CALIFORNIA
AIR RESOURCES BOARD

Draft 2025 Cargo Handling Equipment Technology Assessment

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Table of Contents

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List of Tables

List of Figures

List of Acronyms and Abbreviations

2015 Draft CHE Assessment	2015 Draft Technology Assessment: Mobile Cargo Handling Equipment
2022 CHE Inventory	CARB 2022 Cargo Handling Equipment Emissions Inventory
A	ampere
AB	California Assembly Bill
AC	alternating current
AID	Advanced Infrastructure Demonstration
APM	A.P. Moller-Maersk
ARCHES	Alliance for Renewable Clean Hydrogen Energy Systems
ARPA	American Rescue Plan Act
BE	battery-electric
Caltrans	California Department of Transportation
CARB	California Air Resources Board
CCS	combined charging system
CEC	California Energy Commission
CEQA	California Environmental Quality Act
CHE	cargo handling equipment
CHE Regulation	Mobile Cargo Handling Equipment Regulation
CNG	compressed natural gas
CO2	carbon dioxide
CORE	Clean Off-Road Equipment Voucher Incentive Project
CPORT	Commercialization of POLB Off-Road Technology
DC	direct current
DSNY	New York City Department of Sanitation
EO	executive order
eRTG	electric RTG (can be battery-electric, grid-electric, or diesel-electric hybrid depending on context)
GE	grid-electric
GHG	greenhouse gas
HDSAM	Hydrogen Delivery Scenario Analysis Model
HFC	hydrogen fuel cell
hp	horsepower
HVAC	heating, ventilation, and air conditioning
HVIP	Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project
IBC	inter-box connector
ICE	internal combustion engine
J	Joule(s)
kg	kilogram(s)

km	kilometer(s)
kV	kilovolt(s)
kW	kilowatt(s)
kWh	kilowatt-hour(s)
lb	pound(s)
LCFS	Low Carbon Fuel Standard
LCTI	Low Carbon Transportation Incentives
LIGHTS	Volvo Low Impact Green Heavy Transport Solutions
LSI Regulation	Large Spark-Ignition Engine Fleet Requirements Regulation
MW	megawatt(s)
MWh	megawatt-hour(s)
NOx	oxides of nitrogen
OEM	original equipment manufacturer
OGV	ocean-going vessel
OSHA	Occupational Safety and Health Administration
PEM	polymer electrolyte membrane
PM	particulate matter
POLA	Port of Los Angeles
POLB	Port of Long Beach
PV	photovoltaic
RMG	rail-mounted gantry crane
RTG	rubber-tired gantry crane
SCAQMD	South Coast Air Quality Management District
SCE	Southern California Edison
SDG&E	San Diego Gas and Electric
SDPTA	San Diego Port Tenants Association
SMR	steam methane reformation
START	Sustainable Terminals Accelerating Regional Transformation
SUV	sport utility vehicle
TRL	Technology Readiness Level
U.S. DOE	United States Department of Energy
U.S. EPA	United States Environmental Protection Agency
UTR	utility tractor rig
V	Volt(s)
ZANZEFF	Zero- and Near Zero-Emissions Freight Facilities
ZECAP	Zero-Emissions for California Ports
ZEV	zero-emission vehicle

Introduction

California Air Resources Board (CARB) staff developed this Draft 2025 Cargo Handling Equipment Technology Assessment (Technology Assessment) to evaluate commercially available and developing zero-emission cargo handling equipment (CHE) technologies.

Background

This section provides background information on CHE, as well as related State regulations and policy. It also outlines the purpose of this document, describes the elements staff evaluated for each zero-emission technology, and summarizes the process for developing the assessment.

Cargo Handling Equipment

Cargo handling equipment is any mobile equipment used at seaports and intermodal railyards (facilities) for lifting, moving, or handling freight, bulk materials, and liquid cargo. This equipment also supports scheduled maintenance and repair activities essential to facility operations. CHE includes a wide range of equipment, such as cranes, dozers, excavators, forklifts, loaders, and yard trucks. Depending on the cargo type, specific machines are used for bulk material handling, container transport, and facility upkeep. See the *Overview of Cargo Handling Equipment* section for more information on the different types of CHE.

Cargo Handling Equipment Population and Emissions

There are approximately 5,000 CHE operating at California seaports and intermodal railyards. Most of this equipment runs on diesel engines that emit particulate matter (PM), oxides of nitrogen (NOx), and greenhouse gases (GHG). According to the CARB 2022 Cargo Handling Equipment Emissions Inventory (2022 CHE Inventory),[1] CHE will emit nearly 50 tons on PM2.5, 1,200 tons of NOx, and 432,000 tons of carbon dioxide in 2025. CHE emissions are important because they are concentrated around facilities and combined with other freight-related sources, pose significant health risks to nearby communities. See the 2022 CHE Inventory for more information on CHE population and emissions data.

[1] California Air Resources Board, "Cargo Handling Equipment Emissions Inventory," December 2022. *https://ww2.arb.ca.gov/sites/default/files/2023-04/2022%20CHE%20Emission%20Inventory%20Document_6April2023.pdf*.

Related California Regulations and Policy

Diesel-powered CHE operating at California seaports and intermodal railyards are subject to the Mobile Cargo Handling Equipment Regulation (CHE Regulation). CARB adopted the CHE Regulation in 2005 and amended it in 2011. The regulation requires emission reductions for diesel-powered equipment used to handle cargo or perform routine maintenance activities at California's seaports and intermodal railyards. The CHE Regulation was fully implemented in 2017. Fuel trucks, mobile cranes, and sweepers are exempt from the current requirements of the CHE Regulation.

Diesel-powered CHE not operating at California seaports and intermodal railyards are subject to the In-Use Off-Road Diesel-Fueled Fleets Regulation (In-Use Off-Road Regulation). CARB adopted the In-Use Off-Road Regulation in 2007 and amended it in 2009, 2010, and 2022. The regulation applies to all self-propelled off-road diesel-fueled fleets with vehicle engines rated at 25 horsepower (hp) or greater operated in California. It requires reporting and fleet emission reductions and includes new equipment requirements and limits on engine idling.

Yard trucks not subject to the CHE Regulation or In-Use Off-Road Regulation are subject to the Truck and Bus Regulation. CARB adopted the Truck and Bus Regulation in 2008 and amended it in 2010. The regulation applies to diesel-powered vehicles operating in California, with a gross vehicle weight rating over 14,000 pounds (lb). These vehicles are required to use a 2010 or newer engine and emission system. In 2023, CARB adopted the Advanced Clean Fleets Regulation (ACF Regulation). It requires targeted fleets to phase-in the use of zero-emission vehicles and manufacturers to only build zero-emission trucks starting with the 2036 model year.[2]

Propane and gasoline-powered CHE are subject to the Off-Road Large Spark-Ignition Engine Fleet Requirements Regulation (LSI Regulation). CARB adopted the LSI Regulation in 2006 and amended it in 2010 and 2016. The regulation requires emissions reductions from existing LSI fleets and sets verification procedures for LSI retrofit emissions control systems. It also establishes more stringent NOx and hydrocarbon engine certification standards.

Despite the progress made under existing programs, additional emissions reductions are needed to protect communities from near-source pollution impacts, help meet the current health-based ambient air quality standards across California, and support the State's climate

[2] On January 13, 2025, California withdrew its request to U.S. EPA for a waiver and authorization for the ACF Regulation. As of April 2025, CARB is not enforcing the existing portions of the ACF Regulation that require a federal waiver or authorization, such as the portions of the ACF Regulation that apply to high priority and drayage fleets. The state and local government fleets portion of the ACF Regulation remains unaffected.

goals. In September 2020, Governor Newsom issued Executive Order (EO) N-79-20,[3] which directs CARB, in coordination with other State agencies, United States Environmental Protection Agency (U.S. EPA), and local air districts, to develop and propose technologically-feasible and cost-effective strategies to achieve 100 percent zero-emissions from off-road vehicles and equipment operations in the State by 2035 where feasible. The EO N-27-25[4] reaffirms this goal. In addition, Assembly Bill 617 highlights the need for further emission reductions in communities with high exposure burdens.

Purpose of the Technology Assessment

CARB released the previous CHE technology assessment in 2015. It focused on lower-emission internal combustion and other advanced technologies to help meet the State's goal of lowering emissions from CHE.[5] The purpose of this new Technology Assessment is to evaluate the availability and operational feasibility of zero-emission technologies that are currently available or in development needed to help meet California's multiple risk reduction, air quality, and climate goals, as well as the directives of EO N-79-20 and EO N-27-25. CARB may use the findings of this assessment to inform and support various planning and regulatory actions such as:

- Mobile Source Strategy[6] and State Implementation Plan development[7]
- Scoping Plan Updates[8]
- Funding Plans for Clean Transportation Incentives[9]

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[3] Executive Department State of California, "Executive Order N-79-20," Office of Governor Gavin Newsom, September 23, 2020. *https://www.gov.ca.gov/wp-content/uploads/2020/09/9.23.20-EO-N-79-20-Climate.pdf*.

[4] Executive Department State of California, "Executive Order N-27-25," Office of Governor Gavin Newsom, June 12, 2025. *https://www.library.ca.gov/wp-content/uploads/GovernmentPublications/executive-order-proclamation/40-N-27-25.pdf*.

[5] California Air Resources Board, "Draft Technology Assessment: Mobile Cargo Handling Equipment," November 2015. *https://www.arb.ca.gov/msprog/tech/techreport/che_tech_report.pdf?_ga=2.112080327.297876042.1716210149-1592276699.1662484763*.

[6] California Air Resources Board, "Mobile Source Strategy," Accessed November 25, 2024. *https://ww2.arb.ca.gov/resources/documents/mobile-source-strategy*.

[7] California Air Resources Board, "California State Implementation Plans," Accessed November 25, 2024. *https://ww2.arb.ca.gov/our-work/programs/california-state-implementation-plans*.

[8] California Air Resources Board, "AB32 Climate Change Scoping Plan," Accessed January 8, 2025. *https://ww2.arb.ca.gov/our-work/programs/ab-32-climate-change-scoping-plan*.

[9] California Air Resources Board, "Funding Plan for Clean Transportation Incentives," Accessed December 23, 2024. *https://ww2.arb.ca.gov/our-work/programs/low-carbon-transportation-incentives-and-air-quality-improvement-program/funding*.

Technology Assessment Elements

For this assessment, staff only looked at zero-emission technologies – those with zero exhaust emissions of any criteria pollutant (or precursor pollutant), toxic pollutant, or GHG under any possible operational modes or conditions. This assessment does not include near-zero or other advanced technologies that are not considered zero-emission. Staff evaluated the zero-emission CHE technologies listed below.

- Battery-electric – powered by batteries.
- Grid-electric – connected to the electric power grid through either direct physical contact or electromagnetic connection.
- Hydrogen fuel cells – using hydrogen as a power source.

Each technology section discusses the six key elements listed below.

1) Technology description – describes the zero-emission technology and how it works.
2) Technology readiness – evaluates how developed the technology is. For this assessment, technology readiness is determined by reviewing both the product development level and the operational feasibility.
   a) Commercial availability – identifies if the technology is in the research and development stage, prototype phase, demonstration phase, or is fully commercially available.
   b) Operational feasibility – determines if the technology can meet the operational needs or duty cycle of the CHE it is intended to replace.
3) Emissions benefits and considerations – discusses how the technology can reduce air pollutants and GHGs.
4) Infrastructure requirements and considerations – describes what infrastructure is needed, how it supports the technology, and its current status. The infrastructure section for each of the three technologies includes:
   a) Getting energy to the facility (the upstream energy source).
   b) Setting up on-site infrastructure (charging stations, hydrogen filling stations, or power systems).
   c) Managing operations (logistics for charging, filling, or powering the equipment).
   d) Permitting, standards and safety considerations.
5) Economics – discusses starting capital, operational, maintenance, and infrastructure costs, as well as current production level costs compared to diesel.

6) Technology outlook – describes the advantages and potential challenges for each CHE-technology combination, and provides an outlook on the likelihood that it will achieve functional equivalence with its diesel counterpart within the next 10 years.

Development of the Technology Assessment

Staff researched zero-emission CHE technologies and visited seaports and intermodal railyards to see CHE operations. Staff also met with equipment manufacturers, dealers, owners, operators, fuel suppliers, utilities, and consultants, to gather insights. Statements regarding the state of CHE technology or infrastructure include research and developments through January 2025. Several global events, technology announcements, demonstrations, and other CHE related events happened after January 2025 that are not included or factored into this assessment.

A technology-focused workshop will be held on November 13, 2025, from 9:00 a.m. to 12:00 p.m. to discuss this Technology Assessment. Please send comments and any supporting information to *cargohandling@arb.ca.gov* by December 12, 2025. Stakeholder input will help inform the development of the final document.

Staff is seeking information on zero-emission CHE technology, demonstration projects, costs, and technical details. Requests for information are in callout boxes throughout the document.

Overview of Cargo Handling Equipment

This section provides an overview of different types of CHE and their operational characteristics. CHE is as diverse a group of equipment as the cargo that it handles and the tasks it performs. Cargo that arrives or departs by ship, truck, or train, can include bulk material, containers, and liquid. Liquid cargo, such as petroleum products and chemicals, are often transported via pipelines, so it usually does not require mobile CHE for handling. Below is a description of the most common CHE types, organized into three categories: bulk material, container handling, and facility support.

Types of Cargo Handling Equipment: Operational Characteristics and Considerations

CHE is any mobile equipment used at facilities to handle freight, perform maintenance, or support facility operations. The type of equipment used depends on operational characteristics and considerations, such as the type of cargo handled, activities performed, and lift capacity. Equipment used to handle bulk material includes dozers, excavators, and loaders. Equipment that handles cargo containers includes gantry cranes, reach stackers, side handlers, top handlers, and yard trucks. While forklifts can be used in container or bulk material operations, for the purposes of this assessment, they are included in Bulk Material CHE. Aerial lifts, utility trucks, and other types of equipment used for facility operations are also considered CHE. This assessment addresses the 25 most common types of CHE found at seaports and intermodal railyards. However, there are many more types of CHE. See *Appendix A* for a list of additional types of CHE.

Most CHE at seaports and intermodal railyards are diesel-powered. Facilities have used diesel CHE for decades, and its performance is often used as a benchmark when developing newer and cleaner technologies. The engine power of diesel CHE allows operators to lift and move hundreds of thousands of pounds of cargo daily. Diesel CHE is designed to operate reliably for at least 10 to 15 years when serviced regularly. Large fuel tanks allow for several shifts or even days of operation before refilling. Refueling a CHE diesel tank takes about 10 to 30 minutes depending on the type of CHE. Diesel equipment is refueled by *wet hose* via fuel delivery trucks or by driving up to and connecting to on-site fuel tanks. Larger CHE generally use the wet hose method of fueling. Some facilities use a designated *gearman* to fuel CHE between or after shifts. Facility support equipment may have more downtime than other types of CHE and therefore may need to be refueled less often.

Bulk Material Cargo Handling Equipment

Bulk material operations handle a variety of materials and may not be as uniform as container operations. Bulk material CHE is used for both break bulk and dry bulk cargo.

- Break bulk cargo includes boats, construction equipment, engines, lumber, machinery, palletized material, and steel – items that are transported individually rather than in containers.
- Dry bulk cargo includes cement, petroleum coke, salt, scrap metal, sugar, and sulfur- materials that are shipped in large quantities without packaging.

Different types of equipment transport bulk cargo, including cranes, dozers, excavators, forklifts, haul trucks, and loaders. Log stackers are specialized equipment used at lumber facilities to lift, transport, and neatly stack logs.

Crane

There are several types of cranes used at facilities for bulk materials. Material handling cranes, or *material handlers*, are used to move bulk materials, such as scrap metal. They can use an attachment called a *grapple* (Figure 1) or large magnets for metal scrap cargo. Material handling cranes can lift up to 270,000 lb.

Figure 1: Material Handler

Mobile cranes (Figure 2) are cranes that are designed for on-road travel, but some can operate off-road, as well. They lift large odd-shaped cargo, such as heavy pipes or engines. These cranes are also used as facility support CHE. Mobile cranes can lift up to 180,000 lb.

Figure 2: Battery-Electric Mobile Crane (Zoomlion)

Large mobile harbor cranes are used to hoist massive objects, such as yachts and large electric windmill blades on and off ships. They can use attachments, such as clam shell buckets (also called *grab buckets*) for dry bulk cargo (Figure 3) or giant *grapple claws* used to move lumber (Figure 4). While they can also load and unload containers, they are not as efficient as ship-to-shore cranes for large quantities of containers. Mobile harbor cranes can lift up to 680,000 lb.

Figure 3: Mobile Harbor Crane with Grab Bucket

Figure 4: Mobile Harbor Crane with Log Grapple Attachment

Off-road cranes come in two types: wheeled or tracked, which move on tracks instead of wheels. They are designed to work in off-road conditions on rough and uneven terrain. Wheeled off-road cranes are called *rough-terrain cranes* (Figure 5) and tracked off-road cranes are called *crawler cranes* (Figure 6). They are often used in construction. At seaports and intermodal railyards, they are used for bulk and break-bulk cargo handling. The largest off-road cranes can lift up to 6 million lb, but models used at seaports and intermodal railyards lift up to 320,000 lb.

Figure 5: Battery-Electric Off-Road Wheeled Crane (Tadano)

Figure 6: Battery-Electric Off-Road Crawler Crane (Liebherr)

Dozer

The term dozer (or *bulldozer*) refers to an off-road tractor, with either tracks or wheels, equipped with a large blade in the front used to push bulk material (Figure 7). Dozers are used for dry bulk cargo handling operations. Dozer work capacity is often measured with blade capacity. The medium sized dozers that are used for cargo handling at seaports and intermodal railyards have a blade capacity up to 15 cubic yards of material.[10]

Figure 7: Dozer

Excavator

Excavators (Figure 8) are used for loading and unloading dry bulk cargo. Generally, they have a bucket that reaches into piles of dry bulk material and scoops it up, moving it to a ship or other CHE. Alternatively, the arm can be fitted with attachments for moving specialized cargo such as lumber or scrap. Excavators can lift up to 200,000 lb.

[10] David R. Ledford, "Dozer Size Chart to Choose the Right Bulldozer for Your Job," Codeready.org, March 10, 2024, Accessed May 28, 2025. *https://www.codeready.org/guides/dozer-size-chart*; All dozers reported by California seaports are between 20,000 and 100,000 lb.

Figure 8: Battery-Electric Excavator (Staff photo)

Forklift

Forklifts are multi-purpose industrial vehicles that transport materials by means of one or more steel forks inserted under the load. There are many different types of forklifts. Smaller electric forklifts are used indoors for moving small pallets or loads. Larger forklifts can resemble large construction tractors and operate outdoors on uneven terrain. Some can lift up to 130,000 lb. Forklifts can be powered by batteries, diesel, gasoline, hydrogen, or propane.

The Occupational Safety and Health Administration (OSHA) created seven classifications for forklifts depending on the type of engine, type of wheels, and application.[11] Class I, Class IV, Class V, and Class VII are the most common forklift types used at seaports and intermodal railyards.

[11] United States Department of Labor, Occupational Safety and Health Administration, "Powered Industrial Trucks (Forklift) eTool," Accessed January 7, 2025. *https://www.osha.gov/etools/powered-industrial-trucks/types-fundamentals/types/classes*.

Class I forklifts are electric-powered with either solid rubber tires (called *cushion*) or tires filled with air (called *pneumatic*). Historically, electric forklifts were used for indoor and warehouse environments and smaller in size. Figure 9 shows a typical Class I forklift.

Figure 9: Three-Wheeled Class I Light-Duty Forklift

As the demand for cleaner outdoor equipment has increased, electric forklift technology has advanced. Specifically, the lifting capacity and possible applications of electric forklifts increased. Some electric forklifts can lift up to 100,000 lb. Figure 10 shows a battery-electric Wiggins eBull forklift used at the Port of West Sacramento for lifting dry bulk cargo. See *Appendix B* for a list of commercially available zero-emission CHE.

Figure 10: Heavy Duty Battery-Electric Forklift (Staff photo)

Class IV forklifts are powered by internal combustion engines (ICE) and have three or four cushion tires (Figure 11). This type of tire allows for stability in indoor environments. Class IV forklifts generally have a small turning radius which is better for small spaces. There are many available models of zero-emission cushion-tire forklifts. There are very few diesel-powered Class IV forklifts at California seaports and intermodal railyards. Class IV forklifts can lift up to 60,000 lb.

Figure 11: Cushion Tire Forklift (Class IV)

Class V forklifts are also powered by ICE but have pneumatic tires (Figure 12). Pneumatic tires are like truck tires, made of treaded rubber and filled with compressed air. Pneumatic tires allow for indoor or outdoor applications.

Figure 12: Pneumatic Tire Forklift (Class V)

The most common forklift used for cargo handling at seaports and intermodal railyards is a Class V, diesel-powered forklift that can lift between 24,000 and 60,000 lb. These large capacity Class V forklifts are also called *heavy lifts*. They often have specific attachments for tasks, including moving railcars, large cable spools, steel sheet rolls, and bags of grain. They may need to operate nonstop for up to two shifts when moving bulk cargo. They can also be outfitted with a special attachment to move or rotate (flip) container chassis. The term *chassis flipping* is used to describe the rotation of chassis to stack them on top of one another for storage (Figure 13). Class V forklifts can lift up to 130,000 lb.

Figure 13: Stacked and Flipped Container Chassis (Staff photo)

Class VII forklifts are called *rough terrain forklifts*. According to OSHA, a "rough terrain forklift is a generic term used to describe forklifts typically intended for use on unimproved natural terrain and disturbed terrain construction sites."[12] Class VII forklifts with large tractor-like tires (Figure 14) are used at sites that require a high lifting capacity on uneven terrain, such as construction sites, recyclers, and lumber yards. These forklifts can lift up to 40,000 lb. *Telehandlers* are a subclass of Class VII forklifts that have a telescoping mast to provide extended reach (Figure 15). Other than telehandlers, Class VII forklifts are not commonly used at California seaports and intermodal railyards.

[12] United States Department of Labor, Occupational Safety and Health Administration, "Powered Industrial Trucks (Forklift) eTool." Accessed January 7, 2025. *https://www.osha.gov/etools/powered-industrial-trucks/types-fundamentals/types/classes*.

Figure 14: Rough Terrain Forklift (Class VII)

Figure 15: Telehandler

Seaports and intermodal railyards use nearly all sizes and classes of forklifts for miscellaneous activities that may or may not involve the movement of cargo. Smaller capacity forklifts are often fueled by propane and gasoline using spark-ignition engines. Battery-electric or hydrogen fuel cell versions of smaller capacity forklifts have been commercially available for many years.[13] There are more than 100 commercially available models of battery-electric and hydrogen fuel cell forklifts with lifting capacity less than 24,000 lb that can be purchased in place of Class IV or V ICE models.[14] This assessment

[13] San Pedro Bay Ports, “2018 Feasibility Assessment for Cargo-Handling Equipment,” September 2019. Accessed February 27, 2025. *https://sustainableworldports.org/wp-content/uploads/San-Pedro-Bay-Ports-2018-CHE-Feasibility-Assessment-.pdf* (See Appendix C: Assessment of Small-Capacity Forklifts).

[14] CARB’s Advanced Clean Off-Road Equipment List Fact Sheets document lists nearly 400 models of zero-emission forklifts (California Air Resources Board,” Advance Clean Equipment,” n.d. Accessed April 14, 2025.*https://ww2.arb.ca.gov/our-work/programs/msei/off-road-advance-clean-equipment*) and CARB’s CORE program lists nearly 200 models of zero-emission forklifts (California CORE, “Eligible Equipment Catalog,” n.d. Accessed April 14,2025. https://californiacore.org/equipmentcatalog/).

focuses on zero-emission technologies for heavy lift forklifts that can lift 24,000 lb or more. In the *Zero-Emission Cargo Handling Equipment Technologies* section, the term *forklift* refers to a heavy lift forklift with pneumatic tires that can lift 24,000 lb or greater, unless otherwise specified.

Haul Truck

Haul trucks (Figure 16) are heavy-duty trucks used to move large volumes of dry bulk cargo between locations at a facility. Other bulk material CHE such as loaders or cranes load the haul trucks with dry bulk cargo. Haul trucks can transport up to 140,000 lb.

Figure 16: Haul Truck

Loader and Loader-Excavator

Loaders (or *payloaders*) are off-road tractors, with either tracks or rubber tires, that use a large bucket on the end of movable arms to lift and move material (Figure 17). Loaders are one of the most common types of dry bulk CHE. Loaders include *loader-excavators*, which are also called *backhoes* or *backhoe loaders*, when equipped with a backhoe at the rear of the vehicle (Figure 18). There are many different types of loaders, including but not limited to backhoe, front-end, rubber-tired, skid-steer, and wheeled. Loaders can lift up to 80,000 lb.

Figure 17: Loader

Figure 18: Battery-Electric Loader-Excavator (CASE)

Log Stacker

Log stackers are large tractor-sized CHE with a large clamp, or claw, used to move lumber (Figure 19). Log stackers can lift up to 160,000 lb.

Figure 19: Log stacker

Container Cargo Handling Equipment

Container cargo is the most common type of cargo at seaports and intermodal railyards. AGVs, rail-mounted gantry cranes (RMG), reach stackers, rubber-tired gantry cranes (RTG), ship-to-shore cranes, shuttle and straddle carriers, side handlers, top handlers, and yard trucks transport container cargo. Container operations are well-coordinated with little downtime. See the battery-electric CHE *Charging Practices* section for more information on the operational shifts of a container terminal.

AGV

AGVs transport freight without a human operator on board (Figure 20). They have freight handling capabilities like yard trucks. Operations include loading shipping containers onto the AGVs by ship-to-shore cranes and unloading them with RTGs or RMGs. AGVs transporting containers from dockside to a container stack area move at slow speeds of less than 15 miles per hour and can transport up to 140,000 lb. All AGVs operating in California are zero-emission.

Figure 20: Battery-Electric AGVs (Konecranes)

Gantry Crane (RMG and RTG)

RMGs and RTGs are large container handlers that have a lifting mechanism mounted on a crossbeam (Figure 21). RMGs are also called stacking cranes. They have a crossbeam with a laterally moving crane mechanism attached to vertical legs that run on either rubber tires or rails. The crane moves quickly and can load and unload containers from yard trucks or from stacks at a fast pace. Some RMGs and RTGs can be wide enough to load or unload containers on eight separate stacks of containers. RTGs are common at seaport container terminals and intermodal railyards. Train cars can sit under the RTG while yard trucks pull up next to them, also under the RTG. The RTGs then move the containers between the train cars and adjacent yard trucks. Most RMGs are grid-electric and do not require refueling. RMGs and RTGs can lift up to 130,000 lb.

Figure 21: RTG

Reach Stacker

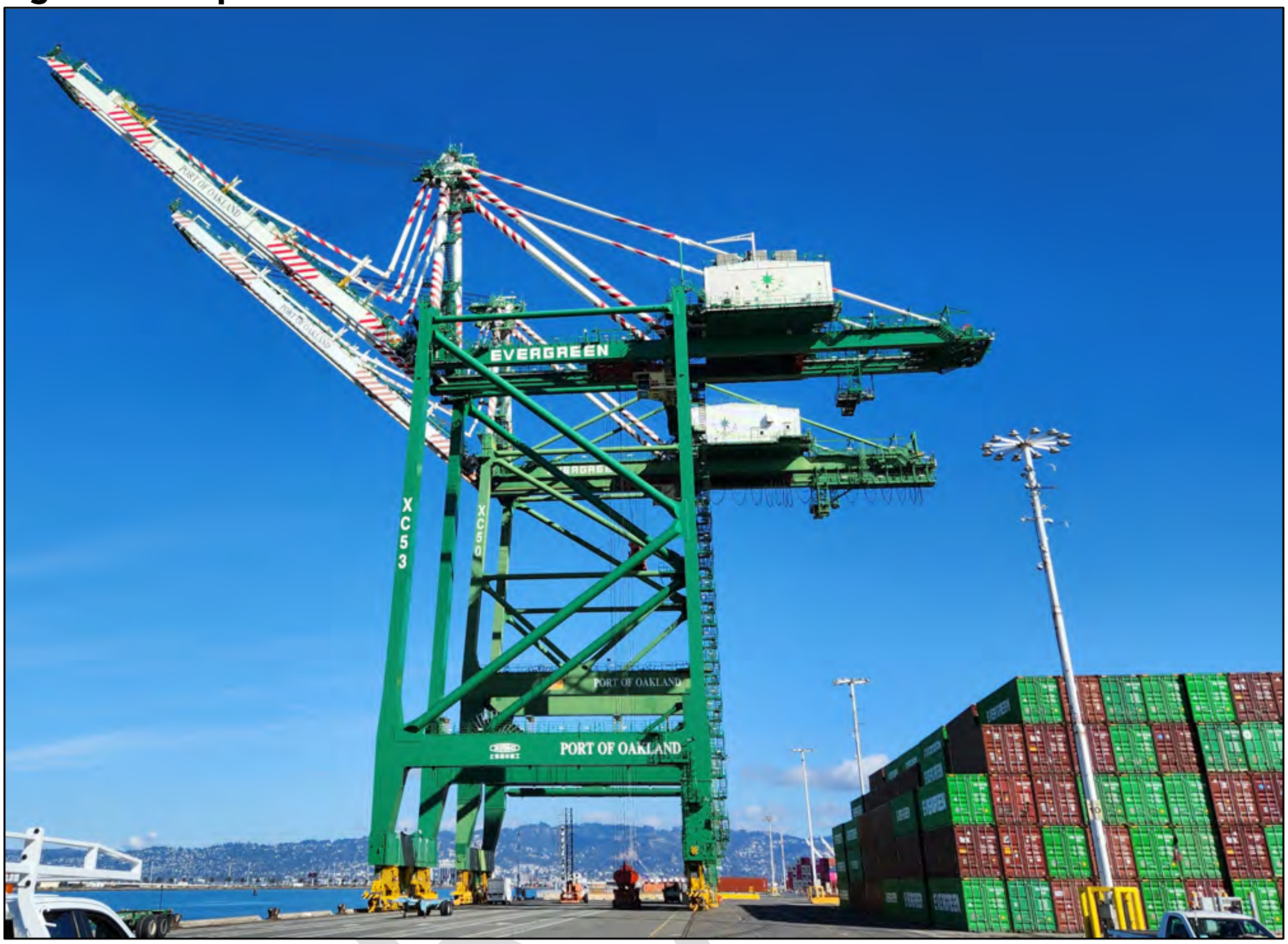
Reach stackers have a telescopic boom that moves upward and outward to reach over two or more stacks of containers (Figure 22). They lock onto the top of containers like RTGs and top handlers. They are not as common as top handlers. Reach stackers can lift up to 120,000 lb.

Figure 22: Reach Stacker

Ship-to-Shore Crane

Ship-to-shore cranes are large dockside gantry cranes used to load and unload containers from ships (Figure 23). They are also called *wharf cranes* because they are confined to moving along tracks on the side of the shore where container ships dock. Ship-to-shore cranes are most often rail-mounted and powered by electric shore power. Few are still powered with diesel generators. Ship-to-shore cranes can lift up to 150,000 lb.

Figure 23: Ship-to-Shore Cranes



Shuttle and Straddle Carriers

Shuttle and straddle carriers are like RTGs with a lifting mechanism mounted on a crossbeam supported on vertical legs that run on rubber tires. But they are smaller and more agile. While RTGs typically follow the same path each day, shuttle and straddle carriers move throughout the facility where they are needed. They travel at less than 20 miles per hour. The lifting mechanism can move quickly and is able to load and unload containers from yard trucks or from stacks at a fast pace. While RTGs are generally three to six containers wide, shuttle and straddle carriers are one container wide, allowing them to efficiently load or unload a yard truck or easily move stacked containers about the seaport. Shuttle carriers (Figure 24) can pick containers up off the ground, move them to another location, and either deposit them on the ground or stack them up to two high. Straddle carriers (Figure 25) are like shuttle carriers but can stack containers up to four high. Shuttle and straddle carriers can lift up to 100,000 lb.

Figure 24: Battery-Electric Shuttle Carrier (Kalmar)

Figure 25: Straddle Carrier

Side Handler

Like top handlers, side handlers (or *side picks*) lift and stack cargo containers (Figure 26). They look like a top handler, but instead of grabbing the containers from the top, they lift containers from the front face or the side. Some side handlers are designed to lift loaded containers, but most are for lifting empty containers. Side handlers can lift up to 20,000 lb.

Figure 26: Battery-Electric Side Handler (Taylor Machine Works)

Top Handler

Top handlers (Figure 27), also known as *top picks*, are large truck-like vehicles with an overhead boom that locks onto the top of containers in a single stack. They stack containers for temporary storage and load containers on and off yard trucks. Top handlers can lift up to 90,000 lb.

Figure 27: Battery-Electric Top Handler (Taylor Machine Works)

Yard Truck

The most common type of CHE at seaports and intermodal railyards is the yard truck (Figure 28). They are also known as *hustlers, spotters, utility tractor rigs* (UTR), *yard goats, yard hostlers, yard shunters*, and *yard tractors*. Yard trucks are like heavy-duty on-road tractor trucks but are designed for moving cargo containers and have off-road engines. Other container handling equipment, such as RTGs or top handlers, load containers onto container chassis that are pulled by yard trucks. Yard trucks move containers around a facility, or yard, for stacking and storing purposes. Yard trucks can transport up to 240,000 lb.

Figure 28: Battery-Electric Yard Truck

Facility Support Cargo Handling Equipment

Some types of equipment used at seaports and intermodal railyards are not used to move bulk material cargo or containers but are used to support facility operations. This equipment most often uses diesel, but some use other fossil fuels. While it is not used for cargo handling, this equipment is considered CHE in this assessment and in the CHE Regulation unless otherwise noted. This equipment includes aerial lifts, cone vehicles, railcar movers, and utility trucks. Facility support CHE may have more downtime than other types of CHE and may need to be refueled less often.

Aerial Lift

Aerial lifts (Figure 29) use a vehicle-mounted device to position personnel so they can perform maintenance and repairs on ships, cranes, and dock structures. They are also called *boom lifts* or *manlifts*. Aerial lifts include extendable boom platforms, aerial ladders, and vertical towers. Aerial lifts can lift up to 1,000 lb.

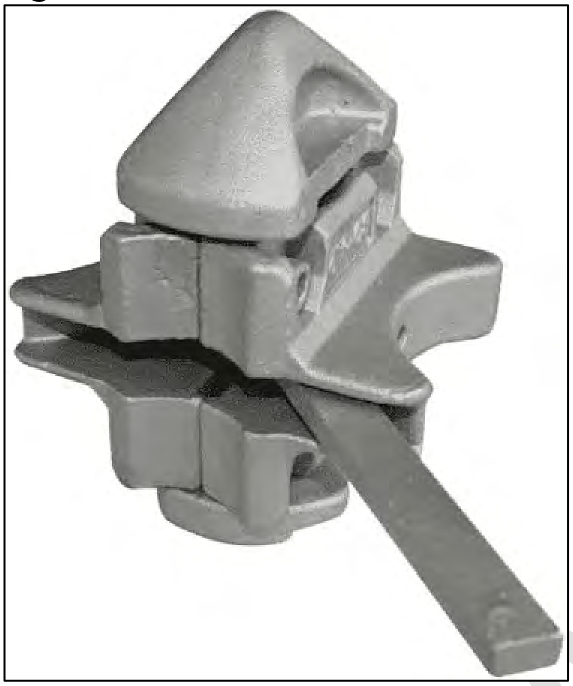
Figure 29: Aerial Lift

Cone Vehicle

Cone vehicles (Figure 30) are also called *cone carts, cone trucks*, or *IBC carts*. Inter-box connectors, or IBCs, are used to connect stacked containers and have a locating pin that resembles a cone (Figure 31). Cone vehicles can lift a worker to the height of a stacked container to install or remove IBCs at intermodal railyards.

Figure 30: Cone Vehicle (Motrec)

Figure 31: Inter-Box Connector



Railcar Mover

Railcar movers (Figure 32) are vehicles that operate on and off railroad tracks to move railroad cars. They are used at seaports with rail operations and intermodal railyards. When locomotives or switchers are not available, railcar movers are used to arrange railroad cars. They are also called *rail pushers*, *rail shunters*, or *shuttlewagons*. Railcar movers can transport up to 40 loaded railcars.[15]

[15] Loaded railcars is a common industry metric for the moving capacity of railcar movers.

Figure 32: Railcar Mover

Utility Truck

Utility trucks, including fuel trucks, street sweepers (*sweepers*), and water trucks, perform a variety of tasks at facilities. To produce fuel or water trucks, a third party will generally start with a heavy-duty cab-and-chassis class 6, class 7, or class 8[16] truck (Figure 33) and equip it with specialized tanks and receptacles (Figure 34).[17]

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[16] Commercial truck classification is based on the vehicle's gross vehicle weight rating (GVWR), which is the maximum loaded weight a vehicle is designed to safely handle. The classes are numbered 1 through 8. Class 6 trucks have a GVWR between 19,501 and 26,000 lb Class 7 trucks have a GVWR between 26,001 and 33,000 lb, and class 8, the heaviest classification for trucks, have a GVWR of 33,001 lb or more.

[17] Chassis cab," Wikipedia, The Free Encyclopedia," Accessed May 27, 2025. *https://en.wikipedia.org/wiki/Chassis_cab*.

Figure 33: Electric Heavy Duty Cab-and-Chassis Truck

Figure 34: Chassis and Cab Fitted with Water Tank, Nozzles, and Connectors

Sweepers are used to clean up remnants of bulk materials such as cement, gravel, or grain. They are also used for general facility cleanliness. Unlike fuel and water trucks, sweepers require a ground-up design to accommodate their large street brushes and vacuum hoses.[18] Other miscellaneous utility trucks support facility operations, maintenance, or repairs. Fuel trucks and sweepers are exempt from the current requirements of the CHE Regulation.

[18] Elgin Sweeper, "Street Sweepers 101: Understanding How They Work and Keep Our Roads Clean," March 26, 2024. Accessed December 18, 2024. *https://www.elginsweeper.com/about/whats-new/how-do-street-sweepers-work*.

Zero-Emission Cargo Handling Equipment Technologies

Zero-emission CHE technologies use electric motors instead of internal combustion engines. Electricity for these motors can come from on-board batteries, a connection to the electric power grid (grid), or hydrogen fuel cells. Each power source has benefits and challenges depending on the CHE type and usage. Table 1 summarizes the primary benefits and potential challenges of each zero-emission technology evaluated in this Technology Assessment.

Table 1: Benefits and Potential Challenges of Each Zero-Emission Technology

Zero-Emission Technology	Benefits	Potential Challenges
Battery-Electric	• Increased mobility compared to grid-electric CHE, which often require cables or busbars for power • Several types of this CHE are commercially available • Battery technology is continually improving: o Increased capacity o Faster charge times o Lower cost	• Heavy[19] • More expensive than diesel • Requires frequent recharging • Takes longer to charge than refueling equivalent diesel-powered CHE • Charging infrastructure occupies facility real estate

[19] Lithium-ion batteries provide about 150–250 Watt-hours of energy per kg while diesel provides nearly 12,000 Watt-hours of energy per kg. Therefore, it takes significantly more battery weight to achieve equivalent energy storage. However, electric motors are much more efficient in converting energy into work than diesel engines. With fuel efficiency factored in, batteries are still much heavier per unit of energy than diesel. For more details see Cunanan, Carlo, et al. "A Review of Heavy-Duty Vehicle Powertrain Technologies: Diesel Engine Vehicles, Battery Electric Vehicles, and Hydrogen Fuel Cell Electric Vehicles." *Clean Technologies* 2021, no. 3(2), (June 1, 2021): 474–89. https://www.mdpi.com/2571-8797/3/2/28.

Zero-Emission Technology	Benefits	Potential Challenges
Grid-Electric	• Provides constant power, reducing or eliminating the need for batteries • Reduces or eliminates long charge times • Several types of this CHE are industry standard and commercially available • New inductive technologies are being developed	• Grid connections (e.g., cables, busbars, etc.) can limit mobility • Infrastructure is expensive, disrupts operations during construction, uses valuable real estate
Hydrogen Fuel Cell	• Same mobility as batteries • Refueling times for hydrogen fuel cell CHE are like those of diesel-powered CHE • Reduces battery-dependency	• Limited commercial availability • Hydrogen supply and support infrastructure are not readily available or reliable • Hydrogen is more expensive than diesel

Staff uses the term *grid* to describe the entire system that carries electricity from where it is generated to where it is used.

Technology Applicability

Staff identified 25 CHE types for this assessment. These represent the most common CHE used at seaports and intermodal railyards. This assessment includes 75 potential zero-emission CHE-technology combinations (25 CHE types x 3 zero-emission technologies). Staff conducted a preliminary screening to determine *Technology Applicability* for each of the CHE-technology combinations using two criteria: *Practicality* and *Technological Potential*. *Appendix C* provides detailed definitions for these terms, but in general, these criteria address two key questions:

- Practicality – Does the technology make functional sense for this CHE type in 2025?
- Technological Potential – Could the zero-emission technology allow the CHE to meet the duty cycle and operational needs of the equivalent internal-combustion CHE within 10 years?

Each CHE-technology combination received a score for both criteria. The combination received a 0 if it did not meet the Practicality criteria or a 1 if it did. It received a 0 if it did not meet the Technological Potential criteria, or a 1 if it did. The two scores were added to provide a Technology Applicability score of 0, 1, or 2.

Technology Applicability Scores:

- 0 – Low potential to perform equivalently to its diesel counterpart within the next 10 years.
- 1 – Some potential to perform equivalently to its diesel counterpart within the next 10 years.
- 2 – High potential to perform equivalently to its diesel counterpart within the next 10 years.

Technology Applicability does not consider:

- Cost of initial equipment investment
- Costs of service and repairs
- Costs of charging or fueling (electricity or hydrogen)
- Cost of infrastructure implementation
- Infrastructure availability
- Fueling and/or charging logistics

Table 2 through Table 4 provide the Technology Applicability score for each CHE-technology combination.

Table 2: Zero-Emission Technology Applicability for Bulk Material CHE

CHE	Battery-Electric	Grid-Electric	Hydrogen Fuel Cell
Crane, Material Handling	2	2	2
Crane, Mobile	2	0	1
Crane, Mobile Harbor	0	2	2
Crane, Off-Road	2	2	2
Dozer	2	0	2
Excavator	2	2	2
Forklift, Heavy Lift	2	0	2
Forklift, Telehandler	2	0	2
Haul Truck	2	0	2
Loader or Loader-Excavator	2	0	2
Log Stacker	2	0	2

Table 3: Zero-Emission Technology Applicability for Container CHE

CHE	Battery-Electric	Grid-Electric	Hydrogen Fuel Cell
AGV	2	0	2
Rail-Mounted Gantry Crane	1	2	1
Reach Stacker	2	0	2
Rubber-Tired Gantry Crane	2	2	2
Ship-to-Shore Crane	0	2	0
Shuttle and Straddle Carriers	2	0	2
Side Handler	2	0	2
Top Handler	2	0	2
Yard Truck	2	1	2

Table 4: Zero-Emission Technology Applicability for Facility Support CHE

CHE	Battery-Electric	Grid-Electric	Hydrogen Fuel Cell
Aerial Lift	2	0	2
Cone Vehicle	2	0	2
Railcar Mover	2	0	2
Utility Truck, Other (fuel trucks, water trucks, etc.)	2	0	2
Utility Truck, Sweeper	2	0	2

Technology Readiness Grading System

The Technology Applicability screening identified 55 CHE-technology combinations that achieve a score of 1 or greater. Staff conducted further evaluation of these CHE-technology combinations and assigned each a *Technology Readiness Grade*. Table 5 describes the four Technology Readiness Grades and includes a *Deployment Assessment* indicating how ready the combination is for broad deployment at seaports and intermodal railyards.

Table 5: Technology Readiness Grades

Technology Readiness Grade	Description	Deployment Assessment
Development	• Early product development to pre-production • CHE-technology combination in testing for CHE in controlled experiments	The CHE-technology combination is still in the development phase and is not ready for deployment.
Demonstration	• Early/limited commercial availability* • Not fully demonstrated in all environments or not reliable in desired environment	Further demonstrations are required to prove the technology before broad deployment. The CHE-technology combination is not ready for full deployment.
Limited	• Commercially available • Manageable lead times • Possible delays with original equipment manufacturer (OEM) support and replacement parts • Possible delays with technical support • May still experience minor reliability issues • Likely first-generation equipment	The CHE-technology combination can be deployed on a limited basis. Owner/operators can use this technology with careful supervision and management. Enforceable customer service agreements with OEMs and equipment vendors are crucial for successful deployment.

Technology Readiness Grade	Description	Deployment Assessment
Equivalence	• Full commercial availability • Duty cycle equivalence to diesel CHE counterpart • Lead times similar to diesel • OEM repair support comparable to diesel • Reliable, with up-times comparable to diesel • Achieves operational equivalency when OEM operating procedures are followed • Likely 2nd, 3rd, or later generation equipment	The CHE-technology combination meets functional and operational equivalency to diesel powered CHE or has replaced diesel equipment completely, becoming the industry standard. Ready for full-scale adoption at most facilities.

*Note: Commercial availability means the zero-emission CHE is offered to the public by an OEM either on their website or through a dealer or distributor.

Staff developed a scoring system to determine technology readiness by assigning points for the *Commercial Availability* and *Operational Feasibility* criteria listed in Table 6. See *Appendix D* for more information on Technology Readiness Grades.

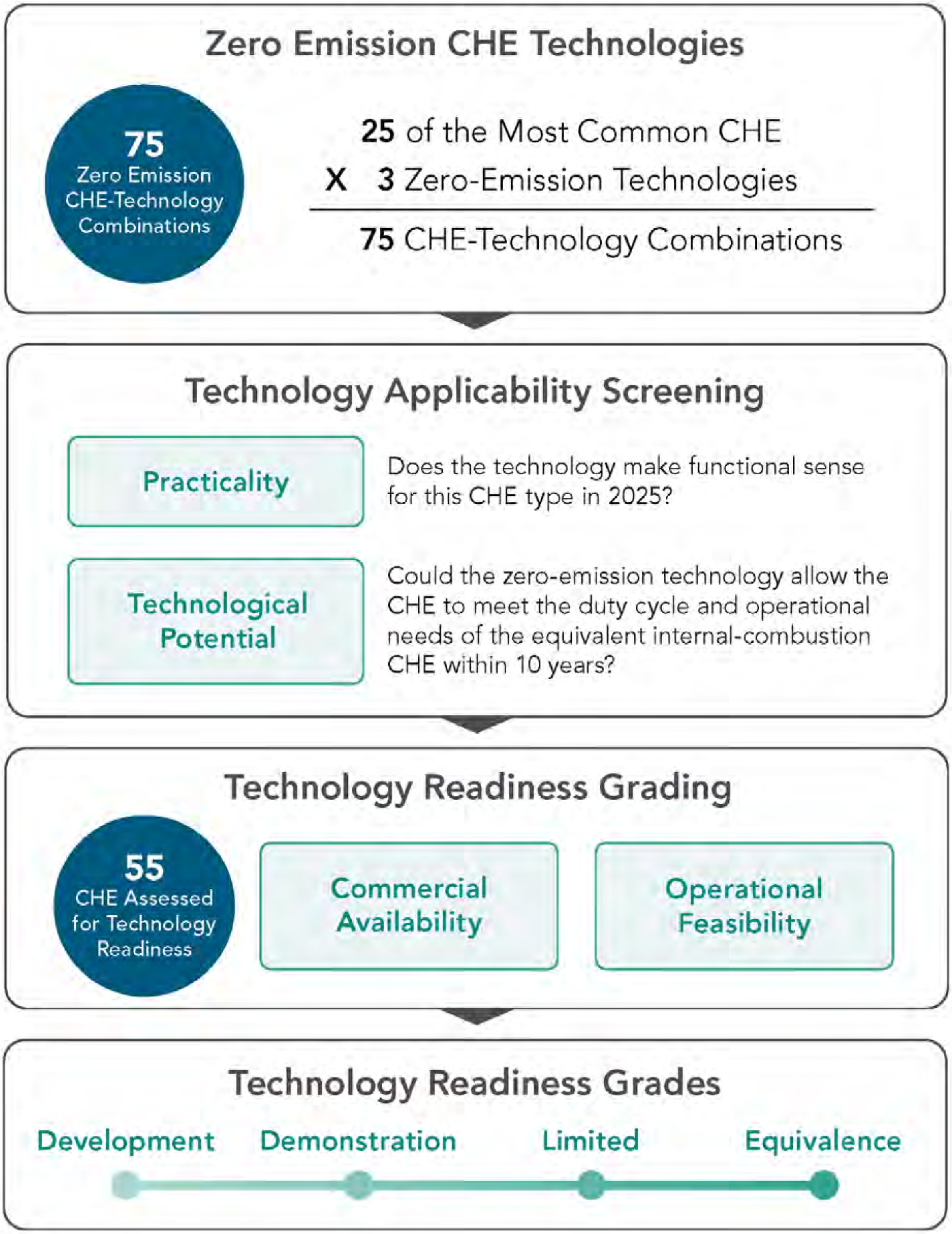
Table 6: Criteria for Assessing Technology Readiness

Technology Readiness Element	Criteria
Commercial Availability	• Is the CHE commercially available? If so, is it available in the U.S.? • If the CHE is not commercially available, where is it in the development cycle? • Are the lead times for new CHE purchases comparable to diesel equivalents? • Are replacement parts readily available comparable to diesel equivalents (less than two weeks to obtain service/spare parts)?

Technology Readiness Element	Criteria
Operational Feasibility	• Can the CHE meet the operational runtime needs? • Can the CHE perform on par with diesel baseline (power, torque, speed, etc.)? • Is the CHE reliable (similar up/down-time to diesel)? • Can the CHE be filled/charged quickly enough to keep operations running without delays, compared to diesel-powered CHE?

To inform the scoring of Commercial Availability, staff interviewed several CHE OEMs and conducted research to find commercially available zero-emission CHE as well as determine if the equipment is available in the U.S. See *Appendix B* for a list of commercially available zero-emission CHE. To inform Operational Feasibility, staff visited several seaports and intermodal railyards. In addition, they conducted research on demonstrations, pilot projects, prototypes, product announcements, and equipment studies that took place between January 2020 and January 2025. See *Appendix E* for a list of demonstrations, pilot projects, prototypes, and product launches. Figure 35 outlines staff's process for assessing the 75 CHE-technology combinations and determining Technology Readiness Grades.

Figure 35: Process for Assessing CHE and Providing Technology Readiness Grades



Economic considerations and infrastructure requirements are evaluated separately for each of the three zero-emission technologies and are considered in the Technology Outlook for each CHE-technology combination that did not achieve a Technology Readiness Grade of Equivalence.

Each type of CHE assessed for technology readiness has a summary table that includes the following:

- *Commercially Available in the U.S.* – The number of CHE models that are commercially available through a U.S.-based dealer or distributor.
- *Commercially Available Outside the U.S.* – The number of CHE models that are commercially available outside the U.S. through a dealer or distributor. CHE that is available both in the U.S. and outside the U.S. is only included in the *Commercially Available in the U.S.* number and not included in this number.
- *Non-Commercial Units* – The number of non-commercial CHE that were used in demonstrations, pilot programs, or prototypes between January 2020 and January 2025. These CHE are either prototype, pre-production, or custom-developed units and are not commercially offered to the public (facilities may use either commercially available or non-commercial CHE for demonstrations).
- *Technology Readiness Grade* – The Technology Readiness Grade assigned using the scoring methodology outlined in *Appendix D*.

Battery-Electric Cargo Handling Equipment

Battery-electric CHE relies on rechargeable batteries to provide electric power for operation. While grid-electric and hydrogen fuel cell CHE often have batteries for temporary operation or movement, they are not considered battery-electric, as batteries are not their *primary* power source. This section describes the benefits and challenges associated with battery-electric CHE.

Technology Description

Because CHE is part of the transportation industry, CHE OEMs leverage battery technologies from medium- and heavy-duty on-road vehicles. Therefore, two different battery chemistries are used for battery-electric CHE: lead-acid and lithium-ion.[20] New

[20] There are many types of lithium-ion batteries, but there are two main types that are currently used for the transportation industry. According to caranddriver.com, "The first, most common in North America and Europe, uses a blend of either nickel, manganese, and cobalt (NMC) or nickel, manganese, cobalt, and aluminum (NMCA)…The second type, far more widely used in China, is known as lithium-iron-phosphate, or LFP." (John Voelcker, "Electric-Vehicle Battery Basics," Car and Driver, July 29, 2024. Accessed April 14, 2025. *https://www.caranddriver.com/features/a43093875/electric-vehicle-battery/*.)

chemistries, such as solid-state cell and sodium-ion batteries, are under development[21] but are not available for CHE.[22] Lead-acid batteries are still very common with some battery-electric CHE, however, lithium-ion batteries offer some advantages including:

- Higher energy density
- Lighter, smaller
- No memory loss even with partial charges
- Longer life span and high charge rates

Although they have advantages over lead-acid batteries, lithium-ion batteries are also more expensive.[23] See the battery-electric CHE *Economics* section for more information on battery costs. While lithium-ion batteries have improved and last longer than lead-acid, their capacity to hold a full charge, like that of lead-acid batteries, gradually diminishes over repeated charging cycles.

Battery lifespan is affected by multiple factors, including battery chemistry, battery system design, amount of discharge, recharging rate, environmental conditions, and the CHE's duty cycle. These factors make it difficult to predict CHE battery-life. Battery-electric CHE is relatively new, and its battery life is still being evaluated, however, one article states that lithium-ion batteries have a limited life of 5 to 7 years for forklifts.[24] Because CHE can last 7 to 20 years,[25] it is estimated that most battery-electric CHE will require at least one battery swap during its lifetime. See the CARB Advanced Batteries for Motor Vehicles *webpage*[26] and the CARB document, *Battery Electric Truck and Bus Energy Efficiency Compared to*

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[21] Automotive Manufacturing Solutions, "Powering the Future: Top 5 EV Battery Chemistries and Formats Across the World," July 24, 2024. Accessed March 26, 2025. *https://www.automotivemanufacturingsolutions.com/top-5-ev-battery-chemistries-and-formats-across-the-world/45901.article*

[22] International Energy Agency, "Global EV Outlook 2023 Catching Up with Climate Ambitions," 2023. *https://iea.blob.core.windows.net/assets/dacf14d2-eabc-498a-8263-9f97fd5dc327/GEVO2023.pdf*.

[23] Power Sonic, "Lithium vs. Lead Acid Batteries: Is the Higher Cost Worth It?" August 22, 2024. Accessed January 8, 2025. *https://www.power-sonic.com/blog/powersonic/lithium-vs-lead-acid-batteries-is-the-higher-cost-worth-it/*.

[24] DC Velocity Staff, "Do You Know How Long a Lithium-Ion Forklift Battery Can Last?" DC Velocity, September 5, 2023. Accessed January 4, 2025. *https://www.dcvelocity.com/articles/58460-do-you-know-how-long-a-lithium-ion-forklift-battery-can-last*.

[25] California Air Resources Board, "Cargo Handling Equipment: Technology Assessment," September 9, 2014. *https://ww2.arb.ca.gov/sites/default/files/classic/msprog/tech/presentation/cargohandling.pdf*.

[26] California Air Resources Board, "Advanced Batteries for Motor Vehicles: Ensuring Battery-powered Vehicles and Equipment Provide Expected Environmental Benefits," December 15, 2023. *https://ww2.arb.ca.gov/resources/fact-sheets/advanced-batteries-motor-vehicles-ensuring-battery-powered-vehicles-and/printable/print*

Conventional Diesel Vehicles for more information about batteries and battery technology for zero-emission transportation.[27]

Unlike passenger cars that need to reduce weight for efficiency, many types of CHE benefit from added weight to counterbalance cargo. The weight increase from adding additional or larger batteries for extended operation time is usually not a design limitation for most CHE. Instead, cost and space constraints are the most common limiting factors.

The amount of batteries required for CHE to achieve duty cycles similar to diesel-powered CHE add significant cost to battery-electric CHE. For this reason, battery-electric CHE often requires *opportunity charging* when not in use, such as during breaks, stops, or downtime, rather than relying solely on scheduled, full charging sessions. See the battery-electric CHE *Infrastructure Requirements and Considerations - Logistics* section for more information on opportunity charging.

Batteries provide untethered mobility, as they are not attached by a cord or mounted on a track. Nearly all CHE using battery-electric technology achieve a Technology Applicability score of 1 or 2 (Table 2), showing potential suitability for nearly all CHE types if availability, cost, and infrastructure are not factors. However, to fully assess the applicability of battery technology for CHE, these factors are addressed below.

Technology Readiness

CARB's *2015 Draft Technology Assessment: Mobile Cargo Handling Equipment* (2015 Draft CHE Assessment) lists commercially available battery-electric CHE, including 1 brand of yard truck, 1 AGV, 11 forklifts, 1 mobile loader, and 6 railcar movers.[28] At that time, lead-acid batteries powered most of these vehicles. Many types of battery-electric CHE are now commercially available, and most are equipped with lithium-ion batteries. See *Appendix B* for a list of commercially available zero-emission CHE.

Battery-electric CHE uses the energy stored in the battery to move both the equipment and its cargo. This adds strain on the batteries when the equipment is continually moving and lifting. Many facilities operate for two or three shifts daily, five or six days a week. Diesel-powered CHE can operate for several shifts without refueling, allowing for scheduled refueling times. Some battery-electric CHE can last two full shifts before recharging,[29] but

[27] California Air Resources Board, "Battery Electric Truck and Bus Energy Efficiency Compared to Conventional Diesel Vehicles," May 2018. *https://ww2.arb.ca.gov/sites/default/files/2018-11/180124hdbevefficiency.pdf*.

[28] The lifting or pulling capacity of the CHE is not indicated.

[29] Businesswire, "Taylor Machine Works Selects ProTerra Battery Technology to Power Electric Port and Industrial Equipment," October 10, 2024. Accessed January 8, 2025. *https://www.businesswire.com/news/home/20241010979179/en/Taylor-Machine-Works-Selects-Proterra-Battery-Technology-to-Power-Electric-Port-and-Industrial-Equipment*.

most do not. Because the demands of CHE can vary between facilities, especially for bulk material operations, it is challenging for terminal operators to predict if batteries will last through the shift before recharging opportunities arise. This uncertainty can present a challenge for the adoption of battery-electric CHE.

Battery-Electric Bulk Material CHE

Many bulk material CHE, including cranes, dozers, and excavators, are also used for construction. Therefore, the availability of these battery-electric bulk material CHE is closely tied to the demand and availability for zero-emission equipment in the construction industry. There are no U.S. or California requirements for zero-emission construction equipment. Production of zero-emission construction equipment in the U.S. is driven by environmentally conscious OEMs, early technology adopters, and noise reduction requirements.[30] In Europe, emissions and noise ordinances drive demand,[31] while China enacts regulations and policies to promote the adoption of cleaner construction equipment.[32]

Less than 2% of bulk material CHE at facilities is battery-electric.[33] The low adoption rate is likely due to high costs and a lack of charging infrastructure. Table 7 provides the technology readiness data summary for battery-electric bulk material CHE. The battery-electric bulk material CHE discussion is divided into four categories based on similar operational needs and duty cycles: cranes, dry-bulk CHE, forklifts, and log stackers.

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[30] CALSTART, "Achieving Zero Emissions in Construction and Agricultural Equipment," Accessed January 8, 2025. *https://calstart.org/achieving-zero-emissions-in-construction-agricultural-equipment/*.

[31] According to a YouTube video, the Netherlands requires construction contractors to "show their green credentials" before they can obtain construction permits. (Victron Energy, "How and Why Is This Crane Battery Powered?" YouTube video, published March 26, 2024, 5:54. Accessed April 9, 2025. *https://youtu.be/QECj2Qa5TWI?si=JVQTkvE1ao3fHh1*.)

[32] Zhenying Shao, "Low-Emission Zones and Zero-Emission Construction Equipment in China: An Untapped Policy Opportunity," International Council on Clean Transportation, *ICCT WORKING PAPER*, Report No. 2022–30 (2022). *https://theicct.org/wp-content/uploads/2022/10/china-hvs-lez-construction-equipment-nov22.pdf*.

[33] Staff calculated less than 2% based on both raw data used for CARB's 2022 Cargo Handling Equipment Emissions Inventory (1.4%) as well as a supportive calculation of only bulk material CHE at the Port of Los Angeles and the Port of Long Beach based on data from their 2023 Air Emissions Inventories which yielded similar results (1.7%) using similar assumptions. Primary assumption was that gasoline, propane, and electric forklifts not found in *Appendix B* were not heavy lift forklifts.

Table 7: Technology Readiness Data Summary for Battery-Electric Bulk Material CHE

Equipment Type	Commercially Available in the U.S.	Commercially Available Outside the U.S.	Non-Commercial Units	Technology Readiness Grade
Crane, Material Handling	4	3	0	Demonstration
Crane, Mobile	8	0	1	Demonstration
Crane, Off-Road	5	0	0	Demonstration
Dozer	0	2	0	Demonstration
Excavator	7	7	0	Demonstration
Forklift, Heavy Lift	39	6	2	Demonstration
Forklift, Telehandler	8	3	1	Demonstration
Haul Truck	1	2	5	Limited
Loader or Loader-Excavator	21	7	3	Demonstration
Log Stacker	0	0	0	Development

Battery-Electric Cranes

Certain cranes handle bulk material and support facility operations. Their duty cycle and operational needs differ from dry bulk CHE. They often manage break bulk cargo and may not operate full shifts over multiple days like CHE used for dry bulk cargo or containers. In these cases, battery-electric cranes offer a practical alternative to their diesel counterparts.

Crane, Material Handling

There are seven commercially available models of material handling cranes. The German company Sennebogen offers two battery-electric models. Sennebogen acknowledges that battery-powered machines currently have limited operating times, but their newer machines can continue to operate even while connected to the grid for recharging. After six hours of use, their battery-electric 817 and 825 Electro Battery material hauling cranes can switch to stationary plug-in mode with a wired power supply. Grid power is used for working movements while simultaneously recharging the batteries.[34]

[34] Sennebogen, "Battery Technology from Sennebogen," n.d. Accessed April 10, 2025. *https://www.sennebogen.com/en/technology/battery-technology*.

Chinese company, Sany, produces an all-electric material handler that has a 50-ton lift capacity and claims a 50% reduction in powering costs.[35] German company, Liebherr, and Italian company, Solmec, also offer several models of battery-electric material handling cranes. However, there are no demonstration or pilot projects for material handling cranes at seaports or intermodal railyards. For this reason, battery-electric material handling cranes achieve a Technology Readiness Grade of Demonstration. Like many zero-emission CHE, while commercial models exist, they still need to be demonstrated at seaports and intermodal railyards to advance technology readiness and widespread deployment for cargo handling.

Crane, Mobile

Eight commercially available mobile crane models are offered by Manitex Valla, Tadano, Zee Crane, and Zoomlion. According to Tadano, the rough-terrain -EVOLT eGR1000XLL-1 can operate up to seven hours of lifting or five hours of lifting and 5.5 miles of jobsite travel on a single charge.[36] Like Sennebogen's Electro Battery material handling cranes, this mobile crane can also operate while plugged in for charging. Zoomlion's mobile crane has a 25-ton lifting capacity on a three-axle carrier and a range of more than 162 miles with a maximum speed of 56 miles/hour.[37] Battery-electric mobile cranes achieve a Technology Readiness Grade of Demonstration.

Crane, Off-Road

There are five commercially available models for off-road, general-purpose crawler cranes. Three Liebherr models currently qualify for CARB's Clean Off-Road Equipment Voucher Incentive Project (CORE), which provides financial incentive to support the deployment of zero-emission off-road equipment.[38] These models can operate while plugged into the grid,

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[35] Sany, "SMHC50V-D 50t Electric Material Handler," n.d. Accessed June 10, 2025. https://www.sanyglobal.com/product/port_machinery/material_handler/70/501/; Sany, "SMHC50V-D," n.d. https://sanyglobal-img.sany.com.cn/prod/20240509/SMHC50V-D%E5%8D%95%E9%A1%B5%20%E8%8B%B1%E6%96%87%E7%89%88_153927.pdf.

[36] Tadano, "Tadano Introduces the US and Canada's First Fully Electric Rough Terrain Crane," October 30, 2024. Accessed January 8, 2025. *https://group.tadano.com/uscan/en/news/tadano-introduces-the-us-and-canadas-first-fully-electric-rough-terrain-crane/*.

[37] Dahm, Alex. "Zoomlion Claims First Electric Truck Crane." *KHL Group*, May 26, 2020. Accessed April 21, 2025. *https://www.khl.com/1144261.article*.

[38] See California CORE Equipment Catalog for a full list of eligible zero-emission off-road equipment. (California CORE, "Eligible Equipment Catalog," n.d. Accessed April 14,2025. https://californiacore.org/equipmentcatalog/.)

or for up to eight hours unplugged.[39] Battery-electric off-road cranes achieve a Technology Readiness Grade of Demonstration.

Battery-Electric Dry Bulk CHE

Dry bulk CHE includes dozers, excavators, haul trucks, and loaders. When developing battery-electric construction equipment, OEMs aim for the equipment to operate for an eight-hour shift on a full battery charge for their equipment to achieve equivalency to diesel counterparts. Only some types of dry bulk CHE achieve this eight-hour goal with the current lithium-ion battery technology, namely excavators and loaders.

Battery-Electric Dozers

There are no battery-electric dozers commercially available in the U.S. However, the Chinese company Shantui Construction Machinery Co Ltd. offers their DE26-X2 Electric Bulldozer[40] and SD17E battery-electric dozer online.[41] The SD17E has a 240-kilowatt-hour (kWh) battery and a 145-kilowatt (kW) electric motor.[42] It began operation in China in 2021 and can operate for 4 to 5 hours per day.[43] Battery-electric dozers have not been demonstrated for cargo handling at a seaport or intermodal railyard and achieve a Technology Readiness Grade of Demonstration.

Battery-Electric Excavators

There are 14 commercially available battery-electric excavators. One model is eligible for funding through CARB's CORE program.[44] In October 2023, staff attended a live demonstration of a Komatsu battery-electric excavator (Figure 36) operating from a portable power station. Komatsu indicated that the equipment was able to operate for a full shift on a

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[39] Liebherr, "LR 1130.1 Unplugged Crawler Crane," n.d. Accessed January 8, 2025. *https://www.liebherr.com/en-us/p/lr1130unplugged-4407440*.

[40] Shantui, "Electric Bulldozer DE26-X2," n.d. Accessed March 27, 2025. *https://www.shantui-global.com/product/pro-detail-327.htm*.

[41] Made-in-China.com, "Shantui SD17e-X Electric Dozer 170HP Crawler Bulldozer for Sale," n.d. Accessed on January 13, 2025. *https://acntruck.en.made-in-china.com/product/WZwtXurvLTYd/China-Shantui-SD17e-X-Electric-Dozer-170HP-Crawler-Bulldozer-for-Sale.html*.

[42] Micah Toll, "This Massive Chinese Electric Bulldozer Could Wreck Your World, Emissions Free!" Electrek, July 22, 2023. Accessed January 13, 2025. *https://electrek.co/2023/07/22/massive-chinese-electric-bulldozer/*.

[43] Phate Zhang, "Pure Electric Bulldozer Goes Into Service in China, First of its Kind in the World," CnEVPost, April 9. 2022. Accessed January 13, 2025. *https://cnevpost.com/2021/06/14/pure-electric-bulldozer-goes-into-service-in-china-first-of-its-kind-in-the-world/*.

[44] See California CORE Equipment Catalog for a full list of eligible zero-emission off-road equipment. (California CORE, "Eligible Equipment Catalog," n.d. Accessed April 14,2025. https://californiacore.org/equipmentcatalog/.)

single charge.[45] Battery-electric excavators achieve a Technology Readiness Grade of Demonstration.

Figure 36: Demonstration Event for Battery-Electric Excavator (Staff photo)

Battery-Electric Haul Trucks

Sany offers a battery-electric haul truck that is commercially available in the U.S. It was developed for the mining industry, but may be suitable for cargo handling. Likewise, Volvo offers two articulated haul trucks for the European market. Several larger battery-electric haul trucks are being tested and demonstrated for the mining industry.[46] These haul trucks are optimized for mining operations and oversized for most dry bulk operations at seaports and intermodal railyards. However, the development of battery-electric haul trucks for mining will likely continue paving the way for haul trucks more suitable for dry bulk cargo at seaports and intermodal railyards. Due to positive initial feedback for a pilot project at a lime quarry, battery-electric haul trucks achieve a Technology Readiness Grade of Limited.

[45] Carmen Capoccia, "Powering the Future," Construction Business Owner Magazine, May 28, 2024. Accessed January 13, 2025. *https://www.constructionbusinessowner.com/popular-now/powering-future*.

[46] See *Appendix E* for hydrogen fuel cell haul truck demonstrations.

Battery-Electric Loaders

Loaders are the most common type of dry bulk CHE, with about 30 operating at the San Pedro Bay Port complex.[47] There are 28 commercially available models of battery-electric loaders that can be used for cargo handling, 21 of which are available in the U.S. Battery-electric loaders achieve a Technology Readiness Grade of Demonstration.

Battery-Electric Forklifts

There are many commercially available battery-electric alternatives for Class IV and Class V forklifts. CORE offers voucher incentives for 147 battery-electric forklifts models.[48] Of these, 68 have pneumatic-tires with lifting capacity more than 24,000 lb.[49] Sixteen of these are powered by lead-acid batteries and the other 52 use lithium-ion batteries. Without considering the different battery configurations offered by the OEMs, there are a total of 45 commercially available models of heavy-lift forklifts.

Various facilities use heavy lift forklifts differently. Some use them for chassis moving and flipping, while others use them for cargo handling. Facilities using battery-electric forklifts for a single shift generally find them adequate, but first-generation models need to be plugged in between shifts to operate for the second shift. Less frequently used forklifts face challenges charging between shifts due to neglect to plug them in after use, rather than labor, contract, or job position issues.

Several facilities reported that first-generation battery-electric forklifts have reliability issues relating to the batteries including thermal incidents and battery packs not lasting through the warranty period (typically three years), requiring early replacement. Facility operators recommended demonstrating smaller quantities of new equipment to provide an opportunity to address these issues before broad adoption of the new technology in new environments. Battery-electric forklifts achieve a Technology Readiness Grade of Demonstration.

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[47] Port of Long Beach, “2023 Air Emissions Inventory,” August 2024. *https://polb.com/download/14/emissions-inventory/20586/2023-air-emissions-inventory.pdf*; Port of Los Angeles, "2023 Air Emissions Inventory," August 2024. *https://kentico.portoflosangeles.org/getmedia/3fad9979-f2cb-4b3d-bf82-687434cbd628/2023-Air-Emissions-Inventory*.

[48] See California CORE Equipment Catalog for a full list of eligible zero-emission off-road equipment. (California CORE, “Eligible Equipment Catalog,” n.d. Accessed April 14,2025. https://californiacore.org/equipmentcatalog/.)

[49] This number includes 27 models with multiple battery configurations. These 27 models are represented as part of the 45 commercially available models listed in *Appendix B*.

Battery-Electric Log Stackers

Log stackers are specialized equipment with a high lift capacity. Batteries are a practical technology for log stackers and there are similar battery-electric CHE such as reach stackers and top handlers. No battery-electric log stacker models are commercially available or in demonstration. Battery-electric log stackers achieve a Technology Readiness Grade of Development.

Battery-Electric Container CHE

Governments, seaports, and shipping industries are setting zero-emission goals. Since most maritime cargo is containerized,[50] there has been more attention given to the development of zero-emission container CHE than bulk material or facility support CHE. Two recent studies funded by the California Energy Commission (CEC) provide valuable insight into zero-emission container operations:

- *A Comprehensive and Replicable Infrastructure Blueprint for Zero-Emission- and Heavy-Duty Vehicles Operating at a Port Terminal*[51]
- *Charging Ahead: The Port Community Electric Vehicle Blueprint*[52]

Significant progress has been made in developing zero-emission container CHE and more specifically, battery-electric container CHE. Table 8 provides the technology readiness data summary for battery-electric container CHE. The discussion of battery-electric container CHE is divided into two categories: predictable path container CHE and highly mobile container CHE.

[50] Aman Chopra, "Global Container Shipping Statistics in 10 Years," Stallion, November 26, 2024. Accessed March 26, 2025. *https://stallionexpress.ca/blog/global-container-shipping-statistics/#what-percentage-of-global-freight-is-carried-by-container-ships*.

[51] Ghazal Razeghi, Micheal Mac Kinnon, and Scott Samuel, "A Comprehensive and Replicable Infrastructure Blueprint for Zero-Emission- and Heavy-Duty Vehicles Operating at a Port Terminal, "California Energy Commission, 2023. https://cleanenergy.uci.edu/PDF_White_Papers/PortTerminalBlueprint2023.pdf. *https://thehelm.polb.com/download/379/zero-emissions/6769/port-community-electric-vehicle-blueprint-042919.pdf*

[52] Grant Farm, "Charging Ahead: The Port Community Electric Vehicle Blueprint," May 2019. *https://thehelm.polb.com/download/379/zero-emissions/6769/port-community-electric-vehicle-blueprint-042919.pdf*.

Table 8: Technology Readiness Data Summary for Battery-Electric Container CHE

Equipment Type	Commercially Available in the U.S.	Commercially Available Outside the U.S.	Non-Commercial Units	Technology Readiness Grade
AGV	3	1	0	Equivalence
Rail-mounted Gantry Crane	0	0	0	Development
Reach Stacker	8	1	1	Demonstration
Rubber-Tired Gantry Crane	2	1	0	Demonstration
Shuttle and Straddle Carriers	2	1	0	Demonstration
Side Handler	9	1	1	Demonstration
Top Handler	3	0	0	Limited
Yard Truck	20	0	2	Limited

Predictable Path Container CHE

This section covers technology readiness for battery-electric AGVs, RMGs, and RTGs, which follow predictable paths during daily operations.

Battery-Electric AGVs

There are four commercially available battery-electric AGVs. While some terminals are still demonstrating these AGVs at their facilities to align with their operational needs, the technology is mature.

CARB's 2015 Draft CHE Assessment highlighted the Konecranes Gottwald AGV with 20 years of operational experience.[53] Since then, the Long Beach Container Terminal has acquired a fleet of 100 of these battery-electric Gottwald AGVs,[54] some in operation since

[53] California Air Resources Board, "Draft Technology Assessment: Mobile Cargo Handling Equipment," November 2015. *https://www.arb.ca.gov/msprog/tech/techreport/che_tech_report.pdf?_ga=2.112080327.297876042.1716210149-1592276699.1662484763*.

[54] Port of Long Beach, "2023 Air Emissions Inventory," August 2024. *https://polb.com/download/14/emissions-inventory/20586/2023-air-emissions-inventory.pdf*.

2015.[55] Instead of charging the batteries while installed, they use a swapping system in which batteries are removed, charged, and replaced. The swap takes about five minutes.[56] AGVs at the Long Beach Container Terminal use lead-acid batteries[57] that take approximately six hours to charge.[58] Newer AGVs equipped with lithium-ion batteries fully charge within 1.5 hours and support a full day of operation.[59] Battery-electric AGVs achieve a Technology Readiness Grade of Equivalence.[60]

Battery-Electric Rail-Mounted Gantry Cranes

While battery-electric RMGs could connect to a charging port to recharge batteries, providing grid power using a cable reel or busbar is more practical. RMGs are confined to their rail system, making grid power more straightforward and reliable than battery charging. Grid-electric is already a mature technology for RMGs. All RMGs at the San Pedro Bay Port complex are electrified using grid power.

All RMGs operating at California facilities are grid-electric.[61] Because grid-electric RMGs are already standard, no companies offer a battery-electric RMG and there are no active demonstrations. Battery-electric RMGs achieve a Technology Readiness Grade of Development.

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[55] Cristina Prinz, "Zero Emission: Automated Guided Vehicles at the Port of Long Beach," March 17, 2017. Accessed March 26, 2025. *https://www.kfw.de/stories/economy/mobility/automatisierter-containertransport-kalifornien/* .

[56] Konecranes, "Konecranes Gottwald AGVs at Long Beach Container Terminal," YouTube video, published October 19, 2018. Accessed May 28, 2025. *https://www.youtube.com/watch?v=KiFfZWvMC7U*.

[57] Konecranes Trade Press Releases, "Konecranes to Deliver Fleet of AGVs to Long Beach Container Terminal," May 18, 2020. Accessed March 26, 2025. *https://www.konecranes.com/press-releases/konecranes-to-deliver-fleet-of-agvs-to-long-beach-container-terminal*.

[58] California Air Resources Board, "Draft Technology Assessment: Mobile Cargo Handling Equipment," November 2015. *https://www.arb.ca.gov/msprog/tech/techreport/che_tech_report.pdf?_ga=2.112080327.297876042.1716210149-1592276699.1662484763*.

[59] Container News, "HHLA Completes AGV Charging Infrastructure Project at Container Terminal Altenwerder," September 13, 2022. Accessed December 13, 2024. *https://container-news.com/hhla-completes-agv-charging-infrastructure-project-at-container-terminal-altenwerder/*.

[60] While there are diesel AGV models available, currently there are none operating in California. Therefore, *equivalence* in this case means battery-electric AGVs are now the industry standard.

[61] Staff confirmed that all rail mounted gantry cranes operating in California are at the San Pedro Bay Port Complex and are grid-electric.

Battery-Electric Rubber-Tired Gantry Cranes

A UC Irvine report stated that diesel-powered RTGs at the Port of Long beach comprised 5% of their total CHE yet produced 20% of the total emissions.[62] Converting RTGs to zero-emission is critical to overall emissions reductions at facilities with many diesel-powered RTGs. However, RTGs operate10-20 hours per day lifting containers that can weigh nearly 80,000 lb, making decarbonization difficult.[63]

There are three commercially available models of battery-electric RTGs. Both Kalmar[64] and Konecranes[65] have announced battery-electric RTG models that are available in the U.S. These models can operate on battery power and connect with charging systems as needed (Figure 37). Battery-electric RTGs achieve a Technology Readiness Grade of Demonstration.

Grid-electric may be a better option than battery-electric if a gantry crane generally follows the same path every shift and every day. These CHE are discussed in the *Grid-Electric CHE* section.

Staff is seeking information on the implementation of battery-electric RMGs and RTGs.

[62] Ghazal Razeghi, Micheal Mac Kinnon, and Scott Samuel, "A Comprehensive and Replicable Infrastructure Blueprint for Zero-Emission- and Heavy-Duty Vehicles Operating at a Port Terminal, "California Energy Commission, 2023. *https://cleanenergy.uci.edu/PDF_White_Papers/PortTerminalBlueprint2023.pdf*.

[63] Marine Log Staff, "Mi-Jack to convert RTG crane to hydrogen powered" Marine Log, March 6, 2023. Accessed February 27, 2025.https://www.marinelog.com/inland-coastal/ports-terminals/mi-jack-to-convert-rtg-crane-to-hydrogen-powered/.

[64] Kalmar Global," Kalmar Zero Emission RTG with Battery Pack: Better Flexibility and No Emissions," October 7, 2019. Accessed December 12, 2024. *https://www.kalmarglobal.com/news--insights/articles/2019/20191007_new-kalmar-zero-emission-rtg-with-a-battery-pack/.*

[65] Konecranes," Konecranes Puts the Battery in RTGs, Straddle Carriers and Mobile Harbor Cranes with Ecolifting," June 15, 2022. Accessed December 12, 2024. *https://www.konecranes.com/en-us/press-releases/konecranes-puts-the-battery-in-rtgs-straddle-carriers-and-mobile-harbor-cranes-with-ecolifting*.

Figure 37: Illustration of Battery-Electric RTG Battery Charging System (Konecranes)

Highly Mobile Container CHE

Reach stackers, shuttle/straddle carriers, side handlers, top handlers, and yard trucks all travel in unpredictable paths and varying distances. Batteries work well for these CHE, as they allow for untethered mobility.

Battery-Electric Reach Stackers and Side Handlers

Reach stackers can lift containers vertically and reach horizontally over stacks of containers. While terminals with RTGs and top picks may not need reach stackers, they are useful for smaller operations that do not have the larger, more expensive RTGs.

Side handlers typically stack only empty containers. Larger facilities with top handlers and RTGs can perform the same container operations, reducing the need for side handlers. Therefore, side handlers are not very common. The San Pedro Bay Port complex operates over 3,700 pieces of CHE. Only 4 are reach stackers and 14 are side handlers, while 408 are top handlers.[66] The lower demand for reach stackers and side handlers may slow the adoption of zero-emission options for these CHE types. However, there are 9 commercially available models of battery-electric reach stackers and 10 commercially available models of battery-electric side handlers.

At busy terminals, AGVs, RMGs, RTGs, shuttle/straddle carriers, top handlers, and yard trucks typically operate for two shifts each day. In contrast, reach stackers and side handlers are more specialized and are used for specific tasks. For these types of CHE, operating for a single shift on a full charge is acceptable at many terminals. Battery-electric reach stackers and side handlers achieve a Technology Readiness Grade of Demonstration due to long lead times and limited proven deployments.

Battery-Electric Shuttle and Straddle Carriers

Shuttle and straddle carriers are mainly used at large container terminals. The Port of Los Angeles operates 160 straddle carriers, of which 132 are diesel-electric hybrids and the rest are diesel-powered. Kalmar offers a battery-electric straddle carrier that can charge manually or be configured with a pantograph, an overhead charging system, for opportunity charging. Figure 38 shows a pantograph charging system. When the equipment needs a charge or is idle, the operator drives the equipment under a mechanical arm that lowers and contacts a dome-shaped electrical receiver.

The straddle carrier comes in two battery configurations: the *high-energy* battery can operate for 4 hours and fully recharge in 45 minutes, while the *high-power* battery option can charge in 5 to 6 minutes and operate for up to 50 minutes before needing another charge.[67] In April 2024, DP World London Gateway Hub took delivery of eight units, forming "the world's first electric straddle carrier fleet."[68] Konecranes also offers a fully battery-electric straddle carrier along with a containerized charging station.[69] There are

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[66] Port of Long Beach, "2023 Air Emissions Inventory," August 2024. *https://polb.com/download/14/emissions-inventory/20586/2023-air-emissions-inventory.pdf*; Port of Los Angeles, "2023 Air Emissions Inventory," August 2024. *https://kentico.portoflosangeles.org/getmedia/3fad9979-f2cb-4b3d-bf82-687434cbd628/2023-Air-Emissions-Inventory*.

[67] Kalmar, "Straddle Carrier for Shuttle Operations," April 22, 2025. *https://www.kalmarusa.com/4adf83/globalassets/media/317754/317754_NB_Kalmar-Straddle-Carriers-for-shuttle-operations_EN_web.pdf*.

[68] Hellenic Shipping News," World's First Electric Straddle Carrier Fleet Arrives at DP World's London Gateway Hub," April 23, 2024. Accessed December 12, 2024. *https://www.hellenicshippingnews.com/worlds-first-electric-straddle-carrier-fleet-arrives-at-dp-worlds-london-gateway-hub/*.

[69] Konecranes, "Battery Konecranes Noell Straddle Carrier," 2022. *https://www.konecranes.com/sites/default/files/2022-06/Battery_Konecranes_Noell_Straddle_Carrier_EN.pdf*.

three commercially available models of shuttle and straddle carriers. Battery-electric shuttle and straddle carriers achieve a Technology Readiness Grade of Demonstration.

Staff is seeking information on the implementation of battery-electric shuttle and straddle carriers.

Figure 38: Pantograph Charging System for Battery-Electric Straddle and Shuttle Carriers (Kalmar)

Battery-Electric Top Handlers

Top handlers are a popular type of CHE. At the San Pedro Bay Port complex, 408 out of 3,725 pieces of CHE are top handlers which is about 11% of the total fleet.[70] Two are battery-electric models, introduced during a year-long demonstration ending in October 2020. They have remained in operation since, operating for 2 shifts on a single

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[70] Port of Long Beach, “2023 Air Emissions Inventory,” August 2024. *https://polb.com/download/14/emissions-inventory/20586/2023-air-emissions-inventory.pdf*; Port of Los Angeles, "2023 Air Emissions Inventory," August 2024. *https://kentico.portoflosangeles.org/getmedia/3fad9979-f2cb-4b3d-bf82-687434cbd628/2023-Air-Emissions-Inventory*.

charge.[71] Taylor Machine Works, Inc. offers 3 models of top handlers capable of lifting up to 90,000 lb. There are three commercially available models of battery-electric top handlers, all of which are offered in the U.S. Battery-electric top handlers achieve a Technology Readiness Grade of Limited due to long lead times for parts and limited data from demonstrations.

Battery-Electric Yard Trucks

Yard trucks are the most common type of CHE at facilities. The San Pedro Bay Port complex has almost 1,800 yard trucks, which is nearly half of their total CHE population. Table 9 summarizes the fuel types for these yard trucks. Only diesel-powered yard trucks are subject to the CHE Regulation.[72]

Table 9: Fuel Types for Yard Trucks at the San Pedro Bay Port Complex

Fuel Type	Quantity	Percent of Total Yard Truck Population
Diesel	1,384	77%
Electric	45	3%
Gasoline	134	7%
Liquid Natural Gas (LNG)	22	1%
Propane	207	12%

A UC Irvine study found that yard trucks operate an average of 6 to 7 hours per day, but some operate for up to 18 hours.[73] At seaport container terminals, diesel-powered yard trucks can operate for two full shifts and possibly a third before needing to refuel. While many commercially available battery-electric yard trucks have been a part of demonstration projects,[74] most cannot operate for two full shifts on a single charge.

Charging between shifts would allow most models to make it through the second shift before needing a recharge. However, several factors make opportunity charging a logistical challenge. See the battery-electric CHE *Infrastructure Requirements and Considerations – Logistics* section for more information on opportunity charging. Given this feedback, OEMs

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[71] Port of Los Angeles, "Port of Los Angeles Unveils World's First Zero-Emissions Top Handlers," YouTube video, published October 2, 2019, 3:26. Accessed April 9, 2025. *https://youtu.be/WB_T804vQSE?si=ke2r9oz9q-4fdZHs*.

[72] CHE using fossil fuel types other than diesel may be subject to other regulations.

[73] Ghazal Razeghi, Micheal Mac Kinnon, and Scott Samuel, "A Comprehensive and Replicable Infrastructure Blueprint for Zero-Emission- and Heavy-Duty Vehicles Operating at a Port Terminal, "California Energy Commission, 2023. *https://cleanenergy.uci.edu/PDF_White_Papers/PortTerminalBlueprint2023.pdf*.

[74] See *Appendix E* for a list of battery-electric yard trucks demonstration projects.

have been working to increase the battery size and range in their next-generation yard trucks. However, increasing battery capacity and size also increases costs.

Battery-electric yard trucks face additional challenges beyond limited full-shift operation. For example, the Port of Long Beach incorporated hands-free charging stations for their 33 battery-electric yard truck demonstration.[75] Technology challenges resulted in considerable down time for the trucks. Facility operators reported delays obtaining replacement parts and service for technical issues, especially for foreign parts and off-shore technical support. These challenges negatively impact the Technology Readiness Grade. Facilities reported that most battery-electric yard trucks can meet the power, acceleration, and operational needs during operation.

Although there are 20 commercially available battery-electric yard truck models and many demonstrations, they do not meet equivalency with their diesel counterparts. Battery-electric yard trucks achieve a Technology Readiness Grade of Limited.

Battery-Electric Facility Support CHE

Facility support CHE represents a small fraction of total CHE at California facilities and generally does not operate for full shifts over multiple days. Due to limited use of these types of equipment at seaports and intermodal railyards, the equipment is generally proven in other industry settings and often without publicized results. Table 10 provides the technology readiness data summary for battery-electric facility support CHE.

Table 10: Technology Readiness Data Summary for Battery-Electric Facility Support CHE

Equipment Type	Commercially Available in the U.S.	Commercially Available Outside the U.S.	Non-Commercial Units	Technology Readiness Grade
Aerial Lift	16	1	0	Demonstration
Cone Vehicle	4	0	0	Demonstration
Railcar Mover	21	1	0	Demonstration
Utility Truck, Other	20	1	1	Demonstration
Utility Truck, Sweeper	4	11	0	Demonstration

[75] Port of Long Beach, "Zero-Emissions Cargo Handlers Debut at Port of Long Beach," November 30, 2023. Accessed December 16, 2024. *https://polb.com/port-info/news-and-press/zero-emissions-cargo-handlers-debut-at-port-of-long-beach-11-30-2023/*.

Battery-Electric Aerial Lifts

There are 17 commercially available models of battery-electric aerial lifts, some of which can charge during operation. Battery-electric aerial lifts achieve a Technology Readiness Grade of Demonstration due to the lack of information regarding demonstrations and deployments.

Battery-Electric Cone Vehicles

Cone vehicles lift personnel to latch the inter-box connectors, or twist-locks, of stacked containers and may need to be available for full shifts. There are 43 cone vehicles at the San Pedro Bay Port complex. Of these, 8 are battery-electric. These battery-electric cone vehicles are designed to operate for a full 8-hour shift, recharge in 8-hours, then rest and cool for another 8-hours before use. Motrec offers lithium-ion options that charge faster and operate longer after a full charge.[76] There are four commercially available battery-electric vehicles that can operate as cone vehicles. Battery-electric cone vehicles achieve a Technology Readiness Grade of Demonstration due to the lack of information regarding demonstrations and deployments.

Battery-Electric Railcar Movers

Railcar movers are very specialized CHE. According to the 2022 CHE Inventory,[77] there are only 11 operating at California seaports and intermodal railyards, and 6 of them are at the San Pedro Bay Port complex.[78] One of the 6 is a battery-electric railcar mover.[79] Another battery-electric railcar mover is being demonstrated at the Port of Stockton.[80] There are 22 commercially available battery-electric railcar movers. Battery-electric railcar movers achieve a Technology Readiness Grade of Demonstration due to the lack of information regarding demonstrations and deployments.

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[76] Discussion with Motrec on 12/18/2024.

[77] California Air Resources Board, "2022 Cargo Handling Equipment Emissions Inventory," December 2022. *https://ww2.arb.ca.gov/sites/default/files/2023-04/2022%20CHE%20Emission%20Inventory%20Document_6April2023.pdf*.

[78] Port of Long Beach, "2023 Air Emissions Inventory," August 2024. *https://polb.com/download/14/emissions-inventory/20586/2023-air-emissions-inventory.pdf*; Port of Los Angeles, "2023 Air Emissions Inventory," August 2024. *https://kentico.portoflosangeles.org/getmedia/3fad9979-f2cb-4b3d-bf82-687434cbd628/2023-Air-Emissions-Inventory*.

[79] Ibid.

[80] Port of Stockton, "The Port of Stockton Charts Course for Sustainable Future," June 25, 2021. Accessed May 9, 2025. *https://www.portofstockton.com/the-port-of-stockton-charts-course-for-sustainable-future/*.

Battery-Electric Utility Trucks

Utility trucks include fuel trucks, water trucks, and other trucks that perform facility support operations. Battery-electric technology readiness for many utility trucks depends on the heavy-duty on-road and off-road truck industry. EO N-79-20 set a zero-emission goal for all medium-and heavy-duty vehicles in the State by 2045 and for drayage trucks by 2035. This will help accelerate the development of medium- and heavy-duty battery-electric trucks that can be used for utility truck cargo handling operations.

There are 21 commercially available medium- and heavy-duty battery-electric trucks that may be fitted to meet the needs of facility support CHE. Trucks approved for California's Hybrid and Zero-Emission Truck and Bus Voucher Incentive Program (HVIP) include those from Mack, Navistar, Volvo, Xos, and Zeus. The HVIP website lists several class 6, class 7, and class 8[81] battery-electric straight trucks or cab-and-chassis trucks that can be fitted with specialized utility equipment including fuel and water tanks. Battery-electric utility trucks achieve a Technology Readiness Grade of Demonstration due to the lack of information regarding demonstrations and deployments.

Battery-Electric Sweepers

There are 15 commercially available battery-electric sweepers that may meet diesel equivalent operations and 4 are available in the U.S. The eSweeper developed by US Hybrid and GEP (Figure 39) was rigorously tested for use by the California Department of Transportation (Caltrans). GEP began production of 18 units for Caltrans in March 2023.[82] The Elgin Electric Broom Bear, released in 2023, is compatible with both level 2 or level 3 fast chargers and claims to have enough battery capacity to handle extended shifts due to its 400-kWh battery storage capacity.[83] There have been no reported demonstrations of this equipment for use at seaports or intermodal railyards, but many public municipalities have

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[81] Details at California HVIP, "Incentives for Clean Truck and Bus," n.d. Accessed April 14, 2025. *https://californiahvip.org/*.

[82] Ideanomics, "Made in California: Ideanomics Subsidiary US Hybrid and Global Environmental Products Begin Manufacturing 18 Zero-Emission Street Sweepers for Caltrans," PR Newswire, March 9, 2023. Accessed December 18, 2024. *https://www.prnewswire.com/news-releases/made-in-california-ideanomics-subsidiary-us-hybrid-and-global-environmental-products-begin-manufacturing-18-zero-emission-street-sweepers-for-caltrans-301766240.html*.

[83] Elgin, "Electric Broom Bear Product Overview," n.d. Accessed May 9, 2025. *https://www.elginsweeper.com/products/all-electric/electric-broom-bear*; Elgin, "We Drove the First All-Electric Street Sweeper in the US, Coming to LA soon," Electrek News, September 5, 2023. https://www.elginsweeper.com/about/whats-new/electrek-electric-broom-bear-article.

demonstrated this equipment in recent years.[84] Battery-electric sweepers achieve a Technology Readiness Grade of Demonstration due to lack of real-world use data.

Figure 39: Global M3EV Plug-In Battery-Electric Sweeper (Global)

Emissions Benefits and Considerations

Replacing fossil-fuel-burning CHE with zero-emission alternatives can help achieve 100% CHE emission reductions at seaports and intermodal railyards. Battery-electric CHE mostly uses battery charging infrastructure that relies on power from California's utility grid.

[84] According to *The Municipal*, the Global electric sweeper has been thoroughly tested and has been in operation in many locations in the United States for nearly a decade (see Jason Condon, "The Learning Curve of Electrification," The Municipal, September 1, 2023, Accessed May 7, 2025. *https://www.themunicipal.com/2023/09/the-learning-curve-of-electrification*). See *Appendix E* for Demonstrations, Pilots, and Prototypes of battery-electric sweepers.

In 2023, 54% of California's electricity came from renewable sources.[85] This is up from 34% in 2021.[86] As California's grid uses more renewable sources, the benefits of using batteries and grid power for CHE will increase. This impacts facilities, communities, as well as State air quality and climate goals.

Infrastructure Requirements and Considerations

Evaluating electric charging and fueling infrastructure readiness and availability is essential to supporting a zero-emission CHE fleet. This section discusses requirements and considerations for the three aspects of battery-electric CHE infrastructure listed below.

- Electricity source - includes an analysis of the existing capacity of California's grid and the requirements for delivering electricity to facilities. Most of the utility grid considerations for battery-electric CHE also apply to grid-electric CHE.
- Charging equipment – includes the equipment, installation, and maintenance of battery-electric charging equipment.
- Logistics - includes various charging interfaces and practices that affect the feasibility of battery-electric charging.

Electricity Source

Supplying sufficient electricity to seaports and intermodal railyards is critical for the deployment of battery-electric and grid-electric CHE. Facilities can obtain electricity from two primary sources: the utility grid or a microgrid. Utilities play a key role in managing and integrating electricity supply, while alternative power sources, like energy storage systems or a local microgrid, can supplement the utility grid.

Seaports and intermodal railyards require significant electricity to support their daily operations. Table 11 shows power demand sources at a typical seaport or intermodal railyard in California and estimates future electricity demand trends and drivers. As more electric equipment is adopted to reduce emissions at seaports and intermodal railyards, electricity demand will continue to increase.

[85] U.S. Energy Information Administration, "California State Profile and Energy Estimates," n.d. Accessed April 9, 2025. *https://www.eia.gov/state/?sid=CA*.

[86] California Energy Commision,"2021 Total System Electric Generation," 2021. *https://www.energy.ca.gov/data-reports/energy-almanac/california-electricity-data/2021-total-system-electric-generation*.

Table 11: Demand Sources for California Seaports and Intermodal Railyards

Source of Electricity Demand	Description	Applicability (S=Seaports, I=Intermodal Railyards)	Projected Electricity Demand and Drivers
General business operations	Includes offices and shops: HVAC system, lights, computers, security, communication systems, etc.	S/I	Static/Possibly Increasing: No current or pending regulations requiring changes. However, increased computing power may be needed for the additional networking and charging equipment listed in this table.
Employee and port/yard fleet charging stations for light-duty vehicles	At least 7% of light-duty vehicles in California are EVs (battery-electric, plug-in hybrids, or hydrogen fuel cell).[87]	S/I	Increasing: California EO N-79-20 set, and EO N-27-25 reaffirmed, a goal for all new passenger cars, trucks, and SUVs sold in California to be zero-emission by 2035[88]
Shore power for ocean-going vessels (OGV)	As of January 1, 2023, container, refrigerated, and cruise OGVs must plug into shore power (grid) within two hours of berthing.[89]	S	Increasing: New vessel type requirements are effective as of 1/1/2025. Additional requirements begin on 1/1/2027.[90]

[87] Veloz.com reports 1,996,931 EV sales in California since 2011 (Veloz, "California EV Market Report," n.d. *https://www.veloz.org/ev-market-report/*). The California Energy Commission reports 27,828,856 non-EV registered in California at the end of 2023 (California Energy Commission, "Light-Duty Vehicle Population in California," n.d. Accessed November, 2024 *https://www.energy.ca.gov/data-reports/energy-almanac/zero-emission-vehicle-and-infrastructure-statistics-collection/light*). 1,996,931/27,828,856=0.072, or 7.2%.

[88] California Air Resources Board, "Cars and Light-Trucks are Going Zero-Emission- Frequently Asked Questions," n.d. Accessed April 9, 2025. *https://ww2.arb.ca.gov/resources/documents/cars-and-light-trucks-are-going-zero-frequently-asked-questions*.

[89] California Air Resources Board, "Regulation to Reduce Emissions from Diesel Auxiliary Engines on Ocean-Going Vessels While At-Berth at a California Port," n.d. Accessed April 9, 2025. *https://ww2.arb.ca.gov/our-work/programs/ocean-going-vessels-berth-regulation*.

[90] Ibid.

Source of Electricity Demand	Description	Applicability (S=Seaports, I=Intermodal Railyards)	Projected Electricity Demand and Drivers
Shore power for commercial harbor craft (CHC)	CHC at seaports can opt in to the Zero-Emission and Advanced Technology (ZEAT) pathway for compliance.	S	Increasing: California EO N-79-20 set, and EO N-27-25 reaffirmed, a goal of 100% zero-emission off-road vehicles and equipment by 2035 where feasible. Many CHC are expected to be repowered or retrofitted to cleaner standards, which may require additional charging capability at seaports.[91]
Shore power for refrigerated ocean containers	Refrigerated ocean containers waiting at seaports or railyards often plug into grid power.	S/I	Increasing: Diesel-powered transport refrigeration unit (TRU) generator sets (as well as domestic shipping container TRUs and railcar TRUs) will likely be phased out with future emission reduction strategies.[92]

[91] CARB, "CHC Factsheet: Facility Requirements," n.d. *https://ww2.arb.ca.gov/sites/default/files/2022-12/FAB22-062%20-%20CHC%20Facility%20Requirements%20Fact%20Sheet%20ADA.pdf*.

[92] See CARB's TRU website for more information: *https://ww2.arb.ca.gov/our-work/programs/transport-refrigeration-unit/new-transport-refrigeration-unit-regulation*.

Source of Electricity Demand	Description	Applicability (S=Seaports, I=Intermodal Railyards)	Projected Electricity Demand and Drivers
Electricity for charging battery-electric CHE	Approximately 8% of CHE in California is battery-electric.[93]	S/I	Increasing: California EO N-79-20 set, and EO N-27-25 reaffirmed, a goal of 100% zero-emission off-road vehicles and equipment by 2035 where feasible. Replacement of diesel-powered CHE with battery-electric CHE is increasing.
Electricity for grid-electric CHE	All ship-to-shore cranes, RMGs, and many other CHE operating in California are grid-electric.	S/I	Increasing: California EO N-79-20 set, and EO N-27-25 reaffirmed, a goal of 100% zero-emission off-road vehicles and equipment by 2035 where feasible. Grid power will become more prevalent for zero-emission CHE such as grid-electric RTGs and mobile harbor cranes.

Statewide Grid Analysis

Staff conducted a preliminary grid impact analysis to estimate the additional grid electricity needed to support a fully zero-emission CHE fleet at California seaports and intermodal railyards. *Appendix F* contains information on the assumptions and methodology used for the grid impact analysis.

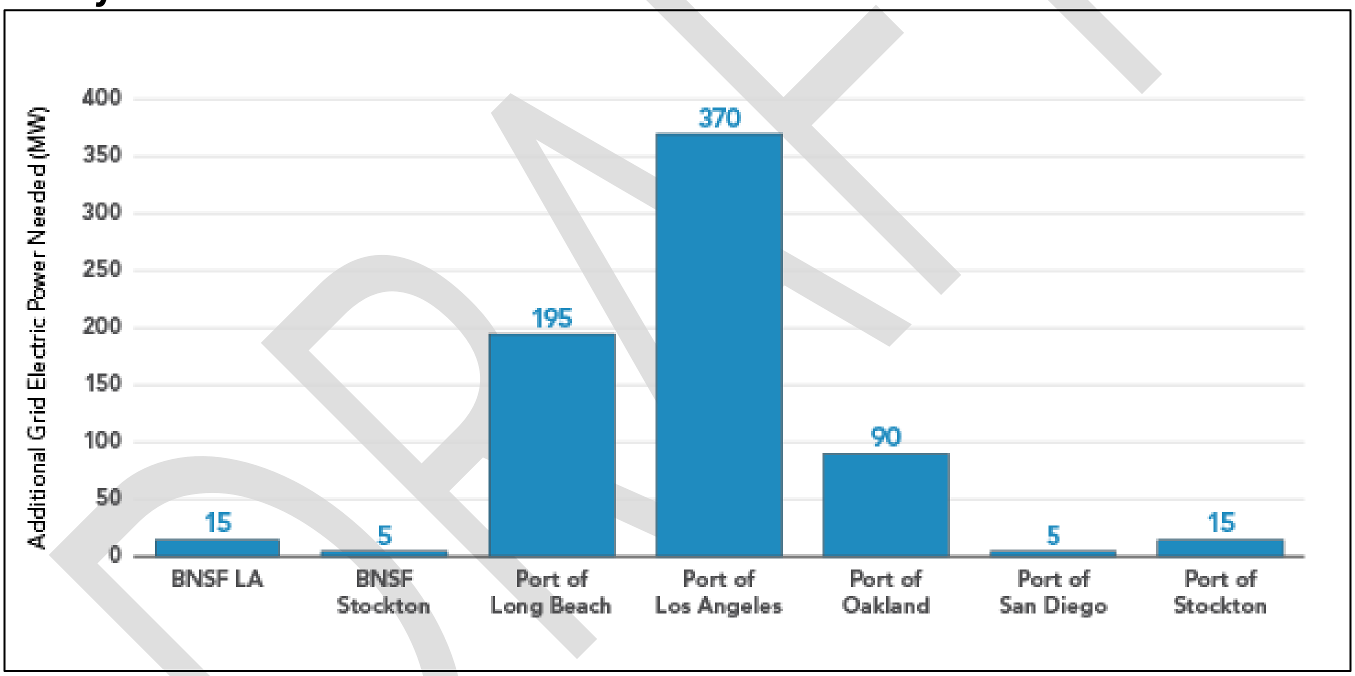
Based on staff's preliminary analysis, approximately 960 megawatts (MW) of total load capacity is needed. This includes both capacity that can be supported by existing infrastructure and additional load required beyond current capacity. Of the estimated 960

[93] California Air Resources Board, "2022 Cargo Handling Equipment Emissions Inventory," 2022. *https://ww2.arb.ca.gov/sites/default/files/2023-04/2022%20CHE%20Emission%20Inventory%20Document_6April2023.pdf*.

MW needed, existing utility-provided load capacity can meet approximately 265 MW (based on staff's analysis conducted in January 2025). To support a zero-emission CHE fleet, utilities will need to upgrade substations near CHE facilities and expand the load capacity to address the remaining 695 MW of unmet demand.

Of the 28 facilities analyzed, the existing utility-provided load capacity is sufficient for 21. These facilities either require less than 5 MW of load capacity or have needs greater than 5 MW that can be met by existing load capacity at nearby substations. The remaining 7 facilities will require substation upgrades to support fully zero-emission CHE operations. Figure 40 shows the facilities requiring additional grid capacity and their estimated power demand. The Port of Long Beach, the Port of Los Angeles, and the Port of Oakland have the largest power deficits, driven by the high population of CHE operating at their terminals.

Figure 40: Additional Load Capacity Needed to Support Fully Zero-Emission CHE by Facility



This preliminary analysis is designed to provide a general understanding of the State's current grid capacity and future electrification needs. It is based on several assumptions that may not reflect operations at all facilities in California and does not account for the other future demand sources shown in Table 11.

Utility Grid and Adding Grid Infrastructure

Utility companies connect seaports and intermodal railyards to the grid. The largest electric utilities in California are Los Angeles Department of Water and Power, Pacific Gas & Electric Company, Southern California Edison, and San Diego Gas & Electric.[94] These utilities provide power to most of California's seaports and intermodal railyards. In some cases, such as the Port of Oakland and the Port of Stockton, the facility can act as its own utility.[95] Some facilities receive power from two different utilities.

California utilities generate electricity from multiple sources, including hydro-electric, natural gas, nuclear, solar, and wind.[96] Utilities route electricity to substations that may serve a combination of facilities, businesses, and residences, or to substations dedicated to a single facility. The electricity passes through a meter that measures the electricity usage for the facility and defines the point of financial responsibility for any upgrade projects. All upgrades and CHE infrastructure installations that occur downstream from the meter are the financial responsibility of the facility. Figure 41 illustrates California's utility grid for CHE. The arrows in Figure 41 represent electricity traveling over distances, which is accomplished with power lines or electric cable inside special conduit.

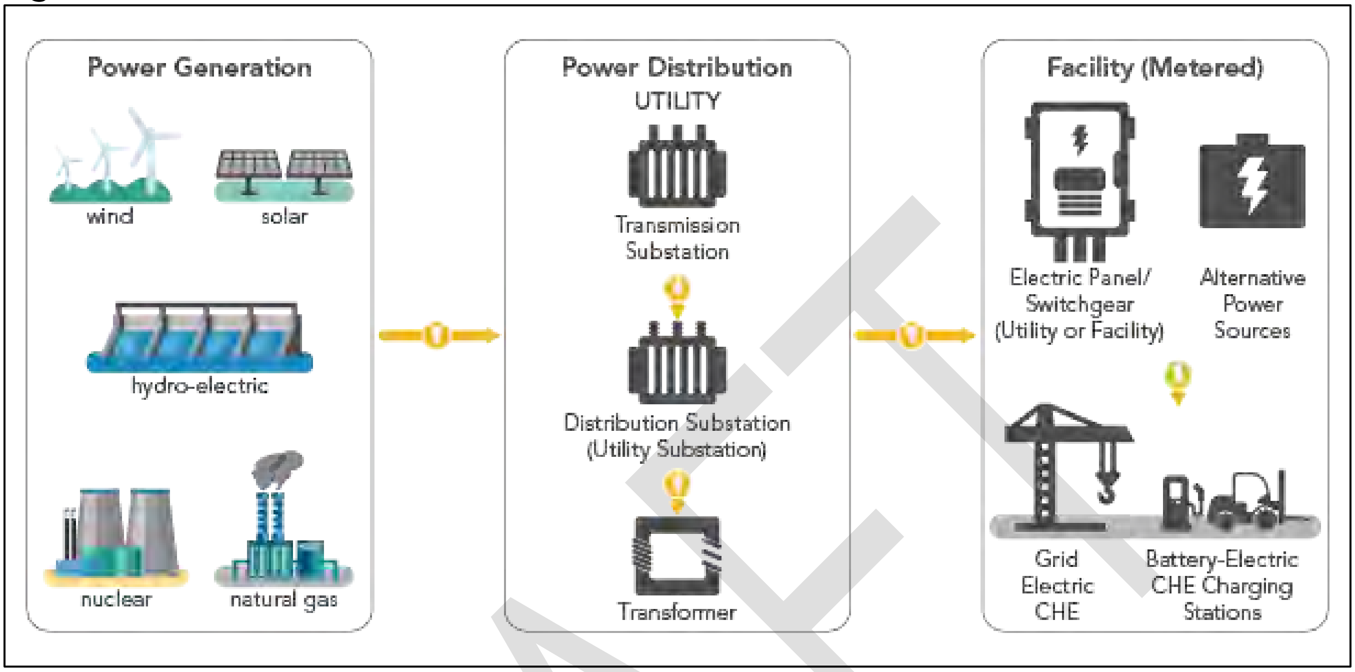
When planning for electric CHE, facilities must minimize the distance between the step-down transformer/alternative power sources and the charging stations/grid-electric CHE to reduce power loss. This can create challenges in finding available space at facilities to install infrastructure close to where the CHE charges or operates.

[94] California Energy Commission," Electric Load-Serving Entities (LSEs) in California," n.d. Accessed April 9, 2025. *https://www.energy.ca.gov/data-reports/energy-almanac/california-electricity-data/electric-load-serving-entities-lses*.

[95] Ibid.

[96] California Energy Commission, "2023 Total System Electric Generation," 2023. *https://www.energy.ca.gov/data-reports/energy-almanac/california-electricity-data/2023-total-system-electric-generation*.

Figure 41: California's Electric Power Grid for CHE



Grid capacity varies depending on the existing utility infrastructure at each facility. Adding more battery-electric and grid-electric CHE will likely require more infrastructure to support the added load and increase demand on the grid. Upstream utility-side infrastructure upgrades may also be necessary to support the facility, local businesses, and residents.

Adding grid infrastructure can be time-consuming and complex. Such projects are a joint effort involving facilities, seaport and intermodal railyard authorities, utilities, vendors, consultants, and others. Although each project varies, adding grid infrastructure generally involves the steps listed below.

1. Infrastructure assessment – facilities, seaport, and railyard authorities coordinate with utilities to assess future electricity load needs and negotiate agreement.
2. Infrastructure planning and permitting – utilities design the most cost-effective upgrades.
   - Smaller upgrades (under 10 MW) can often redistribute loads between neighboring circuits without system upgrades.
   - Larger upgrades (greater than 10MW) may require modifications of existing utility substations or adding new ones, taking 7 to 10 years to complete.[97] This

[97] Conversation between Southern California Edison Staff and Tianbo Tang (CARB) dated November 1, 2024.

includes engineering design/planning, California Environmental Quality Act (CEQA) review, and infrastructure construction.

3. Infrastructure construction and commissioning – includes equipment procurement, installation, system integration, and commissioning.
    - Delays in equipment procurement can hinder utilities' ability to effectively plan and advance infrastructure projects.

Facilities often acquire zero-emission CHE as incentive funding becomes available, then start the infrastructure planning process. Moving forward with small projects allows facilities to take advantage of available funds, even though more projects will be necessary to achieve the long-term goal of 100% zero-emission CHE.

This incremental approach often does not consider potential impacts across different infrastructure components such as charging ports for different types of CHE at seaports and intermodal railyards or shore power and future infrastructure needs for other terminals at the same seaport. Because facilities are unable to provide detailed plans to the utility without funding for specific equipment in place, utilities are sometimes forced to take a piecemeal approach and are unable to plan and build infrastructure for future projects. Over- or under-providing electricity can be costly and affect the overall return on investment in facilities and create duplication of effort and misguided planning for both the utilities and the facilities.

Microgrids

A microgrid is a localized energy system that can operate alone or in parallel with the utility grid. It can include energy sources (such as solar panels, wind turbines, or generators), energy storage (such as batteries, see Figure 42), as well as energy management systems. Using renewable sources such as solar panels or wind turbines offers a sustainable alternative to fossil fuel-derived electricity.

Microgrids can help reduce peak electricity demand and operational costs for battery-electric CHE as well as improve energy resiliency and reliability. They can use battery storage to capture wind and solar power when it is available, then dispense it to CHE when needed. In addition, microgrids with battery storage systems can capture grid energy when it is cheapest. As an example, the Tenth Avenue Marine Terminal at the Port of San Diego installed a renewable, solar-powered microgrid with a 700-kW rooftop solar photovoltaic (PV) array and a 700-kW/2700-kWh lithium-ion battery energy storage system,[98] saving 60% of the terminal's energy.[99]

Figure 42: Battery-Electric Storage System at Port of Long Beach[100]

Deploying microgrids can be costly, but they offer long-term economic benefits. However, microgrids with battery energy storage can only support charging operations up to a defined threshold before needing additional energy sources or grid support. They can also take up space at facilities where real estate is limited. Rooftop solar systems can help conserve space.

Irregularities in the grid, like voltage fluctuations and electrical noise, can harm equipment, reducing charging efficiency and shortening equipment lifespan. Designing infrastructure with energy storage and clean backup power helps achieve consistent operation.

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[98] Port of San Diego, "Energy," n.d. Accessed December 6, 2024. *https://www.portofsandiego.org/environment/energy-sustainability/energy*.

[99] In-person meeting between the Port of San Diego Staff and Tianbo Tang (CARB) dated October 22, 2024.

[100] U.S DOE, "Port Electrification Handbook", May 2024. Accessed October 8th, 2025. *https://www.pnnl.gov/sites/default/files/media/file/Port_Electrification_Handbook_FINAL.pdf*

Microgrids can help protect battery-electric CHE from these fluctuations, ensuring a stable electricity supply.

Charging Equipment

Battery charging equipment is necessary for reliable battery-electric CHE operation as it ensures consistent recharging for optimal functionality. Key considerations for battery charging equipment include costs, physical space, required resources, permitting for new charging infrastructure, and charging station requirements. See the battery-electric CHE *Economics* section for more information on costs for charging equipment.

Space, Permitting, and Certification

Electric and charging infrastructure requires space for several components including:

- Upstream utility substations
- Charging stations
- Switchgear, transformers, conduits, and wiring
- Temporary construction space

Upstream utility substations that supply electricity to charging stations occupy a large amount of space. For example, one 66 kilovolt (kV) utility substation built by Southern California Edison at the Port of Long Beach takes up about 3,000 square feet.[101] Charging stations also require additional space. Unlike diesel fueling pads capable of refueling multiple equipment types at various locations within the facility, battery-electric CHE charging stations are often designed for individual pieces of equipment and are at fixed locations.

Installing transformers, switchgear, conduits, and wiring is often necessary to support charging stations, requiring substantial space at the site. As facilities use more zero-emission equipment, they may need space for battery- or grid-electric CHE infrastructure, and hydrogen storage and filling locations which will reduce space for cargo operations. Infrastructure construction can also lead to delays and disruptions, especially at facilities situated on sites requiring soil remediation.[102] While the space required during construction is temporary, it can still pose logistical challenges and business disruptions.

The permitting process for infrastructure construction varies by location and can be time-consuming. Starting early, meeting with city officials, and maintaining ongoing

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[101] Staff calculated the area based on the Google map of the substation at the Port of Long Beach.

[102] Energetics Incorporated, et al." Final Evaluation Report," California Public Utilities Commission, April 2021. *https://www.cpuc.ca.gov/-/media/cpuc-website/divisions/energy-division/documents/sb-350-te/california-te-prp-final-evaluation-report-presentation.pdf*.

communication can help prevent delays. Some facilities can be self-permitted, but others may need city permits and approvals, as well as compliance with zoning laws, environmental regulations, and fire departments.

Infrastructure projects are typically separated into two categories: *retrofits* and *redevelopments* and estimates that retrofits can take three to five years, while redevelopments can take five to eight years due to increased permitting requirements.[103] Most CHE electrification projects fall into the retrofit category; however, one redevelopment may be faster and more cost-effective than multiple retrofits.

Charging equipment at facilities may require UL certification or third-party testing, which is costly and time-intensive, and may cause months of delay. Several facility operators experienced delays due to unclear certification processes, highlighting the importance of clarity when planning for new charging infrastructure.

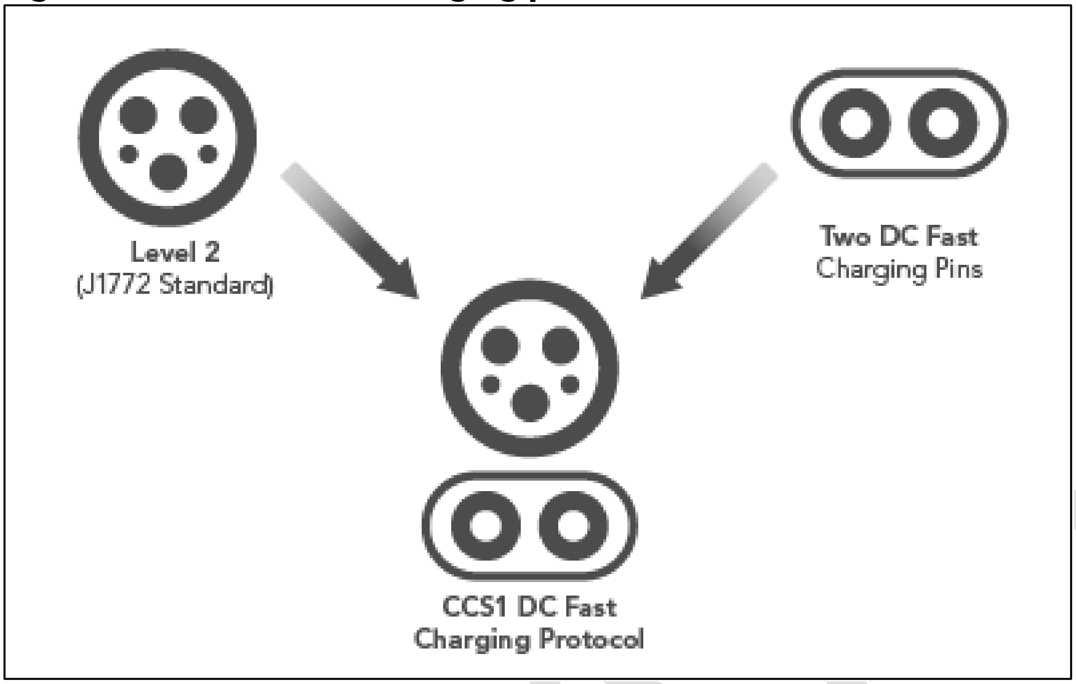
Charging Station

Electric charging stations use the grid to charge battery-electric CHE. Most battery-electric CHE use direct current (DC) fast charging. The combined charging system (CCS) is the most commonly used plug configuration and charging standard. The CCS Combo 1 (CCS1) DC fast charging protocol combines the level 2 (J1772 standard) plug and the two DC fast charging pins into a larger plug (Figure 43). These connectors can support charging power of up to 500 kW, with a voltage of 1000 V and a current of 500 A.[104]

[103] Grant Farm, "Charging Ahead: The Port Community Electric Vehicle Blueprint," May 2019. *https://thehelm.polb.com/download/379/zero-emissions/6769/port-community-electric-vehicle-blueprint-042919.pdf*.

[104] Camilo Suarez, and Wilmar Martinez, "Fast and Ultra-Fast Charging for Battery Electric Vehicles – A Review," 2019 IEEE Energy Conversion Congress and Exposition (ECCE), Baltimore, MD, USA, September 1,2019, pp. 569-575, doi: 10.1109/ECCE.2019.8912594. *https://doi.org/10.1109/ecce.2019.8912594*.

Figure 43: CCS1 DC fast charging protocol



Some OEMs use alternating current (AC) charging to protect battery life, although it takes longer to recharge. For example, one OEM indicated that for their reach stacker, charging could take up to 8 hours for AC versus 2 hours for DC fast charging.[105] The choice between DC and AC charging usually depends on the usage frequency of the CHE. Charging stations for CHE generally require a 480-volt three-phase AC power input.[106] Table 12 compares the benefits and potential challenges of DC fast charging and AC charging.

During staff site visits, several facility operators reported charger reliability issues such as connection problems and troubleshooting delays that rendered their battery-electric CHE unusable for several weeks or months. To avoid these issues, facilities should work with reliable OEMs to install and maintain charging infrastructure and to work with their utility providers to seek advice on utility-approved and vetted charging equipment. Facilities should also ensure that enforceable support contracts are in place after the equipment is purchased and installed, and conduct small-quantity demonstration projects of unproven technology.

[105] Claimed confidential data obtained from an industry source that requested non-attribution.

[106] Grant Farm, "Charging Ahead: The Port Community Electric Vehicle Blueprint," May 2019. *https://thehelm.polb.com/download/379/zero-emissions/6769/port-community-electric-vehicle-blueprint-042919.pdf*.

Table 12: Charging Systems Comparison Between AC and DC Charging for Battery-Electric CHE

Charging Type	Benefits	Challenges
DC Fast Charging	• Quick charge time (under 2 hours)	• Higher costs • Larger footprint • Infrastructure needs (switchgear, transformer, etc.)
AC Charging	• Longer battery lifespan • Lower costs • Smaller footprint • Fewer infrastructure requirements	• Longer charge time (can take up to 8 hours)

Logistics

Charging logistics and practices directly impact operational costs. This section discusses different types of charging interfaces and practices for battery-electric CHE, as well as potential solutions to some of the challenges associated with these logistical considerations.

Charging Interfaces

There are three main types of charging interfaces: manual conductive charging, hands-free conductive charging, and inductive charging.

Manual Conductive Charging

Manual conductive charging, or *manual charging,* for battery-electric CHE is similar to charging electric passenger cars. The charger consists of the charger and a charging cable with a connector (Figure 44). To charge the CHE, the battery-electric CHE operator parks near the charging station, and a facility worker inserts the charging connector into the charging port. This manual interaction ensures a good connection and can provide immediate feedback if there are connection issues. Manual charging is often the standard due to lower initial investment and simple maintenance. Challenges include cable management and staffing resources needed to plug in the CHE.

Figure 44: Battery-Electric CHE Charging Station (Staff photo)

Hands-Free Conductive Charging

Hands-free conductive charging uses automatic hands-free mechanisms for the physical connection between the charging station and the battery-electric CHE. The Port of Long Beach installed hands-free conductive charging systems for 33 battery-electric yard trucks. Figure 45 shows both the receptacle on top of the truck and the hands-free charging prong that protrudes when the truck pulls up to the charging stall and the operator engages the charging system. This enables instant connection after parking, maximizing recharge time. It can be integrated with smart energy management systems to optimize charging times, saving costs and improving grid stability. It allows for opportunity charging to keep the equipment charged without extended charging sessions. Challenges include properly aligned vehicle parking, connection problems, and high initial costs.

Figure 45: Hands-Free Conductive Charging System (Staff photo)

Inductive Charging

Static inductive charging involves embedding charging coils into the ground or mounting them at a fixed location for charging CHE when it is at rest. The CHE has a receiver that connects electromagnetically without a physical connection. This reduces operational costs and cable management issues but has a lower charging efficiency than conductive charging. To compensate, additional charging pads and receivers can be installed, but this additional infrastructure increases costs. Inductive chargers have high initial costs due to OEM retrofits and subsurface work. This method of charging also requires training to address proper alignment of CHE over the charging surface. A.P. Moller-Maersk (APM) Terminals at the Port of New York and New Jersey uses static inductive charging for 7 battery-electric yard tractors. The West Basin Container Terminal at the Port of Los Angeles received grant funding to demonstrate static inductive charging of 10 battery-electric yard trucks.

Table 13 summarizes the benefits and challenges associated with each of these three interfaces.

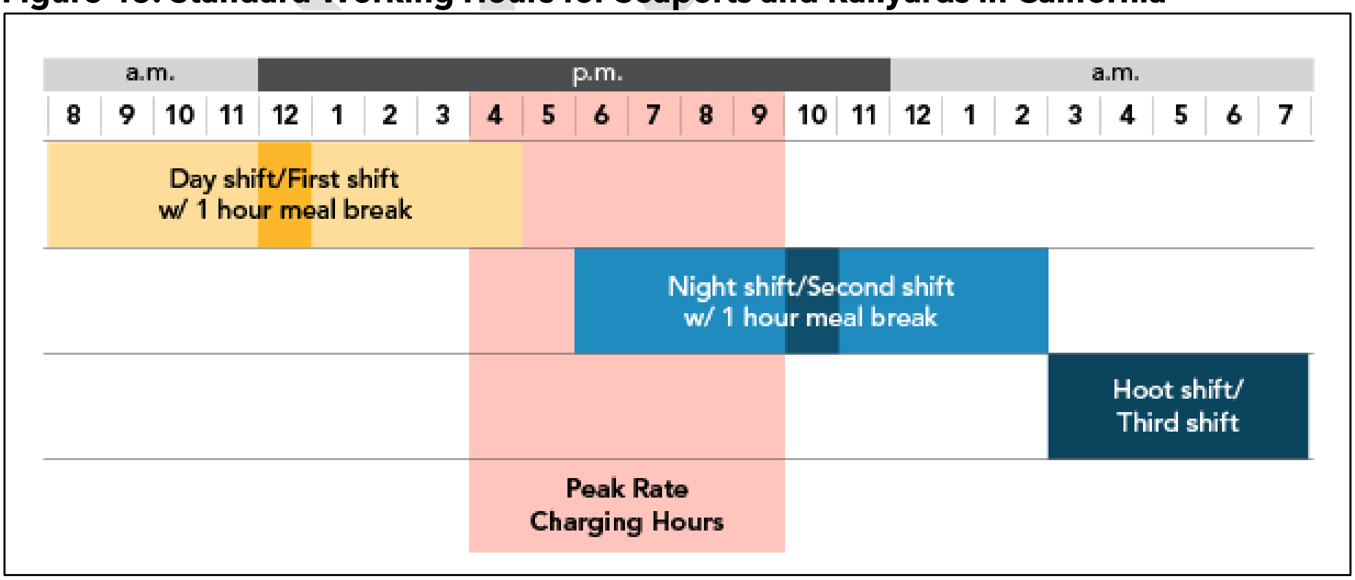
Table 13: Benefits and Challenges of Battery-Electric CHE Charging Interfaces

Charging Interface	Benefits	Challenges
Manual Conductive Charging	• Standard solution • Less initial investment • Simple technology • High charging efficiency	• High operational costs • Cable management issues • Labor intensive
Hands-free Conductive Charging	• Less labor intensive • High charging efficiency • Lower operational costs • Can take advantage of opportunity charging	• High capital costs • Connection problems
Inductive Charging	• Less labor • Lower operational costs • Can take advantage of opportunity charging	• Lower power range • High capital costs • Substantial subsurface work • Parking misalignment

Charging Practices

Seaports and intermodal railyards typically operate on two eight-hour shifts each day. Each shift has a one-hour meal break and there is a one-hour break between the two shifts. Some container terminals have a third shift called a *hoot* shift. Figure 46 shows the standard working hours at seaports and intermodal railyards in California.

Figure 46: Standard Working Hours for Seaports and Railyards in California



Downtime charging means fully charging the battery during non-use periods like meal breaks, overnight, or between shifts. It is the standard practice for recharging equipment but requires substantial grid power and labor if all CHE is charged at the same time.

Scheduling downtime charging during the hoot shift can help avoid peak electricity rates, which can reduce overall cost.

Downtime charging includes managed and unmanaged charging scenarios. Managed charging can include charging during the hoot shift and staggering charging times to avoid peak hours, which may reduce infrastructure needs. Some of the benefits of managed charging are listed below:[107]

- Reduced power systems investment costs
- Reduced operating costs
- Reduced distribution systems investment costs
- Increased distribution systems charging capacity

Unmanaged charging involves charging CHE without any oversight or strategic approach to reduce peak demand or optimize operational costs. This may lead to simultaneous charging of CHE, creating peak load conditions that increase overall power demand and costs. Such load spikes can strain local distribution infrastructure, necessitate upgrades to utility systems, and reduce grid efficiency. Figure 47 presents an example of managed charging and unmanaged charging.

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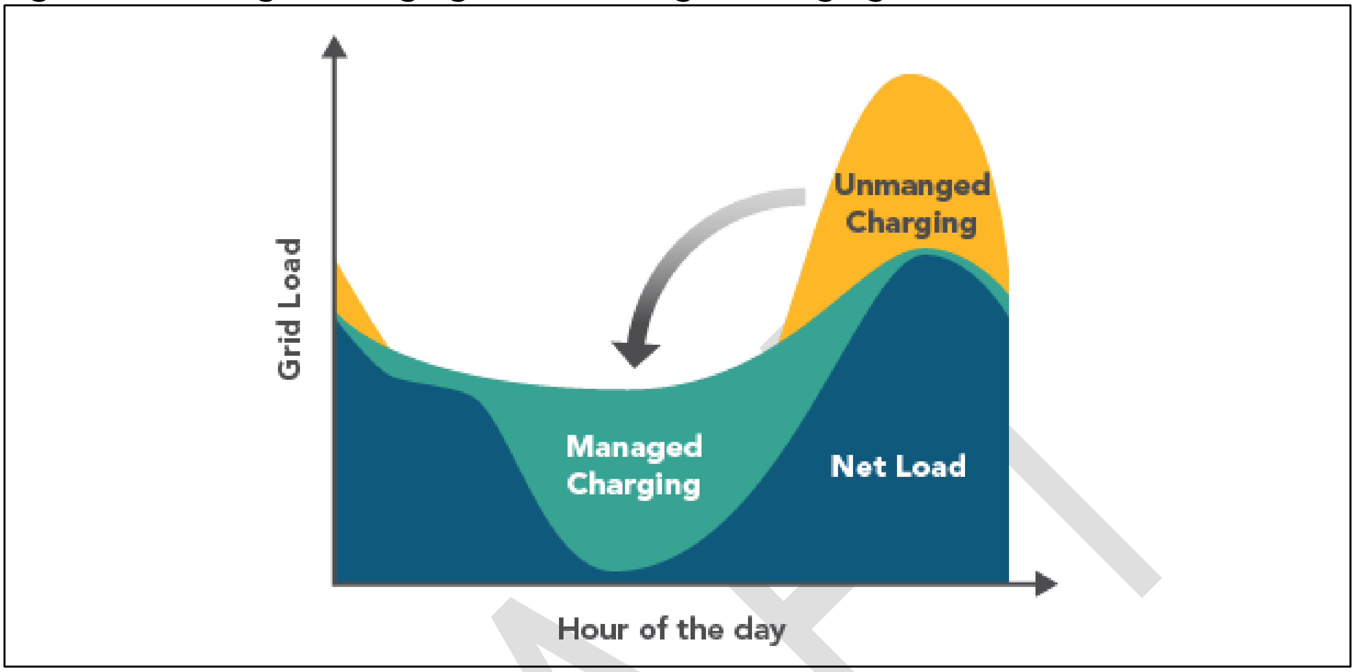
[107] U.S. Department of Energy, "Assessing the Value of Electric Vehicle Managed Charging: A Review of Methodologies and Results," n.d. Accessed December 24, 2024. *https://www.energy.gov/eere/analysis/assessing-value-electric-vehicle-managed-charging-review-methodologies-and-results.*

Figure 47: Managed Charging and Unmanaged Charging



Opportunity charging happens during short, intermittent downtime periods when the CHE is not in use. It maximizes available charging time to avoid peak electric rates or charging congestion between shifts or during meal breaks. This approach helps maintain battery charge levels, ensuring that CHE remains operational for extended periods. A challenge with CHE that requires manual charging at facilities with contracted labor is that fueling requires a dedicated facility worker. Opportunity charging for a CHE fleet would require several facility workers, adding to operational costs and other labor issues. Depending on the CHE's mobility and facility operations, relocating the equipment to the charging station can be time-consuming, making opportunity charging difficult to implement.

First-generation battery-electric container CHE was designed to operate for an eight-hour shift, opportunity charge at breaktime and between shifts, then operate an additional shift. Due to the challenges associated with charging logistics, opportunity and downtime charging is generally inconsistent for battery-electric CHE. To achieve operational equivalence to their diesel counterparts, battery-electric container CHE must be able to operate continuously for two eight-hour shifts and fully recharge in five hours or less. Some OEMs are offering CHE that can meet this demand.

Solutions for Logistical and Infrastructure Challenges

There are potential solutions to address these logistical challenges. These solutions can also be used to provide power at facilities experiencing challenges implementing traditional grid infrastructure or that wish to reduce reliance on grid power. Mobile charging stations provide flexible charging solutions without fixed infrastructure. There are several on the market including the Nuvera hydrocharge™ mobile hydrogen fuel cell AC genset and DC fast charger. It can provide up to 50 kW of power with a hydrogen consumption rate of 3.7 kilograms (kg) per hour.[108]

Ballard Power Systems, Gencell, Generac Power Systems/EODev, and Plug Power provide stationary fuel cell solutions for power generation, offering modular fuel cell generators that can be scaled up to MW levels. These systems are designed for flexible integration while minimizing space requirements.[109] Taylor Machine Works containerized battery storage/charging unit can store 2.1 to 3.4 megawatt-hours (MWh) of energy (4.4 MWh to 6.8 MWh of energy when units are stacked) and provide 180-kW and 200-kW chargers.[110] The feasibility of mobile charging stations depends on the CHE fleet size, as they can only support limited operations before needing additional energy sources or grid support.

Staff is seeking information on infrastructure for battery-electric CHE including power source solutions, charging infrastructure, permitting processes, and operational efficiencies.

[108] Nuvera Fuel Cells, "Revolutionizing Mobile Power: Nuvera® Hydrogen-Powered Genset and DC Fast Charger," June 10, 2024. Accessed December 6, 2024. *https://www.nuvera.com/revolutionizing-mobile-power-nuvera-hydrogen-powered-genset-and-dc-fast-charger/.*

[109] Ballard, "Stationary Power Generation - Ballard," January 3, 2025. Accessed March 4, 2025. *https://www.ballard.com/stationary-power-generation/;* GenCell Energy, "GenCell EVOX," n.d. Accessed April 11, 2025. *https://www.gencellenergy.com/products/*; Generac, "Generac Power Systems and EODev Announce Agreement Bringing Large-Scale, Zero-Emissions Hydrogen Fuel Cell Power Generators to North America," October 3, 2022. Accessed April 11, 2025. *https://investors.generac.com/news-releases/news-release-details/generac-power-systems-and-eodev-announce-agreement-bringing*; Plug Power, "Zero-Emission High-Power Fuel Cell for Larger Applications," n.d. Accessed April 11, 2025. *https://www.plugpower.com/fuel-cell-power/gensure-stationary-power-systems/gensure-mw-scale-power/.*

[110] Staff meeting with Taylor Machine Works.

Economics

The costs associated with battery-electric CHE include both capital costs and ongoing operating costs for the equipment and infrastructure. Table 14 summarizes the capital and operating costs associated with battery-electric CHE. This Technology Assessment incorporates economic data available prior to January 2025. Consequently, global or political developments, including tariffs or other policy changes that may influence costs for CHE and associated infrastructure are not captured in this analysis. This section will cover the equipment-related capital costs, equipment-related operating costs, and infrastructure installation and maintenance costs separately.

Table 14: Battery-Electric CHE Capital Costs and Operating Costs

Capital Costs	Operating Costs

• Equipment
  o CHE
  o Charging station
• Infrastructure installation
	• Equipment fuel
	• Equipment maintenance
	• Midlife battery replacement
	• Infrastructure maintenance

Equipment Capital Costs

Equipment capital costs include the initial costs of purchasing and acquiring battery-electric CHE, the charging equipment, and one or more onboard batteries. These costs have risen in the last five years due to global supply chain disruptions, low production volumes, labor, and inflationary pressures.[111] Economies of scale may reduce equipment capital costs in the future.

Several facilities reported purchasing extra battery-electric CHE to offset downtime arising from reliability issues with the CHE at a rate of 1.5 to 2 times the diesel equipment being replaced. In one reported case, firmware issues with battery-electric CHE took weeks to resolve and the facility relied on this back-up equipment.[112] This extra cost is not included in this assessment.

Equipment Operating Costs

Equipment operating costs include fuel costs and maintenance costs. Maintenance costs include the cost of general maintenance services and midlife battery replacement.

[111] Jason Shihata, "How Have Equipment Prices Changed Since the Pandemic?" EFFI Finance, June 1, 2023. Accessed April 9, 2025. *https://effifinance.com/how-have-equipment-prices-changed-since-pandemic/.*

[112] Claimed confidential data obtained from an industry source that requested non-attribution.

Fuel Costs

Fuel costs for battery-electric CHE refer to electricity costs, which can vary depending on location, charging logistics, and equipment duty cycle. According to the 2024 CEC Integrated Energy Policy Report, the statewide average electricity rate will stabilize at around $0.27/kWh from 2025 going forward for commercial uses.[113] See *Appendix G* for details on the fuel cost calculations for battery-electric CHE.

Maintenance Costs

Maintenance of battery-electric CHE may include:

- Air filter cleaning or replacement
- Lubricant changes
- System inspections
- Hydraulic fluid replacement
- Subscription services for software and firmware management

Maintenance costs for battery-electric equipment are usually lower than for diesel. Battery-electric equipment often shuts off when not in use, reducing idle hours. The absence of oil and diesel exhaust filters can lead to an estimated 35% savings over the life of the equipment.[114] Maintenance costs are uncertain since battery-electric CHE technologies are relatively new. According to some operators, maintenance costs can be up to three times higher than those for diesel equipment due to the high cost of replacement parts. These costs are expected to go down as technology advances and production quantities increase. Maintenance costs can also vary depending on the warranty plans offered.

Operating costs include the cost of midlife battery replacement. Since 2010, the global average cost of battery packs for light-duty vehicles dropped by nearly 90%, decreasing from $1,200 per kWh to $132 per kWh in 2021.[115] Heavy-duty applications face higher battery costs due to their larger energy storage needs and the higher cost of low-volume, purpose-built battery packs. Battery costs for heavy-duty applications vary by battery chemistry. For example, the median cost for lithium iron phosphate and nickel manganese

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[113] California Energy Commission, "2024 Integrated Energy Policy Report Update," n.d. *https://www.energy.ca.gov/data-reports/reports/integrated-energy-policy-report/2024-integrated-energy-policy-report-update*.

[114] Lars Arnold, "How to Maintain Electric Heavy Equipment," Volvo, December 12, 2022. Accessed December 26, 2024. *https://www.volvoce.com/united-states/en-us/resources/blog/2022/how-to-maintain-electric-heavy-equipment/*.

[115] CALSTART, "Component Costs for Zero-Emission Medium- and Heavy-Duty Commercial Vehicles," 2022. Accessed May 22, 2025. *https://calstart.org/wp-content/uploads/2022/10/component_costs_analysis_october_2022.pdf.*

cobalt oxide batteries is projected to decline from approximately $725 per kWh in 2015 to $405/kWh in 2020, and further to $218/kWh by 2030.[116]

Table 15 through Table 22 compare the costs of battery-electric and diesel-powered CHE.

Table 15: Cost Comparison Between a Battery-Electric and Diesel-Powered Crawler Crane

Capital/Operating (Op.) Cost Component	Battery-Electric	Diesel
Capital - CHE	$520,800[117]	[Staff is seeking information]
Capital - Charger	[Staff is seeking information]	N/A
Op. - Fuel	[Staff is seeking information]	[Staff is seeking information]
Op. - Maintenance	[Staff is seeking information]	[Staff is seeking information]
Op. - Battery Replacement	[Staff is seeking information]	N/A

Table 16: Cost Comparison Between a Battery-Electric and Diesel-Powered Excavator (2024$)

Capital/Operating (Op.) Cost Component	Battery-Electric	Diesel
Capital - CHE	$500,000 to $550,000	$220,000 to $235,000
Capital - Charger	[Staff is seeking information]	N/A
Op. - Fuel	[Staff is seeking information]	[Staff is seeking information]
Op. - Maintenance	[Staff is seeking information]	[Staff is seeking information]
Op. - Battery Replacement	$10,000	N/A

[116] CE Delft, Boston Consulting Group, B Nilsson and, and Estimates from Electric Bus OEMs, "Battery Cost for Heavy-Duty Electric Vehicles," *Appendix E*, August 2017. Accessed May 22, 2025. *https://ww2.arb.ca.gov/sites/default/files/2020-06/Appendix%20E%20Battery%20Cost%20for%20Heavy-Duty%20Electric%20Vehicles.pdf.*

[117] Price was converted from the euro (€) to U.S. dollars ($). Price info obtained from website: Silcom North, "Crawler Crane Marchetti CW-25.35-HY," n.d. Accessed February 26, 2025. *https://www.silcomnorth.com/crawler-cranes/crawler-crane-marchetti-cw-25-hy-sherpina-full-electric-battery-powered.*

Note: Data without a footnote was obtained from an industry source that requested non-attribution.

Table 17: Cost Comparison Between a Battery-Electric and Diesel-Powered Forklift (>24k lb) (2024$)

Capital/Operating (Op.) Cost Component	Battery-Electric	Diesel
Capital - CHE	$250,293[118] to $900,000	$240,000 to $420,000
Capital - Charger	$10,000 per charger	N/A
Op. - Fuel	$8,300 per year[119]	$2,200 to $2,900 per year[120]
Op. - Maintenance	$18,750 per year[121]	$25,000 per year[122]
Op. - Battery Replacement	$60,000 to $130,000	N/A

Note: Data without a footnote was obtained from an industry source that requested non-attribution.

Table 18: Cost Comparison Between a Battery-Electric and Diesel-Powered Loader (2024$)

Capital/Operating (Op.) Cost Component	Battery-Electric	Diesel
Capital - CHE	$150,000 to $450,000	$80,000 to $280,000
Capital - Charger	[Staff is seeking information]	N/A
Op. - Fuel	$1,100 per year[123]	$17,100 to $38,400 per year[124]

[118] Sharon Cloward, et al. “San Diego Port Sustainable Freight Demonstration Project,” California Energy Commission, Publication Number: CEC-600-2024-006, March 2024. *https://www.energy.ca.gov/sites/default/files/2024-03/CEC-600-2024-006.pdf* .Note that this was the base unit cost. The grant paid an additional $308,789 for a battery upgrade for a total cost of $559,082 (p. 36).

[119] Cost = 200 kW x 153 h/year x $0.27/kWh = $8,262 per year. The fuel cost calculation does not consider incentives such as the LCFS nor any special electricity rates offered by utility providers.

[120] Cost = 0.71 to 0.95 gallon/h x 733 h/year x $4.13/gallon = $2,149 to $2,876 per year. Fuel efficiency is sourced from web source: Paul Hinz, “How Much Diesel Does a Forklift Use Per Hour?” Adaptalift Group, September 21, 2021. *https://www.adaptalift.com.au/blog/how-much-diesel-does-a-forklift-use-per-hour*.

[121] Dan Wei and Genevieve Giuliano, “Implementation of Action 6 of CSFAP Phase 3 Tracking Economic Competitiveness Part 3: Economic Impacts of Electrification of Cargo Handling Equipment at POLA/POLB,” August 1, 2021. *https://doi.org/10.25554/8drs-9j23*.

[122] Ibid.

[123] Cost = 65 kW x 62 h/year x $0.27/kWh = $1,088 per year. The fuel cost calculation does not consider incentives such as the LCFS nor any special electricity rates offered by utility providers.

[124] Cost = 4 to 9 gallon/h x 1031 h/year x $4.13/gallon = $17,032 to $38,322 per year. Fuel efficiency is sourced from web source: Volvo, “Save on Every Gallon Fuel Efficiency Guarantee,” n.d. Accessed April 14, 2025. *https://www.volvoce.com/united-states/en-us/volvo-services/fuel-efficiency-services/fuel-efficiency-guarantee/*.

Capital/Operating (Op.) Cost Component	Battery-Electric	Diesel
Op. - Maintenance	[Staff is seeking information]	[Staff is seeking information]
Op. - Battery Replacement	$23,000 to $40,000	N/A

Note: Data without a footnote was obtained from an industry source that requested non-attribution.

Table 19: Cost Comparison Between a Battery-Electric and Diesel-Powered Railcar Mover (2024$)

Capital/Operating (Op.) Cost Component	Battery-Electric	Diesel
Capital - CHE	$650,000 to $1,500,000	$320,000 to $840,000
Capital - Charger	[Staff is seeking information]	N/A
Op. - Fuel	$600 per year[125]	$4,300 per year[126]
Op. - Maintenance	[Staff is seeking information]	[Staff is seeking information]
Op. - Battery Replacement	$30,000 to $200,000	N/A

Note: Data without a footnote was obtained from an industry source that requested non-attribution.

Table 20: Cost Comparison Between a Battery-Electric and Diesel-Powered Reach Stacker (2024$)

Capital/Operating (Op.) Cost Component	Battery-Electric	Diesel
Capital - CHE	$1,700,000 to $2,300,000	$830,000 to $860,000
Capital - Charger	$25,000 per charger[127]	N/A
Op. - Fuel	$31,000 per year[128]	$29,600 per year[129]

[125] Cost = 15 kW x 131 h/year x $0.27/kWh = $531 per year. The fuel cost calculation does not consider incentives such as the LCFS nor any special electricity rates offered by utility providers.

[126] Cost = 1.8 gallon/h x 576 h/year x $4.13/gallon = $4,282 per year. Fuel efficiency is sourced from web source: *https://www.mitlift.com/shuttlewagon-railcar-movers/*.

[127] TerminaLift, "New Charging Stations for Sale at Terminalift LLC," n.d. Accessed November 25, 2024. *https://www.terminalift.com/new/charging-stations*.

[128] Cost = 200 kW x 574 h/year x $0.27/kWh = $30,996 per year. The fuel cost calculation does not consider incentives such as the LCFS nor any special electricity rates offered by utility providers.

[129] Cost = 3.4 gallon/h x 2105 h/year x $4.13/gallon = $29,558 per year. Fuel efficiency is sourced from web source: Kalmar, "Guaranteed to Cut Costs," August 10, 2022. *https://www.kalmarusa.com/4ae3fc/globalassets/equipment/reachstackers/eco-reachstacker/kalmar-drg420-600e-eco-reachstacker-brochure_us.pdf*.

Capital/Operating (Op.) Cost Component	Battery-Electric	Diesel
Op. - Maintenance	[Staff is seeking information]	3% to 5% of the initial value of the equipment[130]
Op. - Battery Replacement	$90,000	N/A

Note: Data without a footnote was obtained from an industry source that requested non-attribution.

Table 21: Cost Comparison Between a Battery-Electric and Diesel-Powered Top Handler (2024$)

Capital/Operating (Op) Cost Component	Battery-Electric	Diesel
Capital - CHE	$1,950,000	$250,000 to $500,000
Capital - Charger	[Staff is seeking information]	N/A
Op. - Fuel	$62,000 per year[131]	$47,900 per year[132]
Op. - Maintenance	$67,500 per year[133]	$90,000 per year[134133]
Op. - Battery Replacement	[Staff is seeking information]	N/A

Note: Data without a footnote was obtained from an industry source that requested non-attribution.

[130] Samcovina, "Frequently Asked Questions About Kalmar Container Reach Stackers, "July 25, 2024. Accessed November 25, 2024.*https://samcovina.com/en/frequently-asked-questions-about-kalmar-container-reach-stackers/*.

[131] Cost = 400 kW x 574 h/year x $0.27/kWh = $61,992 per year. The fuel cost calculation does not consider incentives such as the LCFS nor any special electricity rates offered by utility providers.

[132] Cost = 5.5 gallon/h x 2105 h/year x $4.13/gallon = $47,815 per year. Fuel efficiency is sourced from web source: "CSX Intermodal Terminals, Charlotte – Loaded Container Handler Engine Replacement," North Carolina Det environmental Quality," n.d. Accessed April 14, 2025. *https://www.deq.nc.gov/documents/files/csx-intermodal-terminals-charlotte-loaded-container-handler/download*.

[133] Dan Wei and Genevieve Giuliano, "Implementation of Action 6 of CSFAP Phase 3 Tracking Economic Competitiveness Part 3: Economic Impacts of Electrification of Cargo Handling Equipment at POLA/POLB," August 1, 2021. *https://doi.org/10.25554/8drs-9j23*.

[134] Ibid.

Table 22: Cost Comparison of Battery-Electric vs. Diesel-Powered Yard Truck (2024$)

Capital/Operating (Op) Cost Component	Battery-Electric	Diesel
Capital - CHE	$300,000[135] to $400,000	$95,000 to $170,000
Capital - Charger	$30,000 to $60,000 per charger[136]	N/A
Op. - Fuel	$8,400 per year[137]	$18,900 per year[138]
Op. - Maintenance	$28,005 per year[139]	$40,004 per year[140][139]
Op. - Battery Replacement	$85,000 to $260,000	N/A

Note: Data without a footnote was obtained from an industry source that requested non-attribution.

In 2024, the Rocky Mountain Institute and Mission Possible Partnership calculated the 12-year total cost of ownership for various CHE types. They found that battery-electric yard tractors are cost-competitive with diesel yard tractors in California.[141] Their analysis included the upfront equipment, infrastructure, maintenance, and fuel costs along with State incentives offered through the Low Carbon Fuel Standard (LCFS) program and CORE. There are uncertainties regarding maintenance, infrastructure, electricity, and other unforeseen costs. However, the analysis suggests potential economic benefits for replacing some types of diesel CHE with battery-electric technology using available incentives. See *Appendix H* for more information on available incentive programs for battery-electric CHE.

[135] Sharon Cloward, et al. "San Diego Port Sustainable Freight Demonstration Project," California Energy Commission, Publication Number: CEC-600-2024-006, March 2024. *https://www.energy.ca.gov/sites/default/files/2024-03/CEC-600-2024-006.pdf* .

[136] Energetics Incorporated, et al." Final Evaluation Report," California Public Utilities Commission, April 2021. *https://www.cpuc.ca.gov/-/media/cpuc-website/divisions/energy-division/documents/sb-350-te/california-te-prp-final-evaluation-report-presentation.pdf*. OEM reported $50,000 to $60,000 in a meeting with staff.

[137] Cost = 200 kW x 155 h/year x $0.27/kWh = $8,370 per year. The fuel cost calculation does not consider incentives such as the LCFS nor any special electricity rates offered by utility providers.

[138] Cost = 2.4 gallon/h x 1906 h/year x $4.13/gallon = $18,892 per year. Fuel efficiency is sourced from web source: California Air Resources Board, "California Air Resources Board Discussion Draft," April 24, 2017. *https://ww2.arb.ca.gov/sites/default/files/2018-10/170425eerdraftdocument.pdf*.

[139] Dan Wei and Genevieve Giuliano, "Implementation of Action 6 of CSFAP Phase 3 Tracking Economic Competitiveness Part 3: Economic Impacts of Electrification of Cargo Handling Equipment at POLA/POLB," August 1, 2021. *https://doi.org/10.25554/8drs-9j23*.

[140] Ibid.

[141] Mia Reback, et al. "The Time Is Now for Zero-Emissions Cargo Handling Equipment at America's Busiest Cargo Ports," RMI, November 7, 2024. Accessed November 25, 2024. *https://rmi.org/the-time-is-now-for-zero-emissions-cargo-handling-equipment-at-americas-busiest-cargo-ports/*.

In 2019, the Port of Oakland released a feasibility assessment for CHE and calculated the annual total cost of ownership of battery-electric yard tractors.[142] They found that battery-electric yard tractors have a lower total cost of ownership compared with diesel when using CORE vouchers. The study did not include infrastructure related costs.

In addition to capital and operating costs, there may be additional costs associated with the deployment of battery-electric CHE. These include expenses for workforce training to operate and maintain the new equipment, subscriptions for connected services such as remote monitoring and charging management, and extended warranties.

Staff is seeking information on battery-electric CHE costs including capital, fuel, infrastructure, maintenance, operational, and other additional costs.

Infrastructure Costs

Deployments of new battery-electric CHE will likely require new charging stations. While charging stations have a fixed price that can be factored into the total cost of owning and operating battery-electric CHE, infrastructure installation costs vary. Each infrastructure project is unique and requires detailed planning before infrastructure installation costs can be determined and factored in. In some cases, these costs can be significantly higher than the cost of the CHE being deployed. Infrastructure installation costs can include utility grid infrastructure upgrades and charging station installation. Operating costs for battery-electric infrastructure include infrastructure maintenance.

Utility Grid Infrastructure Upgrades

Utility grid infrastructure upgrades can include new substations or modifications of existing ones. Costs differ depending on the utility and the facility's future load needs. In a report from the Port of Los Angeles, the total cost of utility upgrades ranges from $165.7 million to $194.5 million for different scenarios to achieve 100% zero-emission CHE at the port.[143] Utility substation upgrade costs can include:

- Materials such as cables, conduits, transformers, and other electrical equipment as well as construction materials such as concrete and metal
- Engineering planning and design

[142] AECOM, "Zero-Emission Cargo-Handling Equipment Feasibility Assessment," Port of Oakland, November 21, 2019. *https://www.portofoakland.com/wp-content/uploads/pdfs/AECOM%20Zero%20emission%20CHE%20feasibility%20assessment%20Nov%202019.pdf*.

[143] EPRI, "Zero-Emission Planning and Grid Assessment for the Port of Los Angeles," June 29, 2023. *https://www.epri.com/research/products/000000003002025783*.

- Permitting
- Labor costs for construction, trenching, and installation of electrical equipment
- Project contingency.[144]

For substations dedicated to a facility, the costs are typically covered by the facility itself or, in some cases, paid upfront by the utility and recovered through future rate fees, depending on the contract terms.

Charging Station Installation

Charging station installation costs include engineering planning and design, switchgears, conduits/wiring, labor, permitting, trenching, charging equipment certifications, and project contingency.[145] These costs vary depending on the station size, charger type, and charging interface. The seaport or intermodal railyard pays for charging station installation costs as these projects are downstream from the facility meter.

Infrastructure Maintenance

Infrastructure maintenance generally involves securely storing charging cables, inspecting components, and ensuring the charging equipment remains clean. Additionally, chargers may require occasional repairs and troubleshooting.[146] Table 23 provides battery-electric CHE infrastructure related costs.

[144] Contingency is allocated for each project based on the level of acceptable risk, the degree of uncertainty, and the desired confidence in meeting the project budget. For more details on cost contingency, see Shohreh Ghorbani, "How Cost Contingency is Calculated?" projectcontrolacademy.com, n.d. Accessed May 8, 2025. *https://www.projectcontrolacademy.com/cost-contingency-calculation/*.

[145] Charger costs are included in Table 15 through Table 22.

[146] U.S. Department of Energy, "Alternative Fuels Data Center: Operation and Maintenance for Electric Vehicle Charging Infrastructure," n.d. Accessed December 11, 2024. *https://afdc.energy.gov/fuels/electricity-infrastructure-maintenance-and-operation*.

Table 23: Battery-Electric CHE Infrastructure Related Costs

Capital/Operating (Op.) Cost Component	Cost
Capital – New Utility Substation Installation	Varies • Cost information from past projects: o $8,000,000 to $30,000,000 to build a 66kV substation.
Capital – Existing Utility Substation Modification	Varies • Cost information from past projects: o Utility side infrastructure upgrades to support 20 charging ports for yard tractors cost $733,071.[147]
Capital – Charging Station Installation[148]	Varies • Cost information from past projects: o Switchgears, trenching, and installation for 20 charging ports for yard tractors cost $853,181.[149] o 12 kV electrical main and meter switchgear line up cost $500,000.[150] o Trenching, conduit and wires for charging stations for 25 top handlers cost $8,000,000.[151] o Project contingency is 30% of total system installation costs.[152] o $1,000,000 to install 9 chargers to support charging for top handlers.

[147] Energetics Incorporated, et al." Final Evaluation Report," California Public Utilities Commission, April 2021. *https://www.cpuc.ca.gov/-/media/cpuc-website/divisions/energy-division/documents/sb-350-te/california-te-prp-final-evaluation-report-presentation.pdf*.

[148] Charger costs are included in Table 15 through Table 22.

[149] Energetics Incorporated, et al." Final Evaluation Report," California Public Utilities Commission, April 2021. *https://www.cpuc.ca.gov/-/media/cpuc-website/divisions/energy-division/documents/sb-350-te/california-te-prp-final-evaluation-report-presentation.pdf*.

[150] Grant Farm, "Charging Ahead: The Port Community Electric Vehicle Blueprint," May 2019. *https://thehelm.polb.com/download/379/zero-emissions/6769/port-community-electric-vehicle-blueprint-042919.pdf*.

[151] Ibid.

[152] Ibid.

Capital/Operating (Op.) Cost Component	Cost
Op. – Infrastructure Maintenance	[Staff is seeking information]

Note: Data without a footnote was obtained from an industry source that requested non-attribution.

Staff is seeking information on battery-electric CHE infrastructure capital costs and maintenance costs.

Technology Outlook

Out of the 23 types of battery-electric CHE assessed for technology readiness, only 2 do not have commercially available models (log stackers and RMGs). However, only AGVs achieve a Technology Readiness Grade of Equivalence. Table 24 through Table 26 summarize the outlook for the other 23 battery-electric CHE types to achieve a Technology Readiness Grade of Equivalence within the next 10 years, grouped by CHE category.

Table 24: Outlook for Battery-Electric Bulk Material CHE Achieving Equivalence Within 10 Years

Type of CHE	Outlook for Achieving Equivalence Within 10 Years
Crane (Material Handling, Mobile and Off-Road), Dozer, Excavator, Loader or Loader-Excavator	There are several commercially available battery-electric models of this equipment. Europe and China are driving the development and adoption of this equipment as there are more stringent municipal environmental requirements than in the U.S. for construction equipment. With additional emission reduction strategies and incentive programs for both the CHE and the charging infrastructure for the construction and cargo handling sectors, these CHE can achieve Equivalence within 10 years.
Forklift, Heavy Lift	Battery-electric forklifts were only one point away from achieving a Technology Readiness Grade of Limited, but achieve Demonstration due to reliability issues and supply-chain challenges that affect obtaining parts for both manufacturing and support. For battery-electric forklifts to achieve Equivalence, these issues need to be resolved. There has been positive feedback regarding the reliability of the newer forklift models and several facilities in California have placed orders for additional units using CORE funding.[153] Due to the significant number of commercially available models (with some in their second and third generations) and many successful demonstrations, staff anticipates that battery-electric forklifts will achieve Equivalence within 10 years.

[153] CORE's *Voucher Funding Map* allows the user to download a dataset containing all implementations of forklifts using the CORE Voucher Program. See *https://californiacore.org/voucher-funding-map/*.

Type of CHE	Outlook for Achieving Equivalence Within 10 Years
Forklift, Telehandler	Telehandlers are not very common at seaports and intermodal railyards. Implementing infrastructure for one or two pieces of CHE may not be practical. However, as other battery-electric CHE becomes more common, the installed charging infrastructure will make adoption easier for the less-common types of CHE like telehandlers. Facilities will most likely purchase zero-emission telehandlers that use the same zero-emission technology as other CHE at their facilities to leverage the fueling or charging infrastructure. Therefore, with additional emission reduction strategies and incentive programs in place for other battery-electric CHE, battery-electric telehandlers can achieve Equivalence within 10 years.
Haul Truck	Because of the commercial availability and reported success of the Sany battery-electric haul truck at the İzmir lime quarry in Turkey,[154] haul trucks received a Technology Readiness Grade of Limited. This means that they can be readily deployed for cargo handling with limited oversight. However, to achieve Equivalence, battery-electric haul trucks must be thoroughly tested for cargo handling. Progress in the mining industry will continue to drive the development of battery-electric haul trucks. With additional emission reduction strategies and incentive programs in place for both the CHE and charging infrastructure, battery-electric haul trucks can achieve Equivalence within 10 years.

[154] See *Appendix E* for details regarding this pilot project.

Type of CHE	Outlook for Achieving Equivalence Within 10 Years
Log Stacker	Use of log stackers for cargo handling is specific to seaport and intermodal railyard logging terminals, of which there are very few in California. Most bulk material seaport terminals and intermodal railyards have little to no infrastructure for charging battery-electric CHE. Implementing new battery-electric CHE requires new infrastructure projects, including systems upgrades to handle the added electricity load. For smaller logging facilities with only a few log stackers, this could be costly. Furthermore, without demand, OEMs will not develop battery-electric log stackers. Due to their similarities, OEMs can leverage battery-electric reach stacker and top handler designs for the development of battery-electric log stackers. However, due to the extensive development and testing required, only with additional emission reduction strategies and incentive programs for both the CHE and charging infrastructure, can battery-electric log stackers achieve Equivalence within 10 years.

Table 25: Outlook for Battery-Electric Container CHE Achieving Equivalence Within 10 Years

Type of CHE	Outlook for Achieving Equivalence Within 10 Years
Rail-Mounted Gantry Crane	Staff did not find evidence of any battery-electric RMGs under development, thus achieving a Technology Readiness Grade of Development. Grid-electric RMGs are already the industry standard for this equipment type. Battery-electric RMGs will likely not achieve Equivalence within 10 years.
Reach Stacker, Shuttle and Straddle Carrier, Side Handler	Reach stackers, shuttle and straddle carriers, and side handlers are not as common at California seaports and intermodal railyards as top handlers and yard trucks. Therefore, there have been fewer demonstrations and smaller numbers produced by OEMs. As with battery-electric RTGs, while there are commercially available models, several more years of demonstration are required to prove this equipment. With additional emission reduction strategies and incentive programs in place for both the CHE and charging infrastructure, this equipment can achieve Equivalence within 10 years.

Type of CHE	Outlook for Achieving Equivalence Within 10 Years
Rubber-Tired Gantry Crane	RTGs are highly practical CHE due to their ability to move easily between rows or stacks of containers. Therefore, while conversions from diesel to grid-electric will be a popular option for decarbonizing existing diesel RTGs, the demand for a more versatile RTG solution will also increase. But unlike top handlers and yard trucks, battery-electric RTGs have not been proven and would require many years of practical testing. However, with additional emission reduction strategies and incentive programs in place for both the CHE and infrastructure, battery-electric RTGs can achieve Equivalence within 10 years.
Top Handler	Battery-electric top handlers achieve a Technology Readiness Grade of Limited, indicating that they have been proven and are ready for limited, monitored deployment. The primary factor in achieving Equivalence is the availability of parts for both manufacturing and support. Higher demand for similar battery-electric CHE could create demands of scale which could curb this supply chain challenge. With additional emission reduction strategies and incentive programs in place for both the CHE and infrastructure, battery-electric top handlers can achieve Equivalence within 10 years.
Yard Truck	Yard trucks achieve a Technology Readiness Grade of Limited, based on the need for OEMs to improve second and third generation vehicles. Several facilities have used CORE funding to help purchase battery-electric yard tractors instead of diesel.[155] Staff anticipates that as more models are demonstrated and new generations of yard trucks are released, battery-electric yard trucks will achieve Equivalence within 10 years.

[155] CORE's *Voucher Funding Map* allows the user to download a dataset containing all implementations of yard tractors using the CORE Voucher Program. See *https://californiacore.org/voucher-funding-map/*.

Table 26: Outlook for Battery-Electric Facility Support CHE Achieving Equivalence Within 10 Years

Type of CHE	Outlook for Achieving Equivalence Within 10 Years
Aerial Lift, Cone Vehicle, Railcar Mover	Battery-electric aerial lifts, cone vehicles, and railcar movers all have commercially available models, most of which are available in the U.S. Battery-electric cone vehicles and railcar movers are currently in service at California seaports. However, there are currently no reports available regarding their operational feasibility. More research and successful demonstrations are needed to achieve Equivalence. As with all facility support CHE, as charging infrastructure is installed for bulk material and container CHE, battery-electric facility support CHE can leverage those charging stations (similar to how diesel facility support CHE currently leverages diesel fuel infrastructure). With additional emission reduction strategies and incentive programs in place for other CHE, these CHE can also achieve Equivalence within 10 years.
Utility Truck, Other	Most reporting of battery-electric utility trucks has centered on heavy-duty trucks for freight, urban deliveries, and terminal operations. Staff could not find any reports with operational data for zero-emission utility trucks at seaports and intermodal railyards. This contributed to the lower Technology Readiness Grade of Demonstration for battery-electric utility trucks. However, with additional emission reduction strategies and incentives in place for cargo-focused CHE, battery-electric utility trucks can also achieve Equivalence within 10 years.
Utility Truck, Sweeper	Unlike the facility support CHE listed above, there is published information on the successful deployment of battery-electric sweepers in the public sector.[156] While still achieving a Technology Readiness Grade of Demonstration, battery-electric sweepers are being deployed and tested in many municipalities on a global level. Like other facility support CHE, with additional emission reduction strategies and incentives in place for cargo-focused CHE, battery-electric sweepers can achieve Equivalence within 10 years.

[156] See *Appendix E* for demonstrations of zero-emission sweepers.

Battery-electric CHE technology is new but is undergoing testing and proving effective for each CHE application. The market, technology, and governmental drivers listed below are expected to continue over the next ten years:

- Improvements in battery technology.
- Reductions in battery cost.
- Improvements in zero-emission technologies as demand and production increase.
- Availability of incentive funding through programs like the U.S. EPA Clean Ports Program,[157] CORE, and HVIP, promote deployment of battery-electric CHE and infrastructure. (See *Appendix H* for a full list of incentive programs.)

These factors may accelerate the development of battery-electric CHE in early development phases and improve models that have already achieved equivalence.

While battery-electric CHE can generally meet operational needs with proper charging, the high cost of the CHE remains a challenge. Battery-electric CHE is typically 1.5 to 2 times more expensive than diesel counterparts. Without incentives, long-term savings from lower maintenance and fuel costs are not enough to offset the initial cost. Additionally, battery replacement and high-tech replacement parts add to the lifecycle cost. Many facilities purchase additional backup battery-electric CHE due to unexpected downtime, increasing the initial cost.

Infrastructure is also a challenge. Implementing charging equipment and infrastructure often follows a piecemeal approach driven by available incentive funding for demonstration projects. The lack of a coordinated master plan hinders the adoption of battery-electric CHE.

Despite these challenges, the technology outlook for battery-electric CHE is promising. It is nearing functional equivalence with fossil-fuel CHE counterparts. As long as incentive programs are available, facilities will continue acquiring the equipment. However, the inability to execute coordinated infrastructure plans remains the greatest challenge for the adoption of battery-electric CHE.

[157] In December 2024 during the development of this Technology Assessment, the EPA announced the recipients of nearly $3 billion of grant funds for zero-emission port equipment and infrastructure as well as climate and air quality planning. 30% of the selected applications are projects to implement new CHE technologies. This funding will continue to provide funding for demonstration projects for several years to come. The awards are listed on the EPA Clean Ports Program web page at: U.S. Environmental Protection Agency, "Clean Ports Program Selection," n.d. Accessed April 14, 2025. *https://www.epa.gov/ports-initiative/clean-ports-program-selections#selected-applications*.

Grid-Electric Cargo Handling Equipment

The primary power source for grid-electric CHE is electricity from the grid. This provides a consistent, uninterrupted power supply. By connecting directly to the grid, facilities can reduce operational emissions and avoid the environmental and financial costs of diesel fuel or battery replacement and disposal. Grid-electric CHE also enables higher efficiency and performance, as it operates without downtime for refueling or recharging. This works best for facilities with sufficient electricity and infrastructure.

Technology Description

Grid-electric CHE relies on a continuous connection to the grid for both mobility and cargo handling. Grid-electric CHE generally connects to the grid using cables, reel systems, busbars, pantographs, or charged rails, all of which limit mobility. Because of these restrictions, facilities must carefully plan new installations of, or conversions to, grid-electric CHE. Cargo or CHE travel routes within the facility may need to be adjusted to accommodate grid-electric CHE.

Some grid-electric CHE still use batteries, but in smaller quantities than battery-electric CHE. These batteries are needed to provide electricity for the grid-electric CHE to move between grid connection points or to operate temporarily when grid power is unstable or unavailable. The key difference between battery-electric and grid-electric CHE is their primary power source. Some CHE can function as both battery-electric and grid-electric, depending on operational needs.

Connecting to the grid requires significant infrastructure at the facility where the CHE operates. Projects to replace diesel-powered CHE with grid-electric CHE often involve major site construction, which may temporarily disrupt operations. However, maintaining a continuous grid connection provides a long-term zero-emission solution that reduces or eliminates the need for continual refueling or charging batteries.

Grid-electric technology is practical for CHE that is mostly stationary or follows predictable paths. It is generally not suitable for facility support CHE due to their unpredictable paths and higher mobility. For these same reasons, most grid-electric CHE achieve a 0 for both Practicality and Technological Potential for a combined Technology Applicability score of 0 (Table 2).

Two grid-electric technologies that are being developed for charging battery-electric vehicles while stationary, called *static charging*, may also be applicable for charging or powering some CHE while it is moving, called *dynamic charging*. The technologies are *dynamic conductive charging* and *dynamic inductive charging*. A battery is still required for this equipment to operate while not connected to the grid. Therefore, the terms *charging* or *powering* can be used interchangeably for this equipment. Both technologies aim to reduce the battery quantity or size by primarily using grid power.

Vehicles using dynamic conductive charging are equipped with special *pick-ups* that make physical conductive contact with a charged rail that is embedded into the pavement. Vehicles using dynamic inductive charging are equipped with *receivers* that make an electromagnetic, or inductive, connection with coils or plates that are embedded into the pavement. These emerging technologies offer the benefits of continuous, or more frequent, grid connection combined with increased flexibility in operating routes, compared to traditional fixed-grid systems like cables or rails. While static inductive charging is being demonstrated at many seaports and intermodal railyards, dynamic inductive charging technology for mobile CHE is still in development.

Technology Readiness

Grid-Electric Bulk Material CHE

Bulk material CHE often operates on uneven surfaces or along irregular pathways, making fixed electric infrastructure challenging to implement. These limitations affect the feasibility of grid-electric bulk material CHE in many environments. Table 27 provides the technology readiness data summary for grid-electric bulk material CHE.

Table 27: Technology Readiness Data Summary for Grid-Electric Bulk Material CHE

Equipment Type	Commercially Available in the U.S.	Commercially Available Outside the U.S.	Non-Commercial Units	Technology Readiness Grade
Crane, Material Handling	14	1	0	Demonstration
Crane, Mobile Harbor	2	0	2	Demonstration
Crane, Off-Road	4	0	0	Demonstration
Excavator	2	0	0	Demonstration

Staff is seeking information on the implementation of grid-electric bulk material CHE.

Grid-Electric Cranes (Off-Road and Material Handling) and Excavators

Off-road and material handling cranes, and excavators have several commercially available battery-electric models. Many of these models can be plugged into the grid during operation. This means their primary electricity source can be either a battery or the grid. However, a grid connection often limits mobility. These CHE are unique because they can often remain in the same location while loading and unloading dry bulk cargo, such as scrap metal, sand, gravel, or soil.

While a simple cable connection allows grid-electric cranes and excavators to operate while stationary, other systems such as catenary or busbar systems could offer increased mobility. A 2016 YouTube video demonstrated an indoor grid-electric material handling crane, using an overhead cable management system.[158] While this arrangement may not be practical at facilities where operations are primarily outdoors, it highlights the flexibility of grid-electric solutions for material handling cranes and potentially other CHE types. Because these CHE can use batteries or grid connections, they are listed as commercially available CHE in both the battery-electric bulk material CHE data summary (Table 7) and the grid-electric bulk material CHE data summary (Table 27). Grid-electric cranes (off-road and material handling) and excavators achieve a Technology Readiness Grade of Demonstration.

Grid-Electric Mobile Harbor Cranes

Mobile harbor cranes are much larger than material handling cranes and off-road cranes. Although there are commercially available grid-electric mobile harbor cranes equipped with batteries, current battery energy and power densities[159] only support brief or emergency operations or movement between grid power sources. For example, the Konecranes Gottwald HMK 260 E mobile harbor crane has been in operation at the Port of Skellefteå in Sweden since 2022. The crane primarily operates on grid electricity, but batteries store enough energy to move the crane while unplugged for over one hour, handling limited cargo with single crane operations.[160] Similarly, two all-electric mobile harbor cranes began operations at the Port of San Diego in 2024. The cranes are capable of a tandem lift of up to 881,849 lb when connected to the grid.[161] There are two commercially available models. Grid-electric mobile harbor cranes achieve a Technology Readiness Grade of Demonstration.

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[158] Sennebogen – Move Big Things, "Sennebogen 825 Mobile Electric Excavator with Ceiling Power Supply – Scrap Handling - Germany," YouTube video, published July 6, 2016, 2:17. Accessed April 10, 2025. *https://youtu.be/N4pr9nPVdfA?si=Hub98P2MwOux6uVv*.

[159] *Power density* is the measure of how quickly a battery can deliver energy relative to its weight or volume while *energy density* is the measure of how much energy a battery can store relative to its weight or volume. Both factors are especially critical for large CHE which require significant power output for lifting heavy cargo and high energy storage capacity for sustained operation.

[160] Konecranes, "First Battery-Driven Mobile Harbor Crane Operates in Sweden," June 27, 2022. Accessed January 8, 2025. *https://www.konecranes.com/discover/first-battery-driven-mobile-harbor-crane-operates-in-sweden*.

[161] World Cargo News, "Port of San Diego Showcases Tandem-Lift features of New MHCs," September 19, 2024. Accessed April 10, 2025. *https://www.worldcargonews.com/news/2024/09/port-of-san-diego-showcases-tandem-lift-features-of-new-mhcs/*.

Grid-Electric Forklifts

Although grid-electric forklifts achieve a Technology Applicability score of 0, a potential grid-electric solution for this CHE is worth mentioning since forklifts comprise 20% of CHE in California.[162] As discussed in the *Grid-Electric AGVs and Yard Trucks* section, Kalmar plans to test a conductive electric rail system on a reach stacker,[163] that is similar to a forklift in design, duty cycle, and lift capacity. Kalmar also makes several battery-electric forklifts. While the Kalmar testing does not involve forklifts, it may provide useful insight into how conductive grid-electric technology can be applied to heavy lift forklifts.

Grid-Electric Container CHE

Table 28 provides the technology readiness data summary for grid-electric container CHE. AGVs and yard trucks are discussed first, as they serve the same general function.

Table 28: Technology Readiness Data Summary for Grid-Electric Container CHE

Equipment Type	Commercially Available in the U.S.	Commercially Available Outside the U.S.	Non-Commercial Units	Technology Readiness Grade
Rail Mounted Gantry Crane	9	0	0	Equivalence
Rubber-Tired Gantry Crane	9*	3**	0	Demonstration
Ship-to-Shore Crane	8	0	0	Equivalence
Yard Truck	0	0	0	Development

*Includes four new grid-electric RTGs and five conversions from diesel to grid-electric.
**Includes one new grid-electric RTG and two conversions from diesel to grid-electric.

Grid-Electric AGVs and Yard Trucks

All AGVs operating in California are battery-electric. Furthermore, grid-electric AGVs achieve a Technology Applicability score of 0 and therefore were not assessed for technology readiness. However, due to the progress with in-road charging technologies for on-road transportation and a recent announcement regarding these technologies for CHE, it is useful to discuss these new technologies for future AGV deployments. These new

[162] California Air Resources Board, "2022 Cargo Handling Equipment Emissions Inventory," 2022. *https://ww2.arb.ca.gov/sites/default/files/2023-04/2022%20CHE%20Emission%20Inventory%20Document_6April2023.pdf*.

[163] John Hills, "Kalmar and Elonroad trial Potential Dynamic Charging Breakthrough for Heavy Electric Vehicles," Electric Drives, November 28, 2024. Accessed January 3, 2025. *https://electricdrives.tv/kalmar-and-elonroad-trial-potential-dynamic-charging-breakthrough-for-heavy-electric-vehicles/*.

technologies may apply to both AGVs and yard trucks in the future as these CHE serve similar functions at facilities for container transport.

Dynamic conductive charging and dynamic inductive charging are two technologies that may apply to AGVs and yard trucks. Either technology can be referred to as "wireless" charging. One example of dynamic conductive charging technology comes from Elonroad, a Swedish company that conducted a five-year test of an in-ground charged rail system in Lund, Sweden.[164] The project demonstrated dynamic conductive charging for an electric bus using pick-ups that lower from the bottom of the vehicle to make contact with the charged rail (Figure 48) embedded in the road (Figure 49). This setup allows vehicles to take advantage of both static and dynamic charging.[165] International Transportation Service, LLC will demonstrate five yard trucks with this technology at the Port of Long Beach.[166] Kalmar is building a 200-meter-long *electric road* at their facility in Sweden. Kalmar and Elonroad will test their technology on a reach stacker and a yard truck.[167] This technology could be applied to AGVs but has not been demonstrated or announced.

[164] Anna Wieslander, "Evolution Road Paves the Way for Electric Roads," Elonroad, June 12, 2024. Accessed January 3, 2025. *https://www.elonroad.com/blog/evolutionroad*.

[165] Elonroad, "Elonroad Tech English," YouTube video, published May 23, 2021, 2:28. Accessed April 10, 2025. *https://youtu.be/t9w5viunFf4?si=0THs_Ib3T6JMVYk2*.

[166] "International Transportation Service Partners with Elonroad on Zero Emissions at the Port of Long Beach," My New Desk, December 17, 2024. Accessed April 10, 2025. *https://www.mynewsdesk.com/se/elonroad/pressreleases/international-transportation-service-partners-with-elonroad-on-zero-emissions-at-the-port-of-long-beach-3360603*.

[167] John Hills, "Kalmar and Elonroad trial Potential Dynamic Charging Breakthrough for Heavy Electric Vehicles," Electric Drives, November 28, 2024. Accessed January 3, 2025. *https://electricdrives.tv/kalmar-and-elonroad-trial-potential-dynamic-charging-breakthrough-for-heavy-electric-vehicles/*.

Figure 48: Elonroad's Retracting Conductive Arm (Elonroad)

Figure 49: Installation of Elonroad Charged Track (Elonroad)

Dynamic inductive charging is another technology that can be used for powering AGVs and yard trucks using grid power. The same induction technology discussed in the battery-electric CHE *Infrastructure Requirements and Considerations* section is being studied and tested for dynamic charging systems in passenger and transit vehicles.[168] A35 Brebemi and Stellantis built a 1,050-meter-long roadway in Italy with inductive coils embedded beneath the asphalt.[169] This allows a battery-electric passenger vehicle to travel at highway speeds without using stored battery energy.[170] The Michigan Department of Transportation is testing dynamic inductive charging near Michigan Central in Detroit. A

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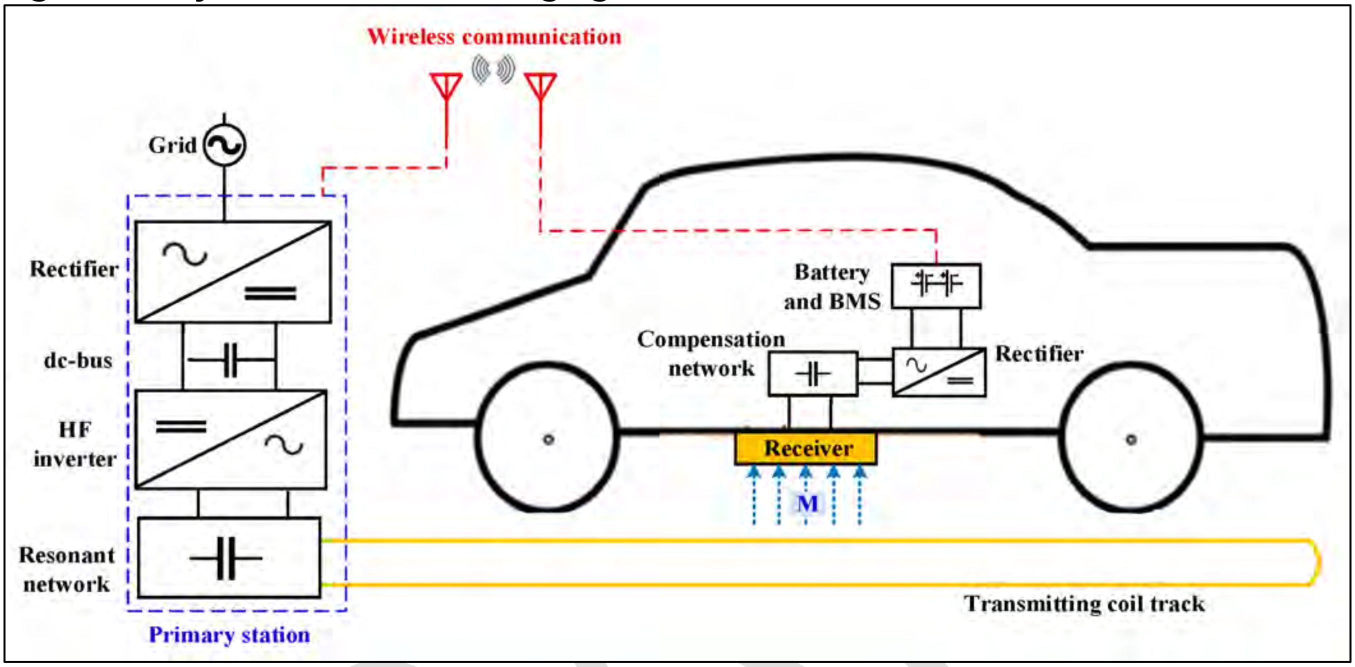
[168] Ahmed A.S. Mohamed, et al. "An Overview of Dynamic Inductive Charging for Electric Vehicles, *Energies* 15, no. 15 (2022): 5613. *https://doi.org/10.3390/en15155613*.

[169] Stellantis, "'Arena del Futuro,' Innovative Dynamic Induction Charging Becomes a Reality," December 2, 2021. Accessed February 13, 2025. *https://www.stellantis.com/en/news/press-releases/2021/december/arena-del-futuro-innovative-dynamic-induction-charging-becomes-a-reality?adobe_mc_ref=&adobe_mc_ref=*.

[170] Ibid.

Ford EV Transit shuttle was tested in 2024 on a quarter-mile strip of “wireless charging roadway.”[171] Figure 50 shows a diagram of a dynamic inductive charging system.

Figure 50: Dynamic Inductive Charging[172]



Dynamic wireless charging could enable continuous operation on grid power without stopping to charge batteries. This could reduce battery size by 50 to 80%.[173] No commercially available CHE offer dynamic wireless solutions since the technology is in the early development phase. However, existing battery-electric AGVs and yard trucks could be retrofitted with wireless receivers like those at the Port of New York and New Jersey and the Port of Los Angeles. Because this technology is still evolving, grid-electric yard trucks achieve a Technology Readiness Grade of Development.

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[171] “Electreon’s Wireless Charging Performance Results.” *Michigan Department of Transportation*, September 2024. Accessed May 5, 2025. *https://www.michigan.gov/mdot/-/media/Project/Websites/MDOT/Travel/Mobility/Mobility-Initiatives/Wireless-Charging/Test-report-September-2024.pdf*; “Wireless Charging Roadway,” Michigan Department of Transportation, n.d. *https://www.michigan.gov/mdot/travel/mobility/initiatives/wireless-charging-roadway*.

[172] Ahmed A. S. Mohamed, et al., “An Overview of Dynamic Inductive Charging for Electric Vehicles,” Energies 2022, 15(15), 5613, *https://doi.org/10.3390/en15155613*.

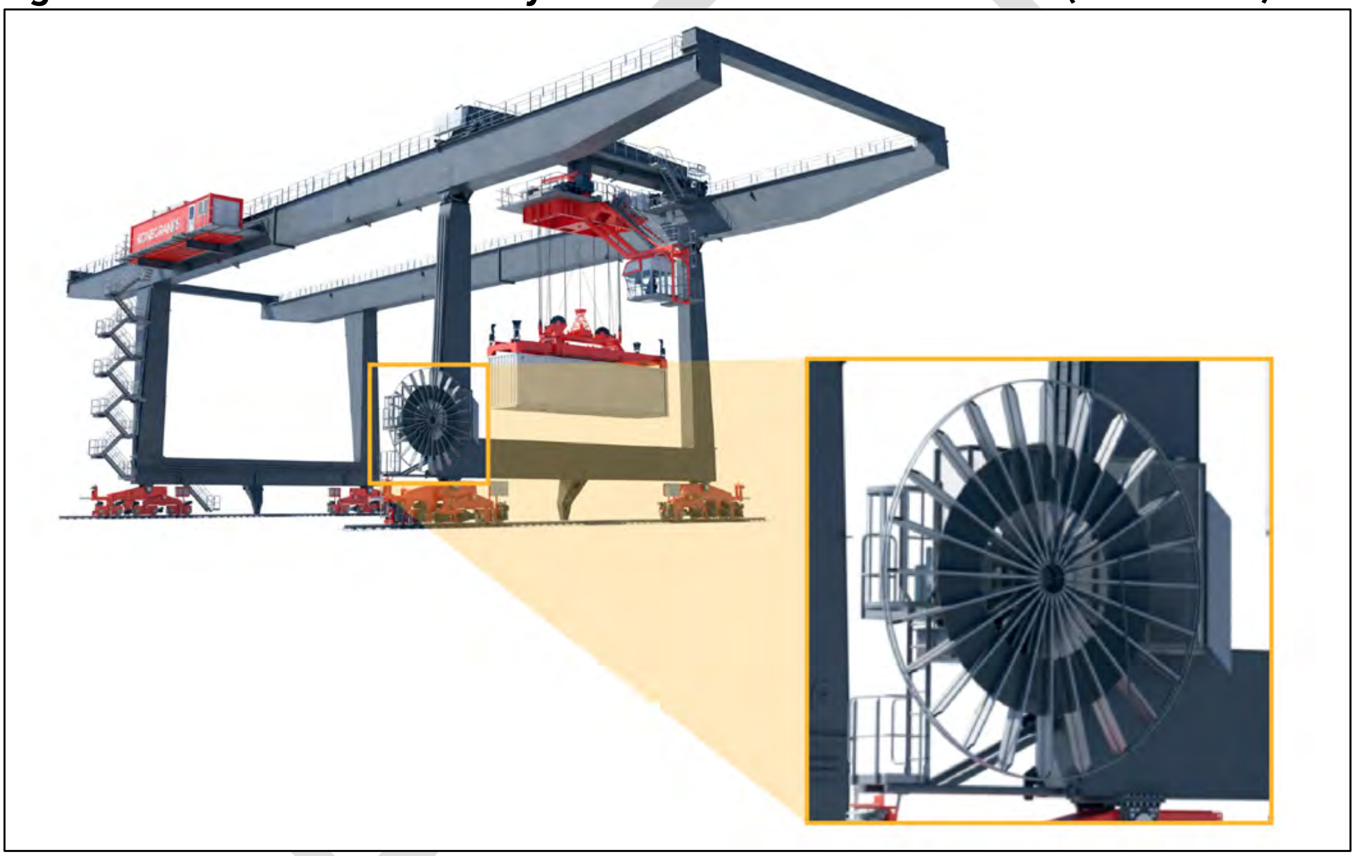
[173] Anna Wieslander, “Evolution Road Paves the Way for Electric Roads,” Elonroad, June 12, 2024. Accessed January 3, 2025. *https://www.elonroad.com/blog/evolutionroad*.

Grid-Electric Gantry Cranes

Grid-Electric Rail Mounted Gantry Cranes

RMGs are well-suited for grid-electric technology due to their fixed operating paths. *Charging Ahead: The Port Community Electric Vehicle Blueprint* mentions that the rail-mounted automatic stacking cranes at the Port of Long Beach operate within a clearly defined path, simplifying the infrastructure requirements for grid electrification.[174] Most RMGs connect to the grid through cable and reel systems. Retracting spool systems collect and disperse the cable as the crane moves (Figure 51). There are nine commercially available models of grid-connected RMGs. As the industry standard, grid-electric RMGs achieve a Technology Readiness Grade of Equivalence.

Figure 51: RMG with Cable Reel System for Grid-Electric Connection (Konecranes)



[174] Grant Farm, "Charging Ahead: The Port Community Electric Vehicle Blueprint," May 2019. *https://thehelm.polb.com/download/379/zero-emissions/6769/port-community-electric-vehicle-blueprint-042919.pdf*.

Grid-Electric Rubber-Tired Gantry Cranes

RTGs generally follow set paths like RMGs, but can reposition freely within the facility to switch loading/unloading lanes or to refuel. For this reason, grid-electric RTGs require on-board battery energy storage to achieve equivalency to their diesel counterpart. Between 2019 and 2022, the Port of Long Beach converted nine diesel-powered RTGs to grid-electric and have been successfully operating since. According to Southern California Edison, these RTGs connect to a stationary grid-power mechanism. This allows the RTG to disconnect and move using a temporary battery system. The high-voltage grid-connection mechanism runs at 4,000 V.[175] A 2019 article claims that Hyundai-Samho, a South Korean heavy equipment manufacturer, offers a commercially available, inductively charged RTG.[176] Additionally, a 2019 YouTube video highlights the benefits of this grid-electric RTG, including regenerative braking that helps charge the on-board battery.[177] However, staff was not able to find any implementations of this offering. As of April 2025, Kalmar deployed 30 "electrified" RTGs at Egypt's Damietta Alliance Container Terminal.[178] There are five manufacturers of new grid-electric RTGs and several companies that convert diesel-

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[175] Energetics Incorporated, et al." Final Evaluation Report," California Public Utilities Commission, April 2021. *https://www.cpuc.ca.gov/-/media/cpuc-website/divisions/energy-division/documents/sb-350-te/california-te-prp-final-evaluation-report-presentation.pdf*.

[176] World Cargo News, "Hyundai-Samho's Inductive Reasoning," January 7, 2019. Accessed April 8, 2025. *https://www.worldcargonews.com/cargo-handling-equipment/2019/07/hyundai-samhos-inductive-reasoning/*.

[177] Hyundai Cranes, "[Hyundai Cranes] Wireless Power Transmission Yard Crane (Eng)," YouTube video, published June 25, 2019, 3:25. Accessed April 8, 2025.*https://www.youtube.com/watch?v=TDUNsD-XOlM*.

[178] Mandra, Jasmina, "10 More eRTGs Arrive in Damietta," World Cargo News, April 14, 2025. Accessed April 15, 2025. *https://www.worldcargonews.com/cargo-handling-equipment/2025/04/10-more-ertgs-arrive-in-damietta/*.

powered RTGs to cable-tied grid-electric RTGs including Cavotec,[179] Conductix-Wampfler,[180] Electroflex, [181] Liebherr,[182] Paceco,[183] Vahle,[184] and ZPMC.[185]

Although there are commercially available grid-electric RTGs, several grid-electric RTG conversions in operation, and multiple service providers who convert diesel-powered RTGs to grid-electric, this CHE-technology combination is not mature. Grid-electric RTGs achieve a Technology Readiness Grade of Demonstration due to lack of operational data.[186]

Staff is seeking information on the implementation of grid-electric RTGs.

Ship-to-Shore Cranes

Ship-to-shore cranes travel along the berth where vessels dock to load and unload containers. Their fixed paths make them ideal for cable connections. They often use cable reel systems to connect to constant grid electricity (Figure 51). The San Pedro Bay Port complex operates 170 ship-to-shore cranes, all powered by grid-electricity.[187] The Port of Oakland also reported that all their ship-to-shore cranes are grid-electric.[188] As the industry

[179] Port Strategy, "Era of the eRTG," January 6, 2023. Accessed April 4, 2025. *https://www.portstrategy.com/era-of-the-ertg/1485459.article*.

[180] Ibid.; Conductix Wampfler, "Conductix-Wampfler Achieves Several Firsts with Port of Montreal's E-RTG Conversion Project," December 19, 2016. Accessed April 3, 2025. *https://www.conductix.us/en/news/2016-12-16/conductix-wampfler-achieves-several-firsts-port-montreals-e-rtg-conversion-project*.

[181] ElectroFlex, "Case Study Electrification of RTG – Navkar CFS Mumbai," n.d. Accessed April 3, 2025. *https://electroflexengineering.com/case-study/electrification-of-RTG-Navkar-CFS-Mumbai.php*.

[182] Port Strategy, "Era of the eRTG," January 6, 2023. Accessed April 4, 2025. *https://www.portstrategy.com/era-of-the-ertg/1485459.article*.

[183] EPRI, "Electric Cable Reel Rubber-Tired Gantry Cranes: Costs and Benefits," March 2010. *https://www.epri.com/research/products/000000003002025783;* "ERTG cable problem," June 1, 2010. Accessed May 5, 2025. *https://www.worldcargonews.com/container/2010/06/ertg-cable-problem/*.

[184] Port Technology Team, "Vahle Electrifies Mexico's Billion Dollar Terminal," Port Technology, March 27, 17. Accessed April 4, 2025. *https://www.porttechnology.org/news/vahle_electrifies_mexicos_billion_dollar_terminal/*.

[185] Web.Services, "RTG Conversion Finishes Ahead of Schedule," Port Technology, July 4, 2014. Accessed April 4, 2025. *https://www.porttechnology.org/news/rtg_to_ertg_conversion_finishes_ahead_of_schedule/*.

[186] Information from *Final Evaluation report: California Transportation Electrification Priority Review projects* was used to calculate the technology readiness score for grid-electric RTGs. According to the report, "The conversion of the RTG cranes to electric was significantly delayed so no data was collected on operations during the evaluation period. Therefore, most of the key findings…are related to the implementation of the electrical infrastructure and eRTG conversion."

[187] Ref both port inventories (2022 and 2023) 88 at POLA ("Electric wharf crane") and 82 at POLB ("STS Crane")

[188] Angela Clapp, Port of Oakland Environmental Supervisor, email, May 14, 2025.

standard configuration, grid-electric ship-to-shore cranes achieve a Technology Readiness Grade of Equivalence.

Grid-Electric Facility Support CHE

There are no commercially available models of grid-electric facility support CHE. All grid-electric facility support CHE achieve a Technology Applicability score of 0, mainly due to the commercial availability of battery-electric versions. Therefore, a technology readiness data summary table is not provided. Battery-electric and fuel cell technology provide zero-emission solutions for this category of CHE.

Emissions Benefits and Considerations

Grid-electric CHE eliminates operational emissions, similar to battery-electric CHE. The emission benefits discussed in the battery-electric CHE *Emissions Benefits* section also apply to grid-electric CHE.

In addition to eliminating emissions, using grid-electricity for CHE can reduce or eliminate battery usage. Battery-electric CHE provides significant emissions benefits over their diesel counterparts, however, because CHE can last longer than their batteries, battery replacements are often required. The number of required batteries can add up in cost and e-waste. Grid-electricity is not an option for many types of CHE. However, using grid-electric solutions where possible can reduce waste from retired batteries. Grid-electricity offers a clean power option with reduced battery dependence.

Another benefit of grid-electric CHE is that it only uses electricity as needed, eliminating the need for similar CHE to charge simultaneously during breaks or between shifts, which can overload the grid during peak demand times. By reducing load demand during peak hours, grid-electric solutions may reduce reliance on *peaker plants*. These backup power plants are typically only used during high demand periods and emit more GHGs than traditional power plants, often in neighborhoods where residents are disproportionately exposed to higher levels of pollution.[189]

Infrastructure Requirements and Considerations

Like battery-electric CHE, grid-electric CHE requires supporting electric infrastructure. This section outlines infrastructure requirements and considerations for grid-electric CHE, including electricity sources, equipment, and operational logistics.

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[189] Angely Mercado," Our Go-To Weapon Against Heatwaves? A Dirty Backup Power Source," Popular Science, June 26,2021. Accessed January 4, 2025. *https://www.popsci.com/environment/peaker-plants-101/*.

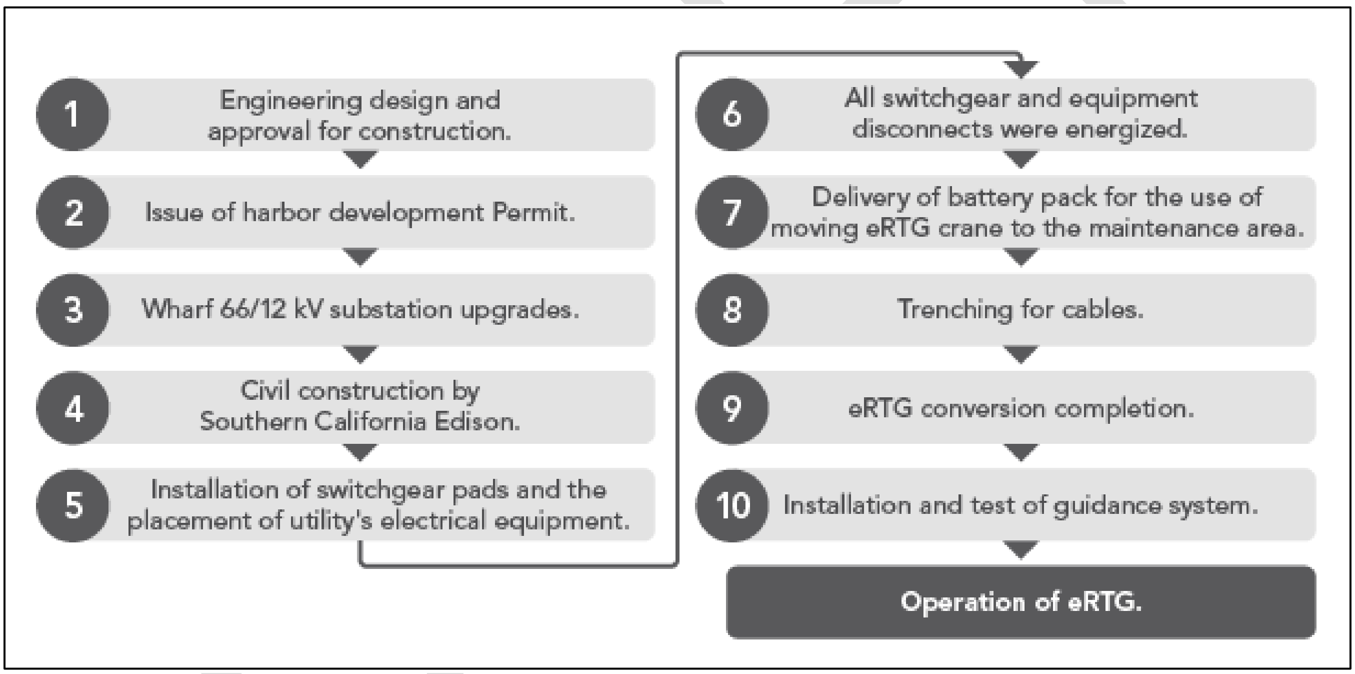
Electricity Source

The power source requirements for battery-electric and grid-electric CHE are similar. See the battery-electric CHE *Electricity Source* section for more information.

Equipment

Unlike battery-electric CHE, grid-electric CHE stays connected directly to the grid. Thus, charging stations are not required. However, as more grid-electric CHE is added to facilities, additional transformers, switchgear, conduit, and wiring are needed to power the grid-electric CHE. Figure 52, taken from the final evaluation report for the conversion of nine diesel-powered RTGs to grid-electric (eRTG) at the Port of Long Beach,[190] is an example of required equipment, permitting, and activities required for repowering diesel-powered CHE to grid-electric.

Figure 52: Diesel to Grid-Electric RTG Conversion Project Steps



Based on the grid-electric CHE conversion project for nine RTGs at the Port of Long Beach, grid-electric projects can take up to four years (including planning, installation, utility construction, equipment acquisition, data collection, and implementation). Other

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[190] Energetics Incorporated, et al." Final Evaluation Report," California Public Utilities Commission, April 2021. *https://www.cpuc.ca.gov/-/media/cpuc-website/divisions/energy-division/documents/sb-350-te/california-te-prp-final-evaluation-report-presentation.pdf*.

grid-electric CHE infrastructure projects could take more or less time depending on the existing grid capacity, the age of the existing grid infrastructure, travel routes of the CHE, location at the site with respect to other equipment, the number of CHE, required permitting, and other factors. See the battery-electric CHE *Charging Equipment* section for more information.

Other than Kalmar's planned testing of a charged rail system for a reach stacker and a yard truck,[191] the dynamic charging technologies discussed for AGVs and yard trucks have not yet been used for CHE. However, the infrastructure challenges described here would apply similarly if those technologies were introduced.[192]

Space, Permitting, and Certification

Grid-electric CHE and battery-electric CHE have similar space requirements, except grid-electric CHE does not need space for charging stations. Instead, electrification for grid-electric CHE includes busbars or cable reel systems that run along the paths where CHE move. These cable systems extend and retract using a large reel or sliding contactors on a busbar. While effective, these systems can take up space otherwise used for cargo or can limit where CHE can be used.

The permitting processes for grid-electric infrastructure construction is similar for both battery-electric and grid-electric CHE. See the battery-electric CHE *Infrastructure Requirements and Considerations* section for more information.

Logistics

Grid-electric CHE is almost always connected to the grid. Busbar or cable reel systems can obstruct the movement of other equipment around the facility when these systems are above ground. However, the use of underground cable systems increases construction costs and may require extra permitting. Such permitting can increase the implementation timeline. Grid-electric CHE such as RTGs face unique challenges. Once plugged in, moving

Staff is seeking information on grid-electric CHE infrastructure, including power source solutions, charging logistics, permitting processes, and operational efficiencies.

[191] John Hills, "Kalmar and Elonroad trial Potential Dynamic Charging Breakthrough for Heavy Electric Vehicles," Electric Drives, November 28, 2024. Accessed January 3, 2025. *https://electricdrives.tv/kalmar-and-elonroad-trial-potential-dynamic-charging-breakthrough-for-heavy-electric-vehicles/*.

[192] Elonroad, "Elonroad Tech English," YouTube video, published May 23, 2021, 2:28. Accessed April 8, 2025.*https://youtu.be/t9w5viunFf4?si=0THs_Ib3T6JMVYk2*.

an RTG from one stack to another can take up to 45 minutes.[193] Backup battery systems can help reduce these delays.

Economics

Grid-electric CHE capital and operating costs are similar to battery-electric CHE. See the battery-electric CHE *Economics* section for more information. Grid-electric CHE does not require charging stations. They often need power cables, connectors, and sockets. Additional equipment such as busbars, cable reels, conduit, and other equipment may also be included in the infrastructure installation costs for grid-electric CHE.

Table 29 summarizes the capital and operating costs associated with grid-electric CHE. Grid-electric CHE primarily draws power directly from the grid, reducing or eliminating the need for onboard battery systems. However, some grid-electric CHE still incorporate batteries within their systems for specific operational purposes such as moving from one power connector to another. Battery costs are included in the capital cost for grid-electric CHE, but unlike battery-electric CHE, midlife replacements are not included for grid-electric CHE operating costs.

Table 29: Grid-Electric CHE Capital Costs and Operating Costs

Capital Costs	Operating Costs
• CHE • Infrastructure o Equipment (e.g., busbars, cables, cable reels, cable management systems, etc.) o Installation	• Equipment fuel • Equipment maintenance • Infrastructure maintenance

Table 30 through Table 32 compare the costs of grid-electric and diesel-powered CHE. Due to limited data availability, staff only obtained cost information for material handling cranes, mobile harbor cranes, and RTG cranes. Table 33 presents infrastructure related costs for grid-electric CHE.

Table 30: Cost Comparison Between a Grid-Electric and Diesel-Powered Material Handling Crane (2024$)

Capital/Operating (Op.) Cost Component	Grid-Electric CHE	Diesel CHE
Capital – CHE	$2,450,000 to $2,850,000	$1,565,000 to $2,240,000
Capital – Infrastructure	[Staff is seeking information]	N/A

[193] Claimed confidential data obtained from an industry source that requested non-attribution

Capital/Operating (Op.) Cost Component	Grid-Electric CHE	Diesel CHE
Op. – Fuel	$301,800 per year[194]	$64,500 to $83,900 per year[195]
Op. – Maintenance	[Staff is seeking information]	[Staff is seeking information]

Note: Data without a footnote was obtained from an industry source that requested non-attribution.

Table 31: Cost Comparison Between a Grid-Electric and Diesel-Powered Mobile Harbor Crane (2024$)

Capital/Operating (Op.) Cost Component	Grid-Electric CHE	Diesel CHE
Capital – CHE	$14,000,000[196]	$3,000,000 to $6,000,000
Capital – Infrastructure	[Staff is seeking information]	N/A
Op. – Fuel	[Staff is seeking information]	[Staff is seeking information]
Op. – Maintenance	[Staff is seeking information]	[Staff is seeking information]

Note: Data without a footnote was obtained from an industry source that requested non-attribution.

Table 32: Cost Comparison Between a Grid-Electric and Diesel-Powered RTG

Capital/Operating (Op.) Cost Component	Grid-Electric CHE	Diesel CHE
Capital – CHE	$1,800,000 to $2,500,000[197]	$1,200,000 to $1,300,000[198]
Capital – Infrastructure	[Staff is seeking information]	N/A

[194] Cost = 716 kW x 1561 h/year x $0.27/kWh = $301,773 per year. The fuel cost calculation does not consider incentives such as the LCFS nor any special electricity rates offered by utility providers.

[195] Cost = 10 to 13 gallon/h x 1561 h/year x $4.13/gallon = $64,469 to $83,810 per year. Fuel efficiency is sourced from web source: Port of Oakland, "Port of Oakland Hybrid Electric Cranes Deliver Emissions Savings," August 24, 2020. Accessed April 14, 2025. *https://www.portofoakland.com/port-of-oakland-hybrid-electric-cranes-deliver-major-emissions-savings/.*

[196] "Port of San Diego Purchases All-Electric Mobile Harbor Cranes, First in North America – Pacific Maritime Magazine," n.d. Accessed January 7, 2025. *https://pacmar.com/article/port-of-san-diego-purchases-all-electric-mobile-harbor-cranes-first-in-north-america/*.

[197] Dan Wei and Genevieve Giuliano, "Implementation of Action 6 of CSFAP Phase 3 Tracking Economic Competitiveness Part 3: Economic Impacts of Electrification of Cargo Handling Equipment at POLA/POLB," August 1, 2021. *https://doi.org/10.25554/8drs-9j23*.

[198] Ibid.

Capital/Operating (Op.) Cost Component	Grid-Electric CHE	Diesel CHE
Op. – Fuel	$144,600 per year[199]	$102,400 to $122,900 per year[200]
Op. – Maintenance	$85,005 per year[201]	$63,754 per year[202]

Note: Data without a footnote was obtained from an industry source that requested non-attribution.

Table 33: Grid-Electric CHE Infrastructure Related Costs

Cost Component	Cost
New Utility Substation Installation	Varies Cost information from past projects: • $8,000,000 to $30,000,000 to build a 66-kilovolt substation. • $8,000,000 to $9,000,000 for substation to support a mobile harbor crane.
Existing Utility Substation Modification	Varies Cost information from past projects: • Utility side infrastructure upgrades to support nine grid-electric RTG cost $2,322,934.[203]

[199] Cost = 216 kW x 2479 h/year x $0.27/kWh = $144,575 per year. The fuel cost calculation does not consider incentives such as the LCFS nor any special electricity rates offered by utility providers.

[200] Cost = 10 to 12 gallon/h x 2479 h/year x $4.13/gallon = $102,383 to $122,859 per year. Fuel efficiency is sourced from web source: Krystle McBride, Catherine Mukai, and Diane Heinze, "Hybrid RTGs on the Path to Zero-Emission," Port of Technology, n.d. Accessed April 14, 2025. *https://www.porttechnology.org/wp-content/uploads/2020/01/AECOM-3.pdf*.

[201] Dan Wei and Genevieve Giuliano, "Implementation of Action 6 of CSFAP Phase 3 Tracking Economic Competitiveness Part 3: Economic Impacts of Electrification of Cargo Handling Equipment at POLA/POLB," August 1, 2021. *https://doi.org/10.25554/8drs-9j23*.

[202] Ibid.

[203] Energetics Incorporated, et al." Final Evaluation Report," California Public Utilities Commission, April 2021. *https://www.cpuc.ca.gov/-/media/cpuc-website/divisions/energy-division/documents/sb-350-te/california-te-prp-final-evaluation-report-presentation.pdf*.

Cost Component	Cost
Electric Infrastructure Installation	Varies Cost information from past projects: • Switchgears, trenching, and installation for nine grid-electric RTGs cost $2,840,000.[204203] • Trenching, conduit and cables for 20 RTGs cost $8,000,000.[205] • Project contingency is 30% of total system installation costs.[206205]
Infrastructure Maintenance	[Staff is seeking information]

Note: Data without a footnote was obtained from an industry source that requested non-attribution.

Based on an analysis from Rocky Mountain Institute and Mission Possible Partnership in 2024, the 12-year total cost of ownership of grid-electric RTGs can be cost-competitive with diesel RTGs in California with the consideration of LCFS and CORE.[207]

Staff is seeking information on costs for grid-electric CHE, including capital, fuel, infrastructure, maintenance, operational, and other additional costs.

Technology Outlook

Of the eight types of grid-electric CHE assessed for technology readiness, seven have commercially available models, including all four bulk material CHE types. Also, RMGs and ship-to-shore cranes achieve a Technology Readiness Grade of Equivalence and all of these

[204] Ibid.

[205] Grant Farm, "Charging Ahead: The Port Community Electric Vehicle Blueprint," May 2019. *https://thehelm.polb.com/download/379/zero-emissions/6769/port-community-electric-vehicle-blueprint-042919.pdf*.

[206] Ibid.

[207] Mia Reback, et al. "The Time Is Now for Zero-Emissions Cargo Handling Equipment at America's Busiest Cargo Ports," RMI, November 7, 2024. Accessed November 25, 2024. *https://rmi.org/the-time-is-now-for-zero-emissions-cargo-handling-equipment-at-americas-busiest-cargo-ports/*.

CHE at California seaports are grid-electric.[208] Table 34 summarizes the outlook for the other 6 grid-electric CHE types to achieve a Technology Readiness Grade of Equivalence within the next 10 years.

Table 34: Outlook for Achieving Equivalence for Grid-Electric CHE Within 10 Years

Type of CHE	Outlook for Achieving Equivalence Within 10 Years
Crane (Material Handling and Off-Road), Excavators	These CHE have limited testing at seaports and intermodal railyards to prove that they can meet duty cycle, operational, and logistical needs. Also, facilities using these cranes often have limited CHE fleets and the cost and operational disruption to install the infrastructure for small quantities of CHE can be significant. There are many commercially available models of material handling cranes, off-road cranes, and excavators that can operate on batteries or connect to the grid while stationary. Because of this flexibility, staff anticipates that with additional emission reduction strategies and incentive programs in place for both the CHE and infrastructure, these CHE can achieve Equivalence within 10 years.
Crane, Mobile Harbor	Mobile harbor cranes are large CHE requiring considerable amounts of electricity and infrastructure upgrades. Additionally, grid connection limits their mobility, making infrastructure and logistical planning essential. Two commercially available models of harbor cranes are being proven at several seaports, globally. Because of the initial success reported for these early implementations,[209] staff anticipates that with additional emission reduction strategies and incentive programs in place for both the CHE and infrastructure, grid-electric mobile harbor cranes can achieve Equivalence within 10 years.

[208] All ship-to-shore cranes operating at the ports of Oakland, Long Beach, Los Angeles, and San Diego are grid-electric. Furthermore, the San Pedro Bay Port complex has all of California's RMGs, a total of 98, and all are grid-electric. (See, Port of Long Beach, "2023 Air Emissions Inventory," August 2024. *https://polb.com/download/14/emissions-inventory/20586/2023-air-emissions-inventory.pdf*; Port of Los Angeles, "2023 Air Emissions Inventory," August 2024. *https://kentico.portoflosangeles.org/getmedia/3fad9979-f2cb-4b3d-bf82-687434cbd628/2023-Air-Emissions-Inventory*).

[209] Staff visited the Port of San Diego to review the implementation of two grid-electric mobile harbor cranes. See *Appendix E* for details of this pilot,

Type of CHE	Outlook for Achieving Equivalence Within 10 Years
Rubber-Tired Gantry Crane	Several grid-electric options are available for RTGs: five OEMs offer new grid-electric RTG models and there are seven service providers who convert diesel RTGs to grid-electric. There are many grid-electric RTGs in operation today, however, there is little published data on their operational performance. The conversion project of nine diesel RTGs to grid-electric at the Port of Long Beach highlighted the following challenges that inhibit the adoption of grid-electric RTGs: • Planned cost savings will take longer to realize due to unforeseen infrastructure costs. • Implementing infrastructure took longer than planned (due to part delays, permitting, managing funding, etc.). • Infrastructure projects can be disruptive to business operations.[210] Despite these challenges, with additional emission reduction strategies and incentive programs in place for both the CHE and infrastructure, grid-electric RTGs can achieve Equivalence within 10 years.
Yard Trucks	Conductive or inductive dynamic powering has not been proven for yard trucks. Implementing this infrastructure would be expensive and potentially disruptive. However, these two technologies could solve many charging logistics challenges for yard trucks. These improvements may enhance terminal layout and productivity, increasing land value.[211] Regardless of these benefits, battery and fuel cell technology have been successfully demonstrated for yard trucks, offering a clearer path to zero-emissions. Therefore, grid-electric yard trucks will likely not achieve Equivalence within 10 years.

Similar to battery-electric charging solutions, grid-electric CHE projects face infrastructure challenges. Permitting and construction timeframes are often longer than expected. Return on investment can be delayed due to unexpected challenges, which can be expensive to

[210] Energetics Incorporated, et al." Final Evaluation Report," California Public Utilities Commission, April 2021. *https://www.cpuc.ca.gov/-/media/cpuc-website/divisions/energy-division/documents/sb-350-te/california-te-prp-final-evaluation-report-presentation.pdf*.

[211] Grant Farm, "Charging Ahead: The Port Community Electric Vehicle Blueprint," May 2019. *https://thehelm.polb.com/download/379/zero-emissions/6769/port-community-electric-vehicle-blueprint-042919.pdf*.

address.[212] One example is the Middle Harbor at the Port of Long Beach. The port added electrical infrastructure to accommodate 800 pieces of electric terminal equipment with a total electrical capacity of nearly 64 MW. This project cost $2 billion and took 10 years to design and construct.[213]

As with battery-electric CHE, facilities will continue to move forward and acquire the equipment as incentive programs become available. However, the inability to execute infrastructure plans cohesively and effectively is the single greatest challenge for the adoption of grid-electric CHE. See *Appendix H* for more information on available incentive programs for grid-electric CHE.

Hydrogen Fuel Cell Cargo Handling Equipment

While battery-electric and grid-electric CHE use energy from the grid, hydrogen fuel cell CHE uses energy generated from onboard hydrogen fuel cells for operation. Fuel cells generate electricity by converting hydrogen's chemical energy through an electrochemical reaction. This energy is used directly for operation or diverted to batteries where it is stored for future operation. As long as hydrogen is supplied, the fuel cell provides a reliable and efficient zero-emission energy source. Hydrogen fuel cell CHE stores the hydrogen fuel onboard in high-pressure tanks. Commercially available hydrogen fuel cell CHE uses gaseous hydrogen as fuel.

Compared to battery-electric and grid-electric CHE, hydrogen fuel cell CHE is not as advanced and is mostly in the development or demonstration phase. Hydrogen fuel cell CHE may be a more suitable option for operations where range or charging downtime is a concern. For facilities with multiple work shifts and limited grid capacity, it offers an alternative to electric CHE. In the future, battery-electric, grid-electric, and hydrogen fuel cell CHE are likely to be used together.

Technology Description

A fuel cell generates electricity through reduction and oxidation reactions between a fuel such as hydrogen and an oxidizing agent (typically oxygen), without combustion. There are several fuel cell technologies including polymer electrolyte membrane (PEM) fuel cells, solid oxide fuel cells, direct methanol fuel cells, alkaline fuel cells, phosphoric acid fuel cells,

[212] Rose Szoke, et al. "Port of Long Beach Zero-Emissions Terminal Equipment Transition Project," California Energy Commission, Publication Number: CEC-600-2024-042, April 2024.

[213] Grant Farm, "Charging Ahead: The Port Community Electric Vehicle Blueprint," May 2019. *https://thehelm.polb.com/download/379/zero-emissions/6769/port-community-electric-vehicle-blueprint-042919.pdf*.

molten carbonate fuel cells, and reversible fuel cells.[214] Non-hydrogen fuels, such as natural gas, ammonia, and methanol, can also be used as fuels for some types of fuel cells. This assessment focuses on hydrogen fuel cells, as they are more developed and commercially available.

Fuel cells convert chemical energy directly to electrical energy with efficiencies up to 60%. When paired with cogeneration systems, fuel cells can exceed 60% efficiency by producing electricity and capturing useful heat at the same time.[215] Several factors affect the power output of a fuel cell including fuel cell type, size, operating temperature, and the pressure of the supplied gases. A single fuel cell generates less than 1.16 volts, which is too low for most applications.[216] To produce more electricity, multiple fuel cells are connected in a series to form a fuel cell stack. These stacks can contain hundreds of cells working together.[217]

PEM fuel cells are practical for CHE due to their high efficiency, power density, low weight, compact size, low operating temperature, and high durability.[218] Figure 53 shows a PEM fuel cell. Like a battery, it has an anode and a cathode. Unlike a battery, it requires a continuous supply of hydrogen from tanks, and oxygen from the atmosphere, to generate a steady flow of electricity. At the anode, hydrogen molecules split into protons and electrons, creating an electric current. At the cathode, protons pass through the electrolyte and combine with oxygen and the returning electrons to form water. This reaction produces heat and water that exit through the exhaust system. Since fuel cells produce no local harmful emissions, they provide a zero-emission power source that can be used to operate electric-powered CHE. The most common type of fuel cell for CHE is PEM.[219] In this section, both *hydrogen fuel cell* and *fuel cell* refer to a hydrogen-powered PEM fuel cell.

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[214] U.S. Department of Energy, "Types of Fuel Cells," n.d. Accessed January 31, 2025. *https://www.energy.gov/eere/fuelcells/types-fuel-cells*.

[215] Office of Energy Efficiency & Renewable Energy, "Fuel Cells for Stationary Power Applications," U.S Department of Energy, n.d. Accessed January 7, 2025. *https://www.energy.gov/eere/fuelcells/articles/fuel-cells-stationary-power-applications*.

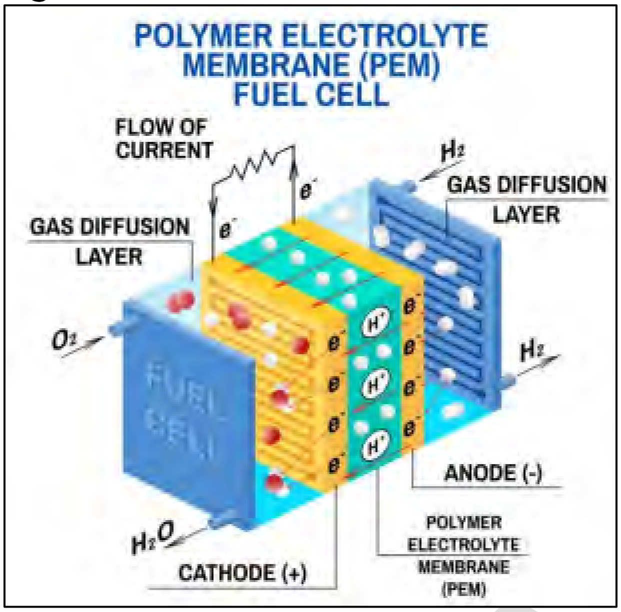
[216] U.S. Department of Energy, "Fuel Cell Animation (Text Version)," n.d. Accessed January 31, 2025. *https://www.energy.gov/eere/fuelcells/fuel-cell-animation-text-version*.

[217] Ibid.

[218] Miriam M. Tellez-Cruz, et al. "Proton Exchange Membrane Fuel Cells (PEMFCs): Advances and Challenges," *Polymers* 13, no. 18 (2021): 3064. *https://doi.org/10.3390/polym13183064.*

[219] Simone, Lombardi, et al. "Optimal Design of an Adaptative Energy Management Strategy for a Fuel Cell Tractor Operating in Ports," Applied Science, Volume 352, 2023, 121917, ISSN 0306-2619. *https://doi.org/10.1016/j.apenergy.2023.121917*.

Figure 53: PEM Fuel Cell



Hydrogen fuel cell CHE technology offers benefits, including fast refueling similar to diesel, reduced grid dependency, low or no charging downtime, and maximized operational efficiency. It provides a longer operational range and is a promising alternative to battery-electric and grid-electric CHE. Use of hydrogen fuel cell CHE could help facilities avoid peak grid demand and simplify charging logistics. A study found that fuel cell-powered lift trucks can reduce refueling and recharging labor costs by up to 80% and need 75% less space than battery charging infrastructure.[220] Fuel cells provide consistent power throughout shifts, unlike batteries, which may lose power output as they deplete. Fuel cell CHE have become more durable and reliable across various equipment types. Advancements in catalyst technology and fuel processing have improved fuel cells, making them better at handling impurities, reducing voltage degradation, while having a longer lifespan, faster start-up times, and working more efficiently in cold weather.[221]

All hydrogen fuel cell CHE have some amount of battery storage to help boost performance and efficiency. The fuel cell can either power the equipment directly or charge the onboard battery. CHE that operates primarily from their onboard batteries and use fuel cells for range extending or increasing operation time, are often referred to as fuel cell-battery

[220] Energy Efficiency & Renewable, "Fuel Cell Technologies Office Early Market: Fuel Cells for Material Handling Equipment," U.S. Department of Energy, n.d. Accessed January 31, 2025. *https://www.energy.gov/eere/fuelcells/articles/early-markets-fuel-cells-material-handling-equipment*.

[221] Eastern Research Group, Inc. "Assessment of Fuel Cell Technologies at Ports," U.S. Environmental Protection Agency, July 2022. *https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1015AQX.pdf*.

hybrids.[222] The battery can capture and store energy from regenerative braking, provide additional power during peak demand, and optimize fuel cell operation for overall efficiency. This hybrid setup ensures smoother power delivery, reduces hydrogen use, and extends the fuel cell lifespan. Throughout this document, all CHE that use hydrogen fuel cell technology are referred to as hydrogen fuel cell CHE. This assessment does not make a distinction between hydrogen fuel cell CHE and fuel cell-battery hybrid CHE.

Technology Readiness

CARB's 2015 Draft CHE Assessment stated that, at the time, only smaller warehouse forklifts were available with hydrogen fuel cell technology. It also mentioned one demonstration for a hydrogen fuel cell RTG. Since then, Cummins acquired Hydrogenics in 2019, and the battery-fuel-cell hybrid RTG discussed in the 2015 assessment was not developed.[223] Six types of hydrogen fuel cell CHE are commercially available. Additionally, OEMs are actively developing and demonstrating several new hydrogen fuel cell CHE models.

Fuel cell stack manufacturers, fuel cell system integrators, and OEMs are working together to make hydrogen fuel cell CHE market-ready. They are focused on solving challenges related to cost, performance, and infrastructure integration by improving fuel cell efficiency and lifespan, reducing production costs through economies of scale, and developing reliable hydrogen storage solutions that meet industry standards. Manufacturers are also working with seaports and intermodal railyards to ensure hydrogen fuel cell CHE meets the operational needs of modern facilities and are cost-effective and reliable for commercial use.

Hydrogen Fuel Cell Bulk Material CHE

Heavy lift forklifts and loaders are the only commercially available hydrogen fuel cell bulk material CHE. However, OEMs are developing and demonstrating several other types of hydrogen fuel cell bulk material CHE. Table 35 provides the technology readiness data summary for hydrogen fuel cell bulk material CHE.

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[222] Eastern Research Group, Inc. "Assessment of Fuel Cell Technologies at Ports," U.S. Environmental Protection Agency, July 2022. *https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1015AQX.pdf*.

[223] After the acquisition, grant funds from CEC were used by Cummins to develop a class 8 drayage truck. See Final Project Report: Hydrogenics Advanced Fuel Cell Vehicle Technology Demonstration for Drayage Truck 2024. *https://www.energy.ca.gov/sites/default/files/2024-02/CEC-600-2024-005.pdf*.

Table 35: Summary of Technology Readiness Data for Hydrogen Fuel Cell Bulk Material CHE

Equipment Type	Commercially Available in the U.S.	Commercially Available Outside the U.S.	Non-Commercial Units	Technology Readiness Grade
Crane, Material Handling	0	0	0	Development
Crane, Mobile	0	0	0	Development
Crane, Mobile Harbor	0	0	1	Development
Crane, Off-road	0	0	1	Development
Dozer	0	0	0	Development
Excavator	0	0	6	Development
Forklift, Heavy Lift	9	0	0	Demonstration
Forklift, Telehandler	0	0	1	Development
Haul Truck	0	0	4	Development
Loader or Loader-excavator	0	1	2	Development
Log Stacker	0	0	0	Development

Hydrogen Fuel Cell Forklifts

There are nine commercially available models of fuel cell heavy-lift forklifts, all of which are manufactured by Wiggins Lift Company. They are eligible for funding through CARB's CORE program and have lift capacities ranging from 26,000 to 70,000 lb.[224] Although these forklifts are commercially available, staff found no publicly available data regarding pilot projects or demonstrations using them. In March 2023, Energy Tech reported that Wiggins hydrogen fuel cell heavy-lift forklifts would be used for bulk cargo handling at seaports and marinas.[225] In 2024, the Nagoya Port Authority in Japan launched a fleet of 20 fuel cell forklifts at five different terminals.[226] However, reports do not specify who manufactured the

[224] There are also five other hydrogen fuel cell models offered by Wiggins with lift capacities lower than 24,000 lb. See *californiacore.org* for details.

[225] EnergyTech Staff, "Wiggins Lift Developing Hydrogen Fuel Cell-Powered Forklift," EnergyTech, March 1, 2023. Accessed February 26, 2025. *https://www.energytech.com/emobility/article/21260998/wiggins-lift-developing-hydrogen-fuel-cell-powered-forklift*

[226] H2 News, "Nagoya Port Implements Hydrogen Forklifts," December 2024. Accessed February 27, 2025. *https://h2-news.com/hydrogen/news/nagoya-port-implements-hydrogen-forklifts/*.

forklifts or their lifting capacity.[227] Although no public data is available on the implementation of hydrogen fuel cell heavy lift forklifts, they achieve a Technology Readiness Grade of Demonstration, as there are several commercially available models ready to be demonstrated at seaports and intermodal railyards.

Other Hydrogen Fuel Cell Bulk Material CHE

In 2023, XCMG put into operation the first commercially available hydrogen fuel cell loader, the XC968-FCEV. By March 2023, it had accumulated over 1,000 hours of operation.[228] Several recent demonstrations have tested other types of hydrogen fuel cell bulk material CHE. However, no operational data is publicly available and most of these demonstrations are focused on construction or mining and were not carried out at seaports or intermodal railyards. See *Appendix E* for more information on hydrogen fuel cell bulk material CHE demonstrations. These hydrogen fuel cell bulk material CHE achieve a Technology Readiness Grade of Development due to no commercially available models and lack of data for demonstrations.

Hydrogen Fuel Cell Container CHE

There are no commercially available hydrogen fuel cell container CHE. However, there are several demonstration programs testing and showcasing five types of CHE showing the potential of this technology. European ports such as the Port of Antwerp, Gothenburg, Hamburg, Rotterdam, and Valencia are using hydrogen fuel cell technologies. In California, the Port of Los Angeles and the Port of Long Beach are at the forefront of adopting hydrogen fuel cell technologies. Table 36 provides the technology readiness data summary for hydrogen fuel cell container CHE.

Table 36: Summary of Technology Readiness Data for Hydrogen Fuel Cell Container CHE

Equipment Type	Commercially Available in the U.S.	Commercially Available Outside the U.S.	Non-Commercial Units	Technology Readiness Grade
AGV	0	0	0	Development
Rail-mounted Gantry Crane	0	0	0	Development

[227] H2 Energy Group, "H2-View News: Nagoya Port Rolls Out Hydrogen-Powered Forklifts for Terminal and Logistics Operation," n.d. Accessed February 27, 2025. *https://h2eg.com/h2-view-news-nagoya-port-rolls-out-hydrogen-powered-forklifts-for-terminal-and-logistics-operations/*.

[228] ChinaSPV, "World's First! XCMG 6-ton hydrogen-powered loader operated in Shanxi," June 26, 2023. Accessed August 29, 2024. https://www.chinaspv.com/news/2023/5549.html.

Equipment Type	Commercially Available in the U.S.	Commercially Available Outside the U.S.	Non-Commercial Units	Technology Readiness Grade
Reach Stacker	0	0	1	Development
Rubber-Tired Gantry Crane	0	0	4	Demonstration
Shuttle and Straddle Carriers	0	0	0	Development
Side Handler	0	0	1	Development
Top Handler	0	0	2	Development
Yard Truck	0	0	5	Demonstration

Hydrogen Fuel Cell AGVs and Yard Trucks

There are no commercially available hydrogen fuel cell AGVs or yard trucks. Gaussin North America offered four commercially available hydrogen fuel cell/battery-hybrid AGVs and two fuel cell yard trucks before they went out of business in December 2024.[229] Hydrogen fuel cell AGVs achieve a Technology Readiness Grade of Development.

There are several demonstrations of hydrogen fuel cell yard trucks underway. Based on continuing development efforts by several OEMs and information from a final report of the Zero Emissions for California Ports (ZECAP) demonstration, hydrogen fuel cell yard trucks achieve a Technology Readiness Grade of Demonstration.[230]

Hydrogen Fuel Cell RTG Cranes

There are four demonstrations underway for hydrogen fuel cell RTGs. In 2024, Yusen Terminal at the Port of Los Angeles announced the first-of-its-kind hydrogen fuel cell RTG crane program (Figure 54). The RTG started operation in May 2024 as part of a four-year demonstration to collect data on the future development of fuel cell technology for RTGs and other CHE.[231] The RTG crane was developed by PACECO in collaboration with Mitsui E&S. The fuel cell power pack is provided by Toyota, using fuel cell and hydrogen tank components from the Mirai fuel cell passenger car. The fuel cell system offers a continuous

[229] Avery, Paul, "End of the road for Gaussin," World Cargo News, December 3, 2024. Accessed July 30, 2025. *https://www.worldcargonews.com/news/2024/12/end-of-the-road-for-gaussin*.

[230] The final report presentation can be seen on CARB's ZECAP website: *ww2.arb.ca.gov/lcti-zero-emissions-california-ports-zecap*.

[231] Yusen Terminals, "Yusen Terminals Launches World's First Hydrogen Fuel Cell RTG Program," May 15, 2024. Accessed March 3, 2025. *https://yti.com/2024/05/yusen-terminals-launches-worlds-first-hydrogen-fuel-cell-rtg-program/*.

power output of 60 kW, a storage capacity of 32 kg at a pressure of 700 bar and can function for up to 16 hours.[232] It takes about 30 minutes to refuel. During a site visit by staff to the Port of Los Angeles, the terminal operator indicated that the crane integrates seamlessly with port logistics, delivering high efficiency and minimal downtime due to equipment failure. Maintenance requirements have been minimal and easy to manage. See *Appendix E* for more information on hydrogen fuel cell RTG demonstrations. Hydrogen fuel cell RTGs achieve a Technology Readiness Grade of Demonstration based on positive initial feedback and operational data from the demonstration at the Port of Los Angeles.

[232] David Blekman, "Hydrogen Crane Deployment at the Port of Los Angeles," Forbes, June 11, 2024. Accessed February 27, 2025. Forbes. *https://www.forbes.com/sites/davidblekhman/2024/06/11/hydrogen-crane-deployment-at-the-port-of-los-angeles/*.

Figure 54: Hydrogen Fuel Cell RTG at the Port of Los Angeles (Staff photo)

Other Hydrogen Fuel Cell Container Cargo Handling Equipment

Hydrogen fuel cell RMGs, reach stackers, shuttle and straddle carriers, side handlers, and top handlers do not have commercially available models and there is no publicly available operational data from the demonstrations. These CHE achieve a Technology Readiness Grade of Development.

Hydrogen Fuel Cell Facility Support CHE

Three types of hydrogen fuel cell facility support CHE are commercially available: aerial lifts, general-purpose utility trucks used for facility support, and sweepers. Table 37 provides the technology readiness data summary for hydrogen fuel cell facility support CHE.

Table 37: Summary of Technology Readiness Data for Hydrogen Fuel Cell Facility Support CHE

Equipment Type	Commercially Available in the U.S.	Commercially Available Outside the U.S.	Non-Commercial Units	Technology Readiness Grade
Aerial Lift	2	0	0	Demonstration
Cone Vehicle	0	0	0	Development
Railcar Mover	0	0	0	Development
Utility Truck, Other	0	0	4	Development
Utility Truck, Sweeper	1	1	0	Limited

Hydrogen Fuel Cell Aerial Lift

There are two models of commercially available aerial lifts. Niftylift manufacturers both of them as part of a joint venture with United Kingdom-based rental company Speedy Hire. Niftylift added hydrogen fuel cell range extenders to two battery-electric aerial lift models.[233] Aerial lifts achieve a Technology Readiness Grade of Demonstration due to lack of real-world operational data.

[233] The Construction Index, "World's First Hydrogen-Electric MEWP is Both Speedy and Nifty," July 5, 2023. Accessed March 3, 2025. *https://www.theconstructionindex.co.uk/news/view/worlds-first-hydrogen-electric-mewp-is-both-speedy-and-nifty*

Hydrogen Fuel Cell Cone Vehicles and Railcar Movers

There are no commercially available fuel cell cone vehicles or railcar movers. Staff has not found evidence of the development of these CHE types. As a result, both types received a Technology Readiness Grade of Development.

Hydrogen Fuel Cell Utility Truck

Utility Truck, General

There are no commercially available hydrogen fuel cell utility trucks that may be converted for facility support at seaports and intermodal railyards. However, several OEMs have announced their intentions to build prototypes or start production of medium- and heavy-duty fuel cell utility trucks. For example, in May 2024, Stellantis group announced plans to produce fuel cell models of the Dodge Ram 5500 in Mexico for North America.[234] In 2024, GM announced a pilot program to demonstrate a truck with an estimated range greater than 300 miles and a 19,500 lb gross vehicle weight rating.[235] Also as part of that program, in 2022, utility provider SoCalGas announced plans to produce a hydrogen fuel cell Ford F-550 Super Duty as part of the U.S. Department of Energy's SuperTruck 3 program.[236] In 2021, Hexagon Purus and Ballard Power Systems announced their intention to produce Class 6 and 7 hydrogen fuel cell trucks with a range of over 400 miles and refueling times comparable to conventional trucks.[237] General-purpose utility trucks that can be converted for use as facility support CHE achieve a Technology Readiness Grade of Development as there are no demonstrations of use at a seaport or intermodal railyard.

234 Stephen Edelstein, "Fuel-cell Ram HD Pickup Included in Stellantis Hydrogen Rollout." Green Car Reports, May 7, 2024. Accessed April 8, 2025. *https://www.greencarreports.com/news/1143092_hydrogen-fuel-cell-ram-hd-pickup-stellantis*.

235 Green Car Congress, "GM Piloting Medium-Duty Fuel Cell Trucks and Low-Emissions Worksites," March 6, 2024. Accessed March 5, 2025. *https://www.greencarcongress.com/2024/03/20240306-gm.html*.

236 Brett Foote, "Ford F-550 Super Duty Hydrogen Fuel Cell Supply Plans Revealed," Ford Authority, September 14, 2022. Accessed March 5, 2025. *https://fordauthority.com/2022/09/ford-f-550-super-duty-hydrogen-fuel-cell-supply-plans-revealed/*.

237 Hexagon Purus, "Class 6 Fuel Cell Electric Truck Powered by Hexagon Purus and Ballard Launched at ACT Expo," August 31, 2021. Accessed March 5, 2025. *https://hexagonpurus.com/news/class-6-fuel-cell-electric-truck-powered-by-hexagon-purus-and-ballard-launched-at-act-expo*.

Utility Truck, Sweeper

There are two commercially available hydrogen fuel cell sweepers. Green Machines, based in the Netherlands, offers a smaller unit, the GM 500H2, in Europe. Global Environmental Products offers a full-size model for the U.S. market. This sweeper offers a speed of 12 miles per hour sweeping speed and sweeps up to three tons of sand per minute.[238] A study was commissioned by the California Department of Transportation (Caltrans) and carried out by the College of Engineering at the University of California at Riverside, comparing this sweeper to compressed natural gas (CNG) and diesel-powered sweepers. The report concluded that hydrogen fuel cell sweepers "are a viable alternative to current street sweeper technologies." See *Appendix E* for more information on this study. With the data provided by this report, hydrogen fuel cell sweepers achieve a Technology Readiness

Staff is seeking information on hydrogen fuel cell CHE demonstration projects and development status.

Grade of Limited.

Emissions Benefits and Considerations

Hydrogen fuel cells produce water and heat as their only byproducts, emitting none of the local emissions of PM2.5, NOx, air toxics, and other harmful pollutants that are produced by diesel-powered CHE. Additionally, hydrogen fuel cell CHE has several potential indirect emissions and environmental benefits. For example, it uses fewer batteries resulting in reduced overall life-cycle emissions and e-waste from spent batteries. This CHE also does not rely on the grid which can help reduce reliance on peaker plants during high demand periods.

There can be upstream emissions associated with hydrogen production, distribution, and storage. Emissions from hydrogen production are dependent upon the source of hydrogen. 95% of the hydrogen produced in the United States is from steam methane reformation (SMR).[239] SMR is an established production method that uses high-temperature steam (700°C to 1,000°C) to generate hydrogen from a methane source, such as natural gas. However, SMR produces CO2, that can be captured but the process is costly and subject to

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[238] Global Environmental Products, "M4/M4HSD Hydrogen Fuel Cell," n.d. Accessed December 9, 2024. *https://globalsweeper.com/products/mechanical/m4hsd-fuel-cell*.

[239] U.S. Department of Energy, "Hydrogen Resources," n.d. Accessed April 10, 2025. *https://www.energy.gov/eere/fuelcells/hydrogen-resources*.

uncertainties in terms of capital expenditures and long-term carbon storage viability. Hydrogen from renewable methane sources can significantly reduce life-cycle GHG emissions.

Electrolysis can be used to produce renewable hydrogen. The process splits water into hydrogen and oxygen, producing no direct emissions, although it requires large amounts of electricity. If electricity is produced via renewable resources, the overall production emissions can be significantly reduced. For additional methods of hydrogen production and associated emissions, see the International Energy Agency's report *Towards Hydrogen Definitions Based on Their Emissions Intensity*.[240]

Transporting hydrogen using fossil fuel trucks produces emissions. Storing hydrogen in either gaseous or liquid form also requires energy, usually in the form of electricity. Depending on the electricity source, emissions associated with storing hydrogen can vary.

Hydrogen is not a GHG but has indirect GHG effects. It is highly reactive and can either produce or extend the lifetime of other GHGs such as methane, ozone, and stratospheric water vapor. Hydrogen leaks, common in hydrogen infrastructure, can weaken climate benefits.[241] Hydrogen's warming potency strongly depends on the time horizon. A recent study found that the estimated 100-year horizon Global Warming Potential (GWP) of hydrogen to be almost 12 times that of CO2.[242] Reducing hydrogen leaks can be difficult, as hydrogen molecules are much smaller and lighter than those of natural gas. One study estimated the hydrogen loss rate during production and storage can be up to 4.2%.[243] The total hydrogen leakage rate from hydrogen infrastructure remains uncertain as data is limited.

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[240] Simon Bennet, et al. "Towards Hydrogen Definitions Based on Their Emissions Intensity," International Energy Agency, April 2023. *https://iea.blob.core.windows.net/assets/acc7a642-e42b-4972-8893-2f03bf0bfa03/Towardshydrogendefinitionsbasedontheiremissionsintensity.pdf*.

[241] Environmental Defense Fund, "STUDY: Emissions of Hydrogen Could Undermine Its Climate Benefits; Warming Effects Are Two to Six Times Higher Than Previously Thought," July 19, 2022. Accessed March 5, 2025. *https://www.edf.org/media/study-emissions-hydrogen-could-undermine-its-climate-benefits-warming-effects-are-two-six*.

[242] Maria Sand, et al. "A Multi-model Assessment of the Global Warming Potential of Hydrogen," *Communications Earth & Environment* 4, no. 203 (2023). *https://doi.org/10.1038/s43247-023-00857-8*.

[243] Iris M. Westra, et al. "First Detection of Industrial Hydrogen Emissions Using High Precision Mobile Measurements in Ambient Air," Scientific Reports 14, no. 24147 (2024). *https://doi.org/10.1038/s41598-024-76373-2*.

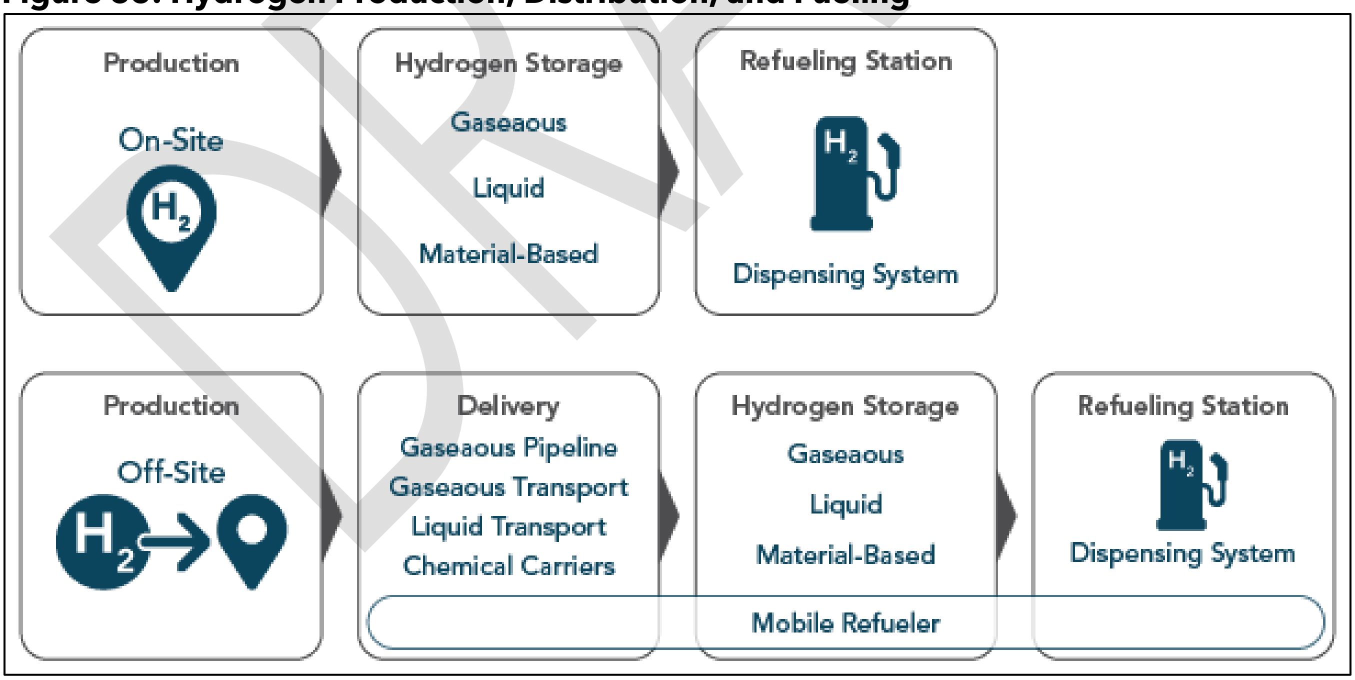
Life-cycle GHGs vary based on the hydrogen source, with renewable hydrogen offering the lowest carbon footprint. As hydrogen production shifts towards cleaner methods, its life-cycle GHG emissions will continue to decrease, making hydrogen more sustainable.

Infrastructure Requirements and Considerations

California has made investments in hydrogen as part of its efforts to reduce emissions, particularly in the transportation and industrial sectors. Hydrogen infrastructure, including hydrogen production, storage, distribution, and refueling stations, is designed to support the growing demand for hydrogen fuel. Figure 55 illustrates the process of hydrogen production, distribution, and fueling for seaport and intermodal railyard uses. This section discusses requirements and considerations for the aspects of hydrogen infrastructure listed below.

- Hydrogen supply – includes hydrogen production methods and current projects intending to increase hydrogen supply in California.
- Hydrogen delivery – includes different hydrogen delivery methods.
    - Mobile refuelers – includes several types of mobile hydrogen refuelers.
- Hydrogen storage – includes different hydrogen storage methods.
- Safety – includes current safety standards for hydrogen.
- Hydrogen fueling station – includes fueling station components, permitting requirements, and hydrogen dispensing codes and standards.

Figure 55: Hydrogen Production, Distribution, and Fueling



Hydrogen Supply

Although hydrogen is abundant, it rarely exists alone in nature and must be extracted from organic compounds before it can be used as fuel for hydrogen fuel cells. Common methods to produce hydrogen include SMR, partial oxidation of methane, gasification of biomass or coal feedstocks, water electrolysis powered by electricity, biomass-to-liquids (ethanol) followed by reformation, microbial biomass conversion (dark fermentation), and ammonia cracking.[244] In 2025, SMR, is the leading hydrogen production method in the U.S.[245]

Each method of hydrogen production has an associated GHG emissions output.[246] Even though fuel cell CHE technology has zero tailpipe emissions, depending on the source, some hydrogen production methods produce emissions that impact air quality and contribute to GHGs and climate change. Renewable hydrogen offers a sustainable alternative to fossil fuel-derived hydrogen.

The U.S. currently produces approximately 10 million metric tons of hydrogen annually. Research indicates that the potential hydrogen demand could reach an estimated 166 million metric tons by 2050.[247] Many projects in California are underway to develop and enhance future hydrogen supply. In July 2024, the U.S. Department of Energy (DOE) and the Alliance for Renewable Clean Hydrogen Energy Systems (ARCHES) signed a $12.6 billion agreement to establish the California Hydrogen Hub.[248] ARCHES projects will cover the entire hydrogen lifecycle, from production and transportation to usage. ARCHES aims to achieve the major initiatives listed below.[249]

- Replace diesel-powered equipment at major seaports with hydrogen fuel cell alternatives.
- Construct over 60 hydrogen fueling stations.

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[244] Eastern Research Group, Inc. "Assessment of Fuel Cell Technologies at Ports," U.S. Environmental Protection Agency, July 2022. *https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1015AQX.pdf*.

[245] Today in Energy, "Natural gas remains the largest source of hydrogen in our long-term projections" U.S. Energy Information Administration, August 4, 2025. Accessed September 16, 2025. *https://www.eia.gov/todayinenergy/detail.php?id=65845*.

[246] "Carbon Intensity of Hydrogen Production Methods Supporting the BC Hydrogen Strategy," Report, *Cice.Ca*, 2023. Accessed March 6, 2025. *https://www2.gov.bc.ca/assets/gov/business/natural-resource-industries/reports/carbon_intensity_of_hydrogen_production_methods.pdf*

[247] Eastern Research Group, Inc. "Assessment of Fuel Cell Technologies at Ports," U.S. Environmental Protection Agency, July 2022. *https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1015AQX.pdf*.

[248] Arches H2, "California's Renewable Hydrogen Hub Officially Launches," July 17, 2024. Accessed December 6, 2024. *https://archesh2.org/arches-officially-launches/.*

[249] Pipeline & Gas Journal, "California Secures $12.6 Billion for Hydrogen Hub Development", July 23, 2024. Accessed December 6, 2024. *California Secures $12.6 Billion for Hydrogen Hub Development | Pipeline and Gas Journal*.

- Convert key power plants to run on 100% renewable hydrogen.

It will take an estimated 7 to 11 years to complete development of the California Hydrogen Hub.[250] In August 2024, ARCHES launched its first hydrogen hub to accelerate the development and deployment of renewable hydrogen.[251] Several individual projects are also boosting hydrogen supply in California. See *Appendix I* for more information on hydrogen projects in California.

On-site hydrogen production eliminates the need for fuel transportation, which simplifies logistics, minimizes leakage risks, and can reduce costs. However, this option presents challenges including feedstock supply, emissions risks, space-constraints at some facilities, and high initial capital costs.

Air Products has developed compact and modular hydrogen generation systems, offering two hydrogen production options: SMR and hydrogen electrolysis. Their system offers advantages such as easy installation, high reliability, and a flexible range of hydrogen production capacity. It can produce 200 to 1800 kg of hydrogen per day.[252] One H2 has designed two models of modular hydrogen production systems with SMR technology. The H200 system can produce up to 200 kg/day of gaseous hydrogen. The H400.B system can produce up to 400 kg/day of gaseous hydrogen. The unit takes around one week to install, and it takes around 630 square feet of footprint.[253]

Hydrogen Delivery

If hydrogen is produced at a centralized production facility, it must be transported to the point of use. There are various methods of hydrogen delivery, each suited to specific applications based on factors such as temperature requirements, cost, use cases, and transport distances.

Gaseous Pipelines

Gaseous pipelines can transport hydrogen in pressurized gas form. Pipelines are the most cost-effective method for transporting large volumes of hydrogen over distances of

[250] California Air Resources Board, "Advanced Clean Fleets Regulation Truck Regulation Implementation Group (TRIG) – Infrastructure Meeting 5," n.d. Accessed December 6, 2024. *https://ww2.arb.ca.gov/sites/default/files/2025-03/241104triginfra_otherslides_ADA.pdf*

[251] Container News, "Port of Oakland Unveils US First ARCHES Hydrogen Hub", September 4, 2024. Accessed December 6, 2024. *Port of Oakland unveils US first ARCHES hydrogen hub - Container News*.

[252] Air Products, "Hydrogen Onsite Generators", n.d. Accessed February 18, 2025. *https://www.airproducts.com/equipment/hydrogen-onsite-generators*.

[253] One H2, "ON-SITE GENERATION", n.d. Accessed February 18, 2025. *https://oneh2.com/solutions/on-site-generation/*.

approximately 1,000 miles or more. In the U.S., approximately 1,600 miles of hydrogen pipelines have been established to facilitate local and regional hydrogen delivery.[254] The high initial capital investment required for new pipeline construction poses a barrier to the expansion of hydrogen pipeline delivery infrastructure.

In Europe, the North Sea Port is establishing a cross-border hydrogen pipeline network to become a key hydrogen hub. Existing pipelines are being upgraded where feasible, while new pipelines are being constructed as needed. The network is expected to be completed by 2026.[255]

Existing natural gas pipelines could potentially be modified for hydrogen transport, minimizing the need for extensive new infrastructure development. The concept of natural gas pipeline modification is still under research.

Gaseous Transport

Gaseous hydrogen is typically produced at low pressures of 20–30 bar and must be compressed before transport. It is transported using *tube trailers*, which are specially designed trucks equipped with long, high-pressure cylinders (Figure 56). Hydrogen is compressed to approximately 180 bar or higher and stored in these cylinders that are stacked on the trailer. The elongated shape of the storage cylinders gives rise to the term tube trailer. Gaseous hydrogen can be a better option for smaller applications and local distribution due to its simpler storage and handling. However, hydrogen compression can be challenging due to the tight tolerances needed for materials to prevent leakage.

[254] Eastern Research Group, Inc. "Assessment of Fuel Cell Technologies at Ports," U.S. Environmental Protection Agency, July 2022. *https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1015AQX.pdf*.

[255] North Sea Port, "Hydrogen: The Potential of North Sea Port," n.d. Accessed March 11, 2025. *https://en.northseaport.com/hydrogen-the-potential-of-north-sea-port*.

Figure 56: High Pressure Tube Trailer for Hydrogen Delivery

Liquid Transport

Liquid hydrogen is more energy-dense and efficient for long-distance transport. A liquid hydrogen tanker can carry around 4,000 kg of hydrogen compared to a gaseous hydrogen tube trailer that holds around 300 kg of hydrogen.[256] When large-scale hydrogen transport is required and pipelines are not available, hydrogen is commonly transported in liquid form. Liquefaction involves cooling hydrogen to cryogenic temperatures of -253°C or -423°F, to convert it into a liquid state. But storing and transporting liquid hydrogen is more challenging than gaseous hydrogen. This is due to the low temperatures required, which necessitates complex and energy-intensive infrastructure. Specialized trucks, known as liquid tankers, are used to transport and deliver liquid hydrogen efficiently (Figure 57). Currently, liquid hydrogen is transported by vacuum-insulated cryogenic tanker trucks over longer distances. Upon delivery, liquid hydrogen is first transferred into a liquid hydrogen storage tank at the station site, then vaporized and pressurized for dispensing. Maintaining a

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[256] Winston Cheng, and Y. Frank Cheng, "A Techno-Economic Study of the Strategy for Hydrogen Transport by Pipelines in Canada," *Journal of Pipeline Science and Engineering* 3, no. 3 (2023): 100112. *https://doi.org/10.1016/j.jpse.2023.100112*.

liquid hydrogen storage tank at an ideal temperature, close to -253°C, consumes energy and hydrogen can be lost through evaporation or *boil-off* of liquefied hydrogen during transportation and tank transfer. Liquid hydrogen delivery can be more expensive per trip than gaseous hydrogen, but it contains more hydrogen mass per trip than a gaseous tube trailer.

Figure 57: Liquified Hydrogen Tankers for Hydrogen Delivery (NASA)

Mobile Refuelers

Mobile refuelers are portable trailer-mounted units designed to deliver hydrogen to remote locations or areas with lower demand. Mobile refuelers are used for hydrogen delivery, storage, and dispensing. There is interest in hydrogen mobile refuelers, as they are an option for fuel distribution that can benefit high-throughput clusters, such as seaports and intermodal railyards, and can serve as a bridge option to encourage early adoption of hydrogen fuel cell CHE while permanent fueling stations are being built.

OEMs such as Nikola and Air Liquide are developing mobile refuelers that are capable of directly fueling medium-duty and heavy-duty fuel cell vehicles at different locations that meet the needs of the drivers.[257] The OneH2 mobile refueler at the Port of Los Angeles (Figure 58) fuels the fuel-cell RTG crane at the Yusen Terminal, delivering hydrogen at 930 bar to fill 700-bar tanks. It supplies 247 kg or 495 kg of hydrogen, depending on the setup.[258]

Figure 58: One H2's Mobile Hydrogen Refueler[259]

The BayoTech GTM1500 mobile refueler has a storage capacity of 146.6 kg, with operating temperatures ranging from -40 ˚C to 65 ˚C.[260] The Air Products HF-150 mobile refueler has an 80 kg capacity, with operating temperatures ranging from -40 ˚C to 65 ˚C, and 450 bar.[261] Nikola/HYLA offers a hydrogen tube storage trailer with 300 kg capacity at 178 bar and 960 kg capacity at 517 bar. The storage trailer is designed to be used in conjunction with the

[257] California Energy Commission, "Senate Bill 643: Clean Hydrogen Fuel Production and Refueling Infrastructure to Support Medium- and Heavy-Duty Fuel Cell Electric Vehicles and Off-Road Applications," January 24, 2024. Accessed December 6, 2024. *https://www.energy.ca.gov/publications/2023/senate-bill-643-clean-hydrogen-fuel-production-and-refueling-infrastructure.*

[258] Word Cargo News, "Refuelling Hydrogen RTG in LA," October 14, 2024. Accessed April 8, 2025. *https://www.worldcargonews.com/cargo-handling-equipment/2024/10/refuelling-hydrogen-rtg-in-la/*.

[259] Port of Long Beach and Port of Los Angeles, "San Pedro Bay Ports Clean Air Action Plan", July 2024. Accessed October 8th, 2025. *https://cleanairactionplan.org/wp-admin/admin-ajax.php?juwpfisadmin=false&action=wpfd&task=file.download&wpfd_category_id=230&wpfd_file_id=5292&token=&preview=1*

[260] California Air Resources Board, "LCTI: Demonstration of Zero-Emission Technologies for Freight Operations at Ports," n.d. Accessed April 14, 2025. *https://ww2.arb.ca.gov/lcti-demonstration-zero-emission-technologies-freight-operations-ports*.

[261] Ibid.

Nikola/HYLA mobile refueler.[262] Hylium Industries created mobile refuelers that can carry up to 2,500 liters of 3 bar low-pressure liquid hydrogen in a 5-ton truck. The units can refuel 6 kg of hydrogen in 5 minutes.[263] Hexagon Purus designed a mobile refueler with high-pressure cylinder systems. The mobile refueler can be modified to serve both on-road and off-road applications.[264]

Chemical Carriers

The use of chemical hydrogen carriers is another emerging hydrogen delivery method. This involves binding hydrogen with other elements to form a variety of compounds, which may be easier or more cost effective to transport. After transport, the hydrogen is separated out before or during consumption.

Table 38 summarizes the common hydrogen delivery methods and their key attributes. Chemical carrier transport is not listed in the table because it has not been proven on a large scale. [265]

Table 38: Different Hydrogen Delivery Methods and Their Key Attributes

Hydrogen Delivery Methods	Attributes
Gaseous Pipeline	• Stored at ambient temperature • High capital cost • Cost effective for long-distance transportation
High Pressure Tube Trailer (Gaseous Hydrogen)	• Stored at ambient temperature • Lower cost per delivery trip than liquid hydrogen • Can be used for small applications/local distribution
Liquefied Hydrogen Tanker	• Stored at -253 ˚C (-423 ˚F) • Higher cost per delivery trip than compressed gas hydrogen • Can be used for short or long-distance transport/large needs

[262] Nikola Corporation, "HYLA Hydrogen Mobile Fuelers," February 2, 2023. Accessed December 6, 2024. *https://www.nikolamotor.com/wp-content/uploads/2023/04/HYL007_HYLA-Mobile-Fuelers-Brochure-02.02.23-1.pdf.*

[263] Hylium Industries Inc., "H2 Refueling Station HYMS350B (Mobile Hydrogen Refueling Station," July 24, 2024. Accessed March 11, 2025. *https://hylium-industries.com/products/?q=YToxOntzOjEyOiJrZXl3b3JkX3R5cGUiO3M6MzoiYWxsIjt9&bmode=view&idx=50363415&t=board&category=1R4X072134*.

[264] Hexagon Purus, "Refueling Systems," April 11, 2024. Accessed March 11, 2025. *https://hexagonpurus.com/our-solutions/refueling-systems*.

[265] U.S. Department of Energy, "Novel Hydrogen Carriers," n.d. Accessed March 6, 2025. *https://www.energy.gov/eere/fuelcells/novel-hydrogen-carriers*.

Hydrogen Delivery Methods	Attributes
Mobile Refueler	• Stored at ambient temperature or -253 ˚C (-423 ˚F) depending on if hydrogen is liquid or compressed gas • High capital cost • Solution for remote locations or areas with lower demand • Can be a temporary solution while waiting for permitting for a permanent solution.

Hydrogen production to end-use delivery generally follows two pathways:

- Centralized delivery - Involves large-scale hydrogen production (50,000-500,000 kg/day) and serves regional or national end-use markets, depending on plant location. Hydrogen can be transported via pipeline, truck, or rail.
- Distributed delivery - Support local or regional end-use markets such as seaports and railyards with on-site or near on-site hydrogen production.

The selection between centralized and distributed hydrogen delivery pathways is influenced by several factors, including the availability and proximity of feedstocks and energy sources, the scale of regional or local markets, the efficiency and cost-effectiveness of hydrogen production methods, and the market, environmental, and socioeconomic impacts associated with hydrogen production.

Hydrogen Storage

Facilities use three hydrogen storage methods. Each method has advantages and challenges. Space requirements and regulatory considerations may also affect the preferred hydrogen storage method.

Gaseous Storage

Gas compression is a well-established technology for hydrogen storage. High-pressure gaseous hydrogen storage typically uses large cylindrical steel storage tanks. The tanks are typically composed of all-steel or steel fiber-wrapped steel. Gaseous hydrogen is typically stored at pressures of 180 bar or above to increase energy density. Hydrogen embrittlement can be a challenge for storing gaseous hydrogen.[266] Modern storage solutions such as Type IV composite tanks with polymer liners have significantly mitigated this risk for many storage applications and ongoing engineering efforts continue to address

[266] TWI, "What Is Hydrogen Embrittlement? - Causes, Effects and Prevention," n.d. Accessed March 6, 2025. https://www.twi-global.com/technical-knowledge/faqs/what-is-hydrogen-embrittlement.

embrittlement in metallic components such as valves and pipelines.[267] Thus, materials required for gaseous hydrogen storage can be costly. Since gaseous hydrogen can exist at ambient temperatures, specialized cooling equipment is not required. As a result, gaseous hydrogen infrastructure is simpler compared to liquid hydrogen infrastructure.

Liquid Storage

Liquid hydrogen storage is ideal for large-scale energy storage due to its high density, although it requires cryogenic temperatures. Storing hydrogen as cryogenic liquid increases the energy density. Liquid hydrogen has density of around 70 kg/m^3. Gaseous hydrogen has a density of around 20 to 40 kg/m^3 depending on the pressure.[268] Thus, liquid hydrogen is favorable for storing large volumes. Additionally, liquid hydrogen refueling systems (filling gaseous storage tanks on equipment), can achieve faster refueling times compared to gaseous systems.[269] High energy requirements for liquefaction is one challenge associated with liquid hydrogen storage. Liquid hydrogen is stored at low pressures in vacuum-insulated tanks with an outer carbon steel shell to maintain its cryogenic state. To prevent over-pressurization, these tanks must be periodically vented to release boil-off hydrogen vapor. Storage of hydrogen as a liquid requires about 1 bar of pressure which is far less pressure than gaseous hydrogen.[270]

Materials-Based Storage

Hydrogen can also be stored on the surfaces of solids by adsorption, or within solids by absorption.[271] Ongoing research is focused on metal hydrides, chemical hydrogen storage, and sorbent materials. Scientists are researching solid-state hydrogen storage technologies due to their high reliability, volumetric efficiency, and safety. However, the technology is new and in the development phase. Other challenges associated with this technology are high costs, small storage capacity, and additional weight for mobile transport.

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[267] Li, Xiang et al., "Review of the Hydrogen Permeation Test of the Polymer Liner Material of Type IV On-Board Hydrogen Storage Cylinders." Materials 16, no. 15 (July 31, 2023): 5366, *https://doi.org/10.3390/ma16155366.*

[268] Quian Cheng, et al., "Review of Common Hydrogen Storage Tanks and Current Manufacturing Methods for Aluminum Alloy Tank Liners," *International Journal of Lightweight Materials and Manufacture* 7, no. 2 (2023): 269–84. *https://doi.org/10.1016/j.ijlmm.2023.08.002*.

[269] Andrew Burke, Joan Ogden, Lewis Fulton, and Simonas Cerniauskas, "Hydrogen Storage and Transport: Technologies and Costs," Institute of Transportation Studies, UC Davis. February 27, 2024. *https://escholarship.org/content/qt83p5k54m/qt83p5k54m_noSplash_8bb1326c13cfb9aa3d0d376ec26d3e06.pdf?t=s9oa2u.*

[270] Ibid.

[271] U.S. Department of Energy, "Hydrogen Storage," n.d. Accessed December 9, 2024. *https://www.energy.gov/eere/fuelcells/hydrogen-storage*

Table 39 summarizes the different hydrogen storage methods, their key attributes, advantages, and disadvantages.

Table 39: Different Hydrogen Storage Methods and Their Key Attributes

Hydrogen Storage Method	Attributes	Advantages	Disadvantages
Gaseous	• Stored at ambient temperature • High pressure (180 bar or above)	• Well-established technology • Simpler storage and handling than liquid hydrogen	• Hydrogen embrittlement • Costly materials
Liquid	• Stored at -253 ˚C (-423 ˚F) • Ambient pressure (around 1 bar)	• High density • Efficient refueling for heavy-duty equipment	• Boil-off losses • High energy requirement for liquefaction
Material-Based	• Stored at ambient temperature • Ambient pressure (around 1 bar)	• High reliability • Volumetric efficiency • Safety	• Immature technology • High capital costs • Small storage capacity • Additional weight

Safety

Proper handling and storage are critical due to hydrogen's high flammability and potential for invisible flames. Key safety measures include regular inspections of storage tanks, use of materials resistant to hydrogen embrittlement, and robust ventilation systems to prevent gas accumulation. Personnel should be well-trained in emergency response procedures. Adhering to safety codes and regulations, such as those from the National Fire Protection Association[272] and the California Fire Code,[273] is critical for maintaining safe operations. For more information on hydrogen refueling station safety codes and standards, see the Office of Energy Efficiency and Renewable Energy's Hydrogen Safety Codes & Standards Applicability Navigator.[274]

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[272] The National Fire Protection Association, "NFPA 2: Hydrogen Technologies Code (2023)," 2023. https://www.nfpa.org/.

[273] California Fire Code, "Section 5809 Flammable Gases and Flammable Cryogenic Fluids, Mobile Gaseous Fueling of Hydrogen-Fueled Vehicles," 2022. *https://up.codes/viewer/california/ca-fire-code-2022-1/chapter/58/flammable-gases-and-flammable-cryogenic-fluids#5809*.

[274] Hydrogen Safety Codes & Standards Applicability Navigator. Accessed September 9, 2025. *https://h2tools.org/hyscan/*.

The permitting process for hydrogen storage and dispensing in the U.S. is still evolving, with local fire departments continuously updating regulations and standards and aligning with international standards. For instance, at the Port of Los Angeles, a special use permit is required for hydrogen handling that must be renewed annually. The approval process for obtaining such permits typically takes around three to six months.

Hydrogen Fueling Stations

A hydrogen fueling station includes compressors, storage tanks, dispensers, chillers, electrical and piping controls, and safety monitoring systems. The fueling process is similar to diesel filling, using a nozzle for quick refueling.

In June 2024, Calvera and CNH2 launched the first portable hydrogen fueling station for railway vehicles in Spain. The station is modular and can operate in different configurations. The portable station consists of four 20-foot containers including a compressor container, two storage containers, and a dispenser.[275]

Some safety and performance standards that apply to hydrogen fueling for heavy-duty vehicles may also apply to fueling stations for CHE. The National Standard of Canada/American National Standard for hydrogen-dispensing systems (HGV 4.1, 2013) outlines requirements for the design, construction, and operation of hydrogen dispensing systems. This standard is currently undergoing modifications. Additionally, the SAE J2601-5 standard establishes high-flow hydrogen fueling protocols for medium- and heavy-duty vehicles. The protocol addresses safety issues while ensuring the fueling performance is competitive with conventional refueling.

There are several documents that provide guidance on the development and operation of hydrogen fueling stations. The *Hydrogen Station Permitting Guidebook* from the California Governor's Office of Business and Economic Development offers guidelines for permitting, best practices, and operating requirements for hydrogen fueling stations.[276] They also provide support and resources to hydrogen station developers and local officials to help educate and expedite permitting processes. The CARB document "Advanced Technology Demonstration and Pilot Projects, Appendix C Hydrogen Refueling Station Requirements"

[275] BH2C, "CNH2 Launches a Portable Hydrogen Refueling Station for Trains as Part of the FCH2RAIL Project," June 28, 2024. Accessed December 6, 2024. *https://www.bh2c.org/en/news/cnh2-launches-portable-hydrogen-refuelling-station-trains-part-fch2rail-project.*

[276] California Governor's Office of Business and Economic Development, "Hydrogen Station Permitting Guidebook," September 2020. *https://business.ca.gov/wp-content/uploads/2019/12/GO-Biz_Hydrogen-Station-Permitting-Guidebook_Sept-2020.pdf.*

discusses minimum technical requirements for hydrogen fueling station to be eligible for fund applications.[277]

Constructing hydrogen fueling stations can be a lengthy process as it requires iterative interactions with the permitting authority and fire department. According to a CEC report, the estimated timeline for commissioning a hydrogen station can take up to 22 months, depending on hydrogen delivery methods.[278] The timeline may also vary based on the station's proposed location, with permitting often taking longer in areas lacking prior experience with hydrogen infrastructure.

Staff is seeking information on hydrogen fueling infrastructure.

Economics

Costs associated with hydrogen fuel cell CHE include both capital costs and ongoing operating costs for the equipment and infrastructure. Table 40 summarizes the capital and operating costs associated with hydrogen fuel cell CHE. This assessment includes the costs for different hydrogen refueling options, which are dependent upon the needs of the facility.

Table 40: Hydrogen Fuel Cell CHE Capital Costs and Operating Costs

Capital Costs	Operating Costs
• Equipment o CHE o Mobile refueler (optional) • Infrastructure installation o On-site hydrogen production system (optional) o Fueling station (optional)	• Equipment fuel • Equipment maintenance • Midlife battery replacement • Infrastructure maintenance • Infrastructure operation • Mobile refueler service (optional)

[277] California Air Resources Board, "Appendix C Hydrogen Refueling Station Requirements," July 2023. *https://ww2.arb.ca.gov/sites/default/files/2023-07/fy21-23demoandpilot_appc.pdf*.

[278] Kate Forrest, et. al, "A Replicable Infrastructure Blueprint for Zero-Emission Medium- and Heavy-Duty Vehicles in the South Coast Air Basin," California Energy Commission, August 2023. *https://cleanenergy.uci.edu/PDF_White_Papers/ARV-21-018_Blueprint.pdf*.

Equipment Capital Costs

The current cost of fuel cell CHE remains significantly higher than that of comparable diesel CHE. Fuel cell CHE capital costs are typically 2.5 to 3 times higher than diesel.[279] The cost disparity is largely due to differences in production scale, with diesel systems benefiting from well-established economies of scale. However, research and development efforts have led to reductions in fuel cell system costs over the past decade and further cost declines are anticipated. The United States Department of Energy (U.S. DOE) projects that as production scales increase, the cost of fuel cell systems for forklifts and stationary generators will decrease by approximately 61% and 37%, respectively.[280] Some facilities may decide to purchase mobile refueling equipment when purchasing hydrogen fuel cell CHE. These costs are discussed in the infrastructure costs below.

Equipment Operating Costs

Hydrogen fuel cell CHE operating costs include equipment fuel and maintenance costs. As hydrogen fuel cells typically work in tandem with batteries, midlife battery replacement costs are also included in the operating costs for fuel cell CHE.

Fuel Costs

Hydrogen fuel costs are highly variable by location. Factors such as feedstock, hydrogen production methods, storage, distribution, and dispensing at fueling stations can affect the point-of-use cost. According to the U.S. DOE, in 2023, the average retail price of hydrogen fuel for transportation is around $13/kg in the U.S.[281] In some areas of California, the price of hydrogen at the pump can be over $36/kg.[282] The high price of hydrogen fuel is related to high operating costs for small-sized stations. Other factors such as maintenance costs, down-time related costs, and lack of hydrogen availability are also contributors to the high price of hydrogen fuel. Future hydrogen prices remain uncertain. Economies of scale for hydrogen production can bring down the price. ARCHES has a goal of achieving a $5 to $6

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[279] Claimed confidential data obtained from an industry source that requested non-attribution.

[280] U.S. Department of Energy, "Hydrogen and Fuel Cell Program Overview," May 13, 2018. Accessed February 19, 2025. *https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review18/01_satyapal_plenary_2018_amr.pdf?Status=Master*.

[281] U.S. Department of Energy, "Hydrogen's Role in Transportation," February 25, 2022. Accessed November 25, 2024. *https://www.energy.gov/eere/vehicles/articles/hydrogens-role-transportation*.

[282] ARCHES Transportation Working Group, "Transportation White Paper," ARCHES H2, October 2024. *https://archesh2.org/wp-content/uploads/2024/10/ARCHES_Transportation_White_Paper-2.pdf.*; Nikesh Kooverjee, "Here's How Much It Costs to Refill a Hydrogen-powered Toyota Mirai," TopSpeed.com, February 17, 2024. Accessed April 11, 2025. *https://www.topspeed.com/how-much-costs-to-refill-hydrogen-powered-toyota-mirai/*.

refueling cost (outside of any taxes and subsidies) for hydrogen dispensed at 700 bar by the year 2030, making it competitive with diesel.[283]

Maintenance Costs

Maintenance costs for hydrogen fuel cell CHE remain uncertain as most are still under development or in the demonstration phase.

Table 41 through Table 43 compare the costs of hydrogen fuel cell and diesel-powered CHE. Due to limited commercial availability and operating data, staff only obtained cost information for hydrogen fuel cell large capacity forklifts, top handlers, and yard trucks.

Table 41: Cost Comparison Between a Hydrogen Fuel Cell and Diesel-Powered Forklift (2024$)

Cost Component	Hydrogen Fuel Cell	Diesel
Equipment Capital	$450,000 to $950,000	$240,000 to $420,000
Battery Replacement	$60,000 to $130,000[284]	N/A
Fuel	$32,800 per year[285]	$2,200 to $2,900 per year[286]
Maintenance	[Staff is seeking information]	$25,000 per year[287]

Note: Data without a footnote was obtained from an industry source that requested non-attribution.

[283] ARCHES Transportation Working Group, "Transportation White Paper," ARCHES H2, October 2024. *https://archesh2.org/wp-content/uploads/2024/10/ARCHES_Transportation_White_Paper-2.pdf.*

[284] CARB staff applied the battery replacement cost of battery-electric large-capacity forklifts to hydrogen fuel cell large-capacity forklifts.

[285] Cost = 200 kW x 153 h/year x 1 kg hydrogen/33.6 kWh x $36/kg hydrogen = $32,786 per year. The fuel cost calculation does not consider incentives such as the LCFS nor any special electricity rates offered by utility providers. In calculation, it is assumed per kg of hydrogen is equal to 33.6 kWh of usable energy. The information is sourced from: Patrick Molloy, "Run on Less with Hydrogen Fuel Cells," RMI, March 2, 2022. *https://rmi.org/run-on-less-with-hydrogen-fuel-cells/*.

[286] Cost = 0.71 to 0.95 gallon/h x 733 h/year x $4.13/gallon = $2,149 to $2,876 per year. Fuel efficiency is sourced from web source: Paul Hinz, "How Much Diesel Does a Forklift Use Per Hour?" Adaptalift Group, September 21, 2021. *https://www.adaptalift.com.au/blog/how-much-diesel-does-a-forklift-use-per-hour.*

[287] Dan Wei and Genevieve Giuliano, "Implementation of Action 6 of CSFAP Phase 3 Tracking Economic Competitiveness Part 3: Economic Impacts of Electrification of Cargo Handling Equipment at POLA/POLB," August 1, 2021. *https://doi.org/10.25554/8drs-9j23*.

Table 42: Cost Comparison Between a Hydrogen Fuel Cell and Diesel-Powered Top Handler (2020$)

Cost Component	Hydrogen Fuel Cell	Diesel
Equipment Capital	$727,078[288]	$584,500[289]
Battery Replacement	[Staff is seeking information]	N/A
Fuel	$124,767 per year[290]	$72,594 per year[291]
Maintenance	$6,767 per year[292]	$5,123 per year[293]

Table 43: Cost Comparison Between a Hydrogen Fuel Cell and Diesel-Powered Yard Truck (2020$)

Cost Component	Hydrogen Fuel Cell	Diesel
Equipment Capital	$225,000[294]	$110,000[295]
Battery Replacement	[Staff is seeking information]	N/A
Fuel	$32,966 per year[296]	$19,181 per year[297]
Maintenance	$5,498 per year[298]	$3,800 per year[299]

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[288] Eastern Research Group, Inc. "Assessment of Fuel Cell Technologies at Ports," U.S. Environmental Protection Agency, July 2022. *https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1015AQX.pdf*.

[289] Ibid.

[290] Ibid.

[291] Ibid.

[292] According to the U.S. EPA assessment, this maintenance costs includes a "onetime lifetime replacement of the fuel cell and battery pack (compared with one engine repower with the diesel unit)."

[293] Eastern Research Group, Inc. "Assessment of Fuel Cell Technologies at Ports," U.S. Environmental Protection Agency, July 2022. *https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1015AQX.pdf*.

[294] Eastern Research Group, Inc. "Assessment of Fuel Cell Technologies at Ports," U.S. Environmental Protection Agency, July 2022. *https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1015AQX.pdf*.

[295] Ibid.

[296] Ibid.

[297] Ibid.

[298] According to the U.S. EPA assessment, this maintenance costs includes a "onetime lifetime replacement of the fuel cell and battery pack (compared with one engine repower with the diesel unit)."

[299] Eastern Research Group, Inc. "Assessment of Fuel Cell Technologies at Ports," U.S. Environmental Protection Agency, July 2022. *https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1015AQX.pdf*.

Infrastructure Costs

Capital Costs for On-Site Production

Infrastructure capital costs for hydrogen fuel cell CHE depend on whether the hydrogen is produced on-site or off-site. On-site hydrogen production can use either SMR or hydrogen electrolysis technologies. The cost of on-site hydrogen production infrastructure varies based on several factors, including production method, production capacity, location, and local regulatory policies.

Capital Costs for Off-Site Production

If hydrogen is produced off-site and fueled on-site, costs can also differ depending on if the fueling station is mobile or stationary. Hydrogen mobile refuelers can be costly due to the high capital investment required for the specialized equipment needed to store and dispense hydrogen under high pressure.

Stationary hydrogen infrastructure costs include hydrogen fueling station installation and operational costs. The capital cost of a hydrogen fueling station can vary depending on the location, daily fueling capacity, and hydrogen storage requirements. Other factors such as engineering planning and design, project contingency, space required for hydrogen storage, etc. should also be considered. According to U.S. DOE, hydrogen refueling stations can cost between approximately $1,200 per kg and $3,000 per kg of hydrogen dispensed per day.[300]

Infrastructure Maintenance

Hydrogen fuel cell infrastructure maintenance costs can include inspection of storage tanks, testing for leaks, and maintenance of compressors and dispensers. Maintenance costs for hydrogen fuel cell infrastructure remain uncertain since there is limited data available.

Infrastructure Operation

Operational costs for hydrogen fueling stations primarily refer to the electricity needed to support hydrogen storage and dispensing operations.

Based on a 2024 analysis from Rocky Mountain Institute and Mission Possible Partnership, the 12-year total cost of ownership of hydrogen fuel cell large-capacity forklifts and yard trucks are economically competitive with battery-electric models in California with the

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[300] Mariya Koleva and Marc Melaina, "DOE Hydrogen Program Record," U.S. Department of Energy, February 11, 2021. *https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/21002-hydrogen-fueling-station-cost.pdf?Status=Master#:~:t*.

consideration of LCFS and CORE (available for forklifts).[301] See *Appendix H* for more information on available incentive programs for hydrogen fuel cell CHE.

In 2022, Argonne National Laboratory released preliminary results of a total cost of ownership analysis for hydrogen fuel cells in off-road heavy-duty applications.[302] They found that the total cost of ownership is lower for fuel cell wheel loaders compared with diesel at $3.25 per gallon and hydrogen at $4.00 per kg.

Argonne National Laboratory has developed the Hydrogen Delivery Scenario Analysis Model (HDSAM) which estimates costs for hydrogen fuel capital, delivery, refueling, operating, and maintenance.[303] The tool could be useful for seaports and intermodal railyard facilities to estimate hydrogen fuel prices at the pump. Table 44 presents hydrogen fuel cell CHE infrastructure related costs.

Table 44: Hydrogen Fuel Cell CHE Infrastructure Related Costs

Cost Component	Cost
On-Site Hydrogen Production	Hydrogen stations producing fuel on-site through water electrolysis with an average storage of 120 kg/day have an estimated total construction and commissioning cost of $3,200,000.[304]
Hydrogen Mobile Refueler	$875,432[305]

[301] Mia Reback, et al. "The Time Is Now for Zero-Emissions Cargo Handling Equipment at America's Busiest Cargo Ports," RMI, November 7, 2024. Accessed November 25, 2024. *https://rmi.org/the-time-is-now-for-zero-emissions-cargo-handling-equipment-at-americas-busiest-cargo-ports/*.

[302] Rajesh Ahluwalia, et al. "Total Cost of Ownership (TCO) Analysis of Hydrogen Fuel Cells in Off Road Heavy-Duty Applications – Preliminary Results," Argonne National Laboratory, 2022. *https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review22/ta065_ahluwalia_2022_o-pdf.pdf?sfvrsn=b1d7af77_0*.

[303] Argonne National Laboratory, "Hydrogen Delivery Scenario Analysis Model (HDSAM)," n.d. Accessed November 25, 2024. *https://hdsam.es.anl.gov/index.php?content=hdsam*.

[304] Hydrogen Fuel Cell Partnership, "Costs and Financing," n.d. Accessed January 10, 2025. *https://h2stationmaps.com/costs-and-financing#retail-station-costs*.

[305] Cost info from HDSAM v4.5. at Veronika Semchukova, et al. "Hydrogen Infrastructure Analysis for Port Applications," National Renewable Energy Laboratory, October 2024. Accessed November 25, 2024. *https://www.nrel.gov/docs/fy25osti/91396.pdf*.

Cost Component	Cost
Hydrogen Fueling Station	Varies • $2,000,000 for stations that use gaseous hydrogen and $2,800,000 for stations that use liquid hydrogen.[306] • The cost for hydrogen fueling stations with a capacity range from 100 to 350 kg/day is estimated to be between $1,510,000 and $2,780,000. The cost for hydrogen fueling stations with on-site production with a capacity range from 100 to 300 kg/day is estimated to be between $2,380,000 and $4,430,000.[307] Cost information from HDSAM v4.5:[308] • $1,750/kg for storage tank • $500,871 for compressor (50 kg/hour) • $1,679/kg for high pressure buffer tank • $142,089 for dispenser (3.6kg/minute) • Project contingency can be 5% of total system installation costs
Hydrogen Fueling Station Operation	• Annual average of $0.48/kWh for electricity for operational costs.[309] • Annual electricity costs range from $3,139 to $9,417 for hydrogen fueling stations with off-site production.[310] • Annual electricity costs range from $7,734 to $415,855 for hydrogen fueling stations with on-site production.[311]

[306] Hydrogen Fuel Cell Partnership, "Costs and Financing," n.d. Accessed January 10, 2025. *https://h2stationmaps.com/costs-and-financing#retail-station-costs*.

[307] Eastern Research Group, Inc. "Assessment of Fuel Cell Technologies at Ports," U.S. Environmental Protection Agency, July 2022. *https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1015AQX.pdf*.

[308] Cost info from HDSAM v4.5. See Veronika Semchukova, et al. "Hydrogen Infrastructure Analysis for Port Applications," National Renewable Energy Laboratory, October 2024. Accessed November 25, 2024. *https://www.nrel.gov/docs/fy25osti/91396.pdf*.

[309] Jacob Goldberg, et al. "Final Project Report The Port of Los Angeles Zero- and Near-Zero-Emission Freight Facilities 'Shore to Store' Project," California Air Resources Board, May 10, 2023.*https://ww2.arb.ca.gov/sites/default/files/2023-05/POLA-Final%20Report.pdf*.

[310] Eastern Research Group, Inc. "Assessment of Fuel Cell Technologies at Ports," U.S. Environmental Protection Agency, July 2022. *https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1015AQX.pdf*.

[311] Ibid.

Cost Component	Cost
Infrastructure Maintenance	• Annual maintenance costs range from $19,530 to $35,620 for hydrogen fueling stations with off-site production.[312] • Annual maintenance costs range from $35,620 to $57,590 for hydrogen fueling stations with on-site production.[313]

Staff is seeking information on costs for hydrogen fuel cell CHE including capital, fuel, infrastructure, maintenance, operational, and other additional costs.

[312] Ibid.
[313] Ibid.

Technology Outlook

Of the 24 types of hydrogen fuel cell CHE assessed for technology readiness, only 4 are commercially available. Of these 4, none achieve a Technology Readiness Grade of Equivalence. While hydrogen fuel cell technology has the potential to perform equivalently to fossil-fuel, has progressed significantly in the last decade, and is being tested in many forms of on- and off-road equipment, it has not made substantial progress with CHE. Table 45 through Table 47 summarize the outlook for each type of hydrogen fuel cell CHE to achieve a Technology Readiness Grade of Equivalence within 10 years, grouped by CHE category.

Table 45: Outlook for Fuel Cell Bulk Material CHE Achieving Equivalence for Within 10 Years

CHE Type	Outlook for Achieving Equivalence Within 10 Years
Crane (Material Handling and Off-Road), Dozer, Loader or Loader-Excavator, Log Stacker	Zero-emission options for these types of CHE closely follow the construction industry. Little progress has been made in the development of hydrogen fuel cell versions of this equipment. There are prototypes and custom-built hydrogen fuel cell versions of some of these types of equipment, but the additional development, testing, demonstration, and piloting required for full commercial deployment as CHE would take at least 10 years. Also, except for log stackers, there are already commercially available battery-electric options for each of these types of CHE. For these reasons, these hydrogen fuel cell CHE will likely not achieve Equivalence within 10 years.
Crane, Mobile	Mobile cranes are a specialized heavy-duty truck with a crane. Therefore, hydrogen fuel cell mobile cranes for cargo handling will follow the adoption of this technology for the heavy-duty and industrial truck industries. This adoption is challenged by the availability of hydrogen refueling infrastructure for long-haul operations outside of California. As the heavy-duty and industrial truck industries adopt more zero-emission heavy duty trucks, hydrogen fuel cell technology will become more prevalent, but at a slower rate than battery-electric models since hydrogen infrastructure is less developed than grid infrastructure. With additional emission reduction strategies and incentive programs for long-haul heavy-duty trucks, hydrogen fuel cell mobile cranes can achieve Equivalence within 10 years.

CHE Type	Outlook for Achieving Equivalence Within 10 Years
Crane, Mobile Harbor	Similar to off-road cranes, smaller mobile harbor cranes will likely follow the construction industry's lead to adopt zero-emission technologies. The challenge for larger mobile harbor cranes is the large electricity demand needed for heavy cargo. Because grid-electric mobile harbor cranes are commercially available and having success in early demonstrations, they will likely continue to lead the market as the primary zero-emission technology option. Therefore, OEMs are not likely to invest heavily in the production of hydrogen fuel cell mobile harbor cranes in the next 10 years. For these reasons, hydrogen fuel cell mobile harbor cranes will likely not achieve Equivalence within 10 years.
Excavator	Hyundai, JCB, and Komatsu have announced the development of hydrogen fuel cell excavators. In some cases, their prototypes have been tested in real-world construction operations. Other companies have converted Liebherr and Volvo excavators to use hydrogen fuel cells, as well. Due to this significant level of development and testing, with additional emission reduction strategies and incentive programs for both the equipment and the hydrogen infrastructure, hydrogen fuel cell excavators can achieve Equivalence within 10 years.
Forklift, Heavy Lift	There are nine commercially available models of hydrogen fuel cell heavy lift forklifts. Also, the Nagoya Port in Japan conducted a demonstration of 20 hydrogen fuel cell heavy lift forklifts in August 2024.[314] Incentive programs such as CARB's CORE program are helping deploy this CHE.[315] However, due to infrastructure and cost challenges with the supply of renewable hydrogen, there is little incentive for industry to adopt this CHE. However, considering the commercial availability of this CHE, with additional emission reduction strategies and incentive programs in place for both the CHE and infrastructure, hydrogen fuel cell forklifts can achieve Equivalence within 10 years.

[314] H2 News, "Nagoya Pot Implements Hydrogen Forklift," December 2024. Accessed March 2, 2025. *https://h2-news.com/hydrogen/news/nagoya-port-implements-hydrogen-forklifts/*.

[315] All nine commercially available models of hydrogen fuel cell forklifts are eligible for CARB's CORE program. See *www.californiacore.org* for details.

CHE Type	Outlook for Achieving Equivalence Within 10 Years
Forklift, Telehandler	While there is only one hydrogen fuel cell telehandler prototype under development, it is being developed by Manitou, a major telehandler manufacturer that also offers two battery-electric models.[316] They plan on releasing an all hydrogen-powered model by 2026. Given this technology backdrop, hydrogen fuel cell telehandlers can be a viable alternative to battery-electric telehandlers at facilities incorporating hydrogen infrastructure for other CHE such as yard trucks and heavy lift forklifts. With additional emission reduction strategies and incentive programs in place for other hydrogen fuel cell CHE, fuel cell telehandlers can achieve Equivalence within 10 years.
Haul Truck	Regulatory and operational emissions restrictions in the mining industry are driving the development of zero-emission haul trucks. For this reason, there have been several demonstrations of hydrogen fuel cell haul trucks for mining operations. The progress made so far with fuel cell technology for mining haul trucks can help translate into the adoption of fuel cell haul trucks for cargo handling. Therefore, with additional emission reduction strategies and incentive programs in place for both the CHE and hydrogen infrastructure, hydrogen fuel cell haul trucks can achieve Equivalence within 10 years.

Table 46: Outlook for Fuel Cell Container CHE Achieving Equivalence Within 10 Years

CHE Type	Outlook for Achieving Equivalence Within 10 Years
AGV	Prior to going out of business in December 2024, Gaussin was the only OEM producing hydrogen fuel cell AGVs. It is not clear if other OEMs will use their intellectual property to continue the production or further development of hydrogen fuel cell AGVs. Until automated hydrogen refueling can be successfully demonstrated, hydrogen fuel cell AGVs will not achieve equivalence to their already available zero-emission battery-electric counterparts. Therefore, hydrogen fuel cell AGVs will likely not achieve Equivalence within 10 years.
Rail-Mounted Gantry Crane	There are no commercially available hydrogen fuel cell RMGs and no demonstrations. This is likely because grid-electric RMGs are already the industry standard. Grid-electric RMGs achieve a Technology Readiness Grade of Equivalence. Therefore, hydrogen fuel cell RMGs will likely not achieve Equivalence within 10 years.

[316] See *Appendix B* for commercially available zero-emission CHE.

CHE Type	Outlook for Achieving Equivalence Within 10 Years
Reach Stacker	Reach stackers are generally used at smaller facilities that do not have multiple RTGs and top handlers that can serve the same function. Therefore, there is less market demand for reach stackers than other container CHE. Accordingly, there are more demonstrations of zero-emission RTGs and top handlers than reach stackers. This is also true for hydrogen fuel cell technology for reach stackers. However, fuel cell reach stackers may be a good option for terminals that employ other hydrogen fuel cell CHE such as yard trucks. The adoption of hydrogen fuel cell reach stackers is more dependent on the development of hydrogen infrastructure and hydrogen cost than it is on the maturing of the technology for the CHE. Therefore, with additional emission reduction strategies and incentive programs in place for other hydrogen fuel cell CHE, fuel cell reach stackers can also achieve Equivalence within 10 years.
Rubber-Tired Gantry Crane	In 2025, the hydrogen fuel cell RTG demonstration at the Yusen Terminal at the Port of Los Angeles is providing valuable information to inform the adoption of fuel cell technology for RTGs and hydrogen infrastructure for cargo handling operations at seaports. Additionally, several fuel cell RTG conversions have been announced.[317] During the four-year RTG demonstration period at Yusen Terminal, the costs of the hydrogen fuel and its delivery are covered with demonstration project funds from Mitsui E&S Co., Ltd. and the Japanese New Energy and Industrial Technology Development Organization.[318] Therefore, the high cost of hydrogen and the challenges of acquiring a steady supply of renewable hydrogen after the demonstration period create uncertainty for sustained deployment of the equipment. However, with additional emission reduction strategies and incentive programs in place for both the CHE and infrastructure, hydrogen fuel cell RTGs can achieve Equivalence within 10 years.

[317] See *Appendix E* for demonstrations of zero-emission CHE.

[318] Vicky Tran, "Deploying Hydrogen-Powered Cranes at the Port of Los Angeles," June 20, 2024. Accessed April 11, 2025. *https://gh2forclimate.org/deploying-hydrogen-powered-cranes-at-the-port-of-los-angeles/*.

CHE Type	Outlook for Achieving Equivalence Within 10 Years
Shuttle and Straddle Carrier, Side Handler, Top Handler	These container CHE are similar in size, function, and duty cycle. There are no commercially available versions of these CHE using hydrogen fuel cell technology. Also, there have been very few demonstrations. The adoption of these CHE will likely follow that of hydrogen fuel cell yard trucks so the hydrogen infrastructure and supply chain can be leveraged at the same facility. Therefore, with additional emission reduction strategies and incentive programs in place for hydrogen fuel cell yard trucks, these CHE can also achieve Equivalence within 10 years.
Yard Truck	There are no commercially available hydrogen fuel cell yard trucks. There have been several demonstrations, but there is little published information on the results of the demonstrations. CARB's ZECAP website shows a video presentation providing results from the demonstration of two Capacity yard trucks equipped with hydrogen fuel cell technology at the TraPac terminal at the Port of Los Angeles (POLA). Feedback was positive regarding the performance of the trucks, helping this CHE to achieve a Technology Readiness Grade of Demonstration. But the presentation did highlight some of the challenges faced in producing the trucks and getting permits for the hydrogen.[319] With additional emission reduction strategies and incentive programs in place for both the CHE and infrastructure, hydrogen fuel cell yard trucks can achieve Equivalence within 10 years.

[319] California Air Resources Board, "LCTI: Zero Emissions for California Ports (ZECAP)," n.d. Accessed April 1, 2025. *https://ww2.arb.ca.gov/lcti-zero-emissions-california-ports-zecap*.

Table 47: Outlook for Fuel Cell Facility Support CHE Achieving Equivalence Within 10 Years

CHE Type	Outlook for Achieving Equivalence Within 10 Years
Aerial Lift	United Kingdom-based rental house Speedy Hire entered into a joint venture with Niftylift to provide hydrogen fuel cell aerial lifts.[320] These have not yet been tested at seaports or intermodal railyards, giving them a Technology Readiness Grade of Demonstration. However, the two available models are based on existing battery-electric platforms that have been proven in real-world applications. With additional emission reduction strategies and incentive programs in place for other CHE, hydrogen fuel cell aerial lifts can achieve Equivalence within 10 years.
Cone Vehicle	There are no commercially available fuel cell cone vehicles or demonstrations of this CHE. The research and development costs would be significant, and the product development would take many years. Because battery-electric cone vehicles are currently being used at facilities,[321] staff anticipates that battery-electric technology will be the primary zero-emission option for cone vehicles at facilities. Due to the high cost of product development and the higher cost of hydrogen compared to electricity to charge a battery-electric cone vehicle, fuel cell cone vehicles will likely not achieve Equivalence within 10 years.
Railcar Mover	Similar to cone vehicles, there are no commercially available fuel cell railcar movers or demonstrations of this CHE. However, there are twenty-two commercially available battery-electric railcar movers, with one in operation at the Port of Los Angeles.[322] Because of the high availability of an alternative zero-emission technology, this CHE will likely not achieve Equivalence within 10 years.

[320] Jordanne Waldschmidt, "UK Companies Launch World's First Hydrogen-Electric Powered Access Platform," Equipment World, July 17, 2023. Accessed April 8, 2025. *https://www.equipmentworld.com/aeriallifting-equipment/aerial-lifts/article/15542244/the-worlds-first-hydrogenelectric-powered-access-platform*.

[321] Port of Long Beach, "2023 Air Emissions Inventory," August 2024. *https://polb.com/download/14/emissions-inventory/20586/2023-air-emissions-inventory.pdf* (There are 8 electric Motrek brand cone vehicles at POLB).

[322] Port of Los Angeles, "2023 Air Emissions Inventory," August 2024. *https://kentico.portoflosangeles.org/getmedia/3fad9979-f2cb-4b3d-bf82-687434cbd628/2023-Air-Emissions-Inventory*. (See "Rail Pusher" Zephir Electric.)

CHE Type	Outlook for Achieving Equivalence Within 10 Years
Utility Truck, Other	Hydrogen fuel cell models of utility trucks that can be adapted for facility support operations will follow the adoption of this technology in the heavy-duty and industrial truck industries. Like mobile cranes, with additional emission reduction strategies and incentive programs in place for long-haul heavy duty trucks, hydrogen fuel cell utility trucks can also achieve Equivalence within 10 years.
Utility Trucks, Sweeper	There are two commercially available fuel cell sweeper trucks: the Global M4HSD and the Green Machines 500H2, which is only available in Europe. While the electric version of the M4HSD sweeper has been thoroughly tested and has been in operation in many locations in the United States for nearly a decade,[323] the fuel cell version only became available in 2018.[324] It has yet to be demonstrated at seaports and intermodal railyards. However, other than obtaining a reliable supply of hydrogen fuel, staff sees no barriers to the immediate adoption of this CHE. With additional emission reduction strategies and incentive programs in place for both the CHE and infrastructure, these CHE can achieve Equivalence within 10 years.

Hydrogen fuel cell CHE technology has the potential to meet the operational demands of seaports and intermodal railyards while reducing reliance on grid electricity. However, the high costs associated with fuel cell CHE listed below are a challenge to widespread adoption.

- Equipment costs – higher upfront costs compared to battery-electric alternatives due to complexity and lower production volumes.
- Hydrogen fuel costs – high cost, especially for renewable hydrogen, which is essential for achieving true zero-emission benefits. Transportation and storage add to the overall costs.
- Infrastructure investment – large capital investment required for developing hydrogen storage and dispensing infrastructure, including refueling stations, installing storage tanks, and ensuring compliance with safety regulations and industry standards.

[323] Jason Condon, "The Learning Curve of Electrification," The Municipal, September 1, 2023, Accessed May 7, 2025. *https://www.themunicipal.com/2023/09/the-learning-curve-of-electrification*.

[324] GlobalSweeper, "Global M4HSD ZE Zero Emissions," YouTube video, published November 30, 2018, 2:59. Accessed April 11, 2025. *https://youtu.be/2Rfo3i6gkUk?si=KjKZJvY1Sp3nkCbx*.

Availability of renewable hydrogen also poses a challenge. To address these issues, continued research, development, and investment in hydrogen fuel cell CHE technology are needed. Regulatory support through financial incentives, grants, and policy frameworks will be critical for accelerating adoption and making hydrogen fuel cell CHE a viable and cost-competitive solution for zero-emission CHE. Several factors will help accelerate the development of hydrogen fuel cell CHE in the future:

- Availability of renewable hydrogen – programs like ARCHES to drive hydrogen production.
- Infrastructure development – building hydrogen production, storage, and refueling infrastructure at seaports and intermodal railyards.
- Technological advancements – improvements in fuel cell efficiency, durability, and onboard energy storage.
- Equipment cost reduction – advancements in fuel cell technology and economies of scale to lower purchase costs.
- Incentive programs – government incentives and financial support to promote zero-emission technologies.
- Safety and standardization – establishing clear safety regulations, codes, and standards to support deployment and operation.

Hydrogen fuel cell CHE technologies are still in the early stages. While significant advancements have been made, widespread adoption remains limited due to high costs of both the CHE and the fuel, limited renewable fuel availability, and infrastructure implementation challenges. Ongoing demonstrations and pilot projects can help validate performance, durability, and operational feasibility of hydrogen fuel cell CHE. With continued research and investment, hydrogen fuel cell technology can play a critical role in achieving zero-emission goals for California seaports and intermodal railyards.

Conclusion

The 2025 Technology Assessment supports the directives of EO N-79-20 and EO N-27-25 to achieve 100 percent zero-emissions from off-road vehicles and equipment operations in the State by 2035. Assessing zero-emission CHE technologies is key to meeting the additional emission reductions necessary to help California achieve its emissions reduction and climate goals, improve air quality, and protect public health. This assessment illustrates that zero-emission technologies are available or in development and can move CHE toward 100% zero-emission operations.

Of the 25 types of zero-emission CHE evaluated in this Technology Assessment, 24 (96%) have commercially available models. Three types (12%) achieve a Technology Readiness Grade of Equivalence. This means that they operate equivalently to their diesel counterparts at seaports and intermodal railyards. In California, 100% of these three types of CHE are zero-emission – comprising over 400 pieces of zero-emission CHE.[325] Two types of CHE (8%) will likely achieve a Technology Readiness Grade of Equivalence within 10 years given the current infrastructure, regulatory, and incentive program environment. However, the remaining 20 types of CHE (80%), do not achieve Equivalence and require market intervention – including incentives and additional emission reduction strategies – to achieve it within 10 years. These strategies may include the following:

- New or amended regulations
- Air quality control programs
- Cooperative agreements, memorandums of understanding, emission reduction agreements, etc.

Challenges, such as high costs, infrastructure needs, and reliability must be addressed. A mix of public and private infrastructure is needed to deploy these zero-emission technologies successfully. Additional emission reduction strategies and incentive programs are needed to assist with this effort. Coordinated planning and execution are essential to overcome the infrastructure and logistical challenges.

[325] The 400 pieces of zero-emission CHE include 100 AGVs, 98 rail-mounted gantry cranes, and 203 ship to shore cranes. See Port of Long Beach, “2023 Air Emissions Inventory,” August 2024. *https://polb.com/download/14/emissions-inventory/20586/2023-air-emissions-inventory.pdf*; Port of Los Angeles, "2023 Air Emissions Inventory," August 2024. *https://kentico.portoflosangeles.org/getmedia/3fad9979-f2cb-4b3d-bf82-687434cbd628/2023-Air-Emissions-Inventory*; and Port of Oakland, “Seaport Facilities,” May 2024. *Oakland_Seaport-map-0624_web.pdf*.

Staff used callout boxes throughout this document to highlight key data gaps in zero-emission CHE technologies. CARB staff will continue to seek this information and assess the evolving state of technology.