

**Step 3: Model formulation**

Linear regression equation:

$$E = a \times TEU + b \times Weight + c \times Volume + \Sigma(d_i \times Equipment_i) + e$$

- $E$ = Energy demand
- $TEU$ = container port throughput
- $Weight$ = cargo weight throughput for bulk / breakbulk
- $Volume$ = cargo weight for
- $Equipment$ = number of each type of cargo handling equipment
- $a, b, c, d$ = coefficients, to be estimated
- $e$ = offset, to be estimated

**Step 4: Coefficient ($a, b, c, d$) Estimation**

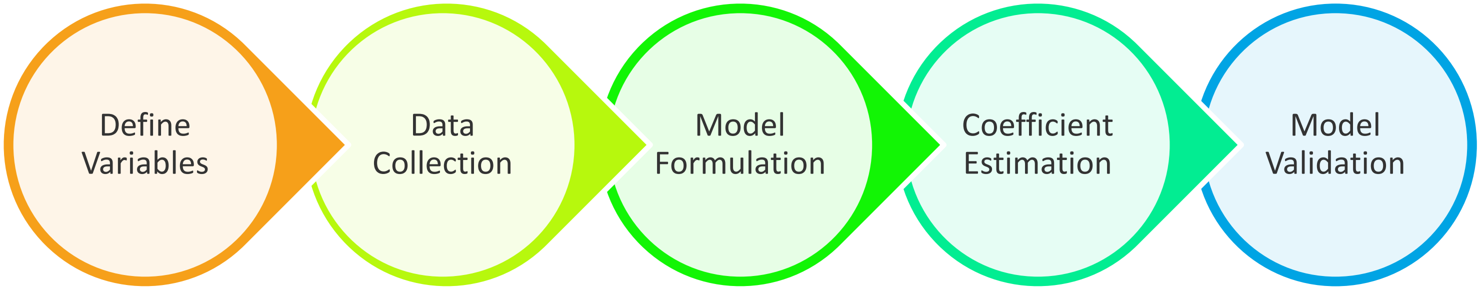
- Using Step 2 data, dataset is prepared to train and validate the model and extract the coefficient

**Step 5: Validating the model**

- Model will be validated with untrained data set.

# Model Development Approach

Task: *“Based on the inventory of equipment, the researchers should develop a flexible model that relates capacity factors (twenty-foot equivalent units, weight, volume, etc.) to equipment inventories and energy demand.”*



# Variable Definition

**Model output (dependent variable)**

- Annual energy demand *(E)*, measured in kWh

**Model inputs (independent variables)**

- Cargo type (bulk, breakbulk, container, Inland Waterway)
- Cargo handling equipment inventory
- Cargo capacity/throughput (measured in twenty-foot equivalent units or tons)

# Data Collection

### Cargo Handling Equipment

Terminal tractor
Top pick
Pickup truck
Mobile harbor crane
Light lorklift
Medium forklift
Heavy forklift
Backhoe
Shiploader
Wheel loader
Skid steer loader
Sweeper
Tractor
Ship-to-shore crane
Side handler
Straddle carrier
Crane truck

### Operational Profile

Shift Hours
Number of shifts per day
Equipment usage hours
Equipment downtime hours
Seasonal changes (e.g., Richmond Inland Waterway port)
Grid connected equipment defined

### Port Energy Consumption

Utility bills
Hourly, monthly, annual energy demand

### Cargo Throughput

Annual or monthly cargo throughput
Historical throughput and estimated growth rates

# Data Collection

Data was collected for each port type: bulk, breakbulk, container, Inland Waterway

- Cargo handling equipment inventory and usage hours
- Operational profile of port (number of shifts and duration, seasonal variations, vessel calls)
- Cargo throughput (by twenty-foot equivalent unit, weight, or volume)
- Port energy consumption

Note: Too few data points were collected for bulk and breakbulk freight, model was only formed with the container and inland waterway ports (with twenty-foot equivalent unit freight)

# Model Formulation

Multivariate linear regression equation:

$$E = a \times TEU + \Sigma(b_i \times Equipment_i) + c$$

- $E$ = Energy demand
- $TEU$ = container port throughput
- $Equipment$ = number of each type of cargo handling equipment
- $a$ & $b$ = coefficients, to be estimated
- $c$ = offset or intercept, to be estimated

# Model Formulation

## Linear Regression Steps

### Data preparation

1. Data cleaning (missing values, duplicates, anomalous values)
2. Splitting dataset into testing and training datasets
3. Dealing with categorical variables (encoding, if applicable)

### Fitting data to linear regression model

- Use of Excel for user friendliness
- Least squares method
- Estimate coefficients through minimizing squared difference between observed and predicted energy demand

### Extract coefficients

- Using fitted model

# Model Formulation

## Raw Data Snapshot

| Port Type | Equipment Type | Equipment Number | Annual Twenty-Foot Equivalent Units | Annual kWh Demand |
|---|---|---|---|---|
| Inland | Top pick | 6 | 52000 | 1171200 |
| | Mobile harbor crane | 1 | | 292800 |
| | Light forklift | 5 | | 49840 |
| | Medium forklift | 2 | | 37960 |
| Container | Ship-to-shore crane | 7 | 1249920 | 13335840 |
| | Medium forklift | 10 | | 270357 |
| | Terminal tractor | 4 | | 55776 |

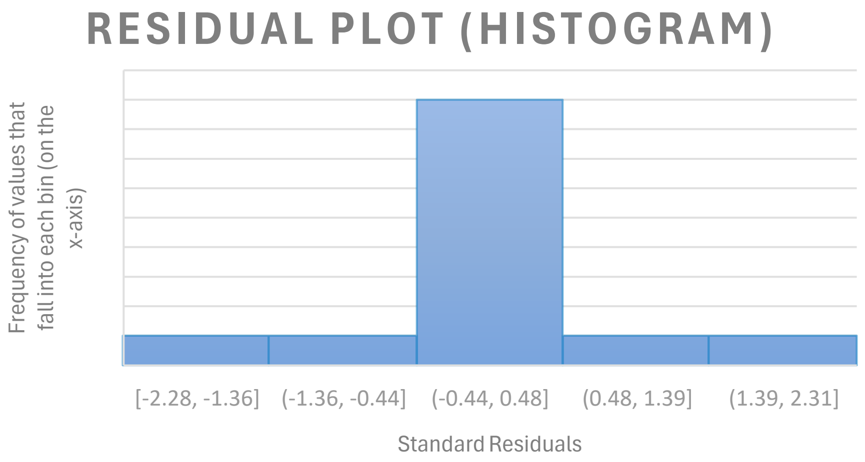
# Regression Model Results

Our initial prediction of a linear relationship between the inputs (equipment inventory and annual throughput) and the annual energy consumption was correct.

The model is a very good fit for the data, meaning that the model explains the relationship between the inputs and the outputs well.

**Regression Statistics**

- **Adjusted R-Square** value of **0.9997—**more than 99% of variance explained by the model
- Normal distribution of residuals (error terms) around zero: the model captures the patterns in the data we predicted and the sources of error in the model are random and independent. If this was not true, then our model would be biased.



# Model Validation

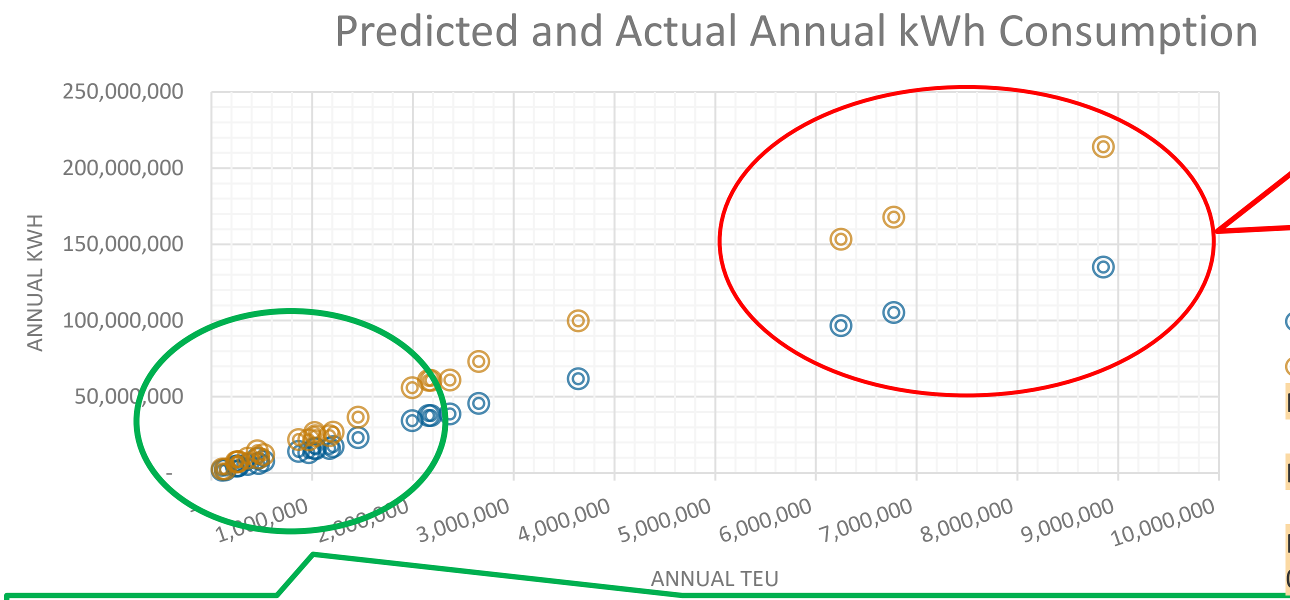
*Model validated on data from the Top 25 United States Container Ports*


**SOURCE**: U.S. Department of Transportation, Bureau of Transportation Statistics, based upon 2021 data (latest available) provided by U.S. Army Corps of Engineers, Waterborne Commerce Statistics Center. Special tabulation as of November 2023.

# Model Validation
## Discussion

The model was validated using the annual twenty-foot equivalent unit (TEU) throughput of the top 25 U.S. ports, and estimated equipment inventories and annual kWh consumed for all-electric cargo handling equipment, leveraging our previous DOE port projects work.

More data from a set of ports with a diverse number of annual TEUs are required to predict the annual kWh at higher tonnages. As the model was trained on smaller ports, the energy consumption of larger ports (tonnage-wise) is not predicted as well. The mean absolute percentage error is 0.6.




Model metrics:

R2: 0.3803

Mean absolute percentage error: 0.5781

The model was trained on data from two ports, with about 52,000 and 1.2 million annual TEU throughput, respectively. Therefore, at lower annual TEUs, the model predicts the annual energy consumption (kWh) better. There is a closer fit between the model predicted data and the validation data. The mean absolute percentage error of 0.57.

# Model Results Discussion

## Multivariate regression model results

- The model was *trained* on the full data for container freight ports that was collected in this project (13 observations).
- The model helps understand the impact of certain variables on the total energy demand.
- R-Squared (measure of variation) = **0.9997 (very close to 1, meaning that the model is a good fit for the data)**
- Normal distribution of residuals (error terms) around zero

## Model validation results

- The model was *validated* on data from the top 25 ports in the United States. The annual twenty-foot equivalent unit throughput was provided by the Bureau of Transportation Statistics. The all-electric cargo handling equipment inventory and annual kWh consumed was calculated, leveraging a previous DOE ports project.
- The model statistics demonstrate that this model is a good fit for understanding the energy demand but systematically underestimates energy demand, especially for ports with higher annual throughput.
- R-squared value = 0.3803 (lower value, meaning that the model requires more refinement to predict the data)
- Sources of variation could include different equipment types being used at ports and operational profiles.

# Future Work Proposed

- Further data collection on all port types: bulk, breakbulk, inland, and container. This would allow model creation and validation to include all ports types (Note that the model was only trained on the container and inland ports [with twenty-foot equivalent units as freight], because there was relatively little data for bulk and breakbulk ports and no data for validation.)

- Data collection on the footprint of each port, to provide a more accurate energy consumption estimation

- Data collection from a diverse range of port sizes (annual freight throughput) to better predict a spectrum of energy consumption

- Data collection and in-depth analysis of the operational profile of a diverse set of ports

# Task 3 Key Takeaways

- Scoping the energy demand model helped identify the main consumers at the port and what variables affect the overall energy demand.
- We developed a model that predicts well the all-electric cargo handling equipment annual energy consumption for ports with annual tonnage of less than 2 million twenty-foot equivalent units
- The model helped us understand the gaps in current data and outline a path forward for future data collection and model refinement.
- The model is a good rubric to follow for further energy demand models that can create a scalable solution to understand the energy needs of cargo handling equipment, whether they are all-electric, hydrogen fuel cell, or powered by another fuel type.

# Task 4: Zero and near-zero emission fuel supply at ports

Evaluation of zero and near-zero emission fuel production and bunkering at ports

# Alternative Maritime Fuels for Ocean-Going Vessels

| | Methanol | Ammonia | Hydrogen |
|---|---|---|---|
| Engine technical readiness level[1] | 9 | 5-6 | 4 |
| Existing applications in deep-sea shipping | Tankers carrying methanol as cargo have used dual fuel engines since 2017 | Tankers carry ammonia as cargo, but engines are still in development | Liquefied hydrogen carrier completed its maiden voyage carrying liquid hydrogen as cargo |
| Global fleet on order added in 2023[2] | 138 vessels, mostly container ships | 11 vessels, the first year with orders | 5 vessels, hydrogen role limited to auxiliary for deep-sea/main power for short-sea |
| Fuel properties under ambient conditions | Liquid | Gas | Gas |
| Fuel energy density under ambient conditions | 15.7 MJ/L<br>19.5 MJ/kg | 11.65 MJ/L<br>22.5 MJ/kg | 8.5 MJ/L for liquid hydrogen<br>120 MJ/kg |
| Fuel safety considerations[1] | Toxic, flammable | Toxic, low flammability range | Nontoxic, wide flammability range |
| Combustion emissions compared to conventional fuel[3] | Lower carbon dioxide ($CO_2$), sulfur oxides (Sox), particulate matter (PM), nitrogen oxides (NOx) | Lower SOx and PM, no direct $CO_2$; higher NOx and $NO_2$. | No direct $CO_2$, $SO_x$, lower PM<br>Potentially higher NOx with internal combustion<br>Zero-emission if using fuel cells |

*1 Eirik O, Longva T, S. Hammer L, Hydle Rivedal N, Endresen Ø, S. Eide M. Maritime Forecast to 2050, Energy Transition Outlook 2022. DNV; 2022.*

*2 DNV. Maritime decarbonization efforts propelled as orders for alternative-fueled vessels grow 2024. https://www.dnv.com/news/maritime-decarbonization-efforts-propelled-as-orders-for-alternative-fueled-vessels-grow-251921/.*

*3 Bureau Veritas Marine & Offshore. Alternative Fuels Outlook for Shipping. 2022.*

# Alternative Maritime Fuels for Ocean-Going Vessels

| Particulars | Methanol | Ammonia | Hydrogen |
|---|---|---|---|
| Regulations | Covered by the International Maritime Organization's (IMO's) Interim Guidelines for Low Flash-Point Fuels and interim guidelines for the safety of ships using methyl/ethyl alcohol as fuel | No prescriptive rules. IMO Working item as a fuel, tentative classification rules available | No prescriptive rules. IMO working item, classification rules working item. Current regulations target fuel cells. |
| On-board storage | Mature solutions for storage, can use established procedures for diesel | Fuel can be compressed or refrigerated to increase volumetric density | Depending on the application, fuel can be compressed or liquified to increase volumetric density. |
| Bunkering | Bunkering is similar to conventional liquid fuels, but additional procedures are required (TTS, STS, BTS demonstrated) | Solutions will need to be developed based on handling ammonia-as-cargo (STS demonstrated in 2024) | Liquid hydrogen bunkering solutions in development. Experience with liquefied natural gas can be applicable (TTS demonstrated). |

## Scope

Due to the properties of hydrogen (i.e. energy density by volume), the scope of marine fuels for deep-seas shipping vessels is limited to:

- Ammonia: bunkering pilots conducted, no regulatory and safety frameworks in place
- Methanol: bunkering validated in various locations, established regulatory guidelines

Hydrogen may be applicable for short-sea shipping (e.g., harbor craft)

TTS: truck-to-ship, STS: ship-to-ship, BTS: barge-to-ship

# Fuel Supply Strategies for Ports

Local production costs

Bunkering demand

**Importing incumbents: high demand, high production costs**

Recommended strategy:

- Importing fuels from low-cost production hubs
- Establishing partnerships with production regions and integrations into import/export corridors

**Producing incumbents: high demand, low production costs**

Recommended strategy:

- Readiest opportunity to become first movers in bunkering by leveraging existing bunkering hub status
- Proactive collaboration to activate demand for new fuels, build infrastructure, develop regulations, permitting

**Bespoke players: low demand, high production costs**

Recommended strategy:

- Adopt a proactive approach to obtain low-cost imports
- Attract demand to lower last mile costs
- Focus on bunkering one fuel in the near term

**Future exporters: low demand, low production costs**

Recommended strategy:

- Develop export markets by activating demand from shipping and other sectors to de-risk the investments and high last-mile costs
- Focus on bunkering one fuel in the near term
- Engage with first-mover segments and consider green corridors, partner with importing incumbents

RMI, 2024.Oceans of Opportunity: Supplying Green Methanol and Ammonia at Ports

# Reference Ports: Case Studies

**Corpus Christi: Future Exporter**

- **Demand**:
  - Small bunkering market (700,000 tons of conventional bunkers per year)
  - Vessel types: tankers
  - 80,000 tons of ammonia required with 5% penetration by 2030
- **Supply/fuel sourcing:**
  - Ammonia in the near-term, potential for methanol in the future
  - Announced projects in the region cover the bunkering quantities
  - Potential constraints: scalable water supply, timing of transmission upgrades
- **Infrastructure:**
  - No existing ammonia storage
  - Opportunities for both new infrastructure and retrofitting liquefied petroleum gas storage
  - Early-stage readiness for bunkering

**Ports of Seattle/Tacoma: Bespoke Player**

- **Demand:**
  - Medium bunkering market (1.7 million tons of conventional bunkers per year)
  - Vessel types: container
  - 170,000 tons of methanol required with 5% penetration by 2030
- **Supply/fuel sourcing:**
  - Focus on methanol
  - Local production constraints: new solar, wind deployment and low capacity factors
  - No established partnerships with suppliers across the country
  - Likely to face competition to secure low-cost methanol
- **Infrastructure:**
  - No existing methanol storage
  - Green shipping corridors with South Korea and Alaska in development
  - No regulatory authority over bunkering
  - Early-stage readiness for bunkering

RMI, 2024.Oceans of Opportunity: Supplying Green Methanol and Ammonia at Ports

# Reference Ports: Case Studies

**Virginia: Bespoke Player**

- **Demand**:
  - Estimated small to medium bunkering market
  - Vessel types: container (60%), dry bulk (22%)[1]
- **Supply/fuel sourcing:**
  - Focus on methanol
  - No existing/announced green methanol projects in the region—closest announced e-methanol facility in Texas[2]
- **Infrastructure:**
  - No existing methanol storage or bunkering[2]
  - Operating port, but bunkering appears to be provided by third-parties
  - Plans for liquefied natural gas bunkering
  - Early-stage readiness for bunkering

**Charleston: Bespoke Player**

- **Demand:**
  - Estimated small bunkering market
  - Vessel types: container (70%), other freight (3%)[1]
- **Supply/fuel sourcing:**
  - Focus on methanol
  - No existing/announced green methanol projects in the region – closest announced e-methanol facility in Texas[2]
- **Infrastructure:**
  - Methanol storage, no bunkering[2]
  - Operating port, but bunkering appears to be provided by third-parties
  - No publicly available plans for alternative fuel bunkering; liquefied natural gas vessel hosted in 2023
  - Early-stage readiness for bunkering

[1] Bureau of Transportation Statistics, 2024. Port Profiles.
[2] Methanol Institute. E-Methanol & Biomethanol Plants and Ports

# Task 4 Key Takeaways

- Hydrogen role as a marine fuel
  - Unlikely for ocean-going vessels due to its properties
  - Potential applications include shore power and harbor craft (e.g., tugboats)
- Port archetypes:
  - Three out of four reference ports classified as Bespoke Player with low bunkering demand and high fuel production cost
  - All reference ports are in early-stage readiness for methanol or ammonia bunkering

# Task 4 References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# Future Work

- Scope: include other hydrogen applications at ports (e.g., shore power for ocean-going vessels, harbor craft, stationary power, potentially consider drayage trucks)
- Powertrain cost comparison:
  - Account for initial equipment cost and compare equipment on a total cost of ownership basis instead of fuel savings
  - Account for average powertrain efficiency informed by equipment duty cycles
- Hydrogen production/delivery: evaluate hydrogen production/delivery opportunities at or near ports (e.g., on-site electrolysis, industrial production on adjacent land for export, import, pipeline)

# Thank You

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