SAN PEDRO BAY PORTS

2024 ZERO-EMISSION CARGO HANDLING EQUIPMENT FEASIBILITY ASSESSMENT

Port of Los Angeles & Port of Long Beach

PROJECT NO. 173664 / 177017

REVISION 3

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List of Abbreviations

Abbreviation	Definition
A	amp
AC	alternating current
ARCHES	Alliance for Renewable Clean Hydrogen Energy Systems
BABA	Build America Buy America
CAAP	Clean Air Action Plan
CapEx	capital expense
CARB	California Air Resources Board
CCS	Combined Charging System
CHE	cargo handling equipment
DC	direct current
DCFC	direct current fast charging
EPA	United States Environmental Protection Agency
EV	electric vehicle
EVSE	electric vehicle supply equipment
IEC	International Electrotechnical Commission
kg	kilogram
kW	kilowatt
kWh	kilowatt hour
LADWP	Los Angeles Department of Water and Power
lb	pound
MCS	Megawatt Charging Standard
LCFS	Low Carbon Fuel Standard
MW	megawatt
NACS	North American Charging Standard
NPV	net present value
NREL	National Renewable Energy Laboratory
NZE	near-zero-emissions
O&M	operations and maintenance
OpEx	operational expense
POLA	Port of Los Angeles

Abbreviation	Definition
POLB	Port of Long Beach
Ports	San Pedro Bay Ports
RTG	rubber-tired gantry
SAE	Society of Automotive Engineers
SCE	Southern California Edison
SOC	state of charge
SPBP	San Pedro Bay Ports
TAP	Technology Advancement Program
TCO	total cost of ownership
TRL	Technology Readiness Level
WBCT	West Basin Container Terminal
YTI	Yusen Terminal
ZE	zero emission

Executive Summary

The 2024 Zero-Emission (ZE) Cargo Handling Equipment (CHE) Feasibility Assessment evaluates the readiness of battery-electric and hydrogen fuel cell yard tractors, top handlers, large-capacity forklifts, and rubber-tired gantry (RTG) cranes to replace internal combustion engine models at the ports of Long Beach and Los Angeles, collectively known as the San Pedro Bay Ports (SPBP or the Ports). This report provides an update on the progress that has been made in developing and deploying ZE CHE since the last 2021 assessment and examines the likelihood of meeting the Clean Air Action Plan (CAAP) goal of transitioning 100% of CHE to ZE technologies by 2030. The assessment focuses on the four CHE that comprise approximately 78 percent of the more than 3,700 SPBP CHE (Table ES-1).

Table ES-1: Assessed ZE CHE

CHE	Battery Electric	Grid Electric	Hydrogen Fuel Cell
Yard Tractor	●		●
Top Handler	●		●
Large-Capacity Forklift	●		●
RTG Crane	●	●	●

Methodology

ZE CHE feasibility was assessed based on the results of technology demonstration projects performed between 2021-2024; surveys of and interviews with marine terminal operators, original equipment manufacturers, and Ports staff; and review of publicly available CHE specifications, inventories, and reports. ZE CHE were evaluated based on five assessment parameters defined in the CAAP Feasibility Assessment Framework:

1. **Commercial Availability:** Number of manufacturers offering ZE CHE models designed for port cargo terminal operations.
2. **Technical Viability:** State of technology readiness based on transition from laboratory testing to prototypes to real world deployments.
3. **Operational Feasibility:** Ability to achieve diesel-equivalent performance, including completing two 8-hour shifts without charging/fueling. Charging/fueling is performed during the 3:00 – 7:00 am hoot shift, which is not commonly used for cargo handling operations.
4. **Infrastructure Readiness:** Charging and fueling infrastructure and supply readiness to support the full transition to ZE CHE.
5. **Economic Workability:** Total cost of ownership (TCO) is equivalent to diesel equivalent models, evaluated with and without incentives.

Key Findings

There have been significant advancements in battery-electric CHE since the 2021 assessment, while fuel-cell CHE are largely in the prototype stage. Technology demonstration projects have provided valuable feedback to manufacturers that have helped improve the performance and range of battery-electric models. From 2021-2024, many battery-electric models and hands-free (mechanized and inductive) chargers had integration and reliability issues that limited their sustained use; however, the most recent generations of battery-electric yard tractors, top handlers, and large-capacity forklifts are achieving the terminal operators' desired operational capability of completing two shifts without opportunity charging. Feasibility assessment summaries for battery-electric and fuel-cell yard tractors, top handlers, large-capacity forklifts, and RTG cranes, as well as grid-electric RTG cranes, are presented in Figures ES-1 – ES-9.

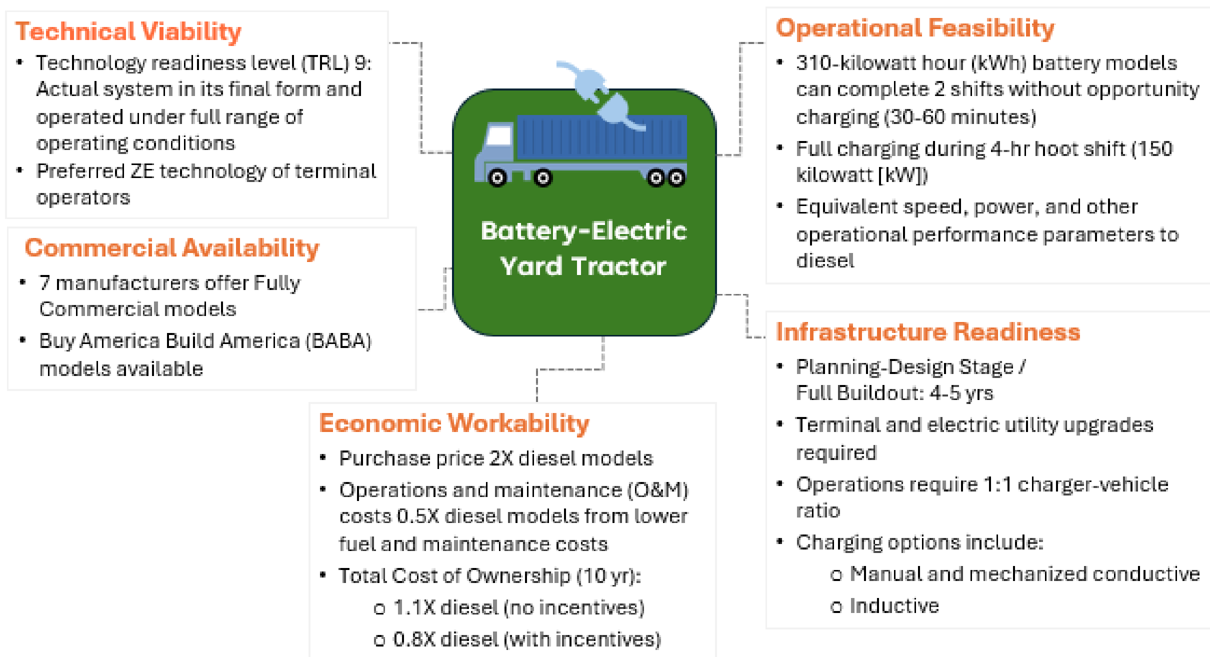

Figure ES-1: Battery-Electric Yard Tractor Feasibility Assessment Summary

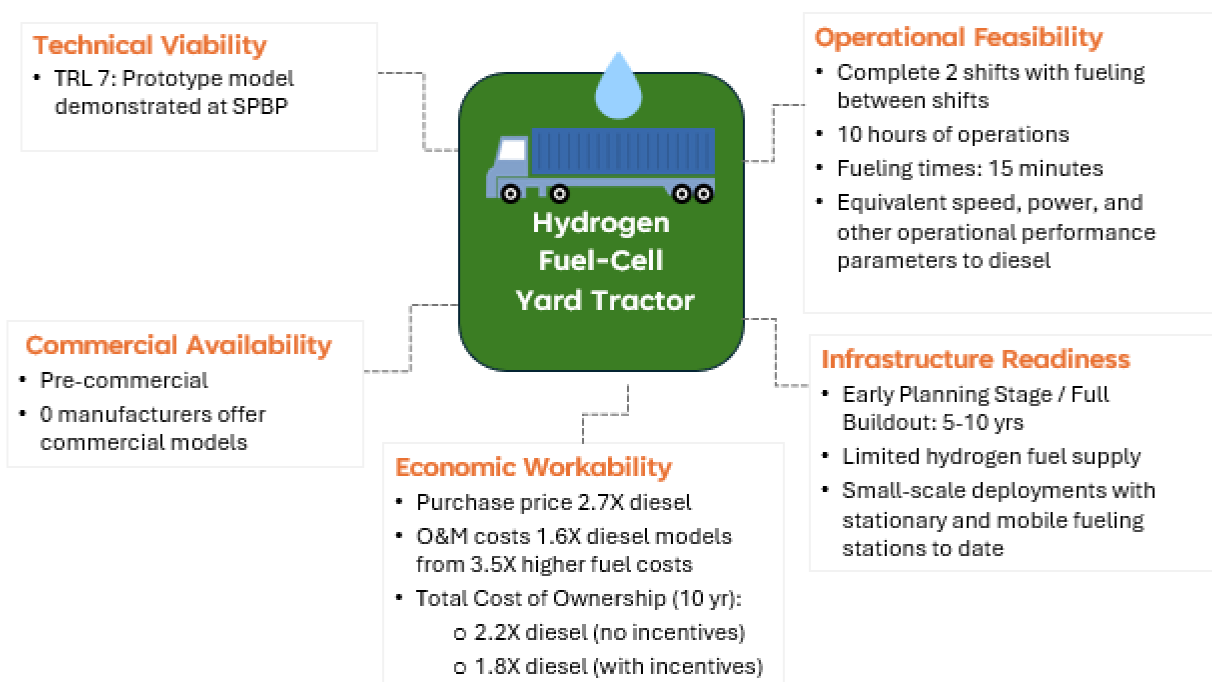

Figure ES-2: Hydrogen Fuel Cell Yard Tractor Feasibility Assessment Summary

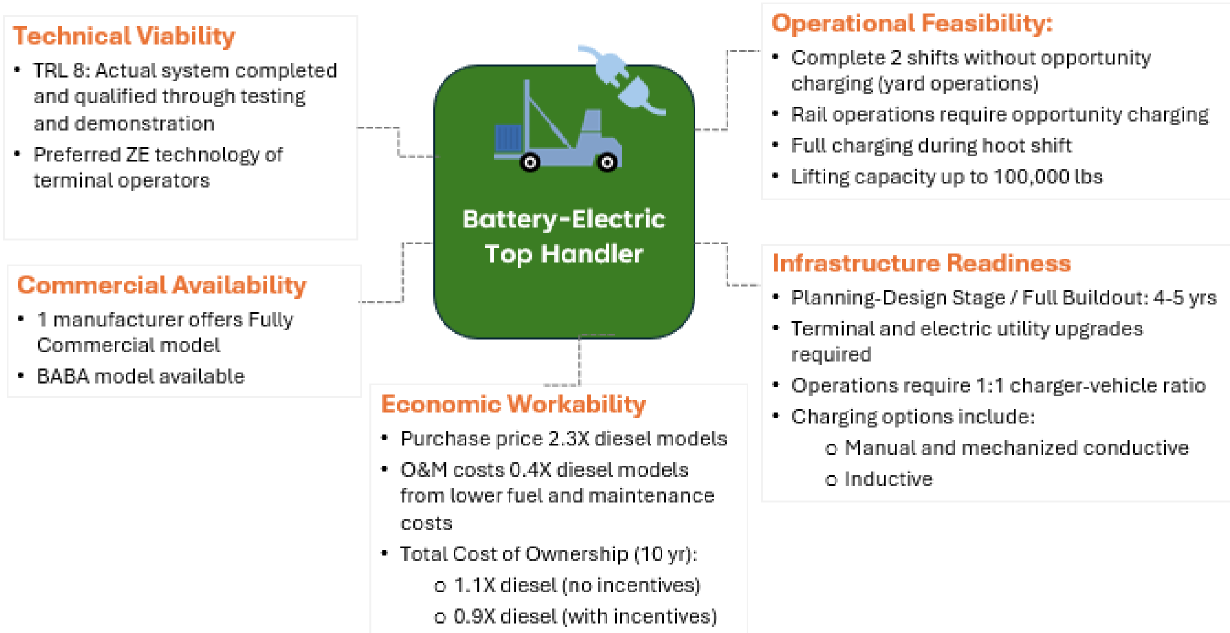

Figure ES-3: Battery-Electric Top Handler Feasibility Assessment Summary

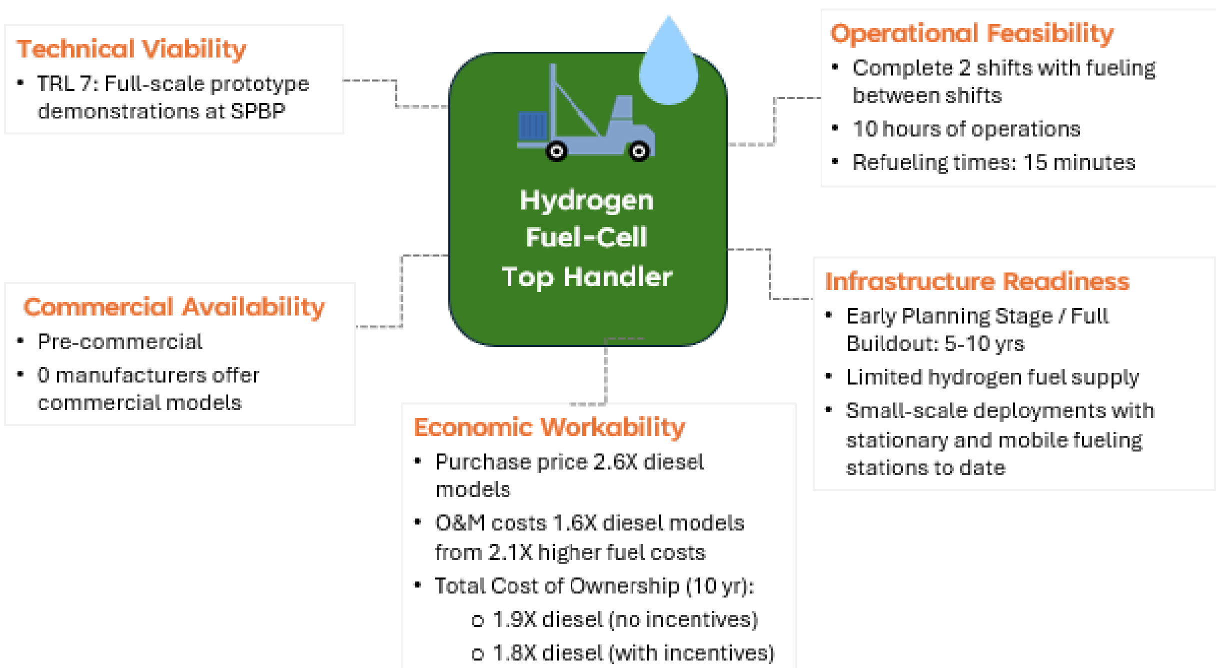

Figure ES-4: Hydrogen Fuel Cell Top Handler Feasibility Assessment Summar

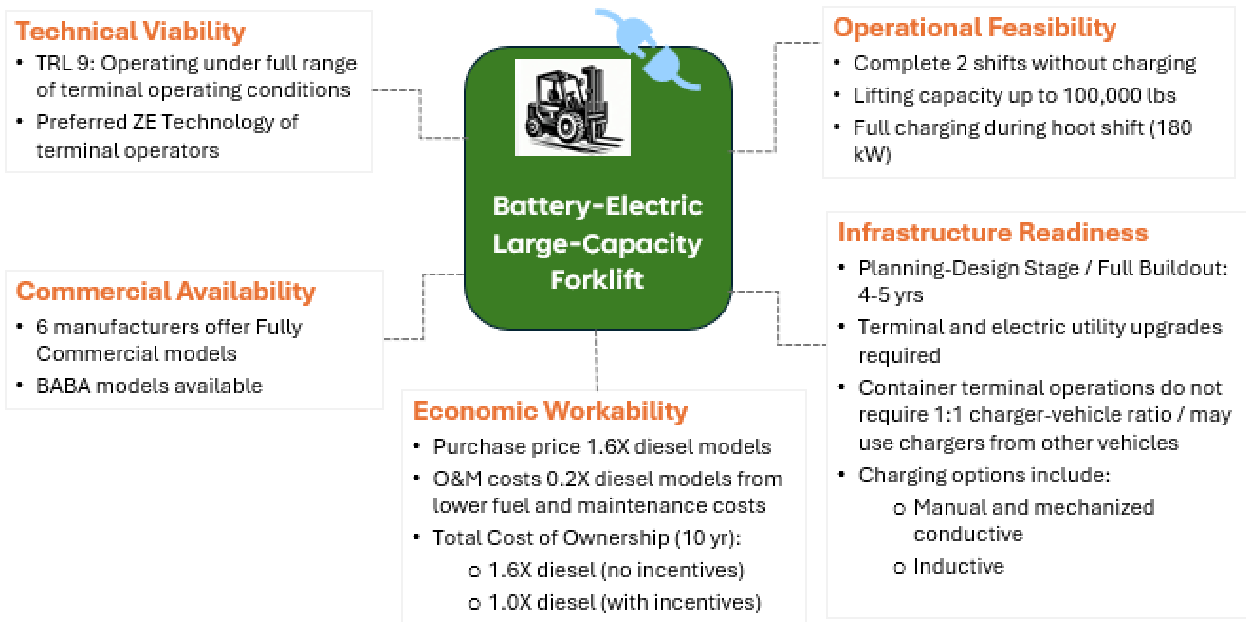

Figure ES-5: Battery-Electric Large-Capacity Forklift Feasibility Assessment Summary

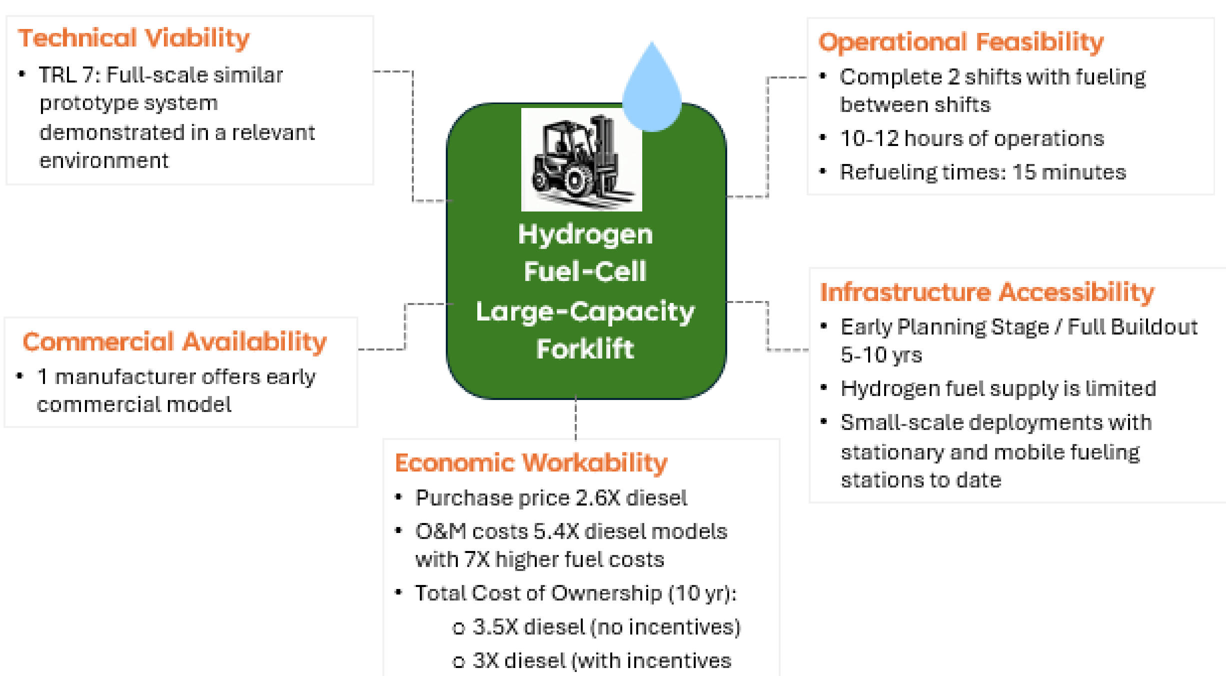

Figure ES-6: Hydrogen Fuel Cell Large-Capacity Forklift Feasibility Assessment Summary

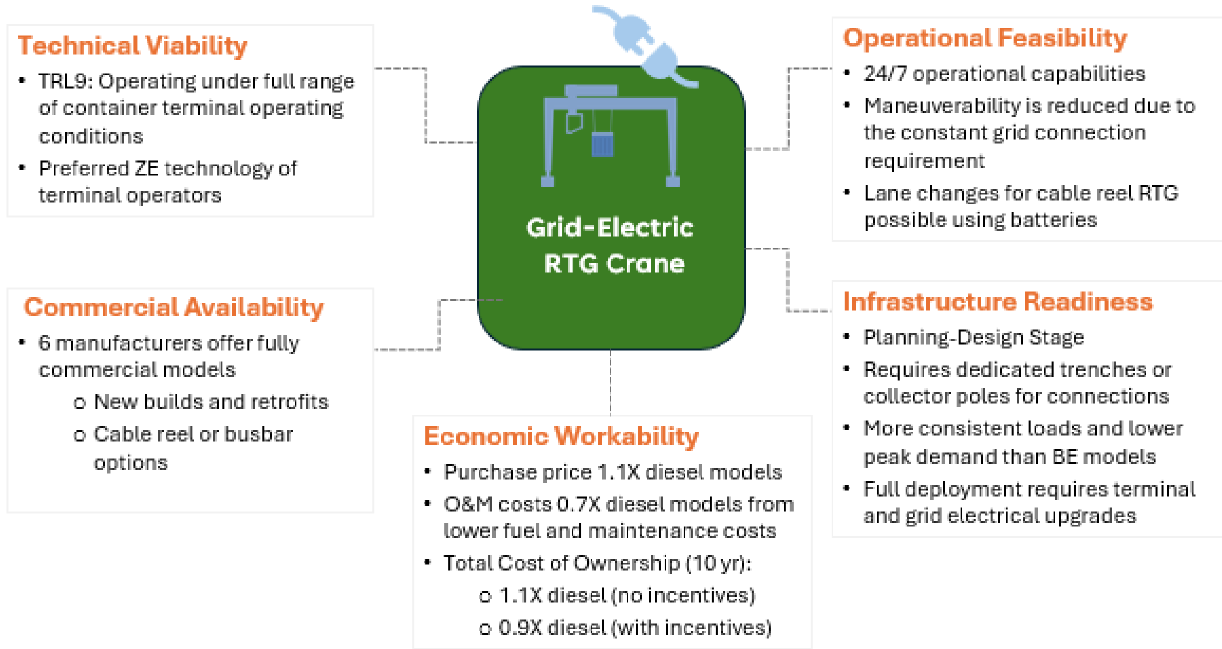

Figure ES-7: Grid-Electric RTG Crane Feasibility Assessment Summary

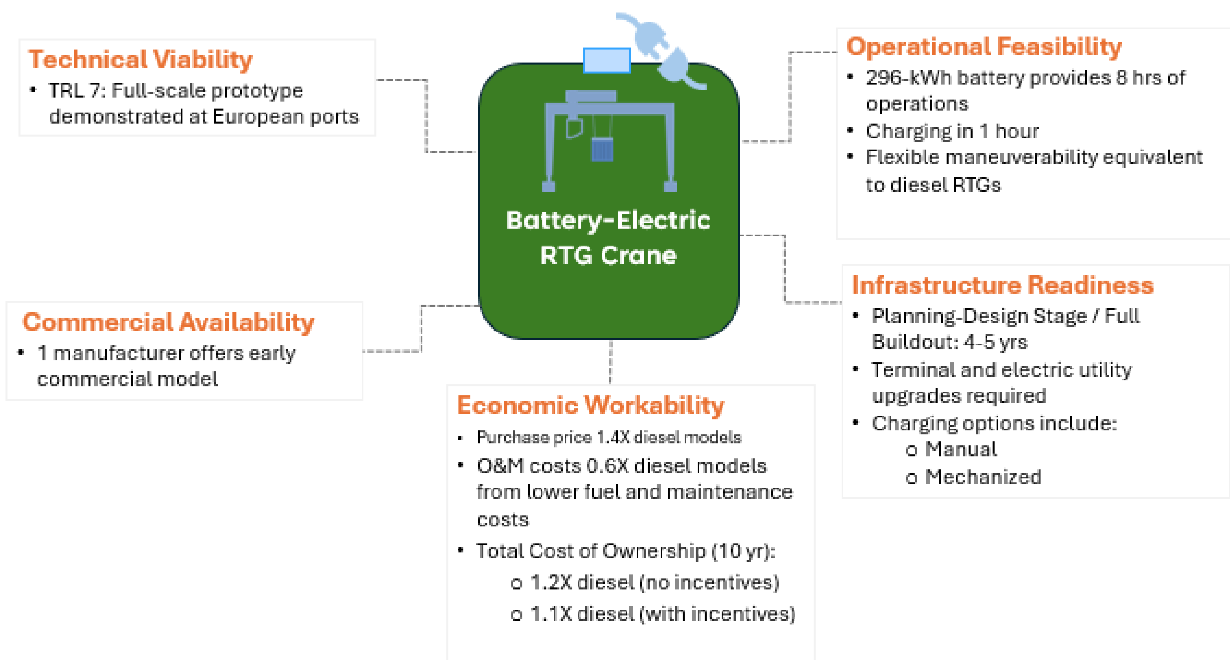

Figure ES-8: Battery-Electric RTG Crane Feasibility Assessment Summary

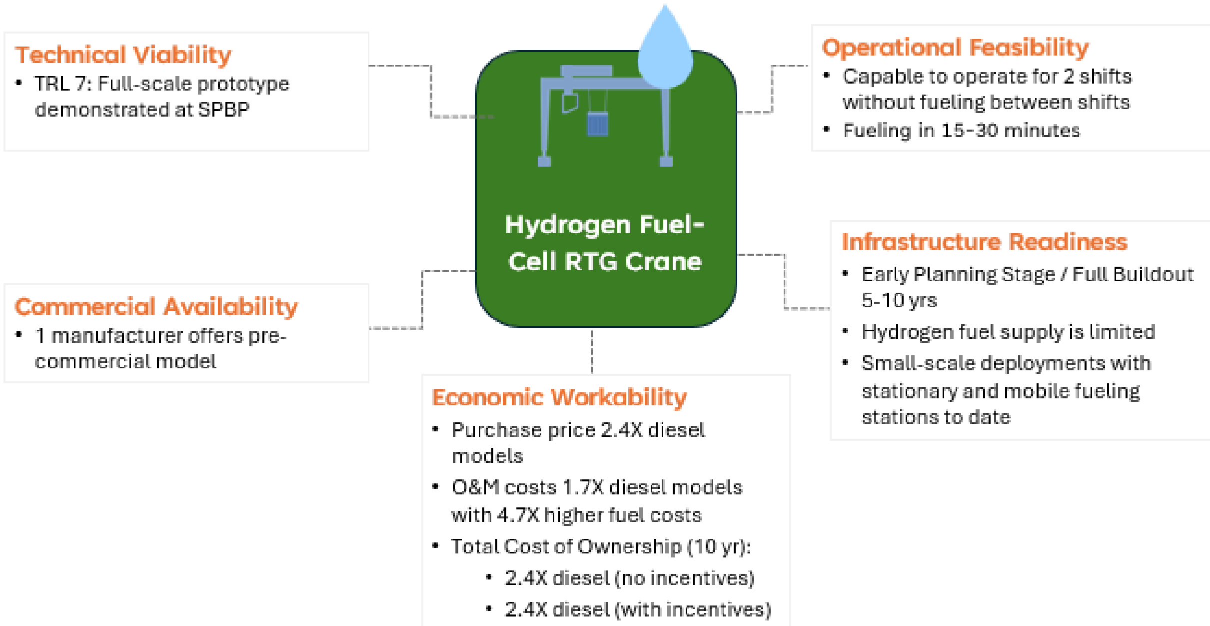

Figure ES-9: Hydrogen Fuel Cell RTG Crane Feasibility Assessment Summary

Commercial Availability: Battery-electric yard tractors, top handlers, large-capacity forklifts, and grid-electric RTG cranes are all at the fully commercial stage with multiple manufacturers offering models that are designed for port terminal operations. Fuel-cell CHE are in the pre-commercial stage with a limited number of manufacturers developing prototype models that are not commercially available.

Technical Viability: Grid-electric RTG cranes, battery-electric yard tractors and large-capacity forklifts are in their final form and are operating across the full range of port conditions (TRL 9) and the latest generation battery-electric top handler is now completed and undergoing the final phase of testing (TRL 8). Fuel-cell CHE are limited to full-scale prototypes that are still in the process of being validated operationally (TRL 7).

Operational Feasibility: Grid-electric RTG cranes and the most advanced battery-electric yard tractor, top handler, and large-capacity forklift models can complete two 8-hour shifts of yard operations without opportunity charging, which allows charging to be completed during the 4-hour hoot shift (i.e., desired operational feasibility). The battery-electric top handler required opportunity charging to complete two shifts for rail operations, which are more energy intensive than yard operations. A fuel-cell RTG crane also can complete two shifts without refueling, while other fuel-cell CHE prototypes can complete one shift before fueling. One benefit of fuel-cell CHE is that fueling can be completed in approximately 15 minutes or less.

Fuel and Infrastructure Readiness: The transition to 100% ZE CHE requires significant investments in infrastructure that requires hundreds of millions of dollars of investment and years to complete permitting, procurement, and construction. Electric infrastructure readiness for the full ZE transition is in the planning and design phase, with construction expected to take an additional 5 years. Hydrogen infrastructure is still in the early planning stage, and design and construction may take an additional 10 years.

- ***Electrical Infrastructure:*** The transition to battery-electric CHE will require the installation of thousands of chargers that will increase the demand on the utility grid by more than three times.[1] The Ports are working with their respective electric utilities and terminal operators to plan and design electrical infrastructure upgrades, which are projected to be completed in the next 4-5 years. Commercially available chargers include manual conductive, mechanized conductive, and inductive options. Deployment, integration, and reliability issues with mechanized and inductive chargers at SPBP between 2021 and 2024 have led most terminal operators to prefer manual chargers for near-term deployments.
- ***Hydrogen Infrastructure:*** Based on the lack of an identified hydrogen fuel supply combined with uncertain hydrogen infrastructure permitting requirements and minimal deployments to date at the Ports, there is a low probability that sufficient hydrogen infrastructure will be in place at the Ports by 2030 to support large-scale deployment of fuel-cell CHE. It is expected that it will take at least 5-10 years before the hydrogen fuel supply and infrastructure will be in place.

Economic Workability: Grid-electric and battery-electric CHE are projected to be economically workable with incentives while fuel-cell CHE are projected to not be economically workable. The TCO of battery-electric and grid-electric CHE are projected to be equivalent to or lower than diesel CHE over a 10-year period when available incentives are included. While the purchase prices of battery-electric CHE are approximately twice those of diesel CHE, the lower energy costs and maintenance costs are projected to help offset the higher capital cost of the vehicle and charger. In contrast, the 10-year TCO of fuel-cell CHE remains 2-3 times higher even when incentives are applied due to the high upfront capital cost and high hydrogen fuel costs.

Overall Feasibility: Grid-electric RTG cranes were determined to have the highest overall feasibility due to their strong performance for multiple years at the Port of Long Beach (POLB), followed by battery-electric CHE. Battery-electric large-capacity forklifts, yard tractors, and top handlers have a strong potential for deployment at scale once electrical infrastructure upgrades and charger installations are completed. Fuel-cell CHE are not ready for full-scale deployment due to the prototype stage of models and lack of an available and affordable hydrogen fuel supply.

Assessment of SPBP Transition Readiness to ZE CHE

There have been substantial advancements in the overall feasibility of battery-electric CHE between 2021 and 2024 that have led most terminal operators to select battery-electric yard tractors, top handlers, and large-capacity forklifts as their ZE platforms of choice. This will require the installation of over 2,000 chargers at SPBP container terminals, as well as upgrades to terminal and utility electrical infrastructure to support. Through collaboration with their electric utilities and terminal operators, both Ports have developed plans to complete electrical infrastructure upgrades within the next 4-5 years, factoring in permitting, design, procurement, and construction timelines.

Many of the battery-electric models deployed at the SPBP between 2021 and 2023 have suffered from integration and reliability issues that have limited their regular ongoing use; however, the newest generation of models are demonstrating to be much more reliable. The most advanced models of battery-electric CHE being deployed in 2024 are demonstrating the capability to complete two shifts of yard operations without opportunity charging, while grid-electric RTGs can operate continuously. Additional deployments at larger scales are needed to provide valuable feedback to manufacturers to continue to improve battery-electric models and prove to terminal

[1] Peak electrical demand is modeled to increase from a baseline of 57 megawatts (MW), including shore power to 211 MW at POLA. Draft Port of Los Angeles Zero Emission Terminal Transition Plan. 2025.

operators that battery-electric CHE are ready for a full ZE transition. Once the new generation of battery-electric CHE can be proven to be operationally reliable, terminal operators will have the confidence needed to invest the collective billions of dollars in equipment and infrastructure required to achieve the ZE transition.

It is likely that this full-scale testing, refinement, procurement, and deployment process may take 5-10 years to ensure that the ZE transition can be accomplished successfully without harming terminal operations.

1.0 Introduction

The SPBP 2017 CAAP Update established the need to conduct regular feasibility assessments of ZE and near-zero-emissions (NZE) technologies for CHE. The Ports developed a "Framework for Developing Feasibility Assessments" to assess the potential for ZE and NZE platforms to replace conventional, combustion engines for CHE and on-road trucks. Feasibility studies were completed in 2018 and 2021 for CHE based on the commercial availability, technical viability, operational feasibility, infrastructure and fuel availability, and economic workability of ZE and NZE technologies.

The 2024 ZE CHE Feasibility Assessment evaluates the potential for transitioning CHE from internal combustion engines to ZE technologies, with a focus on battery-electric and fuel-cell platforms. The 2024 assessment is an update to the 2018 and 2021 assessments, documenting the progress that has been made in improving and deploying ZE CHE since the 2021 assessment through the end of 2024. It also evaluates the potential for achieving the CAAP goal of transitioning 100 percent of CHE to ZE technologies by 2030.

1.1 Cargo Handling Equipment

Consistent with the two prior assessments, the 2024 assessment focuses on the four types of CHE that comprise approximately 78 percent of the 3,725 CHE used in the Ports of Los Angeles (POLA) and POLB – yard tractors, top handlers, RTG cranes, and large-capacity forklifts (Figure 1-1). These four CHE types are traditionally powered by combustion engines, such as diesel, gasoline, propane, and natural gas, contributing approximately 80 percent of all CHE air pollutant emissions.[2]

Figure 1-1: Feasibility Assessment Cargo Handling Equipment

[2] Port of Los Angeles and Port of Long Beach 2023 Air Emissions Inventories. See https://www.portoflosangeles.org/environment/air-quality/air-emissions-inventory https://kentico.portoflosangeles.org/getmedia/3fad9979-f2cb-4b3d-bf82-687434cbd628/2023-Air-Emissions-Inventory for POLA and https://polb.com/environment/air/#emissions-inventory for POLB.

- **Yard Tractors** are designed for transporting containers within terminal boundaries. These vehicles facilitate cargo movement between ships, storage yards, and container stacks. With a focus on maneuverability and durability, yard tractors are critical for managing the logistics of container handling in the confined and high-traffic environments of ports.
- **Top Handlers** are specialized vehicles used to lift, transport, and stack containers, particularly in storage yards or rail-transferred areas. Top handlers lift containers from above, making them efficient for stacking operations. Top handlers are key to managing container logistics beyond the immediate ship-to-shore activities.
- **Rubber-Tired Gantry Cranes** are large, mobile cranes used to stack and move containers within terminal yards. Operating on rubber tires, they are versatile and capable of navigating container stacks without the need for fixed railing systems. RTG cranes are integral to efficient container handling, offering the ability to lift containers to various heights and organize them across multiple rows, enabling high-density storage within terminals.
- **Large-Capacity Forklifts** have a payload capacity of at least 36,000 pounds (lbs) and are designed to handle oversized or heavy cargo, such as truck chassis, bulk goods, steel coils, or heavy containers, that exceed the capacity of standard forklifts. These forklifts are equipped with advanced lifting capabilities and robust designs to handle specialized cargo in terminal operations effectively and safely.

1.2 Zero-Emissions Technologies

This study primarily assesses the feasibility of two ZE technologies – battery-electric and fuel-cell technologies. It also assesses grid-electric or grid-connected technologies for RTGs.

- **Battery-Electric Technologies:** Battery-electric CHE are commonly powered by lithium-ion batteries that power an electric motor, replacing diesel engines and producing zero tailpipe emissions. The batteries are charged by connecting the CHE to chargers (also known as electric vehicle service equipment or EVSE), which can include manual and hands-free technologies (e.g., mechanized and inductive options).

- **Fuel-Cell Technologies:** Fuel-cell CHE are also EVs that use hydrogen that is stored onboard the vehicles in tanks to react with oxygen to generate electricity to power electric motors. Fuel-cell CHE are refueled at stations or with mobile refuelers, similar to diesel CHE.

- **Grid-Electric Technologies:** grid-electric CHE are powered through a direct connection to the electric grid, producing zero tail pipe emissions. Mobile CHE, such as RTG cranes, are connected to a power source via a busbar or cable reel that provides continuous power. The benefit of this technology is that no onboard energy storage is required, but the connection limits mobility.

1.3 Assessment Parameters

Feasibility refers to the ability of ZE CHE to replace diesel CHE at SPBP cargo terminals. In accordance with the "Framework for Clean Air Action Plan Feasibility Assessments," feasibility is assessed using the following five parameters:

- **Commercial Availability:** Evaluation of the number of manufacturers offering ZE CHE models capable of meeting port operational needs and potential of manufacturers to produce ZE CHE at sufficient scale to meet the 2030 goal.

- **Technical Viability:** Evaluation of ZE CHE based their transition from laboratory testing to prototypes to pilot demonstrations to real world deployments on marine terminals consistent with the Department of Energy (DOE) TRLs as described in the published Technology Readiness Assessment Guide.
- **Operational Capability:** Evaluation of the ability of ZE CHE to perform similarly to diesel equivalents across specific SPBP container terminal requirements in terms of power, speed, range, and other metrics. In terms of range, the desired operational threshold for container terminal operations is the ability to complete two shifts without charging/refueling. Additional evaluation criteria include operational reliability, maintenance requirements, and feedback from equipment operators regarding drivability, fueling, and usability.
- **Infrastructure Readiness:** Assessment of the current state and future needs of fuel/power supplies and infrastructure to support the 100-percent ZE CHE goal. Infrastructure components include electric charging systems, hydrogen fueling stations, electric grid capacity, and hydrogen fuel generation, transport, and storage systems.
- **Economic Workability:** Examination of the total cost of ownership, including capital expenditures, operating costs, maintenance, and repairs. It also evaluates the potential for incentives and grant funding to help offset higher capital costs.

The 2024 assessment identifies both progress and challenges in adopting ZE technologies by documenting the current state of ZE CHE platforms and the progress that has been made in advancing these technologies from 2021 through 2024.

2.0 Methodology

This section details the methodology used to assess the feasibility of ZE CHE to meet SPBP terminal operational needs, based on the CAAP Feasibility Assessment Framework published in 2017.[3] Data collection efforts included information from technology demonstrations and pilot projects; publicly available reports and technical specifications of battery-electric and fuel-cell CHE; and surveys / interviews with manufacturers, terminal operators, and Ports staff. The feasibility of both battery-electric and fuel-cell technologies was assessed for yard tractors, top handlers, large-capacity forklifts, and RTG cranes based on a collective summary of the five CAAP Feasibility Assessment Framework evaluation parameters: (1) commercial availability, (2) technical viability, (3) operational feasibility, (4) infrastructure availability, and (5) economic workability.

2.1 Cargo Handling Equipment

The state of ZE CHE deployments and readiness was assessed for the four types of CHE relative to diesel equivalent models as of 2024. Battery-electric and fuel-cell technologies were assessed for yard tractors, top handlers, and large-capacity forklifts while RTG cranes also included grid-electric platforms (i.e., cable reel and busbar connections).

The feasibility of specific charging technologies, including manual plug-in conductive chargers, mechanized plug-in conductive chargers, and inductive chargers, were assessed along with hydrogen fueling technologies as a component of the infrastructure readiness section.

ZE CHE feasibility assessments were based on the most operationally advanced available models as of the end of 2024.

2.2 Data Collection

Data collection consisted of first reviewing the results of technology demonstrations and pilot projects completed between 2021 and 2024 at the Ports; publicly available reports and technical specifications of battery-electric and fuel-cell CHE; and surveys / interviews with manufacturers, terminal operators, and Ports staff.

1. **Technology Demonstrations and Pilot Projects:** Data from reports published between 2021 and 2024 for demonstration and pilot projects were analyzed to evaluate the real-world performance, reliability, and adaptability of ZE technologies in SPBP terminal operations. These sources provided critical insights into operational, maintenance, and repair requirements, as well as overall operational feasibility.

2. **Industry and Regulatory Reports**: Publicly available reports from agencies such as CARB, California Energy Commission, and other agencies and laboratories were reviewed to gain additional information on other technology assessments performed for battery-electric and fuel-cell CHE beyond the SPBP.

[3] San Pedro Bay Ports Clean Air Action Plan 2017 Framework for Developing Feasibility Assessments. November 2017. https://cleanairactionplan.org/2017-clean-air-action-plan-update/

3. **Original Equipment Manufacturer CHE Specifications:** CHE specifications, production timelines, warranties, and pricing for battery-electric and fuel-cell models were obtained for commercially available and pre-commercial models (where possible).

4. **Stakeholder Engagement**: Feedback was gathered from terminal operators, manufacturers, and SPBP staff through surveys and follow-up interviews. This process captured practical insights and diverse perspectives necessary for evaluating the feasibility of technology deployment across the five parameters. manufacturers surveyed are presented in Table 2-1. Ports and terminal operator staff were also surveyed / interviewed.

Table 2-1: Original Equipment Manufacturers Surveyed

Equipment	Technology	Original Equipment Manufacturers
Yard Tractor	Battery Electric	AutoCar, BYD, Capacity, Hyster, Kalmar, Konecranes, MAFI, OrangeEV, Sany, Terberg Taylor
	Hydrogen Fuel Cell	Hyster, Kalmar, Toyota, Terberg Taylor
Top Handler	Battery Electric	Terberg Taylor
	Hydrogen Fuel Cell	Hyster, Toyota
RTG Crane	Grid Electric	Kalmar, Konecranes, PACECO-Mitsui, Rainbow
	Battery Electric	Konecranes
	Hydrogen Fuel Cell	PACECO-Mitsui
Large-Capacity Forklift	Battery Electric	Hyster, Kalmar, Konecranes, Terberg Taylor, Wiggins
	Hydrogen Fuel Cell	Wiggins
Chargers	Inductive	InductEV, WAVE
	Mechanized Conductive	RocSys
	Mobile Conductive	Elonroad
	Manual Conductive	Kempower

2.3 Assessment Parameters

The Feasibility Assessment Framework is designed to evaluate the readiness of ZE CHE for deployment across SPBP terminal operations. Developed as part of the 2017 CAAP Update, the framework supports the Ports in achieving their ambitious environmental goals by systematically addressing the technical, operational, infrastructure, and economic considerations critical to adopting new technologies. Consistent with prior feasibility assessments, the following five parameters were assessed for ZE CHE.

2.3.1 Commercial Availability

Technologies must be market-ready, with manufacturers demonstrating the capacity to deliver equipment in sufficient quantities to meet SPBP-wide demand. Reliability of supply chains, long-term support for maintenance and parts, and robust warranty provisions are essential factors. Technologies that meet these criteria are more likely to see large scale adoption, reducing reliance on interim solutions and facilitating a smoother transition to full ZE operations. Moreover, scalability is crucial—technologies must be capable of mass production at a pace and scale sufficient to meet the needs of the port-wide fleet.

ZE CHE are commercially available when they achieve the following five criteria:

- Major manufacturers produce and sell units.
- There is a network of dealerships to sell and service the ZE CHE.
- Warranties, parts, and long-term product support are available.
- There are sufficient means and timelines to produce ZE CHE that meets SPBP demand.
- There are current and/or near-term equipment orders.

An assessment matrix was designed to evaluate commercial availability parameters, in which scores of 0, 0.5, and 1 were awarded to each criterion per the scoring methodology in Table 2-2. Each category can receive a maximum score of 1, which can total to a commercial availability score of 5.

Table 2-2: ZE CHE Commercial Availability Assessment Scoring Matrix

Commercialization Criteria	Scoring Methodology	
Production and Certification by Major Manufacturers	No commercially available models Only one manufacturer provides commercial model(s) Multiple manufacturers provide commercial models	0 0.5 1
Network of Dealerships to Sell and Service CHE	Manufacturers / Dealerships unable to quote sales price Manufacturer only sells models directly Sales and service network in place	0 0.5 1
ZE CHE Include Warranties and Long-Term Support	No warranties or long-term support Limited / uncertain warranties / support Warranties and support from established manufacturers	0 0.5 1
Ability to Manufacture CHE to Meet Current/Forecasted Demand	Limited manufacturing ability / pilot stage Ability to meet current demand Projected ability to meet full SPBP conversion	0 0.5 1
Backlog of CHE Orders or Credible Expression of Interest	No backlog of orders Terminal operator expression of interest Backlog of orders	0 0.5 1
Total Potential Commercial Availability Score		**5**
Commercial Availability Levels	**Pre-Commercial** **Early Commercial** **Fully Commercial**	**0-2** **2.5-3.5** **4-5**

2.3.2 Technical Viability

In 2018 and 2021, the technical viability of ZE CHE was evaluated in accordance with the DOE Technology Readiness Assessment Guide, which establishes nine technology readiness levels (TRLs) ranging from a low of 1 to a high of 9 (Table 2-3). The 2024 technical viability assessment follows the same technology readiness scoring methodology used in the 2021 feasibility study to support evaluations of improvements in ZE technologies over time.

Table 2-3: Technology Readiness Level Definitions

Relative Stage of Development	TRL	DOE TRL Condensed Definition / Description

Systems Operations	9	Actual system in its final form and operated under full range of operating conditions.
Systems Conditioning	8	Actual system completed and qualified through test and demonstration. The technology has been proven to work in its final form and under expected conditions, representing the end of true system development.
	7	Full-scale, similar prototype system demonstrated in relevant environment.
Technology Demonstration	6	Engineering/pilot-scale demonstration in relevant environment.
Technology Development	5	Laboratory scale, similar system validation in relevant environment.
	4	Component or system validation in laboratory environment.
Research to Prove Feasibility	3	Initiation of active research and development.
	2	Technology concept or application formulation.
	1	Initial scientific research has been conducted.

2.3.3 Operational Feasibility

For a ZE CHE to be considered operationally feasible, it must demonstrate **operational performance equal to or better than diesel equipment under real-world port conditions.** This includes rigorous testing of durability, efficiency, and reliability during diverse cargo handling operations.

SPBP cargo handling activities predominantly take place throughout the first two 8-hour shifts, running from 8:00 am-4:30 pm and 5:00 pm-2:30 am the following morning. A third shift, often referred to as the hoot shift, which runs from 3:00 am – 7:00 am is rarely used for cargo handling operations. terminal operators plan to perform the majority of charging of battery-electric CHE during the hoot shift.

Based on discussions with terminal operators, the overarching desired operational capability of ZE CHE is the ability to operate for two 8-hour shifts under the full range of marine terminal operating conditions without the need for opportunity charging / fueling during the one-hour break between shifts. The full range of operating conditions includes both yard and rail operations, where rail operations typically are more energy intensive.

The SPBP Framework for Developing Feasibility Assessments provides detailed criteria for evaluating operational feasibility. Operational feasibility was assessed based on the following criteria, consistent with the 2021 assessment:

- Basic performance meets terminal operator needs.
- Fuel economy and endurance meet operating time requirements.
- Speed and frequency of fueling / charging does not significantly impact revenue operation.
- ZE CHE meets operator comfort, safety, and fueling logistics
- Replacement parts and support for maintenance and training are available.

An assessment matrix was used to assess operational feasibility parameters, in which scores of 0, 0.5, and 1 were awarded to each criterion based on scoring methodology presented in the operational feasibility assessment scoring methodology (Table 2-4).

Table 2-4: ZE CHE Operational Feasibility Assessment Scoring Matrix

Operational Feasibility Criteria	Scoring Methodology

Capability to Meet Terminal Operator Performance Parameters	Cannot meet performance parameters Meets most performance parameters Meets all performance parameters	0 0.5 1
Ability to Meet Per-Shift and Daily Operating Time Requirements	Cannot complete two 8-hr shifts with charging/refueling Completes two 8-hr shifts with charging/refueling Completes two 8-hr shifts without charging/refueling	0 0.5 1
Fueling / Charging Speed Meets Revenue Operation Requirements	Charging / fueling speed does not meet requirements Charging / fueling speed meets most requirements Charging / fueling speed meets requirements	0 0.5 1
Operator Comfort, Safety, and Fueling Procedures	Does not meet operator requirements Meets most operator requirements Meets operator requirements	0 0.5 1
Available Parts, Maintenance, Training, and Manuals	Not available Partially available Available	0 0.5 1
Total Potential Operational Feasibility Score		**5**
Operational Feasibility Levels	**Non-operational** **Limited** **Partial** **Desired**	**0-0.5** **1-2** **2.5-3.5** **4-5**

2.3.4 Infrastructure Readiness

The infrastructure parameter largely focuses on the readiness of infrastructure and availability of fuel to support the successful deployment of ZE CHE at scale for the SPBP. Fuel and infrastructure readiness requirements are largely consistent for the four types of CHE, primarily differing between electric and hydrogen technologies. To be ready to support the full ZE transition, the following infrastructure improvements must be realized:

1. Terminal electrical infrastructure upgrades are complete and can provide adequate power to achieve the full SPBP conversion.
2. Utility electrical infrastructure upgrades are complete and can provide adequate power to achieve the full SPBP conversion.
3. Hydrogen fuel supply and supporting infrastructure is in place to achieve the full SPBP conversion.

Infrastructure readiness was determined based on the following fuel and infrastructure readiness assessment matrix (Table 2-5). Scores of 0, 0.5, or 1 were awarded to infrastructure criteria in accordance with the scoring methodology.

Table 2-5: ZE CHE Fuel and Infrastructure Readiness Assessment Scoring Matrix

Infrastructure Readiness Criteria	Scoring Methodology	
Charging / Fueling Technology Readiness	Charging/fueling cannot be completed during breaks* Charging/fueling mostly completed during breaks Charging/fueling completed during breaks	0 0.5 1

Terminal Infrastructure Deployed for Full ZE Transition	Terminal infrastructure is not deployed Terminal infrastructure designed / partially deployed Terminal infrastructure deployed	0 0.5 1
Sufficient Utility Capacity or Fuel Supply for Full ZE Transition	Insufficient fuel supply / utility capacity Utility upgrades / fuel supplies identified Utility upgrades / fuel supply in place	0 0.5 1
Infrastructure Buildout Stage	Planning Design Procurement-Construction	0 0.5 1
Existing Codes and Standards / Successful Installation at Terminals	None Codes and standards in place Successful installation of charging / fueling infrastructure	0 0.5 1
Total Potential Infrastructure Readiness Score		**5**
Infrastructure Readiness Levels	**Low** **Moderate** **High**	**0-1.5** **2-3.5** **4-5**

*Charging and fueling breaks include the 4-hour hoot shift and opportunity charging breaks between shifts.

2.3.5 Economic Workability

Economic workability compares the TCO over a 10-year period between ZE and diesel CHE using a lifetime net present value (NPV) framework. TCO projections include both upfront capital expenses (CapEx) and ongoing operating expenses (OpEx) over the assumed service life of the equipment, accounting for discounting, tax incentives, and depreciation-related benefits.

CapEx includes the purchase price of CHE, associated charger / per unit cost of a hydrogen fueling station, applicable taxes, and depreciation. Tax savings from depreciation were calculated using the Modified Accelerated Cost Recovery System (MACRS). Costs of electric utility upgrades, terminal electrical infrastructure upgrades, and hydrogen fuel supply investments required to support the full ZE transition were not included in the TCO analysis because these are up-front infrastructure costs that are considered in the infrastructure readiness assessment.

OpEx includes fuel or electricity costs, factoring in energy prices and energy economy, and maintenance costs derived from CHE usage and the average hourly rates of mechanics. Annual operating costs are assumed to remain constant over the life of the CHE and are converted to NPV of O&M using an industry standard discount rate of 7%.

Energy prices included in this assessment were based on the average price of diesel inclusive of diesel exhaust fluid, the average quoted price of hydrogen from local providers, and the average cost of electricity inclusive of estimated energy and demand charges. Electricity costs were calculated for POLA under the Los Angeles Department of Water and Power (LADWP) Large Commercial Rate A-3 and for POLB under the Southern California Edison (SCE) TOU-8 Option D Rate. The average electricity costs ($/kWh) were calculated to be $0.16/kWh.

Incentive programs such as purchase subsidies or infrastructure grants were deducted to calculate net capital costs. Low Carbon Fuel Standard (LCFS) credits were factored in as an incentive for battery-electric and fuel-cell CHE to offset operating costs.

The SPBP Framework for Developing Feasibility Assessments provides the following criteria for evaluating economic workability:

- The upfront capital cost is comparable to diesel baseline CHE.
- Fuel / energy costs for ZE CHE are affordable and net operational costs help provide an attractive cost of ownership.
- Infrastructure capital and operational costs are affordable.
- There are no major negative economic and/or workforce impacts from transitioning to ZE CHE.
- Financing mechanisms and incentives are in place and are expected to be in place in the foreseeable future to help improve the cost of ownership.

Economic workability was determined based on the following assessment matrix (Table 2-6). Scores of 0, 0.5, or 1 were awarded to economic criteria in accordance with the scoring methodology.

Table 2-6: ZE CHE Economic Workability Assessment Scoring Matrix

Economic Workability Criteria	Scoring Methodology	
ZE CHE Purchase Price is Affordable to Terminal Operators / Comparable to Diesel CHE	ZE CHE purchase price > 2.5 X diesel CHE ZE CHE purchase price 1.5-2.5 X diesel CHE ZE CHE purchase price < 1.5 X diesel CHE	0 0.5 1
ZE O&M Cost is Comparable to Diesel CHE	O&M >1.5 X diesel O&M >1-1.5 X diesel O&M ≤ 1 X diesel	0 0.5 1
Infrastructure Capital and Operational Costs are Affordable to Terminal Operators	Unaffordable Affordable with funding Affordable	0 0.5 1
No Major Economic / Workforce Impacts	Major impacts Limited impacts No major impacts	0 0.5 1
ZE CHE Total Cost of Ownership is Affordable to Terminal Operators / Comparable to Diesel with Available Incentives through 2030	TCO with Incentives >1.5 X diesel TCO with Incentives >1-1.5 X diesel TCO with incentive ≤ 1 X diesel	0 0.5 1
Total Potential Economic Workability Score		**5**
Economic Workability Levels	**Currently Not Economical** **Economical with Funding** **Economical**	**0-1.5** **2-3.5** **4-5**

3.0 Current State of ZE CHE Deployments

The deployment of ZE CHE has continued to increase gradually in the Ports from 2021 to 2024, while regular demonstration projects and small-scale deployments are providing valuable technical and operational data that is helping manufacturers improve their battery-electric and fuel-cell CHE models.

3.1 SPBP CHE Inventory Update

The POLA and Port of POLB Annual Air Emissions Inventories collect data on the numbers of CHE, including their power sources and hours of operation, to quantify emissions levels. The number of CHE by power source platform is compared among years to assess trends in ZE CHE deployment. The most recent emissions inventory released as of the date of this assessment was the 2023 inventory (Table 3-1).

Table 3-1: SPBP Equipment Inventory (2021-2023)

CHE	Non-ZE			ZE (Battery & Grid Electric)*		
	2021	2022	2023	2021	2022	2023
RTG Cranes	118	116	124	0	0	0
Top Handlers	205	215	205	2	2	2
Forklifts	286	278	275	28	33	65
Yard Tractors	917	918	1,070	5	5	11
Total POLA	**1,526**	**1,527**	**1,674**	**35**	**40**	**78**
RTG Cranes	85	93	89	0	9	9
Top Handlers	195	201	200	2	2	0
Forklifts	220	213	223	9	10	17
Yard Tractors	639	645	677	0	1	1
Total POLB	**1,139**	**1,152**	**1,189**	**11**	**22**	**27**
Total SPBP	**2,665**	**2,679**	**2,863**	**46**	**62**	**105**

Source: POLA and POLB Air Emissions Inventory Reports
*ZE RTG cranes are grid electric; all other ZE CHEs are battery electric.

For the four types of CHE included in this assessment, 105 of the total 2,863 SPBP CHE were battery-electric (3.5%) in 2023, while there was no fuel-cell CHE reported. battery-electric forklifts comprised the majority of the battery-electric CHE at 82 (33% of total forklifts), followed by 12 battery-electric yard tractors (7%), 9 grid-electric RTG cranes (4%), and 2 top handlers (0.5%), as shown in Table 3-1 and Table 3-2. It must be noted that the air emission inventory report does not make a distinction between large-capacity and small-capacity forklifts, but in light of the limited number of battery-electric large-capacity forklifts involved in demonstrations (i.e., 2 units), it is assumed that the vast majority were battery-electric small-capacity forklifts.

The total number of battery-electric CHE more than doubled from 46 (1.7%) in 2021 to 105 (3.5%) in 2023. Deployments of battery-electric forklifts increased the most followed by grid-electric RTG cranes and battery-electric yard tractors. ZE CHE deployments have provided valuable data and insights that have helped manufacturers improve current ZE models.

Table 3-2: Electric CHE Percentages at the SPBP (2021-2023)

SPBP	2021	2023
Electric RTG Cranes	0.0%	4.0%
Battery-Electric Yard Tractors	0.3%	0.7%
Battery-Electric Top Handlers	1.0%	0.5%
Battery-Electric Forklifts	14.0%	33.0%
Total Electric CHE	1.7%	3.5%

3.2 SPBP ZE Cargo Handling Equipment Deployments and Demonstration Projects

From 2021 to 2024, over 80 ZE CHE, including yard tractors, top handlers, large-capacity forklifts, and RTG cranes, within SPBP have been tested and demonstrated at the SPBP terminals, as detailed in the SPBP Technology Advancement Program (TAP) 2021-2024 annual reports. Demonstration projects tested ZE CHE on active marine terminals under a range of operational conditions, and included battery-electric and fuel-cell yard tractors, battery-electric and fuel-cell top handlers, battery-electric high-capacity forklifts, grid-electric RTG cranes, and their associated charging and fueling infrastructure (Figure 3-1). Chargers deployed with projects included manual chargers, fast chargers, mechanized plug-in chargers, and inductive chargers. Hydrogen mobile fueling station and mobile fuelers were also demonstrated.

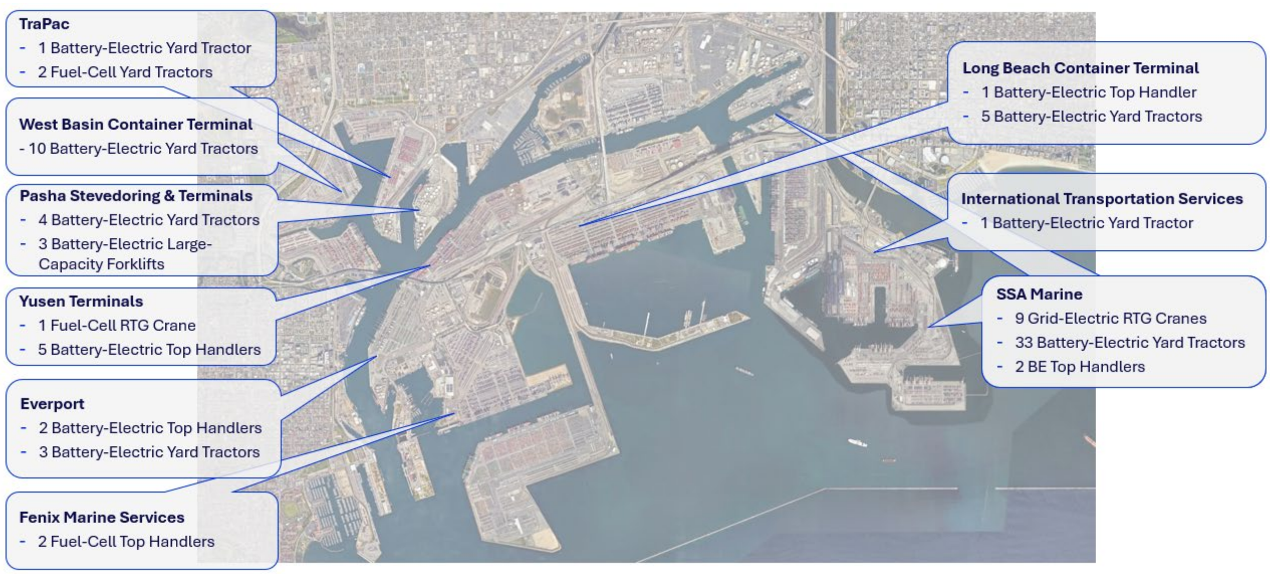

Figure 3-1: Overview of ZE CHE Demonstration Projects from 2021-2024

3.3 Key Lessons Learned from Demonstration Projects

Demonstration projects conducted at SPBP terminals have provided significant data and lessons learned that will benefit future deployments by the Ports, terminal operators, and manufacturers. Key lessons learned include:

1. **Infrastructure and Utility Challenges**

- **Grid Reliability and Power Outages**: Terminal operators noted that power outages can significantly impact grid-electric equipment. Power quality issues, such as voltage spikes and sags, can take gird-electric CHE, such as ship-to-shore and RTG cranes, offline. The operation of battery-electric CHE is not anticipated to be directly affected by these power quality issues because they are not connected to the grid during operations; however, the loss of grid power during charging windows could disrupt operational continuity if CHE cannot be fully charged prior to the first shift.

- **High Infrastructure Costs and Invasive Installations**: Terminal operators reported that transitioning to electric CHE requires extensive investment in power infrastructure, including charging stations, transformers, switchgear, and conduits / conductors. Installation is often invasive, involving trenching, and chargers and supporting electrical infrastructure take up valuable terminal space.

- **Electrical Infrastructure Lead Times**: Terminal operators observed that end-to-end processes for installing chargers and associated electrical infrastructure—design, permitting, procurement, and installation—frequently exceed CHE delivery timelines, underscoring the importance of early planning. On-terminal installations can take 1 to 4 years depending on the permitting process and equipment lead times. Terminal and utility upgrades are currently expected to take 4 to 5 years.

- **Hydrogen Supply and Cost Issues**: Terminal operators using fuel-cell CHE described intermittent hydrogen supply and high fuel costs as obstacles to continuing and future deployments. The absence of a reliable cost-effective hydrogen fuel supply creates challenges for widespread commercial development and adoption fuel-cell CHE. Additionally, an unreliable fuel supply has the potential to impact operational continuity. Permitting challenges have also limited the ability of terminal operators to deploy mobile refuelers at the Ports.

2. **Equipment Performance and Reliability**

- **Reliability Issues with Early-Generation Equipment**: Early-generation ZE CHE often encountered unexpected failures under real-world conditions, leading terminal operators to require frequent manufacturer involvement for troubleshooting and maintenance. terminal operators found reliance on manufacturer support adds operational complexity and can result in increased equipment downtime. terminal operators indicate that they are working to build in-house maintenance and repair expertise.

- **Single Shift Readiness**: Terminal operators reported that ZE equipment generally meets single-shift operational requirements reliably, with both battery-electric and fuel-cell CHE performing well under standard conditions.

- **Improving Performance in Two-Shift Operations**: The ability ZE CHE to complete two 8-hour shifts has improved from 2021 to 2024. Early generations of battery-electric CHE demonstrated within the SPBP often required opportunity charging between shifts to complete a second 8-hour shift and prototype models of fuel-cell yard tractors and top handlers were capable of completing one shift before refueling. By 2024, the fuel-cell RTG crane, 2nd generation battery-electric Taylor top handler, and later generation battery-electric yard tractors demonstrated the ability to complete two shifts of yard operations without refueling/charging. The battery-electric top handler required opportunity charging to complete the second 8-hour shift for rail operations. Rail operations are more energy intensive, requiring more lifts and movements per shift.

- **Challenges with Mechanized and Inductive Charging Systems**: Terminal operators highlighted frequent failures in mechanized and inductive charging systems, which disrupt or limit the rate of charging, consequentially limiting CHE uptime. Due to these issues, terminal operators are planning to primarily deploy manual plug-in chargers for near-term deployments.

3. **Maintenance and Manufacturer Support**

- **Specialized Maintenance Needs**: Terminal operators noted that ZE CHE have high-voltage systems and advanced powertrains, requiring maintenance crews trained in electrical safety and battery management. This new technical requirement has created a need for internal workforce development, including specialized training to maintain equipment reliability.
- **Reliance on Manufacturer Support**: Terminal operators often depend on manufacturers for repairs and replacement parts, which can lead to delays if manufacturers cannot quickly obtain replacement parts or assign personnel to make timely repairs. Many terminal operators value on-site and local manufacturer support to minimize downtime and ensure timely maintenance.
- **Lead Times for Parts and Equipment:** Terminal operators reported varied lead times for battery-electric CHE parts, ranging from 1-2 days to several weeks. To reduce downtime, some manufacturers are working to establish local inventories though availability remains a concern.
- **Training and Safety Adjustments**: Terminal operators indicated that ZE CHE requires adjustments to safety protocols and comprehensive training for staff. Operators have implemented safety modifications and software updates to address unique safety risks (e.g., regenerative braking, thermal events, and charging cable management) associated with ZE equipment.

4. **Economic Considerations and Funding Needs**

- **High Equipment and Infrastructure Costs**: Terminal operators have found the upfront purchase prices of ZE CHE and supporting infrastructure to be significantly more expensive than diesel alternatives, making grant funding critical for offsetting high upfront costs. Without this funding, many terminal operators indicated that ZE adoption would be financially prohibitive.
- **Grant Dependency and Strategic Funding Management**: Managing grant timelines and securing consistent funding are cited as challenges. Terminal operators are careful to align grant funding with long-term transition goals to avoid setbacks in ZE implementation.
- **Labor Demands in Charging Logistics**: Managing charging logistics is noted as labor-intensive for battery-electric CHE, especially where frequent plugging and unplugging is necessary. Terminal operators are seeking solutions to streamline these processes.

5. **Adaptability and Long-Term Strategy**

- **Phased and Pilot-Based Transition Approach**: Many terminal operators stressed the value of pilot projects to identify potential challenges with new ZE CHE before full deployment. This approach allows them to address equipment limitations early and refine processes before expanding ZE operations.
- **Phased Transition to Manage Risks and Costs**: Terminal operators are adopting a phased transition to ZE CHE, which helps spread costs and manage the risks of early-stage technologies. This phased approach enables terminal operators to adapt to improvements in battery and fuel cell technology over time.
- **Safety Concerns and Operational Adjustments**: Terminal operators acknowledged unique safety risks with ZE CHE, such as vehicle speed control, charging cable management, and thermal risks. Safety modifications and operational adjustments are being implemented to maintain a safe environment as ZE fleets expand.

- **Space Constraints for ZE Infrastructure:** Terminal operators reported that ZE infrastructure, including charging and fueling stations, requires them to allocate additional operational space, which can impact revenue-generating activities.

3.4 Summary of ZE CHE Deployment Progress

Since the 2021 assessment, and as of this 2024 status update, several technological achievements have been recorded in the progress towards the transition to ZE CHE.

- **Technology Demonstrations:** The Ports have conducted multiple demonstration programs to evaluate the operational feasibility and performance of ZE CHE under rigorous marine terminal conditions. These demonstrations included deploying ZE yard tractors, RTG cranes, large-capacity forklifts, and top handlers at terminal facilities, with equipment tested across a diverse range of duty cycles to assess reliability, operator acceptance, and maintenance requirements. These projects have provided valuable insights into the performance of ZE CHE and the status of their readiness for broader deployment as of 2024. Technology demonstrations have provided real-world feedback to manufacturers that has helped them substantially improve the operational capabilities and commercialization potential of their products.

- **Incremental Deployment:** Some terminals have initiated limited deployments of ZE CHE, integrating battery-electric CHE into operations, as well as fuel-cell CHE to a lesser extent. These efforts represent foundational steps in the ZE transition of CHE at container terminals. Terminal operators have begun to implement larger-scale deployments to further test ZE technology integration into cargo handling operations at scale.

Infrastructure Development: Investments in electric charging infrastructure have been initiated at terminals to accommodate the energy needs of battery-electric CHE. Terminals are also evaluating future infrastructure requirements, such as substation upgrades for electrification, charging locations, and hydrogen fueling systems, to support a broader range of ZE technologies. In addition, the Ports have been engaging their local electric utilities to identify and plan the electric transmission and distribution upgrades that will be required to accommodate future electricity demands. The Ports are also participating in the Alliance for Renewable Clean Hydrogen Energy Systems (ARCHES) hydrogen hub in an effort to bring renewable hydrogen to the SPBP complex and deploy fuel-cell CHE and trucks.

In summary, feedback from terminal operators on their experience with CHE through the demonstration and deployment projects at the SPBP is generally positive, albeit with some reservations. Despite experiencing various issues and challenges with the demonstrations, terminal operators acknowledge that ZE technologies have advanced in terms of operational performance over the past three years and are encouraged to see new and improved technologies and additional manufacturers entering the CHE market. Terminal operators also noted the positive collaboration that ensued over the course of the demonstration projects and appreciated the manufacturers' willingness to listen to and understand the terminal operators' concerns in seeking to improve the equipment and introduce new models. Over the last three years, terminal operators' outlook on the eventual viability of ZE CHE has improved, although they would like to see additional demonstrations and deployment of ZE CHE that work to address identified issues. Terminal operators also expressed concerns about the relatively higher purchase costs of ZE CHE and the level of infrastructure investments required to support the full-scale deployment of electrified CHE fleets.

4.0 Infrastructure Readiness

Electrical and hydrogen infrastructure investments are critical to realizing a ZE CHE future. Available power, fuel, and supporting infrastructure must be in place to support the full-scale transition to ZE CHE in the SPBP. The availability of sufficient sources of reliable electricity and hydrogen are prerequisites for the deployment of ZE CHE at scale. The ability to realize the CAAP goal of transitioning 100 percent of CHE to ZE technologies will require extensive upgrades to on-terminal infrastructure, the electric grid, and the hydrogen generation, delivery, storage and fuel dispensing system. Prior to making these investments, the Ports and terminal operators must have confidence that the ZE CHE can meet their operational requirements so as not to adversely impact operations. This section evaluates the readiness of electrical charging and hydrogen fueling infrastructure at the Ports.

4.1 Electrical Charging Infrastructure

Electrification of cargo handling operations is projected to increase peak power demand at container terminals by more than three times.[4] Nearly all container terminals will require on-terminal electrical upgrades to increase capacity as well as utility upgrades to provide adequate power for grid and battery-electric CHE. Required upgrades will vary by terminal but are anticipated to include new transformers, switchgear, conduits, and other connecting infrastructure required to connect power to hundreds of chargers.

POLA is engaging with its local utility, LADWP to implement expansion of a receiving station and installation of five new 34.5-kV circuits to meet future electrical demand. It is anticipated that it will take between 4 to 5 years to complete the required electrical upgrades to support electrification. POLB is also engaging with its local utility, SCE, to assess required distribution system upgrades. Utilities typically require multiple years for grid coordination and upgrades since interconnection studies will need to be completed, projects will need to be designed and permitted, and procurement of long-lead-time electrical equipment, which can take two years, must be initiated to be able to install and energize thousands of chargers for battery-electric CHE.

The past few years have seen a significant increase in the number of manufacturers offering standardized charging solutions for CHE, shifting away from the proprietary CHE manufacturer systems that were prevalent in the early stages of demonstration projects. Additionally, developments of higher voltage chargers and handsfree options are becoming more prevalent. Handsfree options, including mechanized conductive chargers and inductive chargers, while commercially available require further testing and refinement to demonstrate operational viability at the Ports.

4.1.1 Plug-in Chargers

Plug-in chargers include conductive chargers that utilize manual and mechanized plug-in options. There are a wide range of plug-in charger sizes, as detailed below. In addition, there are two plug configurations widely on the market – the Combined Charging System (CCS) and North American Charging Standard (NACS).

4.1.1.1 Combined Charging System

The CCS remains the most widely adopted charging standard for medium- and heavy-duty EVs, including CHE, due to its ability to support both alternating current (AC) and high-power direct current (DC) charging through a single

[4] Peak electrical demand is modeled to increase from a baseline of 57 MW, including shore power, to 211 MW at POLA. Draft Port of Los Angeles Zero Emission Terminal Transition Plan. 2025.

connector. In North America, CCS1 is the prevailing standard, incorporating the Society of Automotive Engineers (SAE) J1772 AC interface with additional DC fast-charging pins to accommodate power levels ranging from 50 kW to 350 kW, with newer installations reaching 500 kW for faster charging cycles.

CCS1 has been widely implemented across commercial fleets and is expected to remain a key charging standard for CHE in the coming years. As battery-electric CHE demand higher power levels to support rapid turnaround times, alternative charging solutions like the Megawatt Charging Standard (MCS) are being developed to complement CCS.

4.1.1.2 North American Charging Standard

The NACS was originally developed by Tesla and has gained widespread support from major automakers, including Ford, General Motors, Rivian, Hyundai, and Volvo, which have announced plans to integrate NACS into their future EV models. NACS offers a smaller, more streamlined connector with the capability of handling both AC and DC charging, making it an attractive option for vehicle manufacturers seeking a universal, compact solution.

While NACS is becoming dominant in the passenger vehicle and light-duty commercial segments, its role in heavy-duty and industrial EVs, including CHE, remains under evaluation. The transition of public fast-charging networks to support NACS is expected to increase its adoption across multiple vehicle classes, but for CHE applications, CCS1 and MCS currently provide the necessary high-power charging capabilities.

4.1.1.3 Megawatt Charging Standard

To meet the energy requirements of large battery-electric CHE, the MCS has been developed as the next generation high-power DC fast-charging standard. MCS is designed to provide up to 3.75 MW of power, supporting voltages up to 1,250 V and currents of 3,000 amps (A) DC, making it well-suited for heavy-duty trucks and high-energy-demand CHE, such as battery-electric top handlers and RTG cranes.

The CharIN industry consortium has led the standardization of MCS, with its adoption anticipated to begin commercially between 2025 and 2027, following several successful pilot demonstrations. In North America, ports and logistics hubs are evaluating MCS for fleet-wide electrification, particularly for applications that require rapid charging with minimal downtime.

4.1.2 Hands-Free Charging Systems

There are two classes of hands-free charging systems that are currently being tested at the Ports – mechanized plug-in chargers that use conductive charging and inductive chargers.

4.1.2.1 Mechanized Plug-in Charging

Mechanized charging arms are designed to connect a charging plug to an EV's inlet using a hands-free mechanism when parked. Equipped with advanced sensors and control systems, these systems can identify the vehicle's charging port, navigate the connector into place, initiate the charging process, and disconnect upon completion of charging.

To promote uniformity and safety in automated conductive charging, the SAE J3105 standard was introduced in January 2020. This recommended practice outlines the general physical, electrical, functional, testing, and performance requirements for conductive power transfer systems using automated connection devices. As mechanized charging technology advances, several lessons have emerged from early deployments:

- Mechanized charging systems designed to comply with global standards such as SAE J3105 will be essential to operate consistently across different manufacturer platforms and reduce integration challenges.
- Close collaboration between charging system manufacturers and vehicle manufacturers will allow mechanized chargers to communicate efficiently with EV battery management systems and optimizing charge cycles.

Mechanized charging solutions for battery-electric CHE are offered by Cavotec, Stäubli, and Rocsys. These products are in the early commercial stage because they are relatively new to the market, but have been demonstrated, come with a warranty, and are purchased by the end user.

Three projects have integrated mechanized plug-in charging systems at the Ports. The Cavotec Smart Plug-In System was installed at Everport (POLA) and at International Transportation Service (POLB) to charge BYD yard tractors. The Stäubli automatic charging device combined with Tritium chargers was installed at SSA Pier C (POLB) to charge 38 Dina/Meritor yard tractors. Based on the mechanized charging system deployment at POLB's Pier C operated by SSA Marine, the Stäubli systems required a larger footprint, more robust foundations, and vehicle guides to ensure proper alignment of vehicles in stalls for charging. This additional infrastructure increased up-front infrastructure investment costs and operational complexity. The additional system complexity resulted in more potential failure points, increased potential integration challenges, and required additional specialized maintenance. In addition, Tritium's bankruptcy filing has made it difficult for SSA to obtain service and parts.

Demonstration projects have also highlighted operational and functional challenges of mechanized plug-in technologies. The Cavotec system had vehicle-charger integration issues that limited the use of vehicles. Alignment of the vehicle-mounted funnel with the charger plug was problematic and it was reported that the connection points tended to break, reducing the use of yard tractors. Additionally, proper vehicle alignment is critical to allowing the charger to be plugged into the vehicle. Early deployments have shown that drivers often require mechanical guides to consistently park vehicles within charger tolerances. These systems increase complexity, resulting in more integration challenges and greater numbers of components that can fail and require maintenance / replacement. To date, reliability and maintenance of these systems has been a challenge.

4.1.2.2 Inductive Charging

Inductive charging, or wireless charging, transfers energy through electromagnetic fields between a ground-embedded pad and a vehicle-mounted receiver. The receiver, mounted on the vehicle's underside, resonates at a specific frequency to capture energy from the charging pad. While retrofitting existing battery-electric CHE with wireless charging capabilities is possible, factory-integrated solutions are likelier to offer greater efficiency, reliability, and overall performance benefits. This approach offers opportunity charging without the need for physical connectors, which reduces wear and tear on equipment and can help enhance safety in high-traffic environments by removing potential tripping and collision risks. Given the spatial constraints at ports, wireless charging has the potential to offer an alternative to plug-in charging by minimizing the footprint required for infrastructure deployment.

Regarding standardization, the SAE has made significant strides by publishing the SAE J2954 standard in October 2020. This standard specifies both the vehicle and ground-system requirements for wireless charging of EVs, facilitating charging without the need for physical connectors. It also enables proper alignment for manual and autonomous parking over charging pads. The SAE J2954 standard currently addresses light-duty EVs with power transfer levels up to 11 kW. For heavy-duty applications, higher power levels are necessary. Efforts are underway to develop standards capable of accommodating these requirements, such as the proposed SAE J2954/2, which aims to support wireless charging at power levels up to 500 kW for heavy-duty vehicles.

In addition to SAE's efforts, the International Electrotechnical Commission (IEC) has been developing the IEC 61980 series of standards, which outline requirements for the wireless power transfer systems, including both stationary and dynamic charging scenarios. These standards aim to provide interoperability and safety across different manufacturers and applications.

Manufacturers offering commercial inductive charging for battery-electric CHE include Induct EV and WAVE. Both offer systems that include modular in-ground charging plates that are connected to power cabinets via conduits. The battery-electric CHE are outfitted with a receiver, ideally at the factory by the CHE manufacturer. The battery-electric CHE are inductively charged when parked over the plates. Both Induct EV and WAVE are at the early commercial stage because they are relatively new to the market, but have been demonstrated, come with a warranty, and are purchased by the end user.

While inductive charging has the potential to eliminate the presence of charging pedestals and the need for manual plugging in of vehicles, the significant ground disturbance footprint during installation and overall cost of the systems can present a barrier to use. In-ground inductive charging plates must be positioned within 100-150 feet of the supporting power cabinet, which can potentially increase the need for additional above-ground infrastructure depending on the number of vehicles to be charged. An additional challenge that has been expressed by terminal operators and Port staff is that vehicles must be positioned directly over chargers to realize maximal charging levels.

The installation of the WAVE inductive charging system at WBCT has been a challenging multi-year process. WAVE’s 12 wireless charging pads at WBCT support hands-free connection for 10 battery-electric yard tractors to charge without a physical connection to the power source. Each 250-kW system charges two trucks at up to 125 kW each. The project initially started in 2019, and the final installation and commissioning of chargers were completed in 2024. The installation of in-ground inductive chargers and conduits required extensive ground-disturbance activities. During charging operations, the terminal operator and Port staff reported that vehicles must be positioned directly over chargers to realize maximal charging levels. This pilot project continues to provide valuable feedback regarding the installation and operational challenges that need to be overcome to allow for full-scale deployments.

4.1.2.3 Conductive Charging

Manufacturer Elonroad offers an in-ground conductive charging rail that can charge battery-electric CHE while parked or in motion. The Electric Road System uses conductive charging rails that are installed flush with the road surface in segments. The battery-electric CHE is outfitted with a “collector device” that directly connects to the pavement surface. As the battery-electric CHE drives over a segment, the area directly beneath the vehicle is energized with 750 V DC from the power station, delivering up to 300 kW to the vehicle. As of the date of this report, ITS (POLB) is installing a demonstration of the Elonroad system at their terminal, with construction scheduled to be completed by November 2025. This product is at the pre-commercial stage because it is new to the market and has yet to be demonstrated at a port.

4.1.3 Charging Infrastructure Deployment and Scaling Challenges

The successful deployment of high-power charging infrastructure for CHE requires extensive planning and investment. Several key challenges must be addressed:

- **Rate of Technology Advancement:** Battery-electric CHE and its associated charging infrastructure has been rapidly evolving over the last three years. New models of CHE can now accommodate faster charging, potentially requiring the installation of larger chargers, which can require more robust upgrades to on-terminal and utility electrical systems. Terminal operators will continue to test and deploy new ZE CHE to confirm their ability to meet operational requirements prior to completing large-scale deployments of chargers and supporting electrical upgrades.

- **Distribution System Capacity**: Ports and terminal operators have raised concerns about grid capacity constraints, especially as installation of thousands of chargers within SPBP is contemplated. The existing electrical infrastructure on most container terminals requires significant upgrades as do the utilities' systems to meet forecasted increases in peak demands.

- **Infrastructure Costs and Lead Times**: The installation of high-power CCS, MCS, and automated charging systems requires significant capital investment in the charging systems themselves, as well as the on-terminal and utility electrical systems. Ports have cited multi-year lead times for substation upgrades and charger installations. The estimated costs of infrastructure upgrades are in the range of hundreds of millions to over a billion dollars.

- **Operations and Maintenance Challenges with Charging Systems**: Early trials of mechanized and inductive charging systems have encountered reliability issues, leading some terminal operators to prefer conventional plug-in solutions for near-term deployments. Additionally, maintenance, warranty, and availability of parts have been encountered as issues during deployments at the Ports. Ensuring consistent up time and charging efficiency remains a priority and will be critical as battery-electric CHE are deployed at scale.

4.1.4 Summary of Electrical Charging Infrastructure Readiness

Electrical charging infrastructure is in a moderate state of readiness (Table 4-1). Electrical infrastructure improvements are currently in the planning-design phase of deployment.

Table 4-1: Electrical Charging Infrastructure Availability Assessment Score and Stage

Infrastructure Criteria	Battery-Electric
Charging / Fueling Technology Readiness	1
Terminal Infrastructure Deployed for Full ZE Transition	0.5
Sufficient Utility Capacity or Fuel Supply for Full ZE Transition	0.5
Infrastructure Buildout Stage	0.5
Existing Codes and Standards / Successful Installation at Terminals	1
Infrastructure Availability Score	**3.5**
Infrastructure Readiness Stage	**Moderate**

Charging and associated electrical infrastructure has achieved two of the five framework assessment criteria.

1. **Time Required for Charging:** Both conductive and inductive chargers are capable of charging battery-electric CHE sufficiently between shifts to allow for the completion of subsequent 8-hour shifts. The availability of direct current fast charging (DCFC) with power ratings up to 350 kW provides charging speeds that can charge equipment fully in less than 2 hours and can accomplish opportunity charging within 45 minutes. While charging times can support opportunity charging, this is not the preferred strategy for most terminal operators. Operational changes will be necessary to have CHE operators drive equipment to charging locations between shifts where they will be charged.
2. **Existence of and Compatibility with Standards:** There are abundant standards for the safe deployment and operation of charging equipment, and this charging infrastructure has been deployed at SPBP and other U.S. marine terminals. Manual conductive chargers have been shown to be safe and perform reliably, although they require ongoing maintenance and replacement parts.

The three other criteria are technically feasible but have not been accomplished at the scale required to support full-scale ZE CHE terminal operations throughout the Ports.

1. **Terminal Infrastructure Deployed for Full ZE Transition:** Terminal operators have started developing or have developed plans for the deployment of battery-electric CHE and associated charging infrastructure. While space is a premium and construction is likely to be disruptive, these upgrades can be implemented to support the 2030 ZE CHE goal. Currently, there is not sufficient charging infrastructure or capacity on most container terminals, but upgrades have been identified and plans are in process to accomplish the required system enhancements.
2. **Sufficient Utility Capacity for Full ZE Transition:** The Ports and their respective utilities have identified the need for electrical utility upgrades to support the planned levels of electrification. The Ports, LADWP, and SCE are currently in the planning and design phase for implementing upgrades.
3. **Infrastructure Buildout Timeline:** It is anticipated that both the on-terminal and utility upgrades will take approximately 4-5 years to complete if initiated immediately and expeditiously. Coordination with the respective utilities are ongoing and plans are being developed or have been developed to address projected future electric demands based on full electrification scenarios. Additionally, terminal operators are in the process of planning and designing on-terminal electrical upgrades required to support electrification plans.

4.2 Hydrogen Fueling Infrastructure

Hydrogen fueling infrastructure is still in its early stages, requiring investment in hydrogen supply, transport infrastructure, on-terminal storage and dispensing equipment, including mobile refuelers. While on-site hydrogen production via electrolyzers is possible, space constraints at the Ports and energy requirements limit the viability of this option. The current plan is to secure hydrogen that is generated offsite, transport hydrogen to the Ports via pipelines or trucks, store the hydrogen on terminals, and dispense the hydrogen through a combination of fueling stations and mobile refuelers to fuel fuel-cell CHE.

As of 2024, the deployment of hydrogen fueling infrastructure at the Ports has been limited to two hydrogen fueling stations and one portable refueler to support fuel-cell CHE. For the Cavotec fuel-cell yard tractor project implemented at TraPac, a cascade fill mobile fueling system technology was selected whereby the higher-pressure hydrogen in the storage system was transferred to the lower pressure compressed hydrogen tanks in the fuel cell yard trucks without the use of a compressor or precooling. The use of a temporary fueling station required permits from POLA, Los Angeles Department of Building and Safety, and Los Angeles Fire Department, which were obtained in approximately 11 months. Once commissioned, fueling times with the system ranged from 10 to 30 minutes. Stationary fueling was less desirable than mobile fueling or wet fueling as is the common practice for diesel fueling. Later projects, such as the Hyster fuel-cell RTG demonstration at Yusen Terminals (YTI in POLA) use a mobile fueler that refills the RTG crane daily.

Two of the largest challenges to full-scale deployment of hydrogen are its limited supply and highly variable pricing. For example, in 2022, the average retail cost for hydrogen was $16.59 per kilogram, but by January 2023, it had doubled to $33.48 per kilogram. Negotiating long-term, fixed-price contracts with hydrogen suppliers may help hedge against this pricing volatility, although it will not address the lack of availability. The Ports participation in the ARCHES hydrogen hub is intended to support the buildout of the hydrogen supply chain, bringing renewable hydrogen to the SPBP complex and supporting the deployment of fuel-cell CHE and trucks.

4.2.1 Fueling Standards

Hydrogen fueling for medium- and heavy-duty vehicles, including CHE, is governed by several standards to ensure safety and interoperability.

- **SAE J2600**: Specifies the fueling connection devices for compressed hydrogen vehicles, detailing the design and performance requirements for nozzles and receptacles to ensure a safe and reliable connection during fueling.
- **SAE J2601**: Provides protocols for fueling gaseous hydrogen-powered vehicles, outlining procedures to achieve complete fills efficiently while maintaining safety.
- **SAE J2601-2**: Focuses on fueling protocols for medium- and heavy-duty applications, addressing the specific needs of larger hydrogen storage systems.
- **SAE J2579**: Establishes standards for fuel systems in fuel cell and other hydrogen vehicles, focusing on performance-based requirements to ensure the integrity and safety of hydrogen storage and handling components.
- **SAE J2719:** Specifies the quality standards for hydrogen fuel used in fuel cell vehicles, ensuring that the hydrogen meets purity levels necessary to maintain fuel cell performance and longevity.
- **ISO 19885**: An international standard under development, aiming to establish high-flow fueling protocols for heavy-duty hydrogen-fueled vehicles, facilitating faster fueling times suitable for commercial operations.

4.2.2 Fueling Technologies

Hydrogen fueling stations for CHE are typically designed to meet the high-demand and quick turnaround needs of port operations. Key considerations include:

- **Gaseous Hydrogen Dispensing**: Most stations dispense compressed hydrogen gas, stored onsite in high-pressure tanks. The fueling process involves transferring hydrogen to the vehicle's storage tanks, typically at pressures of 350 bar (5,000 pounds per square inch) for heavy-duty applications. Stationary hydrogen fueling stations include a storage tank, compressor, high-pressure buffer tank, heat exchanger, and dispenser.
- **Mobile Fueling Solutions**: In scenarios where permanent infrastructure is not feasible, mobile hydrogen refuelers offer flexibility. These units can be transported to various locations within the Ports, providing on-demand fueling services at the terminals. For instance, POLA utilized a cascade fill mobile fueling system between 2019 and 2022, sequentially fueling up to two vehicles per day with a capacity of 180 kilograms (kg) at 450 bar. In November 2022, OneH2 and Toyota Tsusho America demonstrated a mobile fueling system at the Fenix Marine Terminal at POLA. A One H2 truck delivered a hydrogen mobile fueler to the terminal's ZE fuel cell top handler, fueled the equipment with sustainable hydrogen fuel, and then returned to the hydrogen production hub outside the Port.
- **On-Site Hydrogen Production**: On-site hydrogen generation through electrolysis uses electricity to split water into hydrogen and oxygen. Electrolyzers require a large footprint of up to 20,000 square feet and strict adherence to safety requirements. Because of these constraints, neither of the Ports have indicated serious interest in on-site production in the near future. Instead, hydrogen is more likely to be delivered from external sources and stored and dispensed through fueling stations or mobile refuelers.

4.2.3 Infrastructure Deployment and Scaling Challenges

Implementing hydrogen fueling infrastructure for CHE presents several challenges:

- **High Capital Investment**: Establishing hydrogen fueling stations requires significant upfront investment. Costs encompass the construction of fueling stations, installation of high-pressure storage tanks, compressors, dispensers, and safety systems. An assessment by the National Renewable Energy Laboratory (NREL) highlighted the substantial capital required for hydrogen infrastructure in port settings, which was estimated to be approximately $25M for the Port of Tacoma.[5]
- **Hydrogen Supply and Distribution**: Ensuring a consistent and sufficient supply of hydrogen is critical. Challenges include the development of production facilities, establishing reliable delivery logistics, and managing storage at the Ports. The high cost of hydrogen fuel and intermittent supply issues have been identified as obstacles to widespread adoption and reliability of fuel-cell equipment in daily operations. The Ports are participating in the ARCHES program as of 2024, which is intended to support the development of hydrogen hubs and deployment of hydrogen at scale within the SPBP complex.
- **Hydrogen Fuel Dispensing:** The terminal operators have expressed interest in using mobile hydrogen fuelers that can travel around the terminals to fuel equipment similar to the way they currently operate. This will require equipment that is easy to use, can offer a pressurized solution and that can be permitted and accepted as safe by the Fire Department.
- **Safety and Regulatory Compliance**: Hydrogen is highly flammable, necessitating stringent safety measures. Compliance with evolving regulations and standards requires continuous monitoring and

[5] NREL Hydrogen Infrastructure Analysis for Port Applications. https://docs.nrel.gov/docs/fy25osti/91396.pdf

adaptation. The development of comprehensive safety protocols and adherence to established standards are critical to mitigating risks associated with hydrogen fueling operations.

- **Technological Maturity and Reliability**: Hydrogen fueling technology is still maturing, and early-generation equipment may encounter unexpected failures under real-world conditions. Terminal operators have reported reliance on manufacturers for maintenance and troubleshooting, which can lead to operational complexities and delays.

4.2.4 Summary of Hydrogen Infrastructure Availability

Hydrogen fueling infrastructure and supply is currently in the early planning stage and it is categorized as having a low infrastructure readiness score (Table 4-2). Hydrogen infrastructure and fuel availability has yet to be developed and deployed at a scale to meet a marine terminal's potential fuel-cell CHE operations but hydrogen fueling does offer two significant advantages in terms of infrastructure – fueling speed and infrastructure footprint.

Table 4-2: Hydrogen Fuel and Infrastructure Availability Assessment Score and Stage

Infrastructure Criteria	Hydrogen Fuel Cell
Charging / Fueling Technology Readiness	1
Terminal Infrastructure Deployed	0.5
Sufficient Utility Capacity or Fuel Supply for Full ZE Transition	0
Infrastructure Buildout Stage	0
Existing Codes and Standards / Successful Installation at Terminals	0
Infrastructure Availability Score	**1.5**
Infrastructure Readiness Stage	**Low**

Hydrogen infrastructure has achieved one criterion.

1. **Time Required for Fueling:** One major advantage of hydrogen is that it can refuel equipment fully within minutes (e.g., 5-10 minutes for fuel-cell yard tractors and 30 minutes for fuel-cell RTG cranes). This fueling time is consistent with diesel equivalents.

The four other criteria are technically feasible but have not been accomplished at the scale required to support full-scale ZE CHE terminal operations throughout the Ports.

1. **Terminal Infrastructure Deployed:** There have been limited deployments of hydrogen fueling infrastructure within the SPBP, and all deployments have been at a small scale. The footprint for hydrogen storage and fueling equipment is similar to diesel tanks and refuelers or fueling stations. Due to the flammability of hydrogen, additional buffer space may be required around storage and fueling infrastructure.
2. **Sufficient Fuel Supply for Full ZE Transition:** The biggest issue for hydrogen is the lack of available and economical hydrogen within the market. Hydrogen production, transport, storage, and fueling infrastructure has yet to be planned and developed within and around the SPBP complex.
3. **Existence of / Compatibility with Standards:** There are a number of standards for the safe use of hydrogen fuel and fueling equipment, as well as for safe storage and transport. Hydrogen has only been deployed at SPBP terminals at a pilot or demonstration scale, so additional work is needed to deploy and demonstrate hydrogen infrastructure at scale. It is anticipated that the agencies having jurisdiction, such

as city departments of building and safety and fire departments will need to develop additional standards for the deployment of hydrogen infrastructure at the Ports.

4. **Infrastructure Buildout Timeline:** Both hydrogen fuel supplies and fueling infrastructure have yet to be developed and deployed at a large scale. To date, deployments have only been of a magnitude to support one or two fuel-cell CHE per terminal. It is anticipated that it may take a minimum of 5 to 10 years to build out a robust hydrogen supply chain and supporting infrastructure to deliver sufficient hydrogen fuel to the Ports.

5.0 Cargo Handling Equipment Feasibility

This section provides an overview of the state of development and deployment of battery-electric and fuel-cell versions of yard tractors, top handlers, high-capacity forklifts, and RTG cranes. A description of ZE deployments at the Ports is provided for each type of CHE, highlighting both challenges and progress made from 2021 to 2024.

ZE CHE feasibility is assessed for each type of CHE based on the five established feasibility assessment parameters – (1) commercial availability, (2) technical viability, (3) operational feasibility, (4) fuel and infrastructure readiness, and (5) economic workability. Discussions of fuel and infrastructure readiness are provided above in Section 4.

5.1 Yard Tractors

Yard Tractors are designed for transporting containers within terminal boundaries. These vehicles facilitate cargo movement between ships, storage yards, and container stacks. With a focus on maneuverability and durability, yard tractors are critical for managing the logistics of container handling in the confined and high-traffic environments of ports. ZE yard tractors were the most commonly demonstrated ZE CHE within the SPBP since 2021. BYD, Capacity, Dina/Meritor, Kalmar, and MAFI yard tractors were involved in demonstrations between 2021 and 2024. Over 60 battery-electric yard tractors and 3 fuel-cell yard tractors were demonstrated at the Ports from 2021-2024 based on reviews of TAP reports and interviews with terminal operators and Ports staff.

5.1.1 SPBP 2021-2024 Deployments

Battery-Electric Yard Tractors: Deployments of battery-electric yard tractors and their associated charging infrastructure demonstrated both the challenges that must be overcome when implementing new technologies and the progress that can be made over three years when the Ports, terminal operators, manufacturers, and regulatory agencies work together. From 2021 to 2024, significant improvements in the design, reliability, and overall operational capabilities of yard tractors were realized. Prototype and first-generation commercial models encountered several issues that limited their use, including infrastructure permitting delays, interoperability problems between chargers and yard tractors, design and manufacturing flaws, software issues, and damage that resulted in thermal events.

While there have been several challenges identified in early deployments of battery-electric yard tractors, an increasing number of manufacturers are offering commercially available models that continue to demonstrate increased reliability and operational capabilities. The consensus of SPBP terminal operators is that battery-electric yard tractors are the platform of choice when transitioning the yard tractor fleets to ZE.

Fuel-Cell Yard Tractors: Fuel-cell yard tractors are being evaluated as an alternative for operations requiring extended runtimes and minimal downtime for fueling. Fuel-cell technology offers the advantage of comparable fueling to diesel models and the potential to operate for extended shifts. However, terminal operators appear to be moving away from plans to deploy fuel-cell yard tractors due to the lack of readily available hydrogen and the slow progress in developing commercially available models.

Two Capacity yard tractors were demonstrated at TraPac in POLA. These are the only two deployments of fuel-cell yard tractors in the SPBP between 2021 and 2024. A mobile refueler was also tested at TraPac to support the Capacity yard tractor demonstration. The Capacity yard tractors were designed in approximately 1.5 years and were demonstrated at TraPac for 1 year. The demonstration project showed that the fuel-cell yard tractors can complete two 8-hour shifts at TraPac when the hydrogen fuel tanks and batteries are at full capacity.[6] It is important to note that the yard tractors were used to move container chassis and perform yard housekeeping operations, spending 64% of shifts idling. As a prototype model, the units experienced reliability and integration issues that can be resolved through design improvements in second-generation models.

5.1.2 Commercial Availability

The commercial availability of battery-electric yard tractors has continued to expand since the 2021 assessment, while there has been limited progress in developing commercially available fuel-cell yard tractors (Table 5-1).

Table 5-1: ZE Yard Tractor Commercial Availability Assessment Score

Commercialization Criteria	Battery Electric	Hydrogen Fuel Cell
Production and Certification by Major Manufacturers	1	0.5
Network of Dealerships to Sell and Service CHE	1	0
ZE CHE Include Warranties and Long-Term Support	1	0
Ability to Manufacture CHE to Meet Current/Forecasted Demand	1	0
Backlog of CHE Orders or Credible Expression of Interest	1	0
Commercial Availability Score	**5**	**0.5**
Commercial Availability Level	**Fully Commercial**	**Pre-Commercial**

Battery-Electric Yard Tractors: There are seven manufacturers offering commercially available models, including Autocar, BYD, Kalmar, MAFI, Orange EV, Terberg Taylor, and TICO. These manufacturers are leading CHE suppliers, offering products, warranties, parts, and maintenance through a network of dealerships. manufacturers offer multi-year warranties for batteries (e.g., 6 years or 18,000 hours for Terberg Taylor) and service either directly by manufacturers or through local dealerships, such as Cal-Lift for SPBP.

With the number of manufacturers providing BE yard tractors, it is reasonable that collectively they will be able to manufacture sufficient units to meet current and forecasted design. For example, Orange EV currently has a manufacturing capacity of 35-45 yard tractors per month and has plans to scale to 200 per month. Terberg Taylor reports their projected manufacturing capacity for yard tractors to be 200 units per year by 2027 and 300 units per year by 2028.

terminal operators consistently stated that their individual plans are to replace diesel yard tractors with battery-electric models; therefore, demand and the backlog of orders for this technology is projected to grow. The US EPA Clean Port program will increase demand and backlog of orders over the next three years, with more than $2.7 billion in awards to support port decarbonization. This investment will support further iterative improvements of battery-electric models and commercial availability of battery-electric yard tractors overall. **Battery-electric yard tractors are fully commercially available.**

Fuel-Cell Yard Tractors: There has been no increase in the commercial availability of fuel-cell yard tractors between 2021 and 2024. While pilot development and demonstration projects have been implemented, including the demonstration of fuel-cell Capacity yard tractors at TraPac in POLA, these projects have not led Manufacturers to develop a commercial product. Fuel-cell yard tractor pilot and demonstration projects are continuing in

[6] Final Report for Zero- and Near Zero-Emission Freight Facilities Project: Zero Emissions for California Ports (ZECAP). October 18, 2023.

European ports (e.g., testing of the ATENA fuel-cell yard tractor at the Valencia Terminal Europa); however, interest in this platform has waned since the last assessment. **Fuel-cell yard tractors are pre-commercial.**

5.1.3 Technical Viability

The technical viability of both battery-electric and fuel-cell yard tractors has improved since the 2021 assessment, with battery-electric yard tractors increasing from TRL 7/8 to 9 and fuel-cell yard tractors increasing from TRL 6/7 to 7 (Table 5-2). battery-electric yard tractors have undergone substantial testing and demonstration at container terminals across the U.S., while fuel-cell yard tractor demonstrations have involved prototypes, as detailed below.

Table 5-2: ZE Yard Tractor Technology Readiness Level

Platform	TRL	Definition / Description
Battery Electric	9	**Systems Operations:** Actual System in its final form and operated under full range of operating conditions
Hydrogen Fuel Cell	7	**Systems Conditioning:** Full-scale, similar prototype system demonstrated in relevant environment.

Battery-Electric Yard Tractors: With seven manufacturers producing commercial models of yard tractors, including making improvements over at least two generations, battery-electric yard tractors have undergone significant testing and demonstration at container terminals, including the SPBP complex. For example, Orange EV has conducted 21 demonstration projects (4-6 weeks) involving port and rail operations, including at the Port of San Diego and Port of Savannah. Battery-electric yard tractors have demonstrated the ability to complete one shift consistently without charging, and there are commercially available models with battery capacities greater than 300 kWh designed to complete two 8-hour shifts without opportunity charging. **Battery-electric yard tractors have been proven to work in a final form and under expected conditions (TRL 9).**

Fuel-Cell Yard Tractors: Prototypes of fuel-cell yard tractors have been demonstrated, including testing two Capacity fuel-cell yard tractors at TraPac with a fueling station. There have also been pilot and prototype tests of fuel-cell yard tractors developed by Terberg and ATENA in Europe. **Fuel-cell yard tractors have now been demonstrated at a prototype level in a relevant container terminal environment (TRL 7).**

5.1.4 Operational Feasibility

The operational feasibility of battery-electric yard tractors has continued to improve as more manufacturers offer new models designed specifically to meet the operational demands of ports. The operational feasibility of fuel-cell yard tractors has also improved since 2021, albeit at a slower pace, as evidenced by far fewer deployments and the lack of commercially available models (Table 5-3).

Table 5-3: ZE Yard Tractor Operational Feasibility Assessment Score

Operational Criteria	Battery-Electric	Hydrogen Fuel Cell
Capability to Meet Terminal Operator Performance Parameters	1	0.5
Ability to Meet Per-Shift and Daily Operating Time Requirements	0.5	0.5
Fuel / Charging Speed Meets Revenue Operation Requirements	1	1
Operator Comfort, Safety, and Fueling Procedures	1	0.5
Available Parts, Maintenance, Training, and Manuals	0.5	0
Operational Feasibility Score	**4**	**2.5**
Operational Feasibility Level	**Desired**	**Partial**

Battery-Electric Yard Tractors: The operational feasibility of yard tractors has continued to improve since the 2021 assessment. Manufacturers have incorporated lessons learned from pilot projects and demonstrations into the designs of their current models. Current battery-electric yard tractors feature battery capacities ranging from 132 kWh to 312 kWh, providing runtimes of 8 to 16 hours under typical operating conditions on a single charge. Fast charging allows battery-electric yard tractors to fully recharge in 1 to 2 hours, depending on the charging rate and battery size. Battery-electric yard tractors manufactured by two manufacturers, Terberg Taylor and TICO, now offer battery capacities over 300 kWh, which can operate for approximately 16-20 hours in the yard, 14-18 hours against a ship, and 10-14 hours in rail-side operations.

Battery-electric yard tractors meet basic operational performance requirements in terms of speed, power, and gross combination weight rating (GCWR). Additionally, manufacturers now offer warranties, parts, and maintenance through a network of dealerships. This includes multi-year warranties for batteries (e.g., 6 years or 18,000 hours for Terberg Taylor) and service either directly by manufacturers or through local dealerships, such as Cal-Lift for SPBP. **As of the end of 2024, battery-electric yard tractors are categorized as operationally feasible.**

Fuel-Cell Yard Tractors: There have been far fewer deployments of fuel-cell yard tractors; however, the demonstration project involving Capacity fuel-cell yard tractors in POLA provided valuable insights into the technology's operational feasibility. At TraPac, fuel-cell yard tractors were demonstrated to be capable of completing two 8-hour shifts before refueling when used in a non-container handling support role where the vehicles spent 64% of the shifts idling and were operated at an average speed of 6 mph. If used for container handling operations, it is anticipated that fuel-cell yard tractors would need to be refueled between shifts. It is common practice for terminal operators to refuel diesel CHE between shifts; the 15-minute fueling time with hydrogen would not result in a significant operational change. The lack of commercially available models currently limits the availability of parts, maintenance, training, and manuals; however, it is anticipated that this will be resolved once this technology matures. The lack of available hydrogen fuel combined with the lack of commercially available models will limit this technology's near-term deployment. Due to these limitations, **Fuel-cell yard tractors are categorized as partially operationally feasible.**

5.1.5 Fuel and Infrastructure Availability

Full-scale deployments of electric and hydrogen CHE throughout SPBP terminals will require major infrastructure upgrades to support charging and fueling operations as detailed in Section 4.

Battery-Electric Yard Tractors: Terminal electrification planning efforts indicate that each battery-electric high-capacity yard tractor will require chargers at a 1:1 ratio, excluding units that are serving in a back-up or redundant role.

Fuel-Cell Yard Tractors: Deployment of hydrogen CHE will require less on-terminal infrastructure upgrades than electrified CHE. To support fuel-cell operations at a limited scale, a mobile refueler would be required. Additional on-terminal equipment would include a storage tank and compressor. The space requirements for mobile hydrogen fueling infrastructure and equipment will be similar to current diesel fueling infrastructure.

5.1.6 Economic Workability

Battery-electric yard tractors are projected to be economically workable with incentives while fuel-cell yard tractors are still not economically workable even when incentives are included (Table 5-4). The 10-year TCO of battery-electric yard tractors without incentives is projected to be approximately 10% higher than diesel yard tractors, while the inclusion of incentives results in a lower projected TCO (Table 5-5, Figure 5-1Figure 5-1, and Figure 5-2). Fuel-cell yard tractors have a higher 10-year TCO both with and without incentives due to both higher capital and operating expenses compared to diesel models.

Table 5-4: ZE Yard Tractor Economic Workability Assessment Score

Economic Criteria	Battery-Electric	Hydrogen Fuel Cell
ZE CHE Purchase Price is Affordable to Terminal Operators / Comparable to Diesel CHE	0.5	0
ZE CHE O&M is Comparable to Diesel	1	0
Infrastructure Capital and Operational Costs are Affordable to Terminal Operators	0	0.5
No Major Economic / Workforce Impacts	1	1
TCO is Comparable to Diesel with Incentives through 2030	1	0
Economic Workability Score	**3.5**	**1.5**
Economic Workability Level	**Economically Workable with Incentives**	**Not Economically Workable**

Battery-Electric Yard Tractors: While the average purchase price of battery-electric yard tractors is approximately two times the average price of diesel models, projected O&M savings reduce the TCO over 10 years to within 10% of the TCO of diesel models without incentives. When incentives are factored in, the battery-electric TCO of $495,900 is $130,200 less than the TCO of diesel ($626,100).

The battery-electric CapEx includes the cost of a charger but excludes the costs of other terminal and utility electrical upgrade costs. Terminal and utility electrical upgrade costs are anticipated to total hundreds of millions of dollars, as discussed in Section 4. While the majority of infrastructure costs will be one-time investments to enhance electric system capacity for decades, the magnitude of the investment in the next five years is substantial.

The O&M savings are driven primarily by the 8.6 times higher energy efficiency of battery-electric yard tractors and 3.7 times lower energy cost per hour relative to diesel models. Maintenance costs were also modeled to be 29% lower than diesel models due to the lower maintenance costs of EVs relative to vehicles with combustion engines.

The transition to battery-electric yard tractors is not anticipated to result in major negative economic or workforce impacts. While this transition requires a substantial CapEx investment, it is not anticipated to significantly increase the costs of goods movement based on the comparable TCO to diesel models. Additionally, battery-electric yard tractors will still require human operation, maintenance, and repairs, and therefore their use is not expected to substantially impact the workforce beyond the need for additional training.

Battery-electric yard tractors are classified as Economically Workable with Incentives.

Fuel-Cell Yard Tractors: The TCO of fuel-cell yard tractors is projected to be 2.2 times higher than diesel yard tractors without incentives and 1.8 times higher with incentives. The higher TCO is driven by both higher CapEx and OpEx. While not commercially available, the estimated purchase price of fuel-cell yard tractors is 2.7 times that of a diesel model and annual energy costs are 3.7 times higher.

The cost of installing a gaseous stationary hydrogen fueling station at a terminal is anticipated to be $160,000 per CHE unit. The benefit of hydrogen is that it will not require additional investment in the utility grid and it will require less investment in terminal electrical equipment. While there is not a robust supply of hydrogen, development costs will be incorporated into the price of hydrogen, which would be realized as an operational expense.

The lack of commercially available models, limited fuel supply, and higher TCO does not support large-scale transition to fuel-cell in the near future. Fuel-cell yard tractors will still require human operation, maintenance, and repairs, and therefore their use is not expected to substantially impact the workforce.

Fuel-cell yard tractors are classified as Not Economically Workable with or without incentives.

Table 5-5: Yard Tractors CapEx and OpEx

Section	Metric	Units	Diesel	Battery Electric	Hydrogen Fuel Cell
Capital Expenses	Purchase Price	$	$187,000	$375,000	$500,000
	Tax	$	$19,168	$38,438	$51,250
	Infrastructure	$	$0	$80,000	$160,000
	Total Capital Cost	***$***	***$206,168***	***$493,438***	***$711,250***
	Purchase Incentive	*$*	($0)	($120,000)	($120,000)
	Infrastructure Incentive	*$*	($0)	($48,000)	($96,000)
	Depreciation	$	($48,243)	($78,979)	($120,189)
	Net Capital Cost (w/ Incentives & Depreciation)	***$***	***$206,168***	***$325,438***	***$495,250***
	Discount Rate	%	7%	7%	7%
	Useful Life	yrs	10	10	10
Operating Expenses	Energy Price	$/unit	4.5	0.16	33
	Energy Economy	unit/hr	2.5	21.5	1.25
	Activity	hr/yr	1,680	1,680	1,680
	Energy Cost ($/hr)	**$/hr**	**$11**	**$3**	**$41**
	Annual Energy Cost	**$/yr**	**$19,606**	**$5,779**	**$69,300**
	Maintenance Cost	$/hr	$28	$20	$24
	Annual Maintenance	$/yr	$47,040	$32,928	$39,514
	Annual LCFS Credits	$/yr	($0)	($3,190)	($0)
	Net Annual O&M Cost	**$/yr**	**$66,646**	**$35,518**	**$108,814**
Total Cost of Ownership	**TCO (without Incentives)**	**$**	**$623,300**	**$684,900**	**$1,353,100**
	TCO (with incentives)	**$**	**$623,300**	**$493,600**	**$1,137,100**

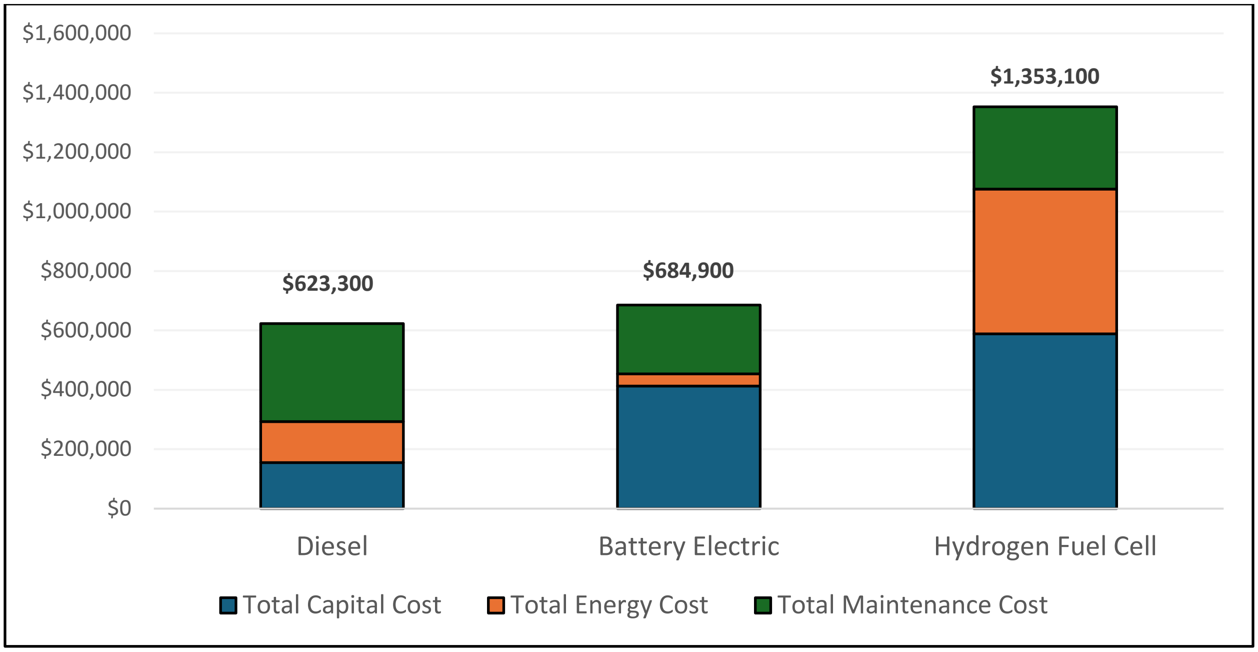

Figure 5-1: Yard Tractor 10-Year Total Capital, Energy, and Maintenance Costs without Incentives

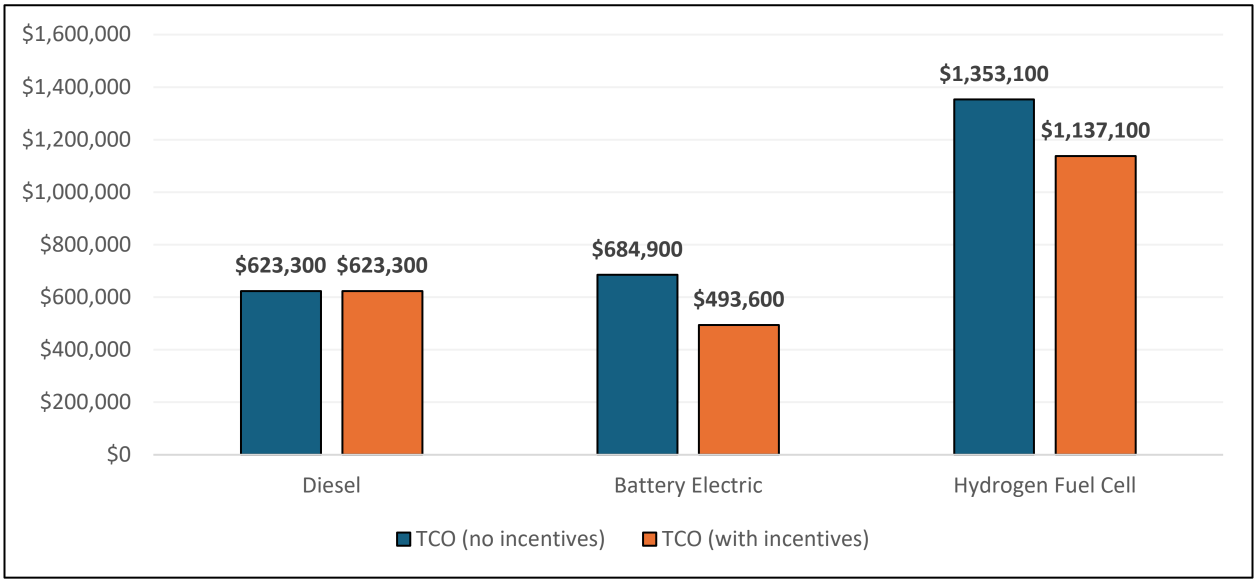

Figure 5-2: Yard Tractor 10-Year Total Cost of Ownership Comparison with and without Incentives

5.2 Top Handlers

Top handlers are specialized lift trucks used to lift, transport, and stack containers, particularly in storage yards or rail-transfer areas. Top handlers lift containers from above, making them efficient for stacking operations.

5.2.1 SPBP 2021-2024 Deployments

Both battery-electric and fuel-cell top handlers have been demonstrated at SPBP terminals, including 10 battery-electric and 2 fuel-cell top handlers.

Battery-Electric Top Handlers: First-generation Taylor Machine Works (Taylor) battery-electric top handlers have been demonstrated by Everport (POLA), Long Beach Container Terminal (POLB), and SSA Pier C (POLB). Second generation Taylor top handlers with upgraded 985-kWh Proterra batteries and wheel end electric traction motors are now deployed at West Basin Container Terminal (WBCT, POLA). First-generation Taylor top handlers experienced reliability, integration, and range issues consistent with other prototype models. The first-generation models, even with megawatt battery packs, were not able to complete two shifts without opportunity charging. Second-generation Taylor battery-electric top handlers deployed at WBCT are greatly improved, commercially available models that are approaching operational equivalency with diesel top handlers. These battery-electric top handlers are now capable of completing two 8-hour shifts of yard operations without opportunity charging; however, they currently cannot complete two shifts of rail-side operations without opportunity charging.

Fuel-Cell Top Handlers: Prototype fuel-cell top handlers from Toyota Tsusho and Hyster with Nuvera fuel cells were demonstrated at Fenix Marine Services (POLA). Toyota Tsusho's prototype is powered by 160-kW fuel cells and includes a 105-kW battery along with 60 kg of hydrogen storage that supports 12 hours of continuous container yard operations. The Hyster top handler is powered by 45-kW hydrogen fuel cells and lithium-ion battery that provide 8-10 hours of runtime and can be refueled in approximately 15 minutes.

5.2.2 Commercial Availability

Commercial availability of battery-electric top handlers is determined to be at the fully commercial stage, while fuel-cell top handlers are at the pre-commercial stage (Table 5-6).

Table 5-6: ZE Top Handler Commercial Availability Assessment Score

Commercialization Criteria	Battery Electric	Hydrogen Fuel Cell
Production and Certification by Major Manufacturers	1	0.5
Network of Dealerships to Sell and Service CHE	1	0.5
ZE CHE Include Warranties and Long-Term Support	1	0.5
Ability to Manufacture CHE to Meet Current/Forecasted Demand	0.5	0.5
Backlog of CHE Orders or Credible Expression of Interest	0.5	0
Commercial Availability Total Score	**4**	**2**
Commercial Availability Level	**Fully Commercial**	**Pre-Commercial**

Battery-Electric Top Handlers: Taylor now offers multiple commercially available battery-electric container handlers, which include the ZLC 994, ZLC-995, and ZLC-996 Electric Loaded Container Handlers in addition to battery-electric reach stackers and empty container handlers. Kalmar and Terminalift offer commercially available reach stackers. CVS Ferrari offers commercial battery-electric empty container handlers. In February 2024, Taylor announced an acquisition of 85 percent of CVS Ferrari shares to further boost battery-electric CHE market opportunities, including for top handlers, side handlers, reach stackers, and empty container handlers in the U.S. As one of the leading U.S. manufacturers of CHE, Taylor offers products, parts, and maintenance through a network of dealerships. **Battery-electric top handlers are categorized as fully commercial**.

Fuel-Cell Top Handlers: Hyster and Toyota Tsusho are two of the main manufacturers focusing on fuel-cell technologies to produce ZE top handlers. Both are conducting pilot demonstrations in the SPBP; however, these demonstrations have yet to prove that these models can meet SPBP operational requirements. While both manufacturers are established companies, the prototype stage of these models does not lend itself to support from dealerships, availability of warranties, readiness to manufacture current models at scale, or a backlog of commercial orders. **Fuel-cell top handlers are categorized as pre-commercial**.

5.2.3 Technical Viability

The technology readiness levels of both battery-electric and fuel-cell top handlers have improved from 2021 and 2024, with the battery-electric top handler TRL increasing from 6/7 to 8 and the fuel-cell top handler TRL increasing from 5/6 to 7 (Table 5-7).

Table 5-7: ZE Top Handler Technology Readiness Level

Platform	TRL	Definition / Description
Battery-Electric	8	**Systems Conditioning:** Actual system completed and qualified through testing and demonstration
Hydrogen Fuel Cell	7	**Systems Conditioning:** Full-scale, similar prototype system demonstrated in relevant environment.

Battery-Electric Top Handlers: Deployment of the Taylor second generation top handler at YTI (POLA) has shown that this technology can now operate for two full 8-hour shifts for yard operations without opportunity charging. The Taylor battery-electric top handler requires opportunity charging between shifts when working the rail yard due to the more energy-intensive nature of that operation. It is anticipated that through a combination of larger battery size, increases in the energy density of lithium-ion batteries, and design upgrades that enhance energy efficiency, the Taylor battery-electric top handler will achieve a TRL 9 within 1-2 years. **Battery-electric top handlers are nearly capable of operating under the full range of operating conditions at SPBP container terminals (TRL 8).**

Fuel-Cell Top Handlers: In 2021, fuel-cell top handlers were determined to be at the laboratory scale to engineering / pilot scale of technology development and demonstration (TRL 5 to 6). Between 2021 and 2024, pilot-scale technology demonstrations are still underway, including testing of Hyster H1050-1150XD-CH and Toyota Tsusho fuel-cell top handlers at SPBP marine terminals. The Hyster fuel-cell top handler is the most advanced fuel-cell model on the market, designed to lift and transport loaded containers. Current models can operate for 8 to 10 hours on a single hydrogen tank, which can be filled in 10-15 minutes. **Fuel-cell top handlers are prototype models that have been operated in container handling operations under expected conditions (TRL 7).**

5.2.4 Operational Feasibility

The operational feasibility of battery-electric top handlers currently exceeds fuel-cell top handlers and is likely to do so because terminal operators currently have plans to procure and deploy more battery-electric models in the foreseeable future due to the lack of commercially available top handlers and limited hydrogen fuel supply (Table 5-8).

Table 5-8: ZE Top Handlers Operational Feasibility Assessment Score

Operational Criteria	Battery-Electric	Hydrogen Fuel Cell
Capability to Meet Terminal Operator Performance Parameters	1	1
Ability to Meet Per-Shift and Daily Operating Time Requirements	0.5	0.5
Fuel / Charging Speed Meets Revenue Operation Requirements	1	0.5
Operator Comfort, Safety, and Fueling Procedures	1	0.5
Available Parts, Maintenance, Training, and Manuals	1	0.5
Operational Feasibility Score	**4.5**	**3**
Operationally Feasibility Level	**Desired**	**Partial**

Battery-Electric Top Handlers: Taylor battery-electric top handlers have a lifting capacity of 90,000 lbs, which is comparable to the lifting capacities of diesel top handlers, which range from 88,000 to 90,000 lbs. Additionally, the Taylor battery-electric model can complete two 8-hour shifts of yard operations without charging between shifts. Opportunity charging is required to complete a second 8-hour shift when performing rail operations. Full charging can be accomplished with a 180-kW charger in approximately 5 hours during the hoot shift, which will support the majority of SPBP two-shift terminal operations. Opportunity charging has been shown to be sufficient to allow completion of the second 8-hour shift during rail operations.

Operation of the Taylor ZLC-966 battery-electric top handler is similar to Taylor's equivalent diesel models, with a couple of notable differences. First the battery-electric model uses regenerative braking, which is absent on diesel models. Vehicles with regenerative braking slow immediately as the operator releases his/her foot from the accelerator. This can take a short adjustment period for drivers to become accustomed to the new operational style. Other than regenerative braking, the other controls and operations of battery-electric top handlers are very similar to other Taylor models by design, and battery-electric models provide a comfortable, smoother, and quieter driving experience than diesel models.

Taylor offers a robust sales, parts, and maintenance system for its models, including diesel and battery-electric top handlers. Terminal operators have reported that Taylor has offered training and responsive service and parts to allow their equipment to remain operational.

In summary, the **Taylor battery-electric top handler is operationally feasible for container terminal yard operations, and it is partially operationally feasible for rail operations** since opportunity charging is still needed. It is anticipated that continued battery storage and energy efficiency improvements will allow the next iterations to accomplish two 8-hour shifts for both yard and rail operations without opportunity charging.

Fuel-Cell Top Handlers: The Hyster fuel-cell top handler is the most advanced model on the market, designed to lift and transport loaded containers. The Hyster top handler is powered by two 45-kW fuel cells along with a lithium-ion battery that supports 8-10 hours of operations. The hydrogen storage tank can be filled in approximately 15 minutes, making it feasible to fuel between shifts.

General operator feedback of fuel-cell models has been positive from the perspective of comfort and safety. Fuel-cell models tend to operate similarly to battery-electric models, offering smoother and quieter driving experiences than diesel models.

While hydrogen fueling can be accomplished in minutes, it does require special safety protocols, such as setbacks from existing infrastructure and avoiding areas with other flammable material and high-power electrical equipment. Operators of mobile refuelers must be adequately trained and provided with safety training and personal protective equipment to perform fueling.

Given that deployments of the Hyster and Toyota Tsusho fuel-cell top handers have been limited to pilot demonstrations and the most advanced model (Hyster) can only operate for one shift without refueling, **fuel-cell top handlers are categorized as partially operationally feasible for container terminal operations.**

5.2.5 Fuel and Infrastructure Availability

Full-scale deployments of ZE CHE throughout SPBP terminals will require infrastructure upgrades to support charging and hydrogen fueling operations, as discussed in Section 4.

Battery-Electric Top Handlers: Terminal electrification planning efforts have determined that each battery-electric top handler will require chargers at a 1:1 ratio, excluding units that are serving in a back-up or redundant role.

Fuel-Cell Top Handlers: Deployment of hydrogen CHE will require less on-terminal infrastructure upgrades than electrified CHE. To support fuel-cell operations at a limited scale, a mobile refueler would be required at a minimum. Additional on-terminal equipment would include a storage tank and compressor. The space requirements for hydrogen fueling infrastructure and equipment will be similar to current diesel fueling infrastructure.

5.2.6 Economic Workability

Battery-electric top handlers are categorized as economically workable with incentives, while fuel-cell top handlers are not economically workable with our without incentives (Table 5-9). The 10-year TCO of battery-electric top handlers with incentives is projected to be less than the TCO of diesel top handlers due to the substantially lower projected O&M costs, while the TCO of fuel-cell with incentives is projected to be higher than diesel models, which is driven by higher capital and operating expenses (Table 5-10, Figure 5-3, and Figure 5-4).

Table 5-9: ZE Top Handler Economic Workability Assessment Score

Economic Criteria	Battery-Electric	Hydrogen Fuel Cell
ZE CHE Purchase Price is Affordable to Terminal Operators / Comparable to Diesel CHE	0.5	0
ZE CHE O&M is Comparable to Diesel	1	0
Infrastructure Capital and Operational Costs are Affordable to Terminal Operators	0	0.5
No Major Economic / Workforce Impacts	1	1
TCO is Comparable to Diesel with Incentives through 2030	1	0
Economic Workability Score	**3.5**	**1.5**
Economic Workability Level	**Economically Workable with Incentives**	**Not Economically Workable**

Battery-Electric Top Handlers: While the average purchase price of battery-electric top handler is approximately 2.3 times the average price of diesel models, projected O&M savings reduce the TCO over 10 years to within 6% of the TCO of diesel models without incentives. When incentives are factored in, the battery-electric TCO of $1.9M is $142,000 less than the TCO of diesel ($2.04M).

The battery-electric CapEx includes the cost of a charger but excludes the costs of other utility and terminal electrical upgrade costs. These electrical infrastructure upgrades are anticipated to total hundreds of millions of dollars across the Ports. While these are largely one-time investments to enhance system capacity for decades, the magnitude of the investment is substantial.

The O&M savings are driven primarily by the 6.2 times lower annual energy costs, which are the product of higher energy efficiency of battery-electric models and lower energy cost per hour of electricity relative to diesel models. Maintenance costs were also modeled to be 29% lower than diesel models due to the lower maintenance costs of EVs relative to vehicles with combustion engines.

As previously discussed for top handlers, transition to battery-electric top handlers is not anticipated to have major economic or workforce impacts.

Due to the projected lower TCO with incentives, **Battery-electric top handlers are classified as Economically Workable with Incentives.**

Fuel-Cell Top Handlers: The TCO of fuel-cell top handlers is projected to be 1.9 times higher than diesel top handlers without incentives. Even when incentives are included, the projected TCO of fuel-cell top handlers is still 1.8 times higher that diesel models. The higher TCO is driven by both higher CapEx and OpEx. While not commercially available, the estimated purchase price of fuel-cell yard tractors is 2.6 times that of a diesel model and annual energy costs are 2.2 times higher. **Fuel-cell yard tractors are classified as Not Economically Workable with or without incentives.**

Table 5-10: Top Handler CapEx and OpEx

Section	Metric	Units	Diesel	Battery Electric	Hydrogen Fuel Cell
Capital Expenses	Purchase Price	$	$800,000	$1,700,000	$1,950,000
	Tax	$	$82,000	$174,250	$199,875
	Infrastructure	$	$0	$120,000	$160,000
	Total Capital Cost	***$***	***$882,000***	***$1,994,250***	***$2,309,875***
	Purchase Incentive	*$*	($0)	($120,000)	$120,000
	Infrastructure Incentive	*$*	($0)	($72,000)	$96,000
	Depreciation	$	($206,387)	($437,378)	($508,150)
	Net Capital Cost (w/ Depreciation & Incentives)	***$***	***$675,613***	***$1,364,872***	***$1,801,725***
	Discount Rate	%	7%	7%	7%
	Useful Life (assumed)	yrs	10	10	10
Operating Expenses	Energy Price	$/unit	4.5	0.16	33
	Energy Economy	unit/hr	10	45	3
	Activity	hr/yr	2,240	2,240	2,240
	Energy Cost ($/hr)	$/hr	$45	$7	$99
	Annual Energy Cost	$/yr	$104,562	$16,128	$221,760
	Maintenance Cost	$/hr	$41	$32	$38
	Annual Maintenance	$/yr	$91,837	$70,644	$84,773
	LCFS Credits	$/yr	$0	$8,901	$0
	Net Annual O&M Cost	**$/yr**	**$196,400**	**$77,871**	**$306,533**
Total Cost of Ownership	**TCO (no incentives)**	**$**	**$2,043,500**	**$2,158,300**	**$3,945,400**
	TCO (with incentives)	**$**	**$2,043,500**	**$1,901,400**	**$3,729,400**

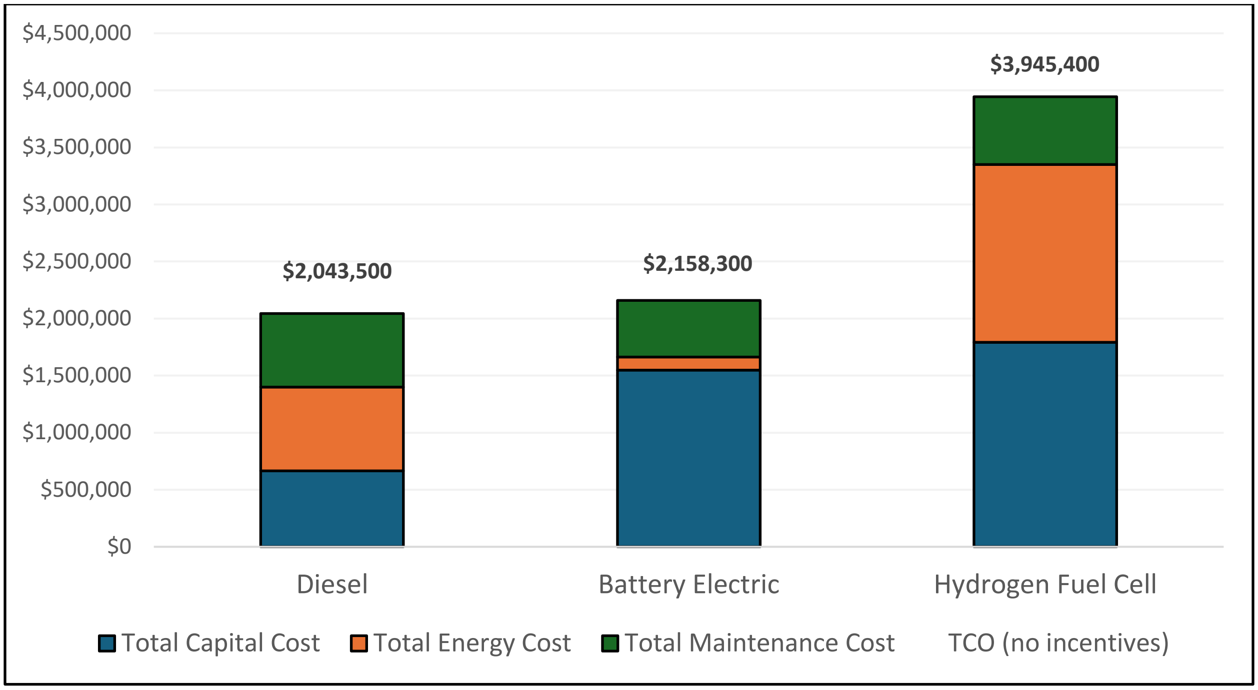

Figure 5-3: Top Handler Total Capital, Energy, and Maintenance Costs

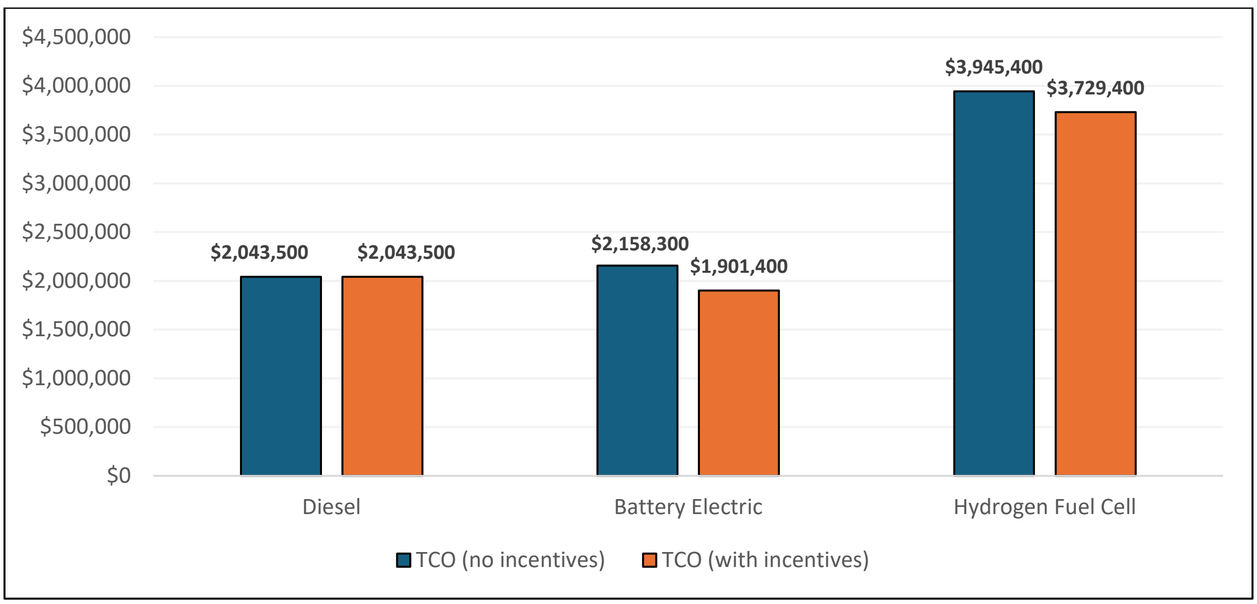

Figure 5-4: Top Handler Total Cost of Ownership with and without Incentives

5.3 Large-Capacity Forklifts

Large-capacity forklifts, also referred to as heavy-lift forklifts, are defined as being capable of lifting at least 36,000 lbs. Large-capacity forklifts share similar platforms to top handlers and are most commonly diesel powered. Large-capacity forklifts tend to experience the most strenuous use on terminals that focus on breakbulk operations where they are used to move bulk goods, steel coils, or other products that exceed the capacity of standard forklifts. On container terminals, large-capacity forklifts are used less intensely since container handling is accomplished with specialized equipment such as top handlers, side handlers, reach stackers, and RTG cranes. battery-electric large-capacity forklifts have been the more prevalent ZE solution in the large-capacity forklifts segment, but we are starting to see some fuel-cell forklifts options being offered by manufacturers.

5.3.1 SPBP 2021-2024 Deployments

While small-capacity forklifts are the most common battery-electric CHE in service at the SPBP, deployments of ZE large-capacity forklifts have been extremely limited.

Battery-Electric Large-Capacity Forklifts: The Wiggins eBull large-capacity forklift was demonstrated during the 2021 reporting period; however, since then, Wiggins has not continued this demonstration in the SPBP. An additional demonstration project attempted to develop and demonstrate large-capacity forklifts at the break bulk terminal operated by Pasha Stevedoring Terminals in the POLA. In this demonstration project, Taylor large-capacity forklifts were repowered using battery-electric drivetrains developed by TransPower and were briefly placed in service in 2022. The repowered forklifts were used to offload breakbulk vessels during a total of two 8-hour day shifts. During those two shifts, the forklifts completed 8 hours of operations with approximately 40 percent state of charge (SOC). While deployments have been limited at SPBP, battery-electric large-capacity forklifts are deployed at other West Coast ports that focus on break bulk operations, including at the ports of San Diego, Stockton, and West Sacramento. The most commonly deployed model at these ports is the Wiggins eBull, which has received positive feedback from terminal operators and port staff.

Fuel-Cell Forklifts: While there is one manufacturer, Wiggins, that currently offers a fuel-cell forklift model for ports, this model has yet to be demonstrated at a marine terminal.

5.3.2 Commercial Availability

The commercial availability of battery-electric large-capacity forklifts has increased to the level of full commercial availability since the 2021 assessment, with multiple manufacturers offering models. The commercial availability of fuel-cell forklifts also improved with Wiggins now offering a commercially available large-capacity model; however, it is the only manufacturer to do so and the model has not been deployed at a marine terminal to date, resulting in a determination fuel-cell high-capacity forklifts are at an early commercial stage (Table 5-11).

Table 5-11 – ZE Large-Capacity Forklift Commercial Availability Assessment Score

Commercialization Criteria	Battery Electric	Hydrogen Fuel Cell
Production and Certification by Major Manufacturers	1	0.5
Network of Dealerships to Sell and Service CHE	1	0.5
ZE CHE Include Warranties and Long-Term Support	1	1
Ability to Manufacture CHE to Meet Current/Forecasted Demand	1	0.5
Backlog of CHE Orders or Credible Expression of Interest	1	0
Commercial Availability Score	**5**	**2.5**
Commercial Availability Level	**Fully Commercial**	**Early Commercial**

Battery-Electric Large-Capacity Forklifts: Manufacturers such as Kalmar, Konecranes, Hyster, Sany, Taylor, and Wiggins offer battery-electric large-capacity forklifts powered by lithium-ion batteries, which can provide sufficient energy for continuous operation over a standard 8-hour shift. battery-electric models have lifting capacities ranging from 36,000 to 100,000 lbs. Current models can be charged using DCFC to support two-shift operations. Of the manufacturers, Taylor has made the largest commercial advancement and is now offering the ZH-1000 electric forklift which has been demonstrated to be capable of completing two 8-hour shifts under typical operations without opportunity charging between shifts.

These manufacturers are leading CHE suppliers, offering products, warranties, parts, and maintenance through a network of dealerships, helping to enhance the long-term commercial viability of battery-electric high-capacity forklifts. In light of the number of manufacturers offering commercial models and the limited total number of large-capacity forklifts in service at the Ports, it is anticipated that manufacturers collectively have the ability to manufacture sufficient battery-electric forklifts to meet SPBP demand.

Battery-electric models are being deployed at several breakbulk or omni terminals, including at the ports of San Diego, Stockton, and West Sacramento, and additional orders are anticipated based on US EPA Clean Ports awards. **Battery-electric high-capacity forklifts were determined to be fully commercial.**

Fuel-Cell Large-Capacity Forklifts: As of 2024, only Wiggins is offering an HFC large-capacity forklift – a hydrogen version of the Yard eBull. The H2 Yard eBull was developed to offer a model with longer run times and less down time for fueling than the battery-electric Yard eBull. While this model is commercially available and Wiggins offers sales, service, parts, warranty, and other support for this model, there has not been deployment and testing of this model at a marine terminal, and we are not aware of a backlog of orders at this time. Like other HFC CHE, HFC forklift deployment faces the challenge of a limited hydrogen supply and price uncertainty. **Fuel-cell high-capacity forklifts were determined to be at an early commercial stage.**

5.3.3 Technical Viability

Significant advances in the technical viability of battery-electric and fuel-cell large-capacity forklifts have occurred between 2021 and 2024, battery-electric forklifts increasing from TRL 6/7 to 9 and fuel-cell forklifts increasing from 5/6 to 7 (Table 5-12).

Table 5-12: Large-Capacity Forklift Technology Readiness Level

Platform	TRL	Definition / Description
Battery-Electric	9	**Systems Operations:** Actual system in its final form and operated under full range of operating conditions.
Hydrogen Fuel Cell	7	**Systems Conditioning:** Full-scale, similar prototype system demonstrated in relevant environment.

Battery-Electric Large-Capacity Forklifts: In 2024, battery-electric high-capacity forklifts have been tested at container and breakbulk terminals, demonstrating lift capacities equivalent to diesel models and the ability to complete two shifts with opportunity charging. While testing and deployment of commercially available models has been limited at the Ports, the full-scale deployments at the ports of San Diego, Stockton, and West Sacramento have shown that these models are capable of meeting operational requirements. **Battery-electric large-capacity forklifts represent actual systems that have been operated under a full range of operating conditions (TRL 9).**

Fuel-Cell Large-Capacity Forklifts: As of the end of 2024, there have been no deployments of the Wiggins fuel-cell Yard eBull at any marine terminal. While the battery-electric eBull yard model, on which the H2 eBull yard model is based, is capable of operating for a full 8-hour shift, the fuel-cell model has yet to be deployed and tested at either a breakbulk or container terminal. **Fuel-cell large-capacity forklifts are currently in the full-scale prototype demonstration stage (TRL 7).**

5.3.4 Operational Feasibility

The operational feasibility of both battery-electric and fuel-cell high-capacity forklifts has increased substantially since the 2021 assessment. In 2021, there were no commercial models available and early demonstration models were still in development. As of 2024, battery-electric high-capacity forklifts have achieved the desired operational feasibility level and fuel-cell high-capacity forklifts have achieved partial operational feasibility (Table 5-13).

Table 5-13: Large-Capacity Forklift Operational Feasibility Assessment Score

Operational Criteria	Battery-Electric	Hydrogen Fuel Cell
Capability to Meet Terminal Operator Performance Parameters	1	1
Ability to Meet Per-Shift and Daily Operating Time Requirements*	1	0.5
Fuel / Charging Speed Meets Revenue Operation Requirements	1	1
Operator Comfort, Safety, and Fueling Procedures	1	0.5
Available Parts, Maintenance, Training, and Manuals	1	0.5
Operational Feasibility Score	**5**	**3.5**
Operational Feasibility Level	**Desired**	**Partial**

Battery-Electric Large-Capacity Forklifts: There are several manufacturers offering battery-electric models with lifting capacities from 36,000 to 100,000 lbs that can complete 8-16+ hours of operations without opportunity charging. Large-capacity forklifts on container terminals are used to move heavy equipment and chassis, but are not directly involved in most container handling operations. They tend to have lower utilization levels, typically used between 5-15% of the time. As such a forklift with an 8-hour range will be capable of completing at least two 8-hour shifts without recharging. Large-capacity forklifts on break bulk terminals receive heavier use and are directly involved in offloading vessels. For breakbulk terminals that operate two 8-hour shifts with a 1-hour break, the ability to perform two shifts without opportunity charging is also preferred.

The Taylor ZH-1000 heavy-duty forklift greatly improved the operational feasibility of battery-electric large capacity forklifts. It provides a maximum lifting capacity of 100,000 lbs and operates with a 660-V battery-electric power drivetrain that can complete two 8-hour shifts under typical operations. The manufacturer reports that the ZH-1000 can be fully recharged in 4.5 hours using a 180-kW charger. Operation of the Taylor high-capacity forklifts is similar to Taylor's equivalent diesel models, with a couple of notable differences. First the battery-electric model uses regenerative braking, which is absent on diesel models. Vehicles with regenerative braking begin to slow immediately as the operator releases his/her foot from the accelerator. This can take a short adjustment period for drivers to become accustomed to the new operational style. Other than regenerative braking, the other controls and operations of battery-electric forklifts are very similar to Taylor diesel models by design. One notable benefit of battery-electric models is that they provide a more comfortable, smoother, and quieter driving experience compared to diesel models.

Taylor offers a robust sales, parts, and maintenance system for its models, including diesel and battery-electric CHE. Terminal operators have reported that Taylor has offered training and responsive service and parts to allow their equipment to remain operational. Other manufacturers also offer robust support networks for their battery-electric forklifts, but the Taylor model is described in greater detail because of its superior operational feasibility.

Battery-electric high-capacity forklifts are operationally feasible for container and breakbulk terminal operations.

Fuel-Cell Large-Capacity Forklifts: The Wiggins hydrogen-powered forklift, fuel-cell Yard eBull, is currently at the prototype phase and has yet to be tested at a marine terminal. The manufacturer designed the H2 Yard eBull to provide up to 12 hours of continuous operation on a single fueling. Like other fuel-cell CHE, fueling can take less than 15 minutes. While the fuel-cell Yard eBull is built on a similar platform as the battery-electric Yard eBull, the lack of testing at a port terminal limits our ability to categorize this platform as fully operational. Until deployment in a port environment is completed, **Fuel-cell high-capacity forklifts are categorized as partially operationally feasible.**

5.3.5 Fuel and Infrastructure Availability

Full-scale deployments of electric and hydrogen CHE throughout SPBP terminals will require major infrastructure upgrades to support charging and fueling operations, as detailed in Section 4.

Battery-Electric Large-Capacity Forklifts: Terminal electrification planning efforts indicate that battery-electric high-capacity forklifts deployed at container terminals have sufficiently low use that multiple forklifts can be served by the same charger or forklifts can be charged using chargers for other classes of battery-electric CHE, such as top handlers.

Fuel-Cell Top Forklifts: Deployment of hydrogen CHE will require less on-terminal infrastructure upgrades than electrified CHE. To support fuel-cell operations at a limited scale, a mobile refueler would be required at a minimum. Additional on-terminal equipment would include a storage tank and compressor.

5.3.6 Economic Workability

The economic workability of battery-electric large-capacity forklifts is at a level where the TCO (with incentives) is projected to be nearly equivalent to diesel top handlers over a 10-year period due to the substantially lower projected O&M costs, while fuel-cell large-capacity forklifts are still not economically workable due to their higher TCO, which is driven by both higher capital and operating expenses relative to diesel models (Table 5-14, Table 5-15, Figure 5-5, and Figure 5-6).

Table 5-14: ZE Top Handler Economic Workability Assessment Score

Economic Criteria	Battery-Electric	Hydrogen Fuel Cell
ZE CHE Purchase Price is Affordable to Terminal Operators / Comparable to Diesel CHE	0.5	0
ZE CHE O&M is Comparable to Diesel	1	0
Infrastructure Capital and Operational Costs are Affordable to Terminal Operators	0	0.5
No Major Economic / Workforce Impacts	1	1
TCO is Comparable to Diesel with Incentives through 2030	0.5	0
Economic Workability Score	**3**	**1.5**
Economic Workability Level	**Economically Workable with Incentives**	**Not Economically Workable**

Battery-Electric Large-Capacity Forklifts: Before incentives, the average purchase price of battery-electric large-capacity forklift is 1.6 times the average price of diesel models and the 10-year and TCO is 58% higher than diesel models. When incentives are factored in, the battery-electric TCO of $419,900 is nearly comparable to $402,600 for diesel. The battery-electric CapEx includes the cost of a charger but excludes the costs of other utility and terminal electrical upgrade costs. The O&M savings are driven primarily by the 2X lower annual energy costs, which are the product of higher energy efficiency of battery-electric models and lower energy cost per hour of electricity relative to diesel models. Maintenance costs were also modeled to be 29% lower than diesel models due to the lower maintenance costs of EVs relative to vehicles with combustion engines. Similar to other human-operated CHE, transition to battery-electric large-capacity forklifts is not anticipated to have major economic or workforce impacts. **Battery-electric large-capacity forklifts are classified as Economically Workable with Incentives.**

Fuel-Cell Large-Capacity Forklifts: The TCO of fuel-cell large-capacity forklifts is projected to be 3.5 times higher than diesel models without incentives and 3.0 times higher with incentives. The higher TCO is driven by both higher CapEx and OpEx. The purchase price of fuel-cell large-capacity forklifts is 2.6 times that of a diesel model and annual energy costs are 2.2 times higher. While the economics does not currently work for fuel-cell forklifts, the eventual transition to this platform is not anticipated to have major economic or workforce impacts. **Fuel-cell large-capacity forklifts are classified as Not Economically Workable with or without incentives.**

Table 5-15: Large-Capacity Forklifts CapEx and OpEx

Section	Metric	Units	Diesel	Battery Electric	Hydrogen Fuel Cell
Capital Costs	Purchase Price	$	$350,000	$550,000	$750,000
	Tax	$	$35,875	$56,375	$76,875
	Infrastructure	$	$0	$100,000	$160,000
	Total Capital Cost	***$***	***$385,875***	***$706,375***	***$986,875***
	Purchase Incentive	***$***	($0)	($120,000)	($120,000)
	Infrastructure Incentive	***$***	($0)	($60,000)	($96,000)
	Depreciation	**$**	($90,294)	($127,743)	($187,079)
	Net Capital Cost (w/ Depreciation & Incentives)	***$***	***$385,875***	***$526,375***	***$770,875***
	Discount Rate	%	7%	7%	7%
	Useful Life	yrs	10	10	10
Operating Costs	Energy Price	$/unit	4.5	0.16	33
	Energy Economy	unit/hr	1.5	21	1.5
	Activity	hr/yr	1,680	1,680	1,680
	Energy Cost ($/hr)	$/hr	$7	$3	$50
	Annual Energy Cost	$/yr	$11,763	$5,645	$83,160
	Maintenance Cost	$/hr	$3	$2	$2
	Annual Maintenance	$/yr	$4,200	$2,940	$3,528
	LCFS Credits	$/yr	($0)	($5,183)	($0)
	Net Annual O&M Cost	**$/yr**	**$15,963**	**$3,402**	**$86,688**
Total Cost of Ownership	**TCO (no Incentives)**	**$**	**$402,644**	**$636,624**	**$1,405,204**
	TCO (with Incentives)	**$**	**$402,644**	**$419,924**	**$1,189,204**

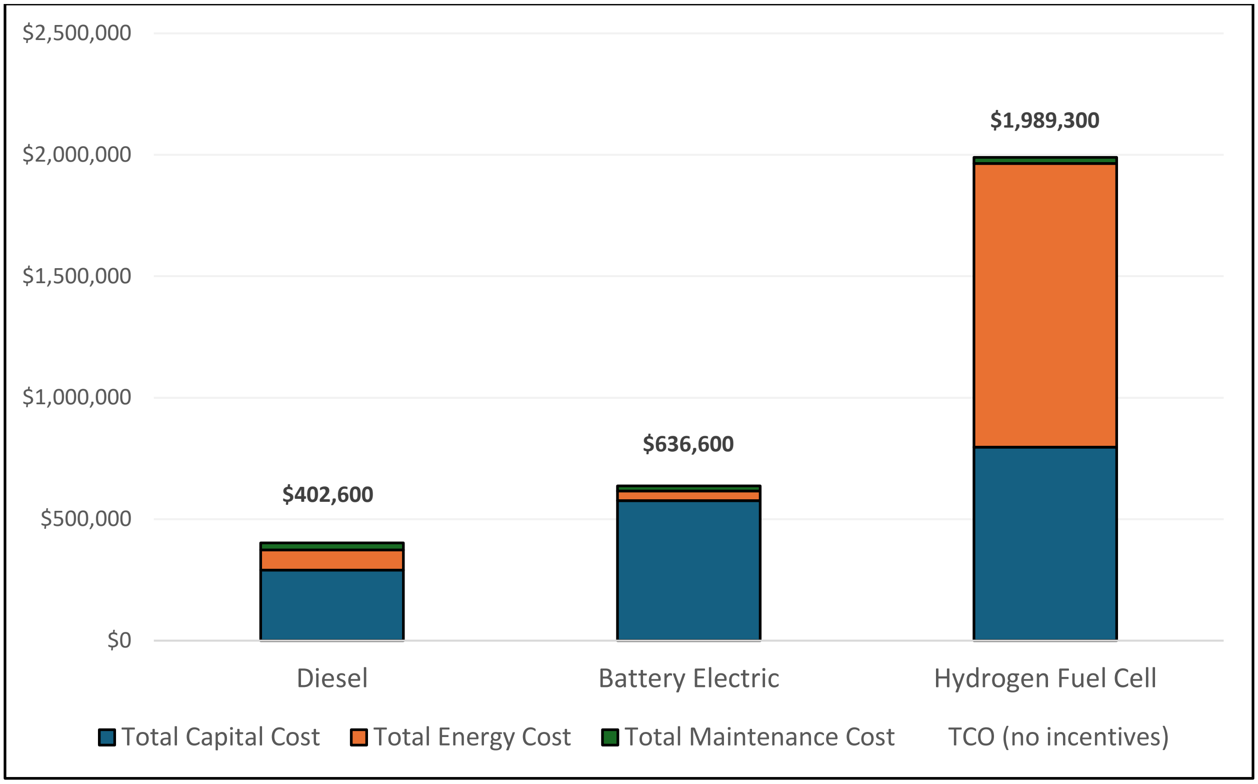

Figure 5-5: Large-Capacity Forklift Total Capital, Maintenance, and Energy Costs

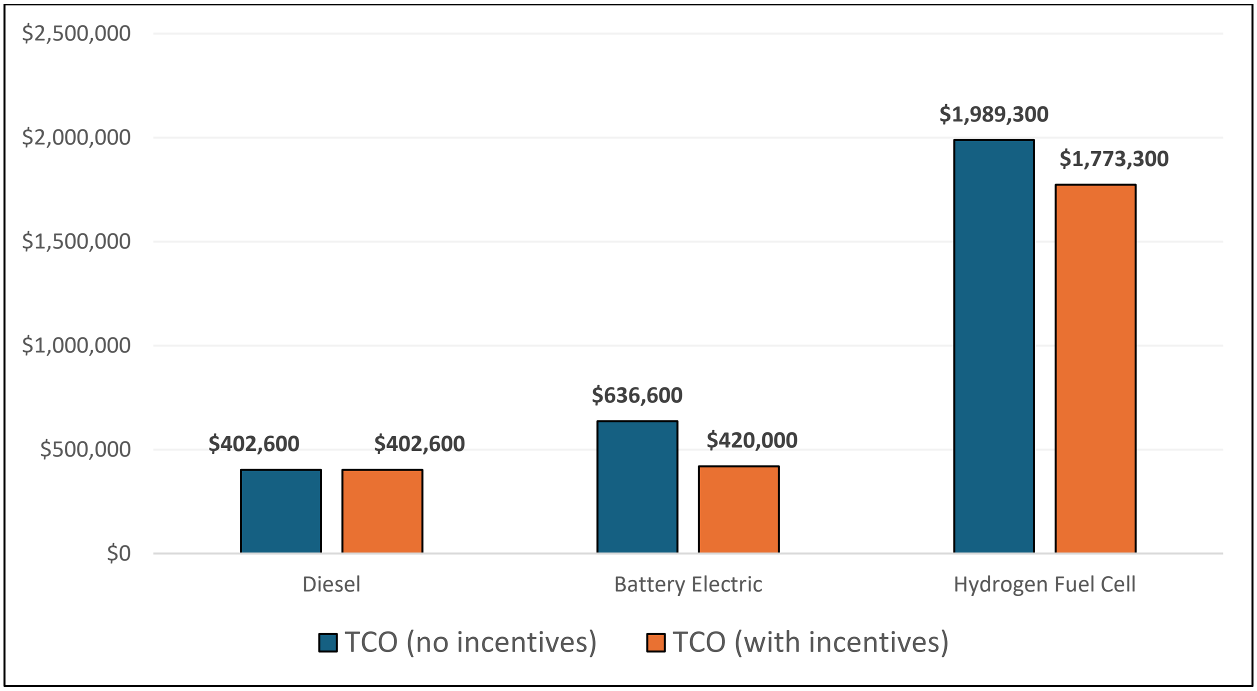

Figure 5-6: Large-Capacity Forklift Total Cost of Ownership with and without Incentives

5.4 Rubber-Tired Gantry Cranes

RTG Cranes are large, mobile cranes used to stack and move containers within terminal yards. Operating on rubber tires, they are versatile and capable of navigating container stacks without the need for fixed railing systems. RTG cranes are integral to efficient container handling, offering the ability to lift containers to various heights and organize them across multiple rows, enabling high-density storage within terminals. ZE RTG cranes are available in three primary configurations: grid-electric, battery-electric, and fuel-cell models.

Grid-Electric RTG Cranes eliminate onboard fuel by drawing power directly from the electrical grid. These systems are currently implemented using two power connection configurations: cable reel and busbar systems.

- **Cable Reel Systems** connect RTG cranes to the grid through retractable cables, which unwind and rewind as the crane moves. This configuration allows some flexibility within operational zones, although mobility is constrained by the cable's length. Konecranes' E-RTG, for instance, leverages this system to operate across container rows. Cable management systems require robust design to prevent wear and operational interruptions, while power supply connections demand significant upfront investment. Grid-electric RTG cranes with cable reels may also include batteries that allow them to move between rows. Container movement activities still require connection to the grid.

- **Busbar Systems** provide continuous power through fixed electrical conductors installed along the RTG's travel path. The implementation of busbar systems introduces certain limitations. One significant constraint is the reduction in operational flexibility, as busbar systems confine crane movement to fixed paths. This fixed infrastructure can make it challenging to reconfigure terminal layouts or adapt to changing operational needs.

Battery-Electric RTG Cranes utilize lithium-ion batteries to power their operations and offer mobility and independence from fixed power sources. Practical limitations for battery-electric RTG cranes include the need for strategically located charging stations, which require electrical upgrades in existing terminals. Moreover, the current runtime of 4 - 8 hours necessitates precise operational planning, potentially including additional breaks within a shift to meet peak operational periods. These RTG cranes may be of use at terminals that prioritize mobility and moderate throughput, but their reliance on intra-shift charging may pose challenges for high-demand operations. Battery-electric RTG cranes have not been deployed in the SPBP complex. Current deployments are limited to Europe, including the Port of Helsinki, Finland.

Hydrogen Fuel Cell RTG Cranes are currently at the prototype phase of development, but early deployments are promising in terms of meeting the operational requirements of SPBP container terminals. Fuel cell RTG cranes mobility is comparable to diesel-powered models, making them suitable for operations without extensive fixed infrastructure; however, the current high cost of hydrogen and uncertainty of supply present a major barrier to adoption.

5.4.1 SPBP 2021-2024 Deployments

Demonstrations of RTG cranes within the SPBP have included both grid-electric and fuel-cell units between 2021 and 2024.

Grid-Electric RTG Cranes: SSA Marine has operated nine repowered grid-electric RTG cranes at Pier J in POLB since 2021. The RTG cranes are manufactured by ZPMC with Cavotec powertrains. The grid-electric RTG cranes are connected to the grid by a cable reel system that directly powers container handling operations. The RTG cranes can be relocated between lanes in approximately one hour. While cable reel systems limit the operational flexibility of the RTG cranes, this technology has been proven to be operationally viable because RTG cranes are capable of meeting all required terminal duty cycles and they have been kept in service two years beyond the end of the demonstration project. Manufacturers have learned valuable lessons from this demonstration and have increased the mobility of grid-electric RTG cranes by also incorporating batteries to facilitate relocations among runs.

Fuel-Cell RTG Cranes: Starting in 2024, PACECO-Mitsui is implementing a pilot deployment of the PACECO H2-ZE Transtainer Crane at YTI in the POLA. Initial testing is demonstrating that the fuel-cell RTG is capable of completing up to 16 hours of continuous operation on a single hydrogen refill. Refueling typically takes less than 15 minutes, making it efficient for high-throughput terminals requiring minimal downtime. The fuel-cell RTG's mobility is comparable to diesel-powered models, making it suitable for operations without extensive fixed infrastructure; however, the high cost of hydrogen and the uncertainty relating to the permitting challenges and timeframe for deploying storage and distribution infrastructure remains a major barrier to wide-scale adoption.

5.4.2 Commercial Availability

The three ZE RTG options range from full commercial availability for grid-electric RTG cranes, early commercial for battery-electric RTG cranes, and pre-commercial for fuel-cell RTG cranes (Table 5-16).

Table 5-16 – ZE RTG Commercial Availability Assessment Score

Commercialization Criteria	Grid-Electric	Battery-Electric	Hydrogen Fuel Cell
Production and Certification by Major Manufacturer	1	0.5	0.5
Network of Dealerships to Sell and Service CHE	1	0.5	0
ZE CHE Include Warranties and Long-Term Support	1	1	0.5
Ability to Manufacture CHE to Meet Current/Forecasted Demand	1	1	0.5
Backlog of CHE Orders or Credible Expression of Interest	1	0	0
Commercial Availability Score	**5**	**3**	**1.5**
Commercial Availability Level	**Fully Commercial**	**Early Commercial**	**Pre-Commercial**

Grid-Electric RTG Cranes: There are seven manufacturers offering commercially available grid-electric RTG cranes in the U.S. They include Kalmar, Konecranes, PACECO-Mitsui, ZPMC, Sandy, Liebherr, and Conductix-Wampfler. Manufacturers offer cable-reel and busbar options that are proven technologies capable of achieving SPBP operational requirements. The nine grid-electric RTG cranes that were placed in service at Pier J in POLB by SSA Marine prior to the 2021 feasibility assessment are still in service, and the terminal operator has reported that they have been able obtain required parts and maintenance. Manufacturers offer sufficient means of production and receive sufficient orders to maintain the viability of grid-electric RTG cranes. **Grid-electric RTG cranes are categorized as fully commercial.**

Battery-Electric RTG Cranes: Konecranes now offers a commercial model and retrofit options for battery-electric RTG cranes that do not require a busbar or cable real to perform operations. The Konecranes B-RTG was first advertised in 2022, and it has since been deployed in Europe. While Konecranes is a global manufacturer that offers a proven network of dealerships and has the production means, the lack of deployments in the U.S. and uncertain market demand results in **Battery-electric RTG cranes being categorized as early commercial**.

Fuel-Cell RTG Cranes: PACECO-Mitsui is currently implementing a pilot deployment of the PACECO H2-ZE Transtainer Crane at YTI (POLA). The terminal operator has reported positive feedback on the manufacturer's maintenance service and 16-hour operational capabilities of the unit. While this pilot deployment is demonstrating operational success, the manufacturer has yet to establish a commercial price for the model. While PACECO is an established manufacturer that is expected to eventually offer robust service, warranties, and maintenance, it is difficult to assess this for the fuel-cell RTG until multiple units are delivered to terminal operators. Lastly, while it is expected that interest in fuel-cell RTG cranes will increase based on the successful pilot deployment, no evidence was provided of a backlog of orders. **Fuel-cell RTG cranes are categorized as pre-commercial**.

5.4.3 Technical Viability

Significant advances in the technical viability of battery-electric and fuel-cell RTG cranes have been realized between 2021 and 2024 (Table 5-17). Grid-electric RTG cranes remain at TRL 9. Technical viability of battery-electric RTG cranes was not evaluated in 2021, and the TRL of fuel-cell RTG cranes improved from 5 to 7.

Table 5-17: ZE RTG Technology Readiness Assessment

Platform	TRL	Definition / Description
Grid-Electric	9	**Systems Operations:** Actual System in its final form and operated under full range of operating conditions
Battery-Electric	7	**Systems Conditioning:** Full-scale, similar prototype system demonstrated in relevant environment.
Hydrogen Fuel Cell	7	**Systems Conditioning:** Full-scale, similar prototype system demonstrated in relevant environment.

Grid-Electric RTG Cranes: Consistent with the 2021 assessment, grid-electric RTG cranes have been demonstrated to be technically viable based on their ongoing deployment by SSA for more than three years and their ability to meet or exceed the capabilities of diesel RTG cranes, including the ability to operate continuously for two or more shifts without fueling. Grid-electric RTG cranes can be connected to the electric grid by either a busbar or cable reel, which provide consistent power cargo handling operations. Some grid-electric RTG cranes are now outfitted with batteries to allow them to be moved between blocks and lanes efficiently on battery power. **Grid-electric RTG cranes are actual systems that are operating under the full range of operating conditions at SPBP container terminals (TRL 9).**

Battery-Electric RTG Cranes: The technical viability of battery-electric RTG cranes was not assessed in 2021. Konecranes now offers a commercially available model that has been deployed in Europe; however, the B-RTG has yet to be deployed in SPBP or other U.S. ports. The manufacturer reports that the B-RTG with the 296-kWh battery is capable of operating for up to 8 hours without charging, so it is unlikely to be able to complete a full shift without charging at a SPBP container terminal. **Battery-electric RTG cranes are now in the systems conditioning stage involved in full-scale deployments at multiple European ports but not at U.S. container ports (TRL 7).**

Fuel-Cell RTG Cranes: The pilot deployment of the PACECO H2-ZE Transtainer Crane at YTI (POLA), which was initiated in May 2024, has shown that a fuel-cell RTG is capable of operating for 16 hours over two shifts before refueling. **The fuel-cell RTG, while still a prototype model, can meet the full range of operating requirements of a SPBP container terminal (TRL 7).**

5.4.4 Operational Feasibility

The operational feasibility of ZE RTG cranes is promising overall in that grid-electric RTG cranes have demonstrated the ability and fuel-cell RTG cranes have shown the potential to meet the operational requirements of SPBP container terminals (Table 5-18). Battery-electric RTG cranes are currently in use at European ports but have yet to be deployed at SPBP or other U.S. ports so their capability to meet SPBP operational requirements is unclear at this time.

Table 5-18: ZE RTG Operational Feasibility Assessment Score

Operational Criteria	Grid-Electric	Battery-Electric	Hydrogen Fuel Cell
Capability to Meet Terminal Operator Performance Parameters	1	0.5	1
Ability to Meet Per-Shift and Daily Operating Time Requirements	1	0	1
Fuel / Charging Speed Meets Revenue Operation Requirements	1	0.5	0.5
Operator Comfort, Safety, and Fueling Procedures	1	1	0.5
Available Parts, Maintenance, Training, and Manuals	1	0.5	0.5
Operational Feasibility Score	**5**	**2.5**	**3.5**
Operational Feasibility Level	**Desired**	**Partial**	**Partial**

Grid-Electric RTG Cranes: Cable reel and busbar RTG cranes have been operational across a full range of terminal applications for many years, as discussed in the 2021 assessment. The nine RTG cranes demonstrated at SSA have been in place for several years, with predominantly positive feedback from the terminal operator. One drawback identified with cable reel electric connectors is a required operational downtime of about one hour when a grid-electric RTG makes a movement from row to row in the yard.

An advance in grid-electric RTG operational performance has been realized through inclusion of batteries. Smaller batteries are used to power row-to-row moves and larger batteries with sufficient capacity are used to maintain operational capability during extended brownouts or other low power situations. With the integration of batteries with cable reel and busbar power supply options, travel between blocks and lanes are made on battery power, whereas all container exchange moves are powered from the grid. Furthermore, large batteries can be used to shave peak electricity demand for RTG operations. As these RTG cranes are constantly connected to the grid, the batteries recharge between moves and the batteries can be used during excess power peaks to flatten or minimize peak power consumption for a fleet of RTG cranes.

Grid-Electric RTG cranes continue to meet all desired operational feasibility criteria in terms of performance, endurance, charging, ability to satisfy terminal operator needs, and maintenance.

Battery-Electric RTG Cranes: Konecranes has developed a battery-electric RTG that has been deployed successfully in various European marine terminals. The Konecranes B-RTG uses lithium-ion batteries to power operations and offers two sizes of battery packs – 4-hour / 222 kWh capacity and 8-hour / 296 kWh capacity. The battery packs have a design life of 8 years, based on a 70-percent remaining SOC. Battery packs can be charged in 1 hour. Konecranes is confident that this technology will be ready to deploy in the U.S. with some testing for local adaptation that may be required for operation at U.S. ports.

While the B-RTG battery packs are sized as either 4-hr (222 kWh) or 8-hr (296 kWh) systems, the run times of the B-RTG are dependent on specific terminal operations. Based on the larger battery size, it is possible that the B-RTG could be capable of completing one 8-hour shift before recharging. Therefore, this technology is not expected to achieve the desired operational goal of completing two 8-hour shifts without charging.

Charging of the B-RTG is accomplished by positioning the unit next to a charging container where it can be plugged in using a mechanized arm or manually. The B-RTG can also be charged by direct connection to the port mains. The manufacturer reports that the batteries can be fully charged in 1 hour.

Due to the lack of deployments in the U.S., there was no information available on the operational comfort and safety of the Konecranes B-RTG. As a global manufacturer, Konecranes offers a network of dealers who provide sales, parts, and maintenance support for their other RTG models, including offering maintenance procedure guidelines, manuals, and training. **Battery-electric RTG cranes are determined to be partially operationally feasible.**

Fuel-Cell RTG Cranes: Starting in 2024, a PACECO H2-ZE Transtainer Crane began demonstration at YTI to provide insights into operational performance and adaptability of the equipment. To date, this demonstration has received positive feedback regarding operational capability, reliability, safety, and low maintenance requirements. It is reported that the fuel-cell RTG crane can easily sustain a two-shift operation without refueling.

Fueling is efficiently performed overnight, resulting in no down time during day shift operations. For this demonstration, the RTG crane is refueled by a mobile refueler truck. Currently, it is challenging to obtain permits for the deployment of permanent fueling solutions at the Ports because authorities having jurisdiction have yet to provide clear guidance.

Fuel-cell RTG cranes are determined to have achieved the partial operationally feasibility level.

Fuel and Infrastructure Availability

The off-terminal electric infrastructure required to deliver power to grid and battery-electric RTG cranes is similar to other types of electric CHE as is the on-terminal and off-terminal hydrogen infrastructure required to support fueling of fuel-cell RTG cranes. Unique infrastructure requirements are described as follows for grid-electric and battery-electric RTG cranes.

Grid-Electric RTG Cranes: Both cable reel and busbar RTG cranes require the installation of permanent electrical infrastructure along runs to provide constant power during container handling operations. Busbars are installed above ground allowing contactors located along the base of the RTG cranes to draw power as they move along runs. Cable reel RTG cranes can be connected to the electric grid using below-grade connections and a trench and covering system that connects below-grade cables to below-grade vaults. Vaults are then connected to on-terminal switchgear and transformers via below-grade conduits. Power is delivered to the grid-electric RTG cranes at 4,160 V. One benefit of grid-electric RTG cranes is that their operation results in more consistent power use than battery-electric RTG cranes because power is provided throughout cargo handling operations rather than at specific charging events (e.g. during shift breaks and during the hoot shift). Grid-electric RTG cranes tend to contribute to lower peak power demand than battery-electric RTG cranes at terminals, reducing peak electrical demand and associated utility demand charges.

Battery-Electric RTG Cranes: The Konecranes B-RTG is charged by either connection to a containerized charging system that contains either a mechanized or manual conductive charging connection. Charging can also be connected to the port mains. The chargers are connected via underground conduits to on-terminal transformers and switchgear, which deliver power to the chargers at 4,160V. The footprint of the charger is a 40-foot shipping container, on which other cargo shipping containers can be stacked.

5.4.5 Economic Workability

Economic workability was determined to be highest for grid-electric RTG cranes since they were modeled to have a 10-year TCO that is nearly equivalent to diesel RTGs even without incentives. Battery-electric RTG cranes were found to be economically workable with incentives, while fuel-cell RTG cranes were not economically workable with or without incentives (Table 5-19). Grid and battery-electric platforms are projected to have substantially lower O&M costs, while fuel-cell RTG cranes are projected to have both higher capital and operating expenses relative to diesel models (Table 5-20, Figure 5-7, and Figure 5-8).

Table 5-19: ZE Top Handler Economic Workability Assessment Score

Economic Workability Criteria	Grid-Electric	Battery-Electric	Hydrogen Fuel Cell
ZE CHE Purchase Price is Affordable to Terminal Operators / Comparable to Diesel CHE	0.5	1	0
ZE CHE O&M is Comparable to Diesel	1	1	0
Infrastructure Capital and Operational Costs are Affordable to Terminal Operators	0.5	0	0.5
No Major Economic / Workforce Impacts	1	1	1
TCO is Comparable to Diesel with Incentives through 2030	1	0.5	0
Economic Workability Score	**4**	**3.5**	**1.5**
Economic Workability Level	**Economically Workable**	**Economically Workable with Incentives**	**Not Economically Workable**

Grid-Electric RTG Cranes: The purchase price of grid-electric RTG cranes is only 10% higher than the average comparable diesel model and the 10-year TCO prior to incentives is just over 8% higher. When incentives are factored in, the 10-year TCO of grid-electric RTG cranes is approximately 10% lower than diesel models. The significant energy savings costs are the major driver of the operational savings along with reduced maintenance costs. Based on the near comparable TCO without incentives and the savings with incentives, **Grid-electric RTG cranes are classified as Economically Workable**.

Battery-Electric RTG Cranes: Before incentives, the average purchase price of battery-electric RTG cranes is 1.4 times the average price of diesel models and the 10-year and TCO is 20% higher than diesel models. When incentives are factored in, the battery-electric TCO of $3.2M is within 7% of the $3.0M average for diesel models. The O&M savings are driven primarily by the 2 times lower annual energy costs, which are the product of higher energy efficiency of battery-electric models and lower energy cost per hour of electricity relative to diesel models. Due to the projected lower TCO with incentives, **Battery-electric RTG cranes are classified as Economically Workable with Incentives.**

Fuel-Cell RTG Cranes: The TCO of fuel-cell RTG cranes is projected to be 2.4 times higher than diesel models without incentives and 2.35 times higher with incentives. The higher TCO is driven by both higher CapEx and OpEx. The purchase price of fuel-cell RTG cranes is 2.85 times that of a diesel model and annual energy costs are 2.2 times higher. **Fuel-cell RTG cranes are classified as Not Economically Workable with or without incentives.**

Table 5-20: RTG Cranes CapEx and OpEx

Section	Metric	Units	Diesel	Grid Electric	Battery Electric	Hydrogen Fuel Cell
Capital Expenses	Purchase Price	$	$2,100,000	$2,250,000	$3,000,000	$6,000,000
	Tax	$	$215,250	$230,625	$307,500	$615,000
	Infrastructure	$	$0	$380,000	$120,000	$160,000
	Total Capital Cost	**$**	**$2,315,250**	**$2,860,625**	**$3,427,500**	**$6,775,000**
	Purchase Incentive	$	($0)	($120,000)	($120,000)	($120,000)
	Infrastructure Incentive	$	($0)	($228,000)	($72,000)	($96,000)
	Depreciation	$	($572,173)	($609,774)	($785,205)	($1,591,765)
	Net Capital Cost (w/ Depreciation & Incentives)	**$**	**$1,743,077**	**$1,902,851**	**$2,450,295**	**$4,967,235**
	Discount Rate	%	7%	7%	7%	7%
	Useful Life (assumed)	yrs	10	10	10	10
Operating Expenses	Energy Price	$/unit	4.5	0.16	0.16	33
	Energy Economy	unit/hr	3	90	90	2
	Activity	hr/yr	2,800	2,800	2,800	2,800
	Energy Cost ($/hr)	$/hr	$13.5	$14.4	$14.4	$66.0
	Annual Energy Cost	$/yr	$39,211	$40,320	$40,320	$184,800
	Maintenance Cost	$/hr	$50	$37	$35	$42
	Annual Maintenance	$/yr	$140,000	$103,600	$98,000	$117,600
	LCFS Credits	$/yr	($0)	($22,253)	($22,253)	($0)
	Net Annual O&M Cost	**$/yr**	**$179,211**	**$121,667**	**$116,067**	**$302,400**
Total Cost of Ownership	**TCO (no incentives)**	**$**	**$3,001,800**	**$3,250,500**	**$3,599,500**	**$7,278,100**
	TCO (with incentives)	**$**	**$3,001,800**	**$2,740,300**	**$3,245,200**	**$7,062,100**

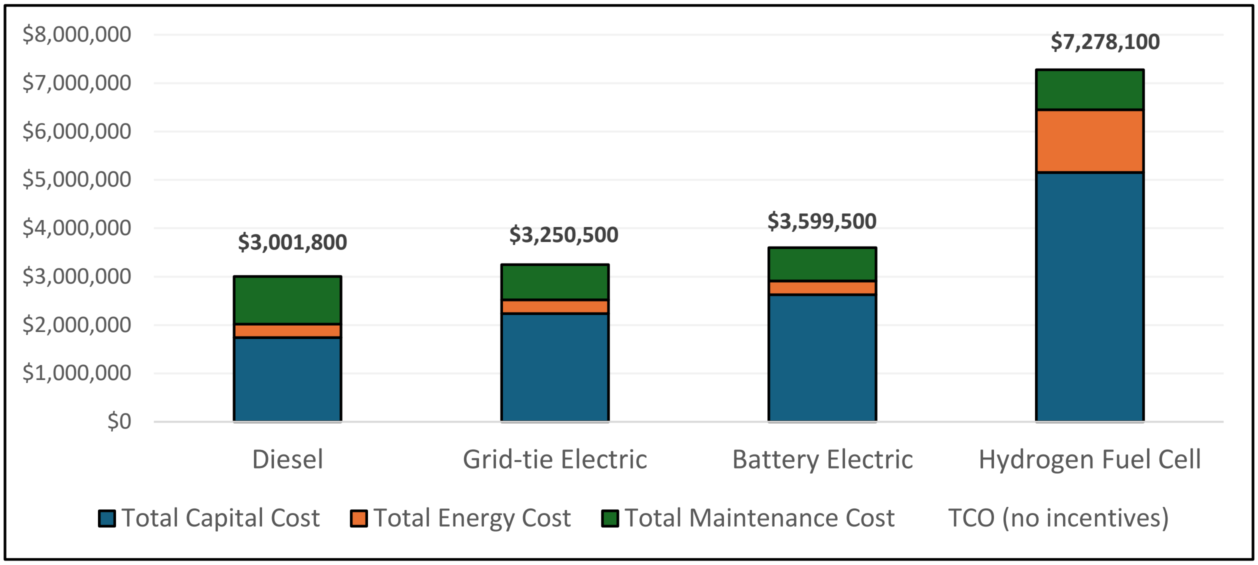

Figure 5-7: RTG Cranes Total Capital, Maintenance, and Energy Costs Without Incentives

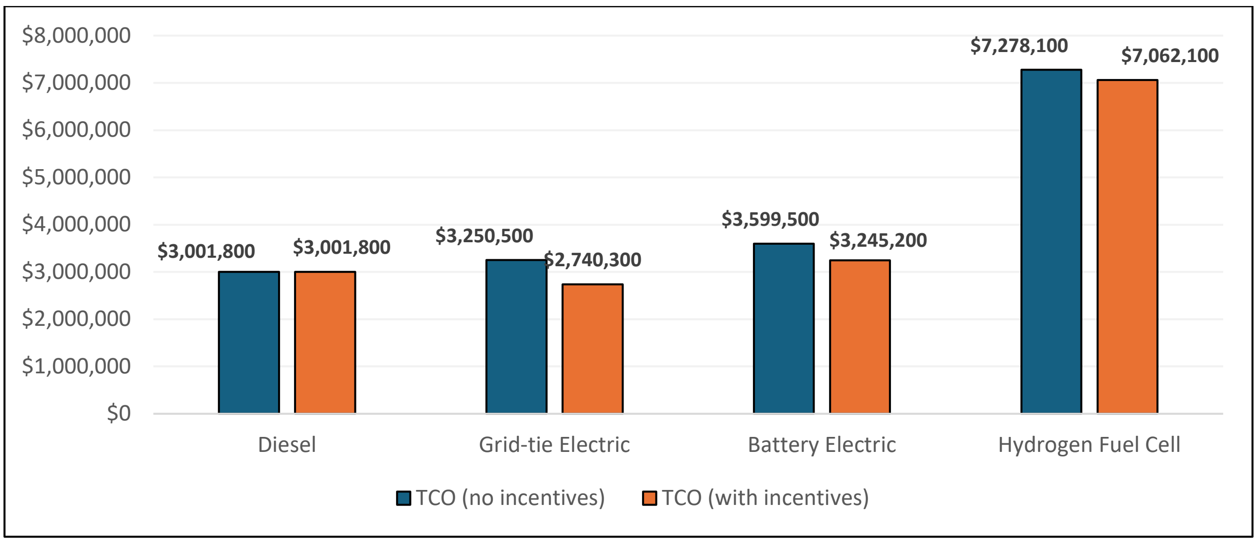

Figure 5-8: RTG Cranes Total Cost of Ownership with and without Incentives

5.5 Zero-Emission Cargo Handling Equipment Feasibility Comparison

Direct comparisons between electric and fuel-cell technologies across the five feasibility assessment parameters indicate that grid and battery-electric CHE are consistently more advanced than fuel-cell CHE.

Commercial Availability of battery-electric CHE ranges from early commercial (battery-electric RTG crane) to full commercial while all fuel-cell CHE are in the pre-commercial stage (Figure 5-9). It is anticipated that commercial availability of battery-electric models will continue to improve over the next 3-5 years due to demand driven by the EPA Clean Ports grants and the SPBP 100% ZE CHE goal. Most manufacturers are delaying further development of most fuel-cell CHE models, potentially other than fuel-cell RTG crane, due to the uncertainty of the hydrogen fuel supply.

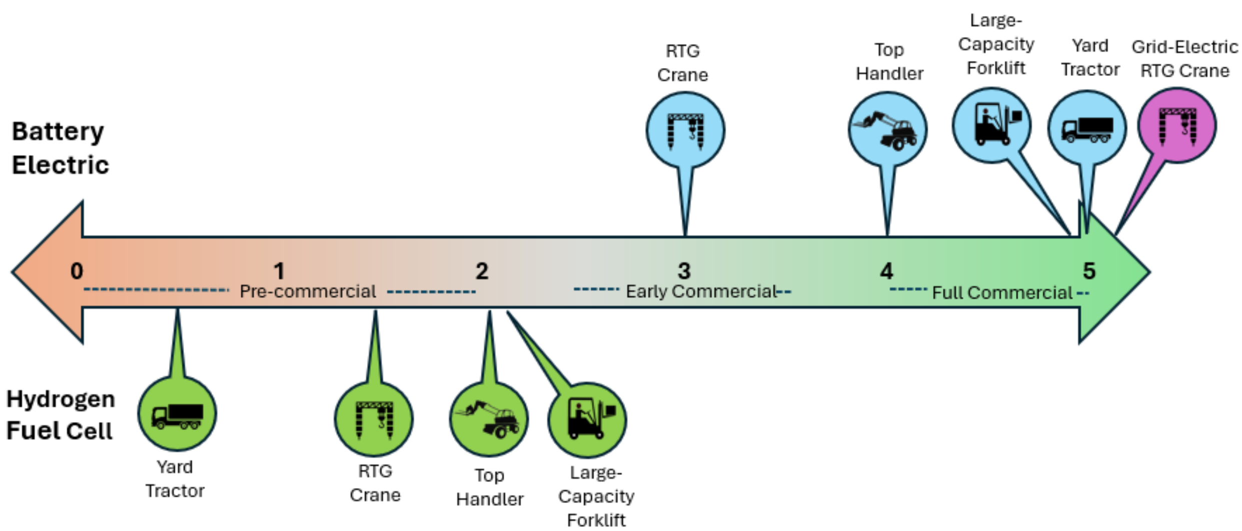

Figure 5-9: Commercial Availability of Zero-Emission Cargo Handling Equipment

Technical Viability of electric CHE ranges from full-scale prototype (TRL 7) to equipment in their final form operating in full conditions (TRL 9) while all fuel-cell CHE were determined to be at the full-scale prototype stage (TRL 7) (Figure 5-10). Further deployments of battery-electric CHE over the next three years are expected to result in all battery-electric CHE achieving TRL 9.

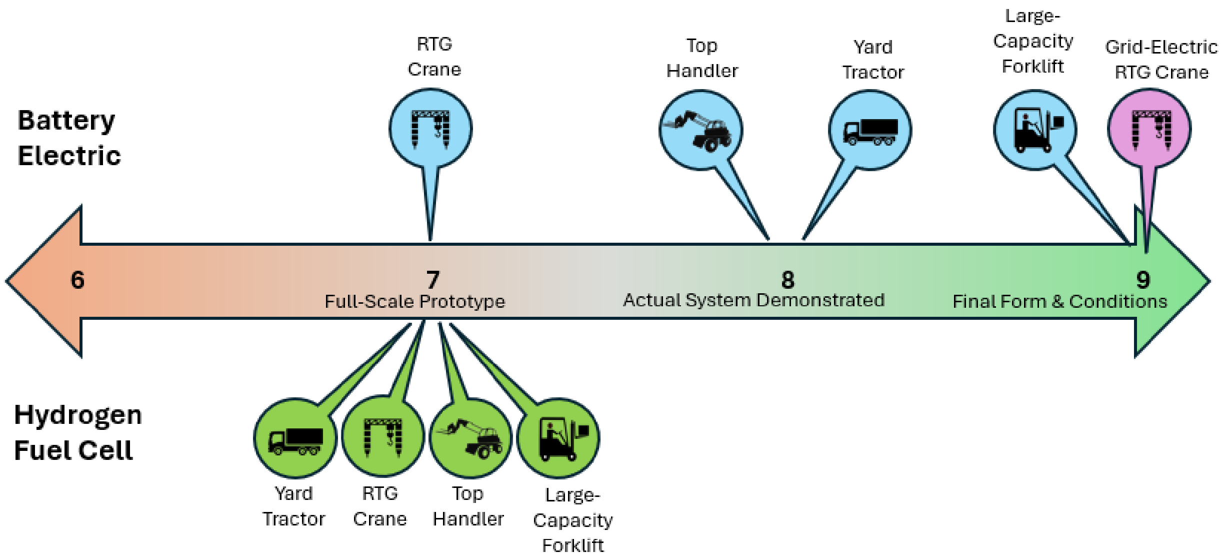

Figure 5-10: Technology Readiness Levels for Zero-Emission Cargo Handling Equipment

Operational Feasibility: Four of five electric CHE are categorized as achieving the desired operational feasibility level based on the specifications of the most advanced commercially available model while only the fuel-cell RTG crane achieved that level (Figure 5-11). All other fuel-cell CHE are categorized as partially operationally feasible.

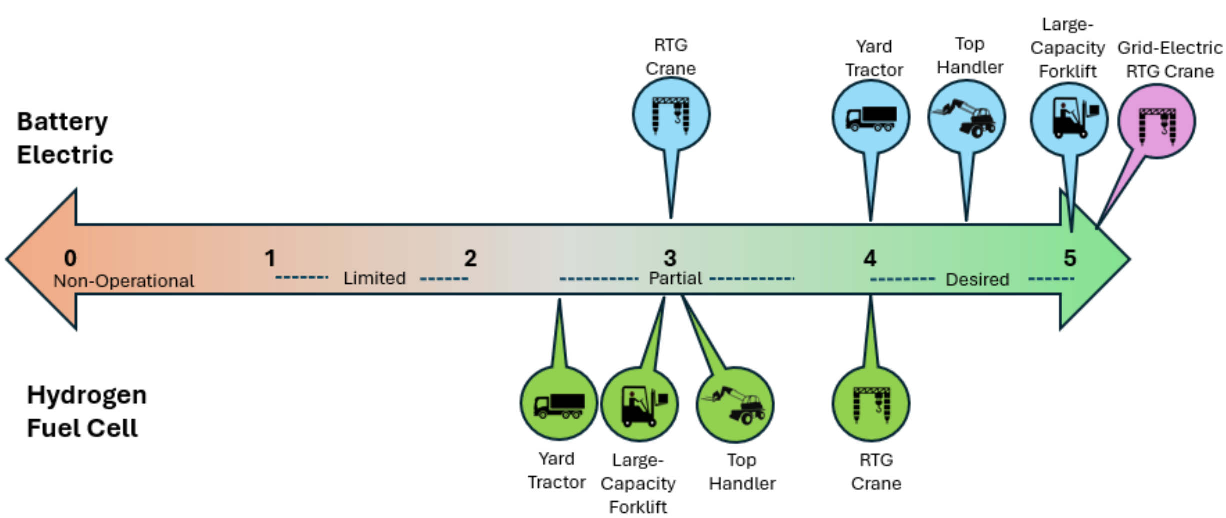

Figure 5-11: Operational Feasibility of Zero-Emission Cargo Handling Equipment

Fuel and Infrastructure Readiness: The transition to electrical and hydrogen CHE requires significant investments in infrastructure to achieve the 100% ZE goal. The Ports are currently working with their utilities and terminal operators to plan, design, and build required electrical upgrades by 2030. These upgrades are currently in the planning-design phase. Continuous progress will be required to complete the upgrades by 2030, allowing time for permitting, procurement of long lead items, construction, and integration. Due to the numerous deployments of similar electrical infrastructure at the Ports, the Ports have a moderate probability of completing electrical infrastructure upgrades by 2030 (Figure 5-10). The lack of an identified hydrogen fuel supply combined with uncertain permitting requirements, and minimal deployments of hydrogen storage and fueling infrastructure at the Ports, there is a low probability that the hydrogen fuel supply and infrastructure will be in place to support large-scale deployments of fuel-cell CHE by 2030.

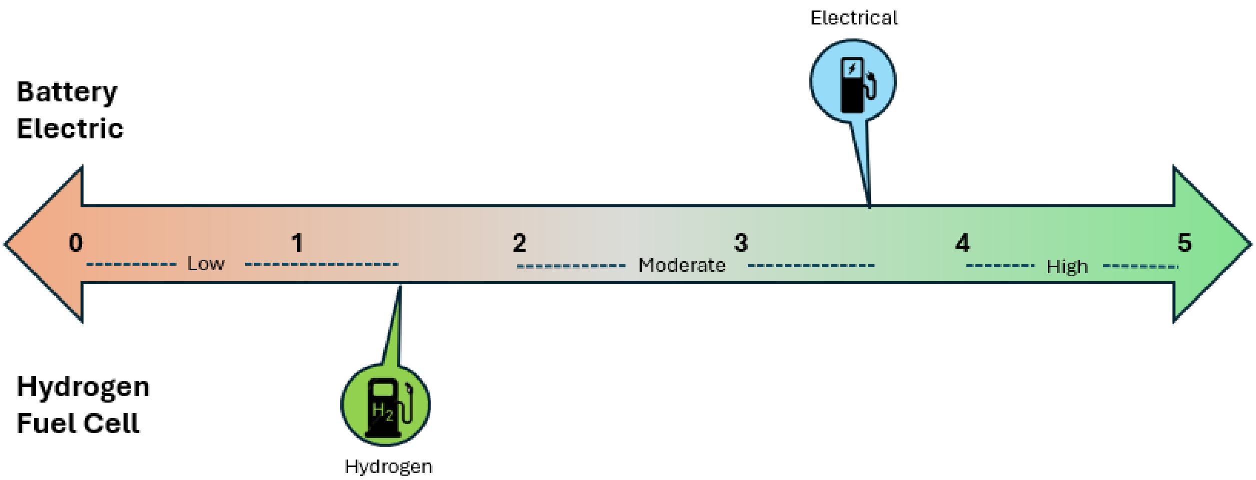

Figure 5-10: Infrastructure Readiness Level

Economic Workability: Battery-electric CHE are anticipated to be economically workable with incentives because they are projected to have 10-year TCOs that are equal to or less than diesel CHE when incentives are applied (Figure 5-11). In contrast, fuel-cell CHE are projected to have 10-year TCOs that are greater than diesel models with and without incentives, making them non-economical. While all ZE CHE have high CapEx, it is the OpEx savings of electric CHE combined with incentives that have the potential to make them economical.

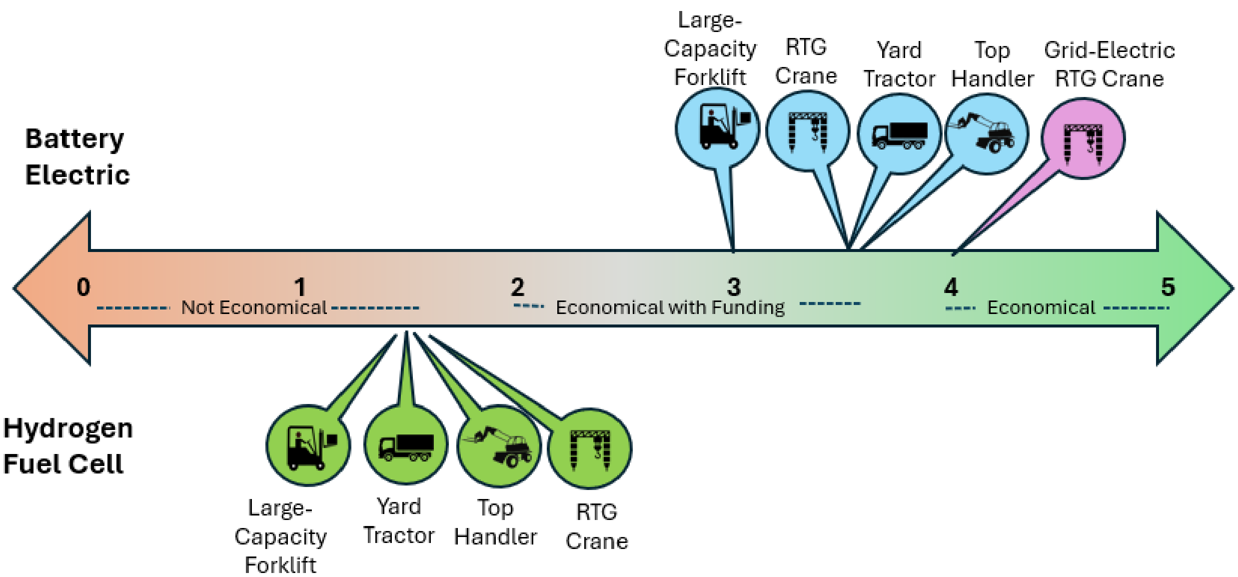

Figure 5-11: Economic Workability of Zero-Emission Cargo Handling Equipment

Overall Feasibility: The overall feasibility of ZE CHE was assessed by combining the scores of all five feasibility assessment parameters and dividing total maximum score (25) to give a percentage feasibility score that could range from 0 to 100%. TRL levels were normalized to 1-5 scale by giving a TRL 9 a score of 5, TRL 8 a score of 4, and TRL 7 a score of 3, which was the lowest score assigned.

Overall feasibility of battery-electric CHE ranges from 62% for battery-electric RTG cranes to 86% for battery-electric large-capacity forklifts while the overall feasibility of fuel-cell CHE ranges from 36% for fuel-cell yard tractor to 48% for the fuel-cell large-capacity forklifts (Figure 5-12). Grid-electric RTG cranes have the highest score of 90% as expected for a commercially available platform that has been successfully deployed at the POLB for multiple years. This summary provides a snapshot of the relative overall feasibility differences between battery-electric and fuel-cell CHE as of the end of 2024. The higher overall feasibility of electric CHE is consistent with the majority of terminal operators plans to primarily electrify CHE to realize the ZE transition.

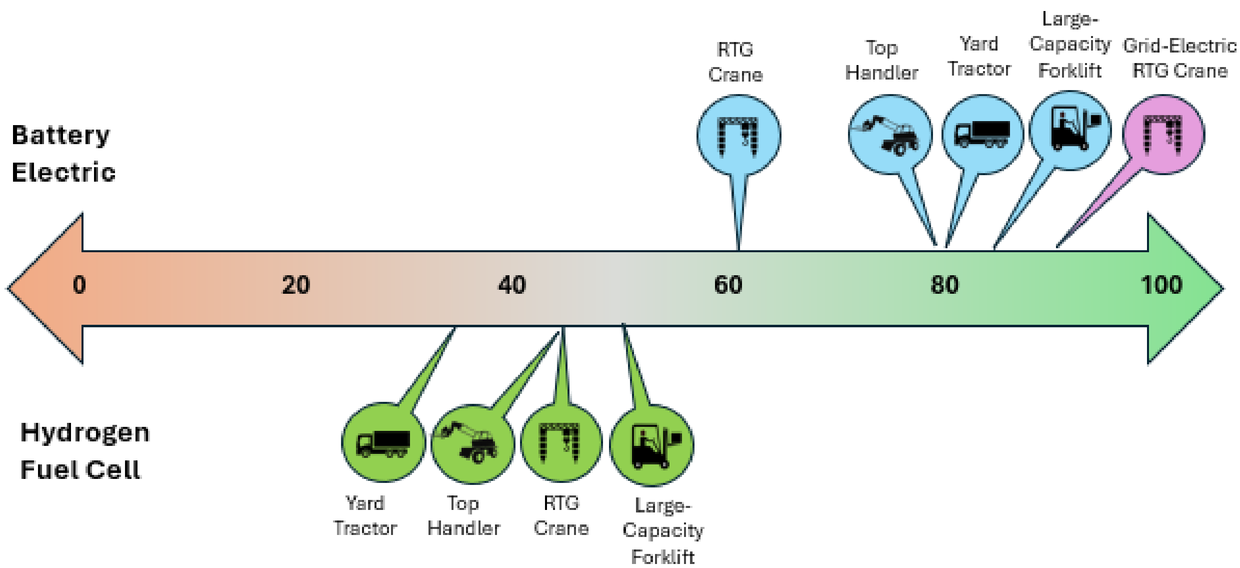

Figure 5-12: Overall Feasibility Scores of Zero-Emission Cargo Handling Equipment

6.0 Assessment of Port Wide Readiness

While there have been significant advances in ZE CHE, particularly for electric CHE, there are several challenges that must be overcome to achieve the full ZE transition. With terminal operators predominantly selecting electrification as their ZE technology of choice, thousands of chargers will need to be deployed at SPBP container terminals, requiring extensive electrical infrastructure upgrades at the terminals and within the distribution systems of the electric utilities – LADWP and SCE. These upgrades still require additional planning, design, permitting, procurement, and construction – a process that is estimated to take at least 4 to 5 years. Additionally, the investment in electrical infrastructure is anticipated to cost hundreds of millions if not billions of dollars.

Battery-electric CHE are just now approaching the operational requirements of SPBP terminal operators. Multiple manufacturers are offering commercial battery-electric yard tractors, top handlers, and large-capacity forklifts that can complete at least one shift without opportunity charging and the most advanced battery-electric models are reported by manufacturers to have the capacity to complete two shifts without opportunity charging. This is a major improvement from the 2021 assessment.

Substantial advancements in battery-electric CHE feasibility have been realized in the last four years, but continued improvements are needed to demonstrate to terminal operators that battery-electric CHE can reliably meet their operational needs over years. Recent deployments have shown that battery-electric CHE reliability is still a challenge, particularly for new models. Additionally, the availability of parts for repairs and maintenance is also an issue that must be improved to support full-scale deployments. Planned large-scale deployments in the next three years funded under the EPA Clean Ports program are expected to test the ability of manufacturers and service providers to provide reliable CHE that can be deployed with high up times at scale. This is the next phase of deployment that is required to prove the viability of deploying electric CHE at SPBP. It is anticipated that these deployments will provide valuable real-world feedback to manufacturers that will allow them to continue to improve the next generations of electric CHE.

While the purchase price of most battery-electric models is still approximately two times more expensive than diesel equivalent models, the 10-year TCO of grid and battery-electric CHE is projected to be lower than diesel models due to lower O&M costs and available incentives. Battery-electric models are anticipated to have lower O&M costs than diesel models due to higher energy efficiency, lower cost of electricity, and the expected lower need for maintenance for battery-electric drives relative to diesel engines and transmissions, which have greater numbers of moving parts. The reality has been that battery-electric models deployed to date at SPBP require more manufacturer support than diesel models due to the need to work out initial design and integration problems, as well as interface issues with chargers. It is anticipated that integration issues will become less common with further commercialization. Additional deployments over multiple years will help validate battery-electric CHE TCO projections. Grant funding and incentives are still required to help offset the substantially higher capital costs of battery-electric CHE, chargers, and electrical infrastructure.