



2025 Cargo Handling Equipment Technology Assessment



September 2026

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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
AB	California Assembly Bill
AC	alternating current
ARCHES	Alliance for Renewable Clean Hydrogen Energy Systems
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
CO ₂	carbon dioxide
CORE	Clean Off-Road Equipment Voucher Incentive Project
DC	direct current
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
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
LSI Regulation	Large Spark-Ignition Engine Fleet Requirements Regulation

MW	megawatt(s)
MWh	megawatt-hour(s)
NO _x	oxides of nitrogen
OEM	original equipment manufacturer
OSHA	Occupational Safety and Health Administration
PEM	polymer electrolyte membrane
PM	particulate matter
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
SMR	steam methane reformation
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)
ZECAP	Zero-Emissions for California Ports
ZEV	zero-emission vehicle

Introduction

California Air Resources Board (CARB) staff developed the 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 support. 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 (NO_x), and greenhouse gases (GHG). According to the CARB 2022 Cargo Handling Equipment Emissions Inventory (2022 CHE Inventory),¹ CHE emitted nearly 50 tons of PM_{2.5}, 1,200 tons of NO_x, 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.

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

¹ CARB, "Cargo Handling Equipment Emissions Inventory," December 2022.
https://ww2.arb.ca.gov/sites/default/files/2023-04/2022%20CHE%20Emission%20Inventory%20Document_6April2023.pdf.

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.

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 emission reductions from existing LSI fleets and sets verification procedures for LSI retrofit emissions control systems. It also establishes more stringent NO_x 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 goals. In September 2020, Governor Newsom issued Executive Order (EO) N-79-20,² 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 reaffirms this goal.³ In addition, Assembly Bill 617 highlights the need for further emission reductions in communities with high exposure burdens.

² 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>.

³ 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>.

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.⁴ 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 Strategy⁵ and State Implementation Plan (SIP) development⁶
- Scoping Plan Updates⁷
- Funding Plans for Clean Transportation Incentives⁸

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 addresses the six key elements listed below.

1) Technology description – describes the zero-emission technology and how it works.

⁴ CARB, "Draft Technology Assessment: Mobile Cargo Handling Equipment," November 2015. https://www.arb.ca.gov/msprog/tech/techreport/che_tech_report.pdf.

⁵ CARB, "Mobile Source Strategy," n.d. Accessed November 25, 2024. <https://ww2.arb.ca.gov/resources/documents/mobile-source-strategy>.

⁶ CARB, "California State Implementation Plans," n.d. Accessed November 25, 2024. <https://ww2.arb.ca.gov/our-work/programs/california-state-implementation-plans>.

⁷ CARB, "AB32 Climate Change Scoping Plan," n.d. Accessed January 8, 2025. <https://ww2.arb.ca.gov/our-work/programs/ab-32-climate-change-scoping-plan>.

⁸ CARB, "Funding Plan for Clean Transportation Incentives," n.d. Accessed December 23, 2024. <https://ww2.arb.ca.gov/our-work/programs/low-carbon-transportation-incentives-and-air-quality-improvement-program/funding>.

- 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. 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.

Staff held a technology-focused workshop on November 13, 2025, to discuss the draft technology assessment and solicit input. In addition, stakeholders submitted comments during the public comment period from October 30, 2025 to December 12, 2025. This final document incorporates changes based on the data, information, and input received during this period.

Staff will continue to gather information on demonstrations, pilots, costs, and other related technical information to further assess the state of zero-emission CHE technology. If you have information or data you would like to share, please send it to [*cargohandling@arb.ca.gov*](mailto:cargohandling@arb.ca.gov).

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 in California. However, there are many more types of CHE. See [Appendix A](#) for a list of additional types of CHE.

Most CHE 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 and is done 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 *gearman*, a designated and trained worker, 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 CHE transport bulk cargo, including cranes, dozers, excavators, forklifts, haul trucks, and loaders. Log stackers are specialized CHE used at lumber facilities to lift, transport, and neatly stack logs.

Crane

Cranes are among the most versatile CHE. Many can be configured to handle a wide range of cargo including dry bulk commodities like grain or aggregates and break bulk cargo such as steel beams or machinery. Some can be configured to move containers. Beyond handling cargo, they can support facilities by assisting with non-cargo equipment moves, maintenance tasks, or loading and unloading other CHE on and off cargo vessels. This adaptability makes them invaluable for facilities that manage diverse cargo types. Although some cranes span all three CHE categories, staff included cranes in the bulk material CHE category since most cranes at facilities are used for that purpose.

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 also operate off-road. 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 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. 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 can operate on both paved and unpaved surfaces. Tracked off-road cranes, which move on tracks instead of wheels, are called *crawler cranes* (Figure 6) and are best suited for working on unpaved surfaces. Off-road cranes 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 can 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.⁹

Figure 7: Dozer



⁹ 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.

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, operators can fit the arm with attachments for moving specialized cargo such as lumber or scrap. Excavators can lift up to 200,000 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 with 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.¹⁰ Class I, Class IV, Class V, and Class VII are the most common forklift types used at seaports and intermodal railyards.

¹⁰ United States Department of Labor, Occupational Safety and Health Administration, "Powered Industrial Trucks (Forklift) eTool," n.d. 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. For example, Figure 10 shows a battery-electric forklift used at the Port of West Sacramento capable of lifting up to 30,000 lb of dry bulk cargo. Some electric forklifts can lift up to 100,000 lb. 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.”¹¹ 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.

Figure 14: Rough Terrain Forklift (Class VII)



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

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.

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.¹² There are more than 100 commercially available models of battery-electric and hydrogen fuel cell forklifts with lifting capacity less than

¹² 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.

24,000 lb that can be purchased in place of Class IV or V ICE models.¹³ This assessment 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



¹³ CARB's Advanced Clean Off-Road Equipment List Fact Sheets document lists nearly 400 models of zero-emission forklifts (CARB, "Advance Clean Equipment," n.d. Accessed April 14, 2025. <https://ww2.arb.ca.gov/our-work/programs/msei/off-road-advance-clean-equipment>). 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/>).

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 containers 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. RMGs and RTGs 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. All RMGs operating in California are zero-emission.

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. All ship-to-shore cranes operating in California are zero-emission.

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 facilities.

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 containers 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 a container. 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*, *UTRs* (utility tractor rig), *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 usually 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

Aerial lifts, cone vehicles, railcar movers, and utility trucks support facility operations. Most of this equipment is diesel-powered, but some use other combustion fuels. While facility support CHE may not be used for cargo handling, this equipment is considered CHE in this assessment and in the CHE Regulation unless otherwise noted. Compared to other CHE types, 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 (IBC), also called twist-locks, are used to connect stacked containers and have a

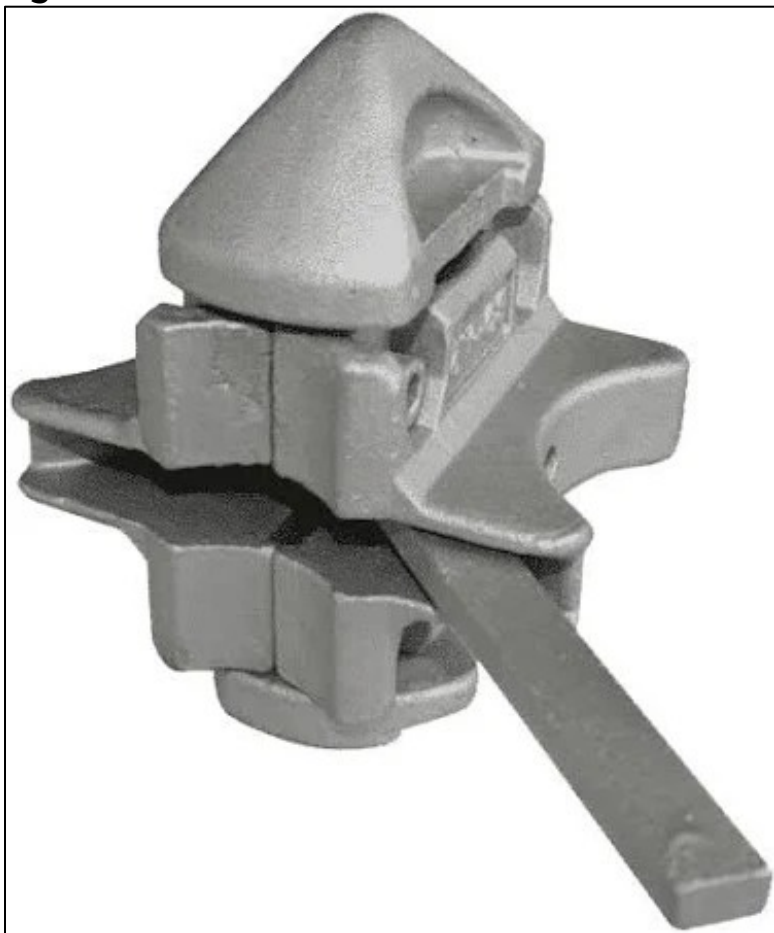
Figure 30: Cone Vehicle (Motrec)



locating pin that resembles a cone (Figure 31). Cone vehicles are specialty utility carts that facility operators use to install or remove IBCs on stacked containers. Manufacturers of cone vehicles generally do not market them as “cone vehicles” as they can be used for many purposes for several industries. Instead, these vehicles are typically sold as specialty lifts or utility carts and meet specific criteria including:

- Able to safely lift and support a worker and potentially hundreds of pounds of IBCs to the height of a stacked container
- Small enough to maneuver around container stacking CHE and railcars on narrow pathways
- Able to move quickly around container stacks and railcars

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.¹⁴

Figure 32: Railcar Mover



Utility Trucks

Utility trucks, including fuel trucks, street sweepers (*sweepers*), and water trucks, perform a variety of tasks at facilities including facility operations, maintenance, or repairs. Staff separated Utility Trucks into two sub-types: *Utility Truck, Other (utility truck)* and *Utility Truck, Sweeper (sweeper)*. Fuel trucks and sweepers are exempt from the current requirements of the CHE Regulation.

The sub-type, utility truck, encompasses large trucks that operators use at facilities for non-cargo-handling activities. This mostly includes water and fuel trucks but can include other custom-designed applications such as bucket trucks or battery-swapping trucks. To produce these trucks, a third party will generally start with a heavy-duty class 6, class 7, or

¹⁴ Loaded railcars is a common industry metric for the moving capacity of railcar movers.

class 8¹⁵ cab-and-chassis truck (Figure 33) and fit it with specialized equipment.¹⁶ For example, Figure 34 shows a cab-and-chassis truck fitted with tanks and receptacles to serve as a water truck.

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



¹⁵ 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.

¹⁶ Chassis cab," Wikipedia, The Free Encyclopedia," Accessed May 27, 2025.
https://en.wikipedia.org/wiki/Chassis_cab.

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



Sweepers (Figure 35) 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.¹⁷

Figure 35: Battery-Electric Sweeper (Global)



¹⁷ 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 onboard batteries, a connection to the electric power grid (grid), or hydrogen fuel cells. In general, all three zero-emission technologies offer quieter operation and less vibration than diesel-powered CHE. Table 1 summarizes some of the 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: ○ Increased capacity ○ Faster charge times ○ Lower cost • Potential cost savings for long-term maintenance and repair	• Heavy¹⁸ • More expensive than diesel • Requires frequent recharging • Takes longer to charge than refueling equivalent diesel-powered CHE • Charging infrastructure occupies facility real estate

¹⁸ 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 information, 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), vol. 3(2), June 1, 2021: 474–89. <https://www.mdpi.com/2571-8797/3/2/28>.

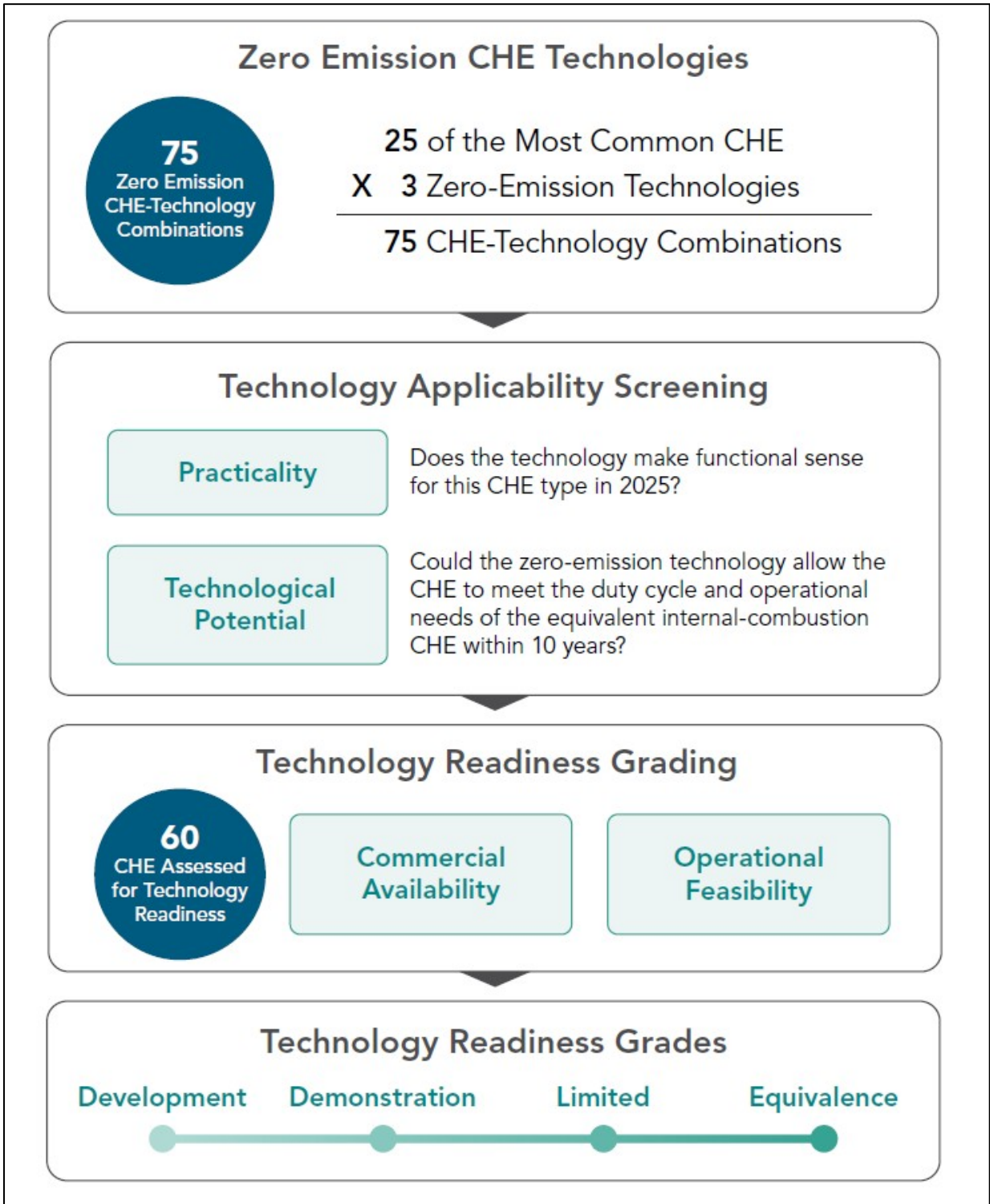
Zero-Emission Technology	Benefits	Potential Challenges
Grid-Electric	• Provides constant power, reducing or eliminating the need for batteries • Reduces or eliminates long charge times • Several types of this CHE are the industry standard and commercially available • Dynamic grid-electric technologies are being developed • Potential cost savings for long-term maintenance and repair	• 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.

Assessment Methodology

Staff identified 25 types of CHE 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). Some of these combinations are either not practical or unlikely to be technologically capable of meeting functional equivalence (runtime, power requirements, etc.) to their diesel counterpart within 10 years. Therefore, staff performed a first-level screening, for *Technology Applicability*. Staff further assessed the combinations that passed this initial screening to determine their *Technology Readiness*. Figure 36 outlines staff's process for assessing the 75 CHE-technology combinations and determining *Technology Readiness Grades*. See [Appendix C](#) and [Appendix D](#) for more details on Technology Applicability and the Technology Readiness grading system, respectively.

Figure 36: Process for Assessing CHE and Providing Technology Readiness Grades



Technology Applicability

Staff conducted a preliminary screening to determine Technology Applicability for each of the 75 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?

Staff assigned each CHE-technology combination a score for both criteria. The combination received a 0 if it did not meet the Practicality criteria or a 1 if it did. The combination 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	1	2
Rail-Mounted Gantry Crane	1	2	1
Reach Stacker	2	1	2
Rubber-Tired Gantry Crane	2	2	2
Ship-to-Shore Crane	0	2	0
Shuttle and Straddle Carriers	2	1	2
Side Handler	2	1	2
Top Handler	2	1	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 60 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 • Includes combinations for which staff found no evidence of development¹⁹	The CHE-technology combination is still in the development phase and is not yet ready for deployment.
Demonstration	• Early/limited commercial availability* • Not yet fully demonstrated in all environments or not yet reliable in desired environment	Further demonstrations are required to prove the technology before broad deployment. The CHE-technology combination is advancing but not yet ready for full deployment.

¹⁹ In cases where staff found no evidence of development, OEMs may still be developing the CHE-technology combination but have not yet publicly disclosed it. Because a lack of information does not necessarily indicate a lack of development, staff did not create a separate category and assigned these combinations a grade of Development.

Technology Readiness Grade	Description	Deployment Assessment
Limited	• Commercially available • Manageable lead times • Possible delays with original equipment manufacturer (OEM) support and replacement parts • Possible delays with international technical support • Achieves equivalence with diesel for most aspects of <i>Operational Feasibility</i>, but not all • 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.
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)?
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 assess 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 assess Operational Feasibility, staff visited seaports and intermodal railyards and researched demonstrations, pilot projects, prototypes, product announcements, and equipment studies that took place from January 2020 through January 2025. See [Appendix E](#) for a list of these projects.

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. If a model is commercially available both in the U.S. and outside the U.S., it is included in this number.
- *Commercially Available Outside the U.S.* – The number of CHE models that are only commercially available outside the U.S. through a dealer or distributor. All commercially available models are listed in [Appendix B](#).
- *Non-Commercial Units* – The number of CHE that were used in demonstrations, pilot programs, or prototypes between January 2020 and January 2025 that are not

commercially available. These CHE are prototype, pre-production, or custom-developed units and are not offered to the public through dealers or distributors (facilities may use either commercially available or non-commercial CHE for demonstrations). These units can be found in [Appendix E](#).

- *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 potential challenges associated with battery-electric CHE.

Technology Description

Because CHE is part of the transportation industry, CHE OEMs often 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 chemistries, such as solid-state cell and sodium-ion batteries, are under development²¹ but are not yet 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
- Little memory loss, even with many partial charges
- Longer life span and high charge rates

Additionally, lithium-ion batteries have a “flat discharge curve.” This means that battery voltage remains relatively constant while powering the CHE, rather than dropping steadily

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/>.)

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>.

as with lead-acid batteries. This allows the CHE to operate at full power until the batteries are nearly empty.

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 some battery-electric CHE may require a battery replacement during its lifetime. As technology improves and more real-world operational data is collected for CHE and similar heavy-duty off-road equipment, positive reports are emerging regarding the lifespan of lithium-ion batteries. For example, a 2024 newsletter reported that a battery-electric loader passed 19,000 hours of operation with only 8% battery degradation.²⁶ This is equivalent to nearly 10 years of full-time operation.²⁷ See the CARB *webpage*, *Advanced Batteries for Motor Vehicles*²⁸ and the CARB document, *Battery Electric Truck and Bus Energy Efficiency Compared to Conventional Diesel Vehicles* for more information about batteries and battery technology for zero-emission transportation.²⁹

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.

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 CARB, "Cargo Handling Equipment: Technology Assessment," September 9, 2014. <https://ww2.arb.ca.gov/sites/default/files/classic/msprog/tech/presentation/cargohandling.pdf>.

²⁶ Etrucks, "April 2024 Newsletter," n.d. Accessed February 3, 2026. <https://etrucks.co.nz/april-2024-newsletter/>.

²⁷ If operating 40 hours per week for 50 weeks per year.

²⁸ CARB, "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>.

²⁹ CARB, "Battery Electric Truck and Bus Energy Efficiency Compared to Conventional Diesel Vehicles," May 2018. <https://ww2.arb.ca.gov/sites/default/files/2018-11/180124hdbvefficiency.pdf>.

The amount of batteries required for CHE to achieve runtime similar to diesel-powered CHE can 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.

Battery-electric CHE can move freely because they are not attached by a cord or mounted on a track. However, charging battery-electric CHE can take hours, depending on:

- Battery type
- Capacity
- State of charge
- Charger power
- Other conditions such as temperature or battery age³⁰

Battery *swapping* offers a faster option by replacing a depleted battery with a charged one. This method has worked for nearly a decade at the Long Beach Container Terminal. An automated system can swap a lead-acid battery pack in about five minutes for one of their 100 AGVs.³¹ A 2024 YouTube video shows a Sany battery-electric reach stacker with a 10-minute battery swap capability. However, the video does not provide details about the exchange system or deployments of the reach stacker.³² Battery swapping can also help reduce costs and ease grid demand by avoiding charging during peak electricity use. For example, in late 2024, Yantian Port launched the first in-port battery-swapping station for heavy-duty truck chassis. Optimized charging cycles for lithium-ion batteries streamlined operations and cut energy costs.³³

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 if availability, cost, and

³⁰ As an example, one report about battery-electric top handlers indicates that they are “capable of running two-full shifts under normal work cycles, then ready-to-go after a five-hour boost using a 180W recharger.” (WorldCargo News, “Yusen Terminals in LA puts into action electric top handlers,” June 26, 2024. Accessed February 6, 2026. <https://www.worldcargonews.com/cargo-handling-equipment/2024/06/yusen-terminals-in-la-puts-into-action-nations-first-electric-top-handlers/>.)

³¹ Konecranes, “Konecranes Gottwald AGVs at Long Beach Container Terminal,” YouTube video, published on October 19, 2018, 3:07. Accessed February 3, 2026. <https://www.youtube.com/watch?v=KiFfZWvMC7U>; LBCT, “Long Beach Container Terminal (LBCT) Final Phase 2021,” YouTube video, published on June 27, 2022, 3:18. Accessed February 3, 2026. <https://www.youtube.com/watch?v=H6hrdK7ljOI>.

³² Sany Marine, “SANY Electric Reach Stacker SRSC45E3A,” YouTube video, published on May 22, 2024, 1:19. Accessed February 9, 2026. <https://youtu.be/XG0gZkA6PtM?si=P13O7xRT0t1ZmhhK>.

³³ CATL, “World’s First In-port Heavy-duty Truck Chassis Battery Swapping Station Officially Put into Operation,” November 27, 2024. Accessed February 3, 2026. <https://www.catl.com/en/news/6338.html>; Hailey, “CATL heavy-duty truck battery swap solution - QIJI Energy,” TYCORUN Energy, June 19, 2023. Accessed February 2, 2026. <https://batteryswapcabinet.com/catl-heavy-duty-truck-battery-swap-solution/>.

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 model of yard truck, 1 AGV, 11 forklifts, 1 mobile loader/material handler, and 6 railcar movers.³⁴ 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 between shifts or during the morning, or *hoot* shift. Some battery-electric CHE can last two full shifts before recharging,³⁵ but most do not. Because the demands of CHE can vary between facilities, especially for bulk material operations, some terminal operators find it challenging 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. However, with experience and continued improvements to battery capability, this uncertainty will likely diminish.

Battery-Electric Bulk Material CHE

Many bulk material CHE, including cranes, dozers, and excavators also serve the construction industry. The demand for zero-emission equipment in construction closely influences the availability of battery-electric bulk material CHE. There are many incentive programs for zero-emission construction equipment, including CARB's Clean Off-Road Equipment (CORE) voucher incentive program.³⁶ There are no U.S. or California requirements for zero-emission construction equipment.³⁷ In the U.S., production of

³⁴ The lifting or pulling capacity of the CHE is not indicated.

³⁵ Business Wire, "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>.

³⁶ 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/>.)

³⁷ Federal incentive programs include Section 179 Deduction, Bonus Depreciation, Commercial Clean Vehicle Credit (IRC 45W), Alternative Fuel Vehicle Refueling Property Credit (IRC 30C), SBA 7(a) and 504 Loan

zero-emission construction equipment is driven by environmentally conscious OEMs, early technology adopters, and noise reduction requirements.³⁸ In Europe, emissions and noise ordinances drive demand,³⁹ while China enacts regulations and policies to promote the adoption of cleaner construction equipment.⁴⁰

Less than 2% of bulk material CHE at California facilities is battery-electric.⁴¹ 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.

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	7	3	0	Demonstration
Crane, Mobile	8	0	1	Demonstration
Crane, Off-Road	5	0	0	Demonstration
Dozer	0	2	0	Demonstration
Excavator	6	9	0	Demonstration
Forklift, Heavy Lift	39	6	2	Limited
Forklift, Telehandler	9	2	1	Demonstration

Programs, EPA's Diesel Emissions Reduction Act, EPA's Clean Heavy-Duty Vehicles Grant Program, and the Federal Department of Transportation's Congestion Mitigation and Air Quality. There may also be available state local air district grants. California's SIP and Scoping plan include zero-emission off road equipment in their modeling for meeting deadlines and targets.

³⁸ CALSTART, "Achieving Zero Emissions in Construction and Agricultural Equipment," n.d. Accessed January 8, 2025. <https://calstart.org/achieving-zero-emissions-in-construction-agricultural-equipment/>.

³⁹ 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>.)

⁴⁰ 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, November 2022. <https://theicct.org/wp-content/uploads/2022/10/china-hvs-lez-construction-equipment-nov22.pdf>.

⁴¹ 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. A primary assumption was that gasoline, propane, and electric forklifts were not heavy lift forklifts and therefore, were removed from the calculation.

Equipment Type	Commercially Available in the U.S.	Commercially Available Outside the U.S.	Non-Commercial Units	Technology Readiness Grade
Haul Truck	1	2	5	Demonstration
Loader or Loader-Excavator	21	14	3	Demonstration
Log Stacker	0	0	0	Development

Battery-Electric Cranes

Cranes can lift heavy loads and switch attachments. They handle oversized or specialized cargo that other types of CHE cannot manage. Because of this flexibility, some cranes sit idle until the right cargo arrives. This downtime allows battery-electric cranes to recharge between jobs. In contrast, specialized cranes help facilities manage materials like scrap metal or grain. These cranes can run full shifts, making opportunity charging difficult. Cranes often remain stationary as their slewing unit rotates up to 360 degrees to handle cargo. This design allows electric cranes to stay plugged in and charge while they work.

Crane, Material Handling

There are ten commercially available models of battery-electric material handling cranes. The German company Sennebogen offers two battery-electric models. They acknowledge that battery-powered machines currently have limited operating times, but 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 handling 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.⁴²

Chinese company, Sany, produces an all-electric material handler that has a 50-ton lift capacity and claims a 50% reduction in powering costs.⁴³ German company, Liebherr, and Italian company, Solmec, also offer several models. However, there are no demonstration or pilot projects for battery-electric 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, OEMs still need to demonstrate them at seaports and intermodal railyards to advance technology readiness and widespread deployment for cargo handling.

⁴² Sennebogen, "Battery Technology from Sennebogen," n.d. Accessed April 10, 2025.

<https://www.sennebogen.com/en/technology/battery-technology>.

⁴³ 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.

Crane, Mobile

Manitex Valla, Tadano, Zee Crane, and Zoomlion offer eight commercially available mobile crane models. 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.⁴⁴ 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.⁴⁵ 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 CORE. These models can operate while plugged into the grid, or for up to eight hours unplugged.⁴⁶ 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 Bulldozer⁴⁷ and SD17E battery-electric dozer online.⁴⁸ The SD17E has a 240-kilowatt-hour (kWh) battery

⁴⁴ 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/>.

⁴⁵ Dahm, Alex. "Zoomlion Claims First Electric Truck Crane," *KHL Group*, May 26, 2020. Accessed April 21, 2025. <https://www.khl.com/1144261.article>.

⁴⁶ Liebherr, "LR 1130.1 Unplugged Crawler Crane," n.d. Accessed January 8, 2025. <https://www.liebherr.com/en-us/p/lr1130unplugged-4407440>.

⁴⁷ Shantui, "Electric Bulldozer DE26-X2," n.d. Accessed March 27, 2025. <https://www.shantui-global.com/product/pro-detail-327.htm>.

⁴⁸ 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>.

and a 145-kilowatt (kW) electric motor.⁴⁹ It began operation in China in 2021 and can operate for up to 8 hours per day depending on work conditions.⁵⁰ Battery-electric dozers have not yet been demonstrated for cargo handling at a seaport or intermodal railyard and achieve a Technology Readiness Grade of Demonstration.

Battery-Electric Excavators

There are 15 commercially available battery-electric excavators. One model is eligible for funding through CARB's CORE program.⁵¹ In October 2023, staff attended a live demonstration of a Komatsu battery-electric excavator (Figure 37) operating from a portable power station. Komatsu indicated that the equipment was able to operate for a full shift on a single charge.⁵² Battery-electric excavators achieve a Technology Readiness Grade of Demonstration.

⁴⁹ 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/>.

⁵⁰ 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/>.

⁵¹ 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/>).

⁵² Carmen Capoccia, "Powering the Future," Construction Business Owner Magazine, May 28, 2024. Accessed January 13, 2025. <https://www.constructionbusinessowner.com/popular-now/powering-future>.

Figure 37: 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.⁵³ 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. Battery-electric haul trucks achieve a Technology Readiness Grade of Demonstration.

Battery-Electric Loaders or Loader-Excavators

Loaders are the most common type of dry bulk CHE, with about 30 operating at the San Pedro Bay Port complex.⁵⁴ There are 35 commercially available models of

⁵³ See [Appendix E](#) for hydrogen fuel cell haul truck demonstrations.

⁵⁴ 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>.

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.⁵⁵ Of these, 68 have pneumatic-tires with lifting capacity more than 24,000 lb.⁵⁶ 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.

Some 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. However, reports for newer generation forklifts have been positive with increased battery reliability as OEMs have improved relationships with battery suppliers. Facility operators recommend 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 Limited.

Battery-Electric Log Stackers

Log stackers are specialized equipment with a high lift capacity. While there are no battery-electric log stacker models that are commercially available or in demonstration, batteries may be a practical technology for log stackers in the near future. OEMs may be able to use designs from similar battery-electric CHE such as reach stackers and top handlers for the development of battery-electric log stackers. Battery-electric log stackers achieve a Technology Readiness Grade of Development.

⁵⁵ 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/>).

⁵⁶ 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 Container CHE

The cargo-handling industry has focused more on the development of zero-emission CHE for containers than it has for bulk-material or facility support CHE for the following reasons:

- Modern trade relies heavily on containerized shipping to move high-value goods efficiently.⁵⁷
- Many governments, seaports, and shipping industries are setting zero-emission goals for container operations.
- Container facilities have operating profiles more compatible with available zero-emission technologies.⁵⁸

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*⁵⁹
- *Charging Ahead: The Port Community Electric Vehicle Blueprint*⁶⁰

OEMs have made significant progress in developing battery-electric container CHE. Table 8 provides the technology readiness data summary for battery-electric container CHE. The battery-electric container CHE discussion is divided into two categories: predictable path container CHE and highly mobile container CHE.

⁵⁷ 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>.

⁵⁸ Container terminals run on predictable work shifts and regular, continuous vessel schedules. They also use equipment built for standardized containers, so the needed types of CHE are limited and consistent. In contrast, bulk terminals use many types of equipment and have less regular work patterns, which makes electrification more challenging. For more information, see APM Terminals, "Reaching a tipping point in Battery-Electric Container Handling Equipment," October 26, 2023. <https://cms-cd.apmterminals.com/-/media/mainsite/global/corporate/whitepaper/apm-terminals-dp-world-white-paper-battery-electric-container-handling-equipment.pdf>.

⁵⁹ Ghazal Razeghi, Micheal Mac Kinnon, and Scott Samuelsen, "A Comprehensive and Replicable Infrastructure Blueprint for Zero-Emission Medium- and Heavy-Duty Vehicles Operating at a Port Terminal," CEC, 2023. https://cleanenergy.uci.edu/PDF_White_Papers/PortTerminalBlueprint2023.pdf.

⁶⁰ Grant Farm, "Charging Ahead: The Port Community Electric Vehicle Blueprint," Port of Long Beach, 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	2	2	Limited
Rubber-Tired Gantry Crane	3	0	0	Demonstration
Shuttle and Straddle Carriers	2	0	0	Demonstration
Side Handler	9	3	2	Limited
Top Handler	3	0	2	Limited
Yard Truck	16	0	4	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.⁶¹ Since then, the Long Beach Container Terminal has acquired a fleet of 100 of these battery-electric Gottwald AGVs,⁶² some in operation since 2015.⁶³ 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.⁶⁴

⁶¹ CARB, "Draft Technology Assessment: Mobile Cargo Handling Equipment," November 2015.

https://www.arb.ca.gov/msprog/tech/techreport/che_tech_report.pdf.

⁶² Port of Long Beach, "2023 Air Emissions Inventory," August 2024. <https://polb.com/download/14/emissions-inventory/20586/2023-air-emissions-inventory.pdf>.

⁶³ Cristina Prinz, "As if by magic," March 17, 2017. Accessed March 26, 2025.

<https://www.kfw.de/stories/economy/mobility/automatisierter-containertransport-kalifornien/>.

⁶⁴ Konecranes, "Konecranes Gottwald AGVs at Long Beach Container Terminal," YouTube video, published on October 19, 2018, 3:07. Accessed May 28, 2025. <https://www.youtube.com/watch?v=KiFfZWvMC7U>.

AGVs at the Long Beach Container Terminal use lead-acid batteries⁶⁵ that take approximately six hours to charge.⁶⁶ Newer AGVs equipped with lithium-ion batteries fully charge within 1.5 hours and support a full day of operation.⁶⁷ Battery-electric AGVs achieve a Technology Readiness Grade of Equivalence.⁶⁸

Battery-Electric Rail-Mounted Gantry Cranes

OEMs could develop battery-electric RMGs that connect to a charging port between loading operations like some battery-electric RTGs. However, 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 technology is a mature technology for RMGs. All RMGs operating at California facilities are grid-electric.⁶⁹ Because grid-electric RMGs are already the industry standard, no companies offer a battery-electric RMG and there are no active demonstrations. Battery-electric RMGs achieve a Technology Readiness Grade of Development.

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.⁷⁰ Converting RTGs to zero-emission is critical to overall emissions reductions at facilities with many diesel-powered RTGs. However, RTGs operate 10-20 hours per day lifting containers that can weigh nearly 80,000 lb, making decarbonization difficult.⁷¹

⁶⁵ 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>.

⁶⁶ CARB, "Draft Technology Assessment: Mobile Cargo Handling Equipment," November 2015. https://www.arb.ca.gov/msprog/tech/techreport/che_tech_report.pdf.

⁶⁷ 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/>.

⁶⁸ 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.

⁶⁹ Staff confirmed that all rail mounted gantry cranes operating in California are at the San Pedro Bay Port Complex and are grid-electric.

⁷⁰ Ghazal Razeghi, Micheal Mac Kinnon, and Scott Samuelsen, "A Comprehensive and Replicable Infrastructure Blueprint for Zero-Emission Medium- and Heavy-Duty Vehicles Operating at a Port Terminal," CEC, 2023. https://cleanenergy.uci.edu/PDF_White_Papers/PortTerminalBlueprint2023.pdf.

⁷¹ 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/>.

Haudelift,⁷² Kalmar,⁷³ and Konecranes⁷⁴ each offer a battery-electric RTG model in the U.S. There have been no reported demonstrations of these units. Available literature indicates that the Kalmar battery-electric RTG primarily uses a grid connection with cables or busbars and uses the battery to travel between container stacks or to maintenance areas. The Konecranes battery-electric RTG operates on battery power and connects with a charging system as needed (Figure 38). 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.

⁷² Haudelift offers diesel straddle carriers for both general-purpose cargo handling as well as container handling. They also offer general purpose diesel-powered RTGs. Staff considers the product shown as “electric straddle carrier” to be an RTG and not a traditional straddle carrier used for container handling. See Haudelift, “Electric Straddle Carrier | Zero Emissions,” September 6, 2024. Accessed April 3, 2025. <https://www.haudelift.com/blog/electric-straddle-carrier-zero-emissions/>.

⁷³ 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/.

⁷⁴ 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 38: 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 handlers 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 often 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 3,725 pieces of CHE. Only 4 are reach stackers and 14 are side handlers, while 408

are top handlers.⁷⁵ The lower demand for reach stackers and side handlers may slow the adoption of zero-emission options for these CHE types. However, manufacturers offer 10 commercially available models of battery-electric reach stackers and 12 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 Limited primarily due to commercial availability and two-shift endurance.

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. 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 39). 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 Kalmar 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.⁷⁶ In April 2024, DP World London Gateway Hub took delivery of eight units, forming “the world’s first electric straddle carrier fleet.”⁷⁷ Konecranes also offers a fully battery-electric straddle carrier along with a containerized charging station.⁷⁸ There are two commercially available models of shuttle and straddle carriers. Battery-electric shuttle and straddle carriers achieve a Technology Readiness Grade of Demonstration.

⁷⁵ 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>.

⁷⁶ 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.

⁷⁷ 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/>.

⁷⁸ Konecranes, “Battery Konecranes Noell Straddle Carrier,” June 2022. https://www.konecranes.com/sites/default/files/2022-06/Battery_Konecranes_Noell_Straddle_Carrier_EN.pdf.

Figure 39: 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.⁷⁹ Two of the world's first battery-electric top handlers were demonstrated at the Port of Los Angeles in 2019 and 2020 and have remained in operation since. They can operate for 2 shifts on a single charge.⁸⁰ The demonstration was successful and 8 more electric top handlers were purchased by the facility.⁸¹ Taylor Machine Works, Inc. offers top handlers capable of lifting up to 90,000 lb. There are 3 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 commercial availability and performance and reliability comparable to diesel units.

⁷⁹ 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>.

⁸⁰ Port of Los Angeles, "Port of Los Angeles Unveils World's First Zero-Emissions Top Handlers," YouTube video, published on October 2, 2019, 3:26. Accessed April 9, 2025. https://youtu.be/WB_T804vQSE?si=ke2r9oz9q-4fdZHs.

⁸¹ WorldCargo News, "Yusen Terminals in LA puts into action electric top handlers," June 26, 2024. Accessed February 6, 2026. <https://www.worldcargonews.com/cargo-handling-equipment/2024/06/yusen-terminals-in-la-puts-into-action-nations-first-electric-top-handlers/>.

Battery-Electric Yard Trucks

Yard trucks are the most common type of CHE at facilities. The San Pedro Bay Port complex has 1,804 yard trucks, which is nearly half of their total CHE population.⁸² Table 9 summarizes the fuel types for these yard trucks. Only diesel-powered yard trucks are subject to the CHE Regulation.⁸³

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

Fuel Type	Quantity	Percent of Total Yard Truck Population
Diesel	1,429	79%
Electric	12	1%
Gasoline	134	7%
Liquid Natural Gas (LNG)	22	1%
Propane	207	11%

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.⁸⁴ 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,⁸⁵ most cannot yet 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 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.⁸⁶ Technology challenges resulted in considerable down time for the trucks. Facility operators reported delays obtaining

⁸² 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>.

⁸³ CHE using fuel types other than diesel may be subject to other regulations.

⁸⁴ Ghazal Razeghi, Micheal Mac Kinnon, and Scott Samuelsen, "A Comprehensive and Replicable Infrastructure Blueprint for Zero-Emission Medium- and Heavy-Duty Vehicles Operating at a Port Terminal," CEC, 2023. https://cleanenergy.uci.edu/PDF_White_Papers/PortTerminalBlueprint2023.pdf.

⁸⁵ See *Appendix E* for a list of battery-electric yard trucks demonstration projects.

⁸⁶ 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/>.

replacement parts and service for technical issues, especially for foreign parts and off-shore technical support. These challenges negatively impact the Technology Readiness Grade. However, facilities reported that newer battery-electric yard trucks can meet the power, acceleration, and operational needs during operation.

Although there are 16 commercially available battery-electric yard truck models and many demonstrations, they do not yet meet equivalency with their diesel counterparts. There are no models that demonstrated 2 full shifts of operation without needing an opportunity charge. However, it is likely that newer yard trucks will soon offer this capability. In addition, reliability is improving on second and third generation yard trucks. 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	20	1	0	Demonstration
Utility Truck, Other	22	2	2	Demonstration
Utility Truck, Sweeper	6	10	0	Limited

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.⁸⁷ 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 specialized CHE. According to the 2022 CHE Inventory,⁸⁸ there are only 11 operating at California seaports and intermodal railyards and 6 of them are at the San Pedro Bay Port complex.⁸⁹ One of these is a battery-electric railcar mover.⁹⁰ Another battery-electric railcar mover is being demonstrated at the Port of Stockton.⁹¹ There are 21 commercially available battery-electric railcar movers. Additionally, several companies offer innovative attachment systems that can be used with battery-electric or hydrogen fuel cell loaders to move railcars including Dymax, Mitchell Rail Gear, and SAS Forks.⁹² Battery-electric railcar movers achieve a Technology Readiness Grade of Demonstration due to the lack of information regarding demonstrations and deployments.

Battery-Electric Utility Trucks

Utility trucks include fuel trucks, water trucks, and other trucks that perform facility support operations. The availability and technology readiness of battery-electric utility trucks are closely related to advancements in the heavy-duty on-road and off-road truck sector. 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. Industries that require general-purpose and specialized trucks such as mining and airport ground support equipment are also adopting battery-electric utility

⁸⁷ Staff discussion with Motrec on December 18, 2024.

⁸⁸ CARB, "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.

⁸⁹ 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>.

⁹⁰ Ibid.

⁹¹ 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/>.

⁹² Dymax Rail, "Railcar Couplers for Wheel Loaders and Tractors," n.d. Accessed December 9, 2024. <https://dymaxrail.com/railway-attachments/railcar-quick-couplers/>; Mitchell Rail Gear, "Loader Railcar Mover Front End Loader Railcar Movers," n.d. Accessed August 6, 2024. <https://www.mitchell-railgear.com/product-listing/10/19>; SAS Forks, "Railcar Coupler Attachment to Use Wheel Loader to Move Railcar," n.d. Accessed November 9, 2024. <https://sasforks.com/product/railroad-coupler/>.

trucks. Manufacturers can often customize these trucks to meet the needs of seaports and intermodal railyards.

There are 24 commercially available medium- and heavy-duty battery-electric trucks that may be fitted to meet the needs of facility support CHE. One example of this is an XCMG E700 upfitted as a water truck being demonstrated at the Eastland Port in New Zealand.⁹³ 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 8⁹⁴ 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 16 commercially available battery-electric sweepers with 6 available in the U.S. The eSweeper developed by US Hybrid and GEP was rigorously tested for use by the California Department of Transportation (Caltrans). GEP began production of 18 units for Caltrans in March 2023.⁹⁵ 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.⁹⁶ Global M4ZE Series literature indicates that the 210 kW battery capacity can last for 10 to 11 hours of operation on the M3 model and 8 to 9 hours on the M4 model.⁹⁷ Although there is no available information on the performance of battery-electric sweepers at seaports and intermodal railyards, the Port of Long Beach recently purchased a battery-electric sweeper⁹⁸ and many

⁹³ See [Appendix E](#) for details.

⁹⁴ California HVIP, "Incentives for Clean Truck and Bus," n.d. Accessed April 14, 2025. <https://californiahvip.org/>.

⁹⁵ 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>.

⁹⁶ Elgin, "Electric Broom Bear Product Overview," n.d. Accessed May 9, 2025. <https://www.elginsweeper.com/products/all-electric/electric-broom-bear>; Jameson Dow, "We Drove the First All-Electric Street Sweeper in the US, Coming to LA soon," Electrek News, September 5, 2023. Accessed May 9, 2025. <https://www.elginsweeper.com/about/whats-new/electrek-electric-broom-bear-article>.

⁹⁷ Global, "Global M4 ZE-Series," n.d. Accessed April 23, 2025. https://globalsweeper.com/images/pdfs/M3-M4_ELECTRIC_BOOKLET.pdf.

⁹⁸ Port of Long Beach, "CEO Mario Cordero and the Port of Long Beach's first zero-emissions street sweeper!" Instagram, December 9, 2024. Accessed December 17, 2025. <https://www.instagram.com/p/DDYKw72TIKx/?hl=en>; Port of Long Beach, "CEO Mario Cordero and the Port of Long Beach's first zero-emissions street sweeper!" LinkedIn, December 2024. Accessed December 17, 2025. https://www.linkedin.com/posts/port-of-long-beach_ceo-mario-cordero-and-the-port-of-long-beachs-activity-7272043518066327552-SYw.

public municipalities have demonstrated this equipment in recent years.⁹⁹ Due to commercial availability, evidence of meeting endurance requirements, and positive reports of performance, battery-electric sweepers achieve a Technology Readiness Grade of Limited.

Emissions Benefits and Considerations

Replacing CHE that use diesel and other carbon-intensive fuels with zero-emission alternatives eliminates CHE tailpipe emissions at seaports and intermodal railyards. Battery-electric CHE mostly uses battery charging infrastructure that relies on power from California's utility grid. In 2023, 54% of California's electricity came from renewable sources.¹⁰⁰ This is up from 34% in 2021.¹⁰¹ As California's grid uses more renewable sources, the emissions benefits of using batteries and grid power for CHE will increase. This positively 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

⁹⁹ 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 (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).

¹⁰⁰ U.S. Energy Information Administration, "California State Profile and Energy Estimates," n.d. Accessed April 9, 2025. <https://www.eia.gov/state/?sid=CA>.

¹⁰¹ CEC, "2021 Total System Electric Generation," n.d. Accessed July 29, 2026. <https://www.energy.ca.gov/data-reports/energy-almanac/california-electricity-data/2021-total-system-electric-generation>.

integrating electricity supply, while alternative power sources, like energy storage systems or local microgrids, 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 projected future electricity demands and drivers. As more electric equipment is adopted to reduce emissions at seaports and intermodal railyards, electricity demand will continue to increase.

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). ¹⁰²	S/I	Increasing: California EO N-79-20 set, and EO N-27-25 reaffirmed, a goal for all new passenger cars, trucks, and sports utility vehicles sold in California to be zero-emission by 2035 ¹⁰³

¹⁰² 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 CEC reports 27,828,856 non-EV registered in California at the end of 2023 (CEC, "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%.

¹⁰³ CARB, "Report to the Governor in Response to Executive Order N-27-25 on Zero-Emission Vehicle Deployment," n.d. Accessed February 9, 2026. https://ww2.arb.ca.gov/sites/default/files/2025-08/August%202025%20Report%20to%20the%20Governor%20in%20Response%20to%20Executive%20Order%20on%20ZEV%20Deployment%20FINAL_0.pdf.

Source of Electricity Demand	Description	Applicability (S=Seaports, I=Intermodal Railyards)	Projected Electricity Demand and Drivers
Shore power for ocean-going vessels	As of January 1, 2023, container, refrigerated, and cruise ocean-going vessels must plug into shore power (grid) within two hours of berthing. ¹⁰⁴	S	Increasing: New vessel type requirements are effective as of January 1, 2025. Additional requirements begin on January 1, 2027. ¹⁰⁵
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. ¹⁰⁶
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. ¹⁰⁷

¹⁰⁴ CARB, "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>.

¹⁰⁵ Ibid.

¹⁰⁶ 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>.

¹⁰⁷ 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. ¹⁰⁸	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 staff used for the grid impact analysis.

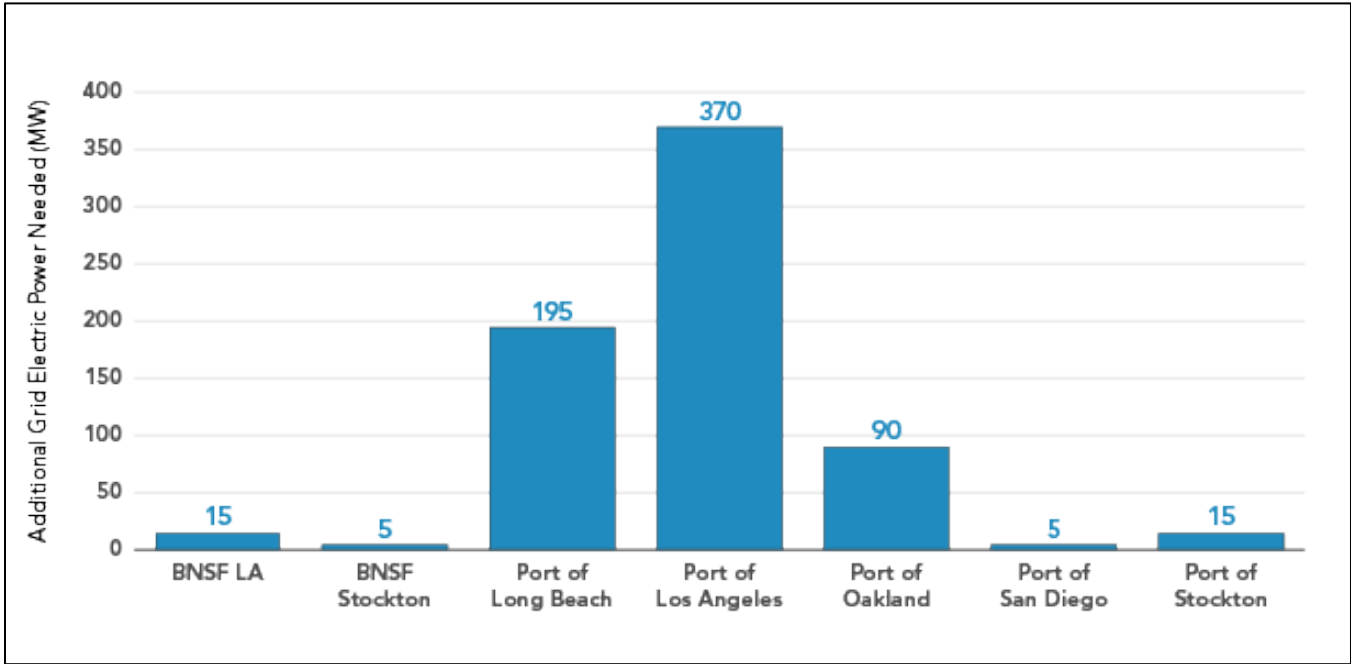
Based on staff's preliminary analysis, approximately 960 megawatts (MW) of total load capacity is needed. This includes both capacity that can be supported by existing infrastructure and additional load required beyond current capacity. Of the estimated 960 MW needed, existing utility-provided load capacity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

The existing utility-provided load capacity is sufficient for 21 of the 28 facilities analyzed. These facilities either require less than 5 MW of load capacity or have needs greater than 5 MW that existing load capacity at nearby substations can meet. The remaining 7 facilities will require substation upgrades to support fully zero-emission CHE operations. Figure 40

¹⁰⁸ CARB, "2022 Cargo Handling Equipment Emissions Inventory," 2022.
https://ww2.arb.ca.gov/sites/default/files/2023-04/2022%20CHE%20Emission%20Inventory%20Document_6April2023.pdf.

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

Seaports and intermodal railyards are connected to the utility grid for their power supply. The largest electric utilities in California are Los Angeles Department of Water and Power, Pacific Gas & Electric Company, San Diego Gas & Electric, and Southern California Edison.¹⁰⁹ 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.¹¹⁰ Some facilities receive power from two different utilities.

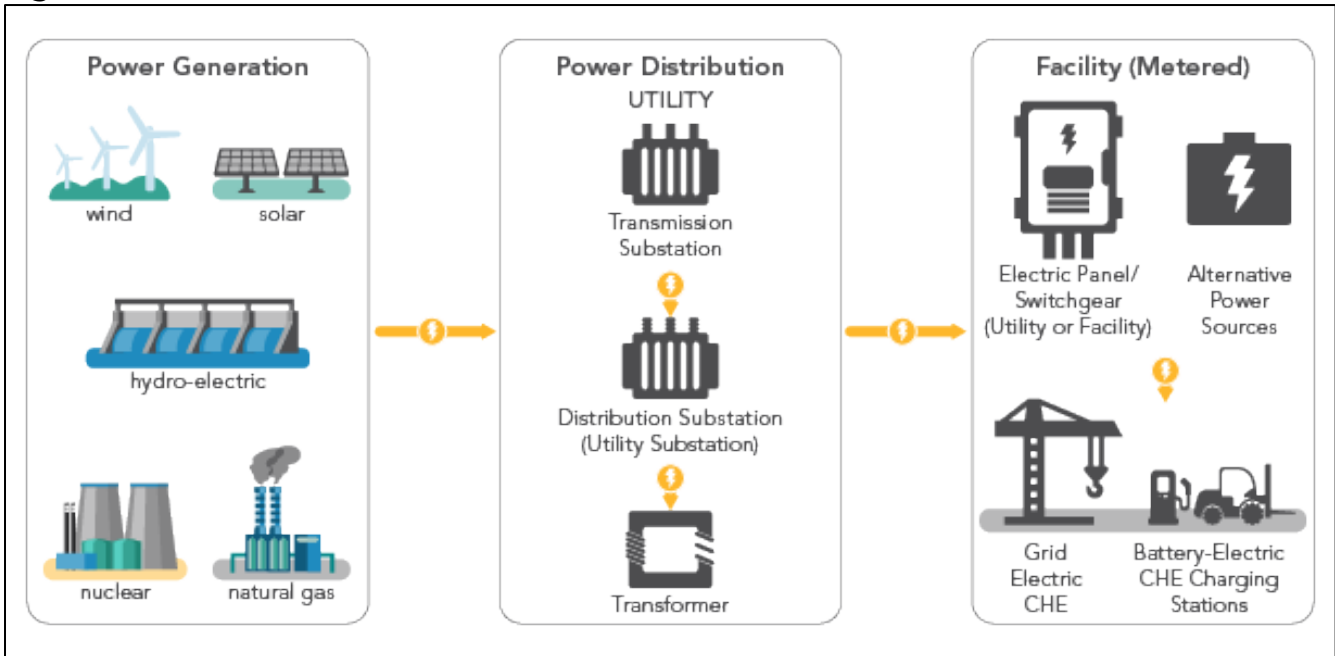
¹⁰⁹ CEC, “Electric Load-Serving Entities (LSEs) in California,” n.d. Accessed April 9, 2025. <https://www.energy.ca.gov/data-reports/energy-almanac/california-electricity-data/electric-load-serving-entities-lses>.

¹¹⁰ Ibid.

California utilities generate electricity from multiple sources, including hydro-electric, natural gas, nuclear, solar, and wind.¹¹¹ 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 generally defines the point of financial responsibility for any upgrade projects. 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.

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.

¹¹¹ CEC, "2023 Total System Electric Generation," n.d. Accessed July 29, 2026.
<https://www.energy.ca.gov/data-reports/energy-almanac/california-electricity-data/2023-total-system-electric-generation>.

Adding grid infrastructure can be time-consuming and complex. Such projects are a joint effort involving 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 - seaport and intermodal 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, sometimes taking 7 to 10 years to complete.¹¹² This 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. For example, transformer lead times have increased in recent years, rising from approximately 50 weeks in 2021 to an average of 120 weeks in 2024. Large transformers, including substation power transformers and generator step-up transformers, have lead times ranging from roughly 80 to 210 weeks.¹¹³

Grid Reliability

Grid reliability is another consideration when incorporating grid power for CHE. Many aspects of grid reliability can affect facility operations. Including:¹¹⁴

¹¹² Conversation between Southern California Edison staff and CARB staff on November 1, 2024.

¹¹³ The National Infrastructure Advisory Council, "Addressing the Critical Shortage of Power Transformers to Ensure Reliability of the U.S. Grid," June 2024. Accessed February 3, 2026.
https://www.cisa.gov/sites/default/files/2024-09/NIAC_Addressing%20the%20Critical%20Shortage%20of%20Power%20Transformers%20to%20Ensure%20Reliability%20of%20the%20U.S.%20Grid_Report_06112024_508c_pdf_0.pdf.

¹¹⁴ Many terms are used to define the ability of a power system to deliver adequate electricity to all points of consumption within accepted standards. In addition to reliability, some of these terms include resiliency, adequacy, and security. For more information regarding these terms and grid reliability, see E. Ciapessoni, D. Cirio, A. Pitto, M. Van Harte, M. Panteli, "Power System Resilience: definition, features and properties," CIGRE Science & Engineering, No. 30, October 2023. <https://cse.cigre.org/cse-n030/power-system->

1. Continuously available power – When electricity demand rises significantly or during extreme weather events, some areas can experience *brownouts* (power dips) or *blackouts* (outages). Facilities need enough capacity and backup options to keep equipment running in these events.
2. Clean, stable power – Utilities work to provide clean, stable power to the grid. However, at times power can vary in voltage or quality. This variability can damage equipment or cause it to shut down, especially for grid-electric equipment.
3. Reliable communication and control systems that support grid operations – Meters, control signals, and grid-connected devices communicate with each other. If these systems fail, the grid may not deliver power correctly or may block onsite equipment from operating as expected.

Increasing electricity demand and extreme weather events continue to put pressure on grid reliability.¹¹⁵ Because electric CHE depends on the expanding grid and will add additional load, facilities should account for grid reliability in all stages of infrastructure planning.

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 available, then dispense it to CHE when needed. 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 array and a 700-kW/2700-kWh lithium-ion battery energy storage system,¹¹⁶ saving 60% of the terminal's energy.¹¹⁷

[resilience-definition-features-and-properties.html](#); John Peiserich and John Dulude, "Perspectives, Rethinking Energy Reliability with Modern Power Systems," J.S. Held, LLC, 2023. https://www.jsheld.com/uploads/Rethinking-Energy-Reliability-with-Modern-Power-Systems-Final_2025-03-06-205635_khqi.pdf; and U.S. DOE, "Secure Communications: Interoperability in the Power Grid," September 2023. <https://www.energy.gov/sites/default/files/2023-09/Secure%20Communications%20Interoperability%20Challenges%20in%20the%20Power%20Grid.pdf>.

¹¹⁵ CEC, "California Energy Resource and Reliability Outlook, 2024," August 2024.

<https://www.energy.ca.gov/publications/2024/california-energy-resource-and-reliability-outlook-2024>.

¹¹⁶ Port of San Diego, "Energy," n.d. Accessed December 6, 2024.

<https://www.portofsandiego.org/environment/energy-sustainability/energy>.

¹¹⁷ In-person meeting between the Port of San Diego staff and CARB staff dated October 22, 2024.

Figure 42: Battery-Electric Storage System at Port of Long Beach¹¹⁸



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. 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

¹¹⁸ Pacific Northwest National Laboratory, "Port Electrification Handbook," U.S DOE, May 2024.
https://www.pnnl.gov/sites/default/files/media/file/Port_Electrification_Handbook_FINAL.pdf.

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.¹¹⁹ 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.¹²⁰ 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. Facilities can reduce delays by starting the permitting process early, meeting with city officials, and maintaining ongoing communication. 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*. One report estimates that retrofits can take three to five years, while redevelopments can take five to eight years due to increased permitting requirements.¹²¹

¹¹⁹ Calculated from a Google map of the substation at the Port of Long Beach.

¹²⁰ 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>.

¹²¹ Grant Farm, "Charging Ahead: The Port Community Electric Vehicle Blueprint," Port of Long Beach, May 2019. <https://thehelm.polb.com/download/379/zero-emissions/6769/port-community-electric-vehicle-blueprint-042919.pdf>.

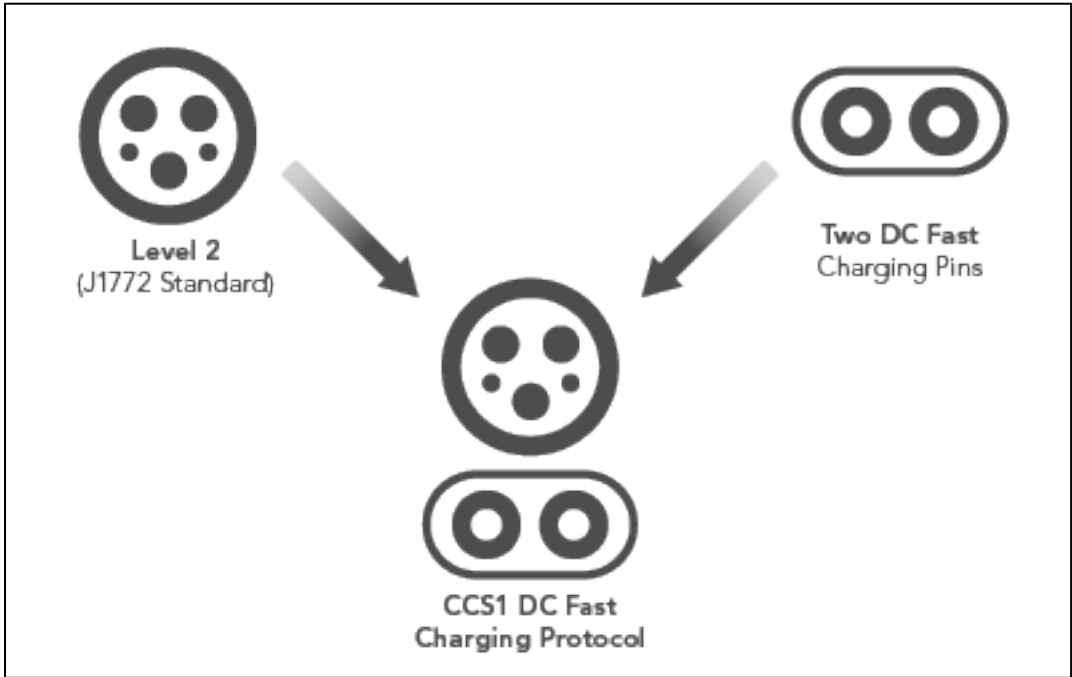
Most CHE electrification projects fall into the retrofit category; however, one redevelopment may be faster and more cost-effective than multiple retrofits.

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.¹²²

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.¹²³ The choice between

¹²² 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, 569-575. <https://doi.org/10.1109/ecce.2019.8912594>.
¹²³ Claimed confidential data obtained from an industry source that requested non-attribution.

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.¹²⁴ 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 select 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.

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

¹²⁴ Grant Farm, "Charging Ahead: The Port Community Electric Vehicle Blueprint," Port of Long Beach, May 2019. <https://thehelm.polb.com/download/379/zero-emissions/6769/port-community-electric-vehicle-blueprint-042919.pdf>.

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. Hands-free charging methods - conductive or inductive - may require training to address proper alignment of CHE with the charging mechanism. A.P. Moller-Maersk Terminals at the Port of New York and New Jersey uses static inductive charging for 7 battery-electric yard trucks.¹²⁵ The West Basin Container Terminal at the Port of Los Angeles received grant funding to demonstrate static inductive charging of 10

¹²⁵ Charles Morris, "APM Terminals to pilot electric terminal tractors with inductive charging at New Jersey port," Charged EV Fleets & Infrastructure News, June 16, 2024. Accessed March 17, 2026.
<https://chargedevs.com/newswire/apm-terminals-to-pilot-electric-terminal-tractors-with-inductive-charging-at-new-jersey-port/>.

battery-electric yard trucks.¹²⁶ *Appendix E* lists additional demonstration projects involving inductive charging.

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

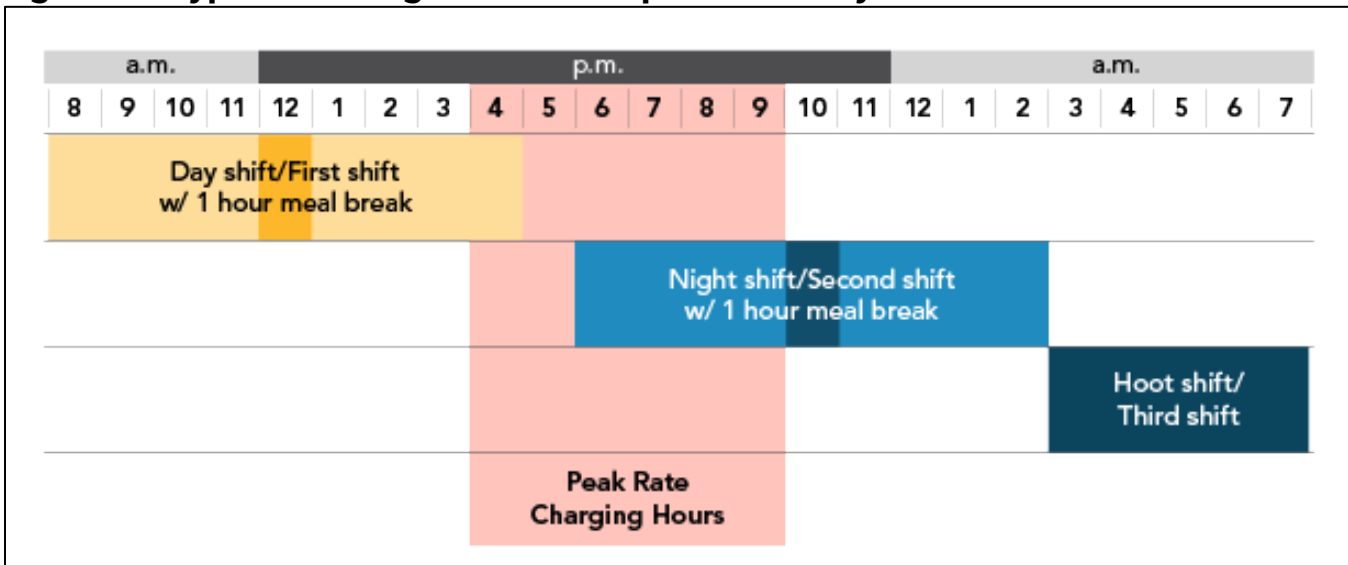
Charging Interface	Benefits	Challenges
Manual Conductive Charging	• Standard solution • Less initial investment • Simple technology • High charging efficiency	• Cable management issues • Labor intensive
Hands-free Conductive Charging	• Less labor intensive • High charging efficiency • Lower operational costs • Can take advantage of opportunity charging	• High capital costs • Connection problems
Inductive Charging	• Less labor intensive • 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, or hoot shift. Figure 46 shows the typical working hours at seaports and intermodal railyards in California.

¹²⁶ The Port of Los Angeles, “Zero Emission Freight Vehicle Advanced Infrastructure Demonstration (AID) Project,” n.d. Accessed April 2, 2025. <https://kentico.portoflosangeles.org/getmedia/ffe04622-f7bc-47b4-afbd-5d385531a4d3/aid-cec-fact-sheet>.

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



Downtime charging means charging the battery during non-use periods like meal breaks, overnight, or between shifts. This is a common practice for recharging equipment. However, rates are often the highest during the hour between the first and second shift. Scheduling downtime charging during the hoot shift can help avoid peak electricity rates, but requires substantial grid power and labor if all CHE is charged at the same time.

Downtime charging includes *unmanaged* and *managed* charging scenarios. Unmanaged charging involves charging CHE without any oversight or strategic approach to reduce compounded demand or optimize operational costs. Simultaneous charging of CHE can create peak load conditions that increase overall power demand and costs. Such load spikes can strain local distribution infrastructure, necessitate additional CHE infrastructure, require upgrades to utility systems, and reduce grid efficiency.

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:¹²⁷

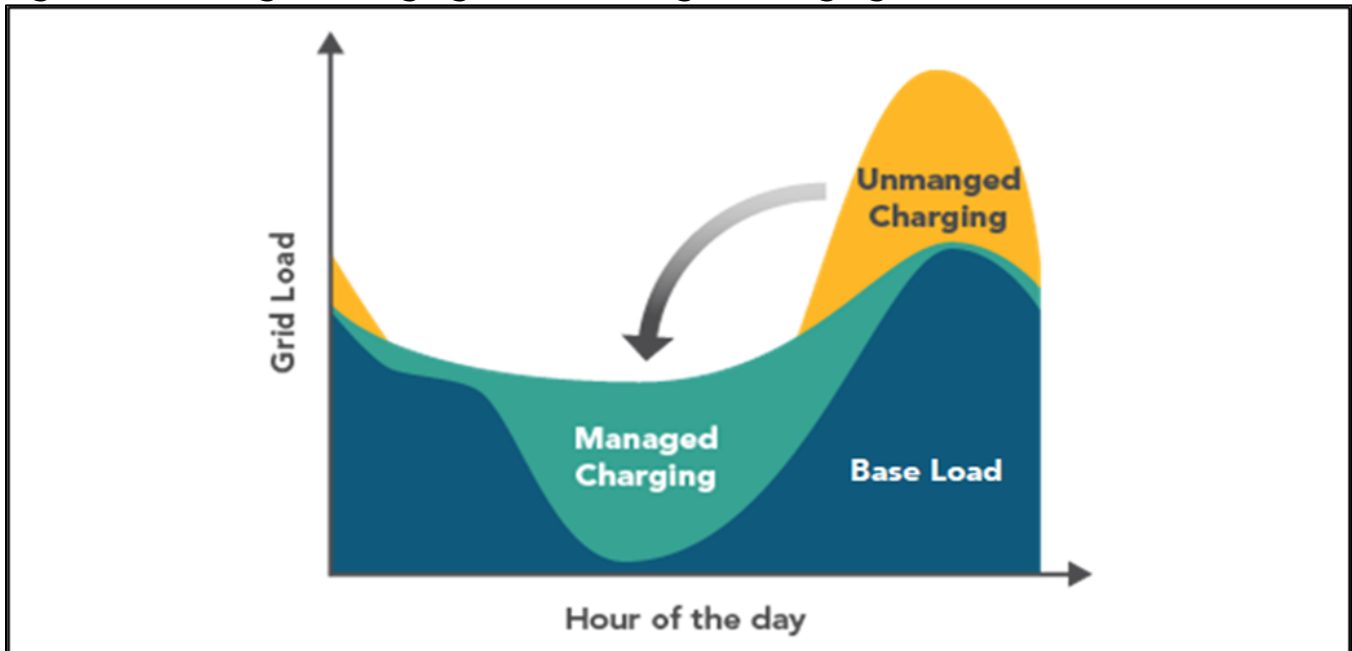
- Reduced power systems investment costs
- Reduced operating costs
- Reduced distribution systems investment costs
- Increased distribution systems charging capacity

Figure 47 illustrates how grid load from CHE can differ under unmanaged versus managed charging. *Base load* reflects grid demand before any CHE charging occurs. *Unmanaged*

¹²⁷ Muhammad Bashir Anwar et. al., "Assessing the value of electric vehicle managed charging: a review of methodologies and results," Energy & Environmental Science (2022), vol. 15(2): 466-498. <https://doi.org/10.1039/d1ee02206g>.

charging shows the compounded load created when all CHE charge simultaneously without coordination. *Managed charging* demonstrates how effective charge management can shift a portion of that demand away from peak periods to times of lower grid use, reducing the peak load required to support CHE fleet charging.

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 mobility of the CHE and facility operations, relocating the equipment to the charging station can be time-consuming, making opportunity charging difficult to implement. Additionally, work shifts may flex or extend by up to one hour earlier or later presenting challenges for opportunity charging. Continued progress in charging technologies such as reduced charging times through higher-power charging systems like the megawatt charging system, mobile charging solutions, and alternative charging interfaces such as inductive charging, may enable broader application over time.

First-generation battery-electric container CHE was designed to operate for an eight-hour shift, opportunity charge at breakeven 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.¹²⁸

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.¹²⁹ 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.¹³⁰ 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.

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 through 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.

¹²⁸ 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/>.

¹²⁹ 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/>.

¹³⁰ Staff meeting with Taylor Machine Works.

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

Capital Costs	Operating Costs
• Equipment ○ CHE ○ Charging station • Infrastructure installation	• Equipment fuel • Equipment maintenance • Infrastructure maintenance • Potential midlife battery replacement

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.¹³¹ Economies of scale may reduce equipment capital costs in the future similar to battery-electric passenger vehicles.¹³² However, this has not yet been realized for zero-emission CHE.

Some 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.¹³³ 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 a potential midlife battery replacement.

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

¹³¹ 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/>.

¹³² According to the International Energy Agency, "Electric car affordability has made significant strides over the past decade, primarily driven by falling battery prices, intensifying market competition and carmakers reaching economies of scale." (International Energy Agency, "Trends in electric car affordability," n.d. Accessed March 26, 2026. <https://www.iea.org/reports/global-ev-outlook-2025/trends-in-electric-car-affordability>.)

¹³³ Claimed confidential data obtained from an industry source that requested non-attribution.

around \$0.27/kWh from 2025 going forward for commercial uses.¹³⁴ See [Appendix G](#) for more information 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.¹³⁵ 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. However, as discussed in the battery-electric [Technology Description](#) section, battery life is continually improving. Therefore, a midlife battery replacement may not be necessary. As more data is collected, this cost can be more accurately estimated.

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 2021.¹³⁶ 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 cobalt oxide batteries is projected to decline from

¹³⁴ Integrated Energy Policy Report electricity costs account for time of use and demand charges. See CEC, "2024 Integrated Energy Policy Report Update," October 09, 2025. <https://www.energy.ca.gov/data-reports/reports/integrated-energy-policy-report/2024-integrated-energy-policy-report-update>.

¹³⁵ 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/>.

¹³⁶ 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.

approximately \$725 per kWh in 2015 to \$405/kWh in 2020, and further to \$218/kWh by 2030.¹³⁷

Table 15 through Table 22 compare the costs of battery-electric and diesel-powered CHE. All costs reflect reported values and do not account for any incentives.

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

Capital/Operating (Op.) Cost Component	Battery-Electric	Diesel
Capital - CHE	\$520,800 ¹³⁸	[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. - Potential 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. - Potential Battery Replacement	\$10,000	N/A

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

¹³⁷ CARB, "Staff Report: Initial Statement of Reasons, Appendix E: Battery Cost for Heavy-Duty Electric Vehicles," August 7, 2018. <https://ww2.arb.ca.gov/sites/default/files/2020-06/Appendix%20E%20Battery%20Cost%20for%20Heavy-Duty%20Electric%20Vehicles.pdf>.

¹³⁸ 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-shepina-full-electric-battery-powered>. Price was converted from the euro (€) to U.S. dollars (\$).

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 to \$900,000	\$240,000 to \$420,000
Capital - Charger	\$10,000 per charger	N/A
Op. - Fuel	\$8,300 per year	\$5,800 to \$12,000 per year
Op. - Maintenance	\$18,750 per year	\$25,000 per year
Op. - Potential 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 ¹³⁹	\$12,400 to \$38,400 per year ¹⁴⁰
Op. - Maintenance	[Staff is seeking information]	[Staff is seeking information]
Op. - Potential Battery Replacement	\$23,000 to \$40,000	N/A

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

¹³⁹ 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 or special electricity rates offered by utility providers.

¹⁴⁰ Cost = 4 to 9 gallon/h x 1031 h/year x \$3.00 to \$4.13/gallon = \$12,372 to \$38,322 per year. (Fuel efficiency values are from, Volvo, "Save on Every Gallon Fuel Efficiency Guarantee," n.d. Accessed April 14, 2025. <https://www.volvoc.com/united-states/en-us/volvo-services/fuel-efficiency-services/fuel-efficiency-guarantee/>.)

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 ¹⁴¹	\$3,200 to \$4,300 per year ¹⁴²
Op. - Maintenance	[Staff is seeking information]	[Staff is seeking information]
Op. - Potential 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 ¹⁴³	N/A
Op. - Fuel	\$31,000 per year ¹⁴⁴	\$21,500 to \$29,600 per year ¹⁴⁵
Op. - Maintenance	[Staff is seeking information]	3% to 5% of the initial value of the equipment ¹⁴⁶

¹⁴¹ 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 or special electricity rates offered by utility providers.

¹⁴² Cost = 1.8 gallon/h x 576 h/year x \$3.00 to \$4.13/gallon = \$3,110 to \$4,282 per year. (Fuel efficiency values are from, Miami Industrial Trucks, "Shuttlewagon Railcar Movers in Kentucky, Ohio and West Virginia," n.d. Accessed January 24, 2025. <https://www.mitlift.com/shuttlewagon-railcar-movers/>.)

¹⁴³ Terminalift, "New Charging Stations for Sale at Terminalift LLC," n.d. Accessed November 25, 2024. <https://www.terminalift.com/new/charging-stations>.

¹⁴⁴ 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 or special electricity rates offered by utility providers.

¹⁴⁵ Cost = 3.4 gallon/h x 2105 h/year x \$3.00 to \$4.13/gallon = \$21,471 to \$29,558 per year. (Fuel efficiency values are from, 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.)

¹⁴⁶ 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/>.

Capital/Operating (Op.) Cost Component	Battery-Electric	Diesel
Op. - Potential 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 ¹⁴⁷	\$34,800 to \$47,900 per year ¹⁴⁸
Op. - Maintenance	\$67,500 per year ¹⁴⁹	\$90,000 per year ¹⁵⁰
Op. - Potential Battery Replacement	[Staff is seeking information]	N/A

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

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

Capital/Operating (Op.) Cost Component	Battery-Electric	Diesel
Capital - CHE	\$300,000 ¹⁵¹ to \$400,000	\$95,000 to \$170,000
Capital - Charger	\$30,000 to \$60,000 per charger ¹⁵²	N/A

¹⁴⁷ 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 or special electricity rates offered by utility providers.

¹⁴⁸ Cost = 5.5 gallon/h x 2105 h/year x \$3.00 to \$4.13/gallon = \$34,733 to \$47,815 per year. (Fuel efficiency values are from, CSX Intermodal Terminals, Inc., "CSX Intermodal Terminals, Charlotte - Loaded Container Handler Engine Replacement: Case Study Follow-up visit on 8-12-14," n.d. Accessed April 14, 2025. <https://www.deq.nc.gov/documents/files/csx-intermodal-terminals-charlotte-loaded-container-handler/download>.)

¹⁴⁹ 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," University of Southern California, prepared for the U.S. Department of Transportation, Office of the Assistant Secretary for Research and Technology, August 2021. <https://doi.org/10.25554/8drs-9j23>.

¹⁵⁰ Ibid.

¹⁵¹ Sharon Cloward, et al., "San Diego Port Sustainable Freight Demonstration Project," CEC, Publication Number: CEC-600-2024-006, March 2024. <https://www.energy.ca.gov/sites/default/files/2024-03/CEC-600-2024-006.pdf>.

¹⁵² 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.

Capital/Operating (Op) Cost Component	Battery-Electric	Diesel
Op. - Fuel	\$8,400 per year ¹⁵³	\$13,800 to \$18,900 per year ¹⁵⁴
Op. - Maintenance	\$28,005 per year ¹⁵⁵	\$40,004 per year ¹⁵⁶
Op. - Potential 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 analyzed the 12-year total cost of ownership for various CHE types. They found that battery-electric yard trucks are cost-competitive with diesel yard trucks in California.¹⁵⁷ 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.

In 2019, the Port of Oakland released a feasibility assessment for CHE and calculated the annual total cost of ownership of battery-electric yard trucks.¹⁵⁸ They found that battery-electric yard trucks 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

¹⁵³ 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 or special electricity rates offered by utility providers.

¹⁵⁴ Cost = 2.4 gallon/h x 1906 h/year x \$3.00 to \$4.13/gallon = \$13,723 to \$18,892 per year. Fuel efficiency is sourced from, CARB, "California Air Resources Board Discussion Draft," April 24, 2017. <https://ww2.arb.ca.gov/sites/default/files/2018-10/170425eerdraftdocument.pdf>.

¹⁵⁵ See *ibid.*, 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."

¹⁵⁶ *Ibid.*

¹⁵⁷ Mia Reback, et al., "The Time Is Now for Zero-Emissions Cargo Handling Equipment at America's Busiest Cargo Ports," Rocky Mountain Institute, 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/>.

¹⁵⁸ 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>.

operate and maintain the new equipment, subscriptions for connected services such as remote monitoring and charging management, and extended warranties.

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 facilities can determine and factor in installation costs. 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.¹⁵⁹

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
- Permitting
- Labor costs for construction, trenching, and installation of electrical equipment
- Project contingency.¹⁶⁰

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.¹⁶¹ These costs vary depending on the station size, charger type, and charging

¹⁵⁹ EPRI, "Zero-Emission Planning and Grid Assessment for the Port of Los Angeles," June 29, 2023. <https://www.epri.com/research/products/000000003002025783>.

¹⁶⁰ 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 information on cost contingency, see, Shohreh Ghorbani, "How Cost Contingency is Calculated?" [projectcontrolacademy.com](https://www.projectcontrolacademy.com), n.d. Accessed May 8, 2025. <https://www.projectcontrolacademy.com/cost-contingency-calculation/>.

¹⁶¹ Charger costs are included in Table 15 through Table 22.

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.¹⁶² Table 23 provides battery-electric CHE infrastructure related costs.

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: ◦ \$8,000,000 to \$30,000,000 to build a 66kV substation.
Capital - Existing Utility Substation Modification	Varies • Cost information from past projects: ◦ Utility side infrastructure upgrades to support 20 charging ports for yard trucks cost \$733,071.¹⁶³

¹⁶² U.S. DOE, "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>.

¹⁶³ 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>.

Capital/Operating (Op.) Cost Component	Cost
Capital – Charging Station Installation ¹⁶⁴	Varies - Cost information from past projects: - Switchgears, trenching, and installation for 20 charging ports for yard trucks cost \$853,181.¹⁶⁵ 12 kV electrical main and meter switchgear line up cost \$500,000.¹⁶⁶ - Trenching, conduit and wires for charging stations for 25 top handlers cost \$8,000,000.¹⁶⁷ - Project contingency is 30% of total system installation costs.¹⁶⁸ \$1,000,000 to install 9 chargers to support charging for top handlers.
Op. – Infrastructure Maintenance	[Staff is seeking information]

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

Technology Outlook

Out of the 23 types of battery-electric CHE assessed for technology readiness, only log stackers and RMGs do not have commercially available models. But only AGVs achieve a Technology Readiness Grade of Equivalence. Table 24 through Table 26 summarize the outlook for the other 22 battery-electric CHE types to achieve a Technology Readiness Grade of Equivalence within the next 10 years, grouped by CHE category.

¹⁶⁴ Charger costs are included in Table 15 through Table 22.

¹⁶⁵ 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>.

¹⁶⁶ Grant Farm, "Charging Ahead: The Port Community Electric Vehicle Blueprint," Port of Long Beach, May 2019. <https://thehelm.polb.com/download/379/zero-emissions/6769/port-community-electric-vehicle-blueprint-042919.pdf>.

¹⁶⁷ Ibid.

¹⁶⁸ Ibid.

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 achieve a Technology Readiness Grade of Limited. There have been 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. ¹⁶⁹ 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.
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.

¹⁶⁹ 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
Haul Truck	Because of the commercial availability and reported success of the Sany battery-electric haul truck at the İzmir lime quarry in Turkey, ¹⁷⁰ haul trucks receive a Technology Readiness Grade of Demonstration. 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.
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 likely not develop battery-electric log stackers. However, OEMs can leverage designs from battery-electric reach stackers and top handlers due to their similarities to log stackers. But considerable development and testing would be needed. With additional emission reduction strategies and incentive programs for both the CHE and charging infrastructure, battery-electric log stackers can 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, therefore battery-electric RMGs will likely not achieve Equivalence within 10 years.

¹⁷⁰ See [Appendix E](#) for details regarding this pilot project.

Type of CHE	Outlook for Achieving Equivalence Within 10 Years
Reach Stacker, Shuttle and Straddle Carrier	Reach stackers and shuttle and straddle carriers 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, more demonstrations 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.
Rubber-Tired Gantry Crane	RTGs are practical container CHE due to their ability to move easily between rows or stacks of containers. Therefore, while conversions from diesel to grid-electric will likely 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 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.
Side Handler, Top Handler	Battery-electric side handlers and top handlers achieve a Technology Readiness Grade of Limited, indicating that they have been proven and are ready for limited, monitored deployment. One 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 side handlers and top handlers can achieve Equivalence within 10 years.

Type of CHE	Outlook for Achieving 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 trucks instead of diesel models. ¹⁷¹ 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.

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 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 is little information regarding their operational feasibility. More research and successful demonstrations are needed. As charging infrastructure is installed for bulk material and container CHE, this 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 of the available information on battery-electric utility trucks has centered on heavy-duty trucks for freight, urban deliveries, and terminal operations. However, with 24 commercially available truck models that can be fitted to serve as facility support CHE and one demonstration of a battery-electric water truck with positive initial feedback at the Eastland Port in New Zealand, battery-electric utility trucks achieve a Technology Readiness Grade of Demonstration. With additional emission reduction strategies and incentives in place for cargo-focused CHE, battery-electric utility trucks can achieve Equivalence within 10 years.

¹⁷¹ CORE's *Voucher Funding Map* allows the user to download a dataset containing all implementations of yard trucks using the CORE Voucher Program. See <https://californiacore.org/voucher-funding-map/>.

Type of CHE	Outlook for Achieving Equivalence Within 10 Years
Utility Truck, Sweeper	There is extensive published information on the successful deployments of battery-electric sweepers in the public sector. ¹⁷² Battery-electric sweepers are being deployed and tested in many municipalities on a global level and one is now operating at the Port of Long Beach. ¹⁷³ 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.

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,¹⁷⁴ 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 may not be enough to offset the initial cost. Additionally, battery replacement and high-tech replacement parts can 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

¹⁷² See [Appendix E](#) for demonstrations of zero-emission sweepers.

¹⁷³ See [Battery-Electric Sweepers](#) Section above for references.

¹⁷⁴ 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 (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>).

projects. The lack of coordinated infrastructure plans can slow the adoption of battery-electric CHE.

Despite these challenges, the technology outlook for battery-electric CHE is promising. Many battery-electric CHE are nearing functional equivalence with diesel-powered CHE. As long as incentive programs and additional emission reduction strategies are in place, facilities will continue acquiring the equipment.

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. In addition, because grid-electric CHE does not depend primarily on large batteries, costs for battery replacement and disposal may be reduced or avoided. 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 not suitable for many CHE with unpredictable paths and higher mobility. For these reasons, roughly half of grid-electric CHE combinations 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 some 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	28	1	1	Demonstration
Crane, Mobile Harbor	2	0	2	Demonstration
Crane, Off-Road	4	0	0	Demonstration
Excavator	1	3	0	Demonstration

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 that 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 limits mobility. These CHE are unique because the base can 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.¹⁷⁵ 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 only support brief or emergency operations or movement between grid power sources.¹⁷⁶ 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.¹⁷⁷ 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.¹⁷⁸ There are two commercially available models. Grid-electric mobile harbor cranes achieve a Technology Readiness Grade of Demonstration.

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

¹⁷⁵ Sennebogen – Move Big Things, “Sennebogen 825 Mobile Electric Excavator with Ceiling Power Supply – Scrap Handling - Germany,” YouTube video, published on July 6, 2016, 2:17. Accessed April 10, 2025. <https://youtu.be/N4pr9nPVdfA?si=Hub98P2MwOux6uVv>.

¹⁷⁶ *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.

¹⁷⁷ 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>.

¹⁷⁸ WorldCargo 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/>.

California.¹⁷⁹ As discussed in the *Other Grid-Electric Container CHE* section, Kalmar plans to test a conductive electric rail system on a reach stacker which is similar to a forklift in design, duty cycle, and lift capacity.¹⁸⁰ 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 in the future.

Grid-Electric Container CHE

Grid-electric is the industry standard power offering for both RMGs and ship-to-shore cranes. Also, many facilities are converting their diesel-powered RTGs to grid-electric. Demonstrations using new inductive and conductive technologies for container CHE are in the planning phase. Table 28 provides the technology readiness data summary for grid-electric container CHE. Container CHE with commercially available models are discussed first.

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
AGV	0	0	0	Development
Rail-Mounted Gantry Crane	9	0	0	Equivalence
Reach Stacker	0	0	1	Development
Rubber-Tired Gantry Crane	10*	3**	0	Limited
Ship-to-Shore Crane	7	1	0	Equivalence
Shuttle and Straddle Carrier	0	0	0	Development
Side Handler	0	0	0	Development
Top Handler	0	0	0	Development
Yard Truck	0	0	2	Development

*Includes six 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.

¹⁷⁹ CARB, "2022 Cargo Handling Equipment Emissions Inventory," 2022.

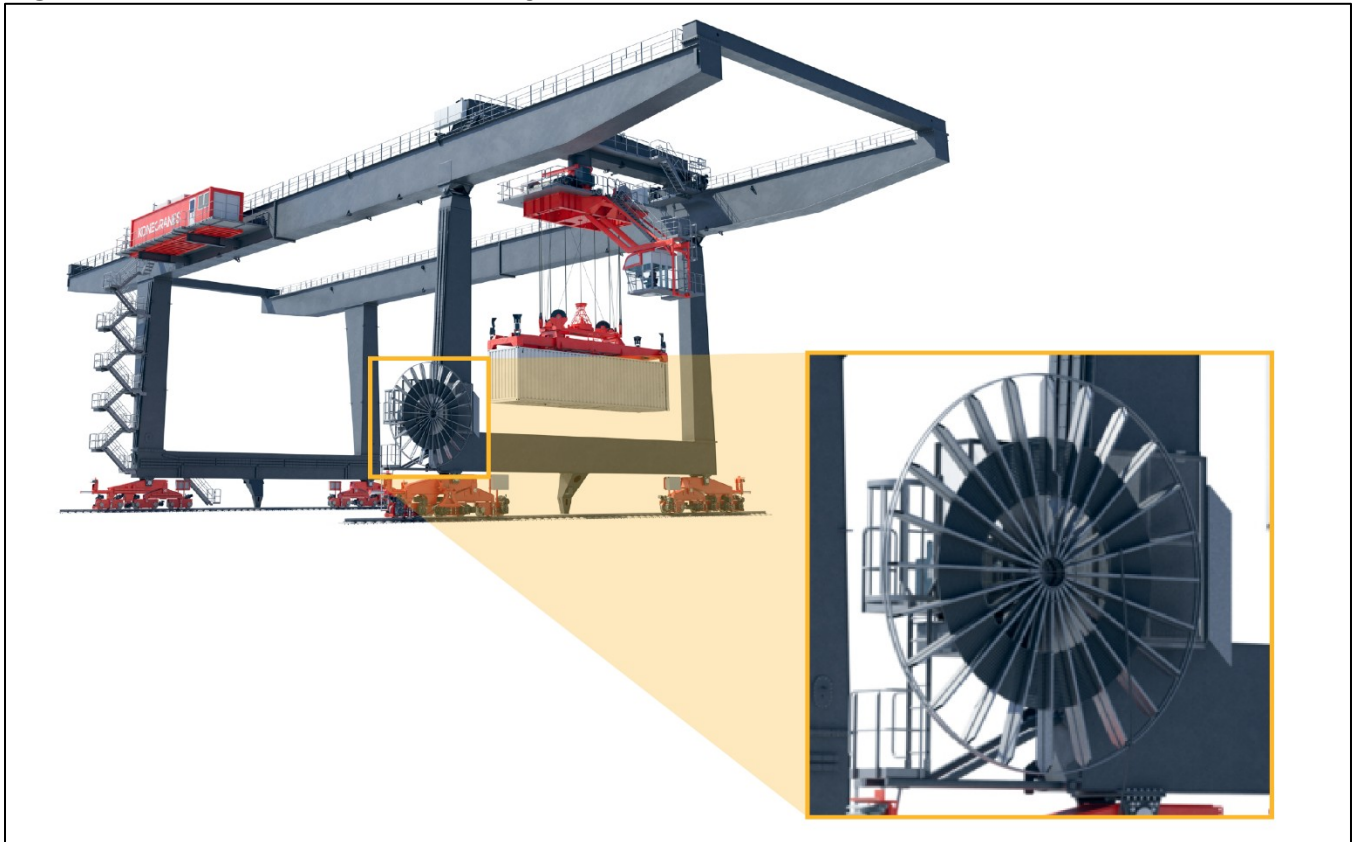
https://ww2.arb.ca.gov/sites/default/files/2023-04/2022%20CHE%20Emission%20Inventory%20Document_6April2023.pdf.

¹⁸⁰ 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/>.

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 stacking cranes at the Port of Long Beach operate within a clearly defined path, simplifying the infrastructure requirements for grid electrification.¹⁸¹ Most RMGs connect to the grid through cable and reel systems. Retracting spool systems collect and disperse the cable as the crane moves (Figure 48). 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 48: RMG with Cable Reel System for Grid-Electric Connection (Konecranes)



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 onboard battery energy storage to achieve equivalency to their diesel counterparts. Between 2019 and 2022, the Port of Long Beach converted nine diesel-powered RTGs to

¹⁸¹ Grant Farm, "Charging Ahead: The Port Community Electric Vehicle Blueprint," Port of Long Beach, May 2019. <https://thehelm.polb.com/download/379/zero-emissions/6769/port-community-electric-vehicle-blueprint-042919.pdf>.

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.¹⁸² A 2019 article claims that Hyundai-Samho, a South Korean heavy equipment manufacturer, offers a commercially available, inductively charged RTG.¹⁸³ Additionally, a 2019 YouTube video highlights the benefits of this grid-electric RTG, including regenerative braking that helps charge the onboard battery.¹⁸⁴ 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.¹⁸⁵ There are six manufacturers of new grid-electric RTGs and several companies that convert diesel-powered RTGs to cable-tied grid-electric RTGs including Cavotec,¹⁸⁶ Conductix-Wampfler,¹⁸⁷ Electroflex,¹⁸⁸ Liebherr,¹⁸⁹ Paceco,¹⁹⁰ Vahle,¹⁹¹ and ZPMC.¹⁹²

There are several commercially available grid-electric RTGs, many grid-electric RTG conversions in operation, and multiple service providers who convert diesel-powered RTGs to grid-electric. However, because of the limited number of new grid-electric RTG

¹⁸² 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>.

¹⁸³ WorldCargo 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/>.

¹⁸⁴ Hyundai Cranes, “[Hyundai Cranes] Wireless Power Transmission Yard Crane (Eng),” YouTube video, published on June 25, 2019, 3:25. Accessed April 8, 2025. <https://www.youtube.com/watch?v=TDUNsDXOIM>.

¹⁸⁵ Mandra, Jasmina, “10 More eRTGs Arrive in Damietta,” WorldCargo News, April 14, 2025. Accessed April 15, 2025. <https://www.worldcargonews.com/cargo-handling-equipment/2025/04/10-more-ertgs-arrive-in-damietta/>.

¹⁸⁶ Port Strategy, “Era of the eRTG,” January 6, 2023. Accessed April 4, 2025. <https://www.portstrategy.com/era-of-the-ertg/1485459.article>.

¹⁸⁷ 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>.

¹⁸⁸ 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>.

¹⁸⁹ Port Strategy, “Era of the eRTG,” January 6, 2023. Accessed April 4, 2025. <https://www.portstrategy.com/era-of-the-ertg/1485459.article>.

¹⁹⁰ EPRI, “Electric Cable Reel Rubber-Tired Gantry Cranes: Costs and Benefits,” March 2010. <https://www.epri.com/research/products/000000003002025783>; WorldCargo News, “ERTG cable problem,” June 1, 2010. Accessed May 5, 2025. <https://www.worldcargonews.com/container/2010/06/ertg-cable-problem/>.

¹⁹¹ Port Technology Team, “Vahle Electrifies Mexico’s Billion Dollar Terminal,” Port Technology, March 27, 2017. Accessed April 4, 2025. https://www.porttechnology.org/news/vahle_electrifies_mexicos_billion_dollar_terminal/.

¹⁹² Port Technology International, “RTG Conversion Finishes Ahead of Schedule,” July 4, 2014. Accessed April 4, 2025. https://www.porttechnology.org/news/rtg_to_ertg_conversion_finishes_ahead_of_schedule/.

installations and the challenges of converting operating diesel-powered RTGs to grid-electric, this CHE-technology combination is not fully mature. Grid-electric RTGs achieve a Technology Readiness Grade of Limited due to commercial availability and proven performance.¹⁹³

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 48). The San Pedro Bay Port complex operates 170 ship-to-shore cranes, all powered by grid-electricity.¹⁹⁴ The Port of Oakland also reported that all their ship-to-shore cranes are grid-electric.¹⁹⁵ As the industry standard configuration, grid-electric ship-to-shore cranes achieve a Technology Readiness Grade of Equivalence.

Other Grid-Electric Container CHE

Dynamic conductive charging and dynamic inductive charging are two technologies that are currently being considered for reach stackers 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.¹⁹⁶ The project demonstrated dynamic conductive charging for an electric bus using pick-ups that lower from the bottom of the vehicle (Figure 49) to make contact with the charged rail embedded in the road (Figure 50). This setup allows vehicles to take advantage of both static and dynamic charging.¹⁹⁷ International Transportation Service, LLC will demonstrate five yard trucks with this

¹⁹³ Information from *Final Evaluation report: California Investor-Owned Utility 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.” (Energetics Incorporated, et al., “Final Evaluation Report: California Investor-Owned Utility Transportation Electrification Priority Review Projects,” 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>.)

¹⁹⁴ There are 88 at the Port of Los Angeles (listed as “Electric wharf crane”) and 82 at the Port of Long Beach (listed as “STS Crane”). (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>.)

¹⁹⁵ Angela Clapp, Port of Oakland Environmental Supervisor, email, May 14, 2025.

¹⁹⁶ Anna Wieslander, “Evolution Road Paves the Way for Electric Roads,” Elonroad, June 12, 2024. Accessed January 3, 2025. <https://www.elonroad.com/blog/evolutionroad>.

¹⁹⁷ Elonroad, “Elonroad Tech English,” YouTube video, published on May 23, 2021, 2:28. Accessed April 10, 2025. https://youtu.be/t9w5viunFf4?si=0THs_Ib3T6JMVYk2.

technology at the Port of Long Beach.¹⁹⁸ 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.¹⁹⁹ These demonstrations are further discussed in [Appendix E](#).

Figure 49: Retracting Conductive Arm (Elonroad)



¹⁹⁸ "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>.

¹⁹⁹ 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 50: Installation of Charged Track (Elonroad)



Dynamic inductive charging is another wireless grid-electric technology that can be used for container CHE. The same induction technology for static charging that is discussed in the battery-electric CHE *Infrastructure Requirements and Considerations* section is being studied and tested for dynamic charging in passenger and transit vehicles.²⁰⁰ A35 Brebemi and Stellantis built a 1,050-meter-long roadway in Italy with inductive coils embedded beneath the asphalt.²⁰¹ This allows a battery-electric passenger vehicle to travel at highway speeds without using stored battery energy.²⁰² The Michigan Department of Transportation is testing dynamic inductive charging near Michigan Central in Detroit. A Ford EV Transit

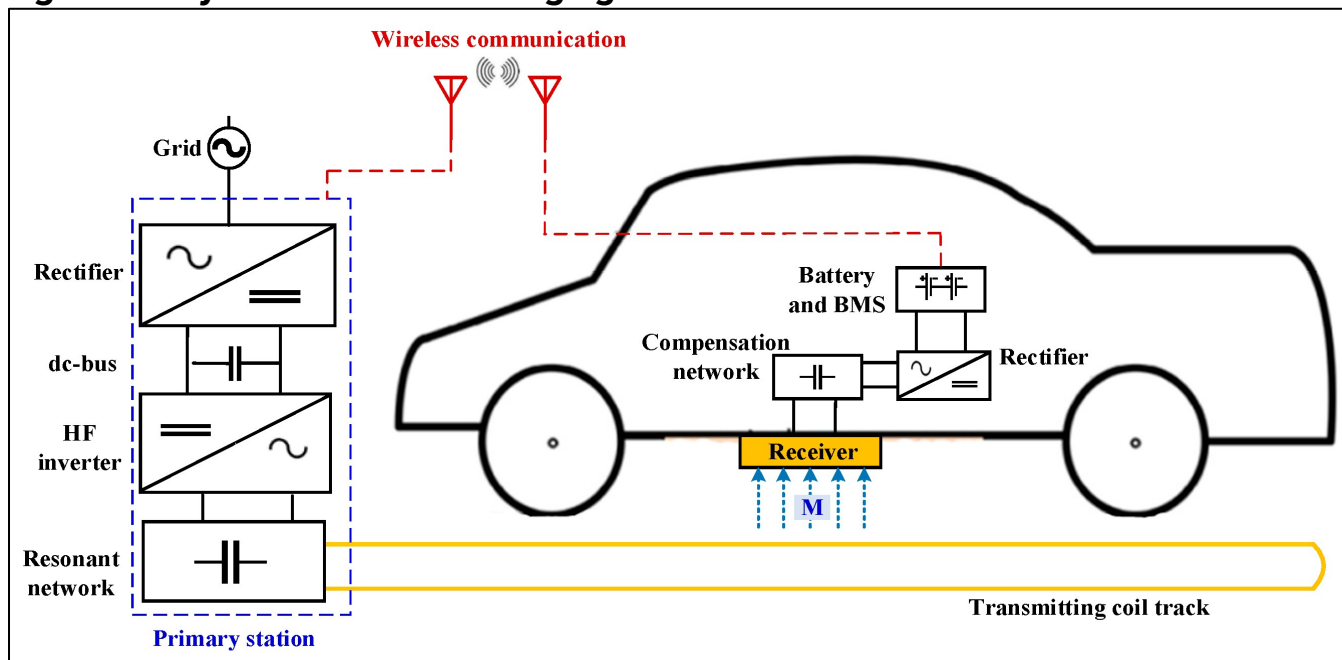
²⁰⁰ Ahmed A.S. Mohamed, et al., "An Overview of Dynamic Inductive Charging for Electric Vehicles," *Energies* (2022), vol. 15(15): 5613. <https://doi.org/10.3390/en15155613>.

²⁰¹ 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=.

²⁰² Ibid.

shuttle was tested in 2024 on a quarter-mile strip of “wireless charging roadway.”²⁰³ Figure 51 shows a diagram of a dynamic inductive charging system.

Figure 51: Dynamic Inductive Charging²⁰⁴



Dynamic wireless charging could enable continuous operation on grid power without stopping to charge batteries. This could reduce battery size by 50 to 80%.²⁰⁵ Existing battery-electric container CHE could be retrofitted with wireless receivers like those at the Port of New York and New Jersey and the Port of Los Angeles.

While there are planned demonstrations for wireless dynamic charging for reach stackers and yard trucks, this technology has not yet been demonstrated or announced for other container CHE. Because this technology is still in early development, grid-electric AGVs, reach stackers, shuttle and straddle carriers, side handlers, top handlers, and yard trucks achieve a Technology Readiness Grade of Development.

²⁰³ Michigan Department of Transportation, “Electreon’s Wireless Charging Performance Results,” 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>; Michigan Department of Transportation, “Wireless Charging Roadway,” n.d. Accessed May 5, 2025. <https://www.michigan.gov/mdot/travel/mobility/initiatives/wireless-charging-roadway>.

²⁰⁴ Ahmed A. S. Mohamed, et al., “An Overview of Dynamic Inductive Charging for Electric Vehicles,” *Energies* (2022), vol. 15(15): 5613, <https://doi.org/10.3390/en15155613>.

²⁰⁵ 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 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 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.²⁰⁶

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.

Electricity Source

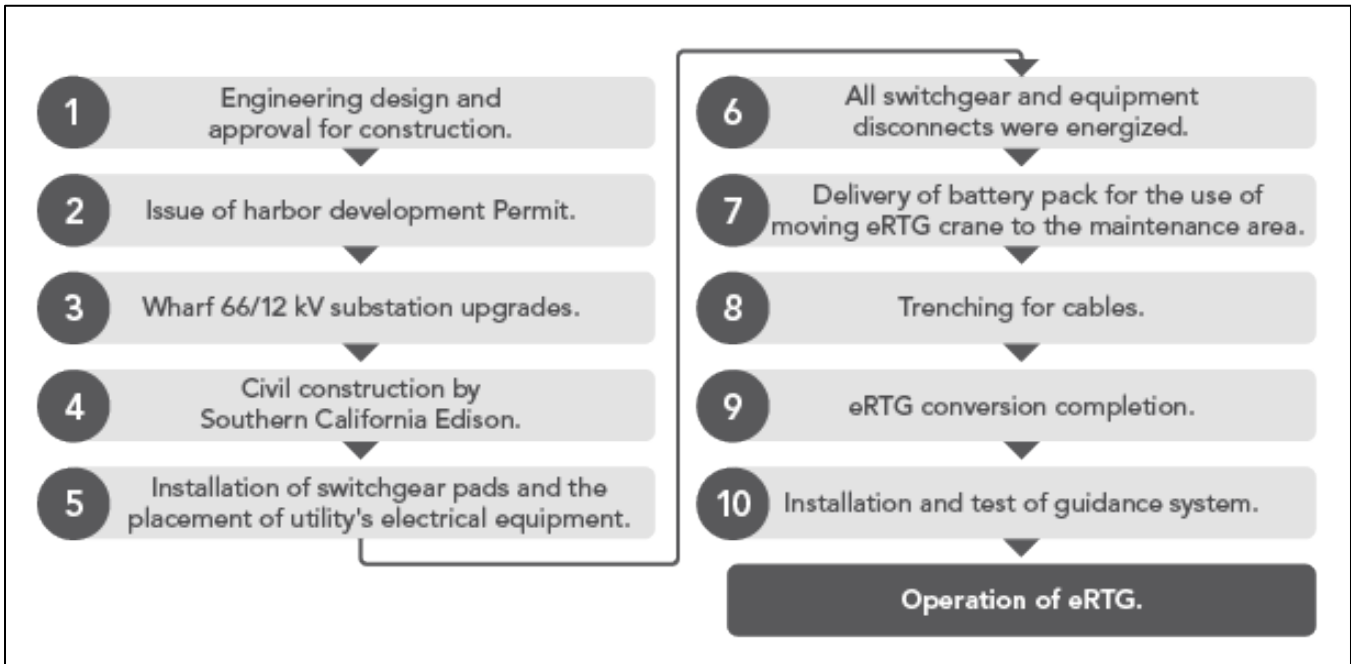
The power source requirements for battery-electric and grid-electric CHE are similar. See the battery-electric CHE [Electricity Source](#) section for more information.

²⁰⁶ Angely Mercado, "Our Go-To Weapon Against Heatwaves? A Dirty Backup Power Source," Popular Science, June 26, 2021. Accessed January 4, 2025. <https://www.popsoci.com/environment/peaker-plants-101/>.

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 them. 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, is an example of required equipment, permitting, and activities required for repowering diesel-powered CHE to grid-electric.²⁰⁷

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



Based on the grid-electric CHE conversion project 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 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 of CHE 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 the planned testing of a charged rail system for a reach stacker and a yard truck discussed in the [Other Grid-Electric Container CHE](#) section, dynamic charging technologies

²⁰⁷ 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>.

have not yet been used for CHE. However, the infrastructure challenges described here would apply similarly if those technologies were introduced.²⁰⁸

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 an RTG from one stack to another can take up to 45 minutes.²⁰⁹ 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 typically require 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, potential midlife replacements are not included for grid-electric CHE operating costs.

²⁰⁸ Elonroad, "Elonroad Tech English," YouTube video, published on May 23, 2021, 2:28. Accessed April 8, 2025. https://youtu.be/t9w5viunFf4?si=0THs_Ib3T6JMVYk2.

²⁰⁹ Claimed confidential data obtained from an industry source that requested non-attribution.

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

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

Table 30 through Table 32 compare the costs of grid-electric and diesel-powered CHE. All costs reflect reported values and do not account for any incentives. 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
Op. - Fuel	\$301,800 per year ²¹⁰	\$46,900 to \$83,900 per year ²¹¹
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	\$14,000,000 ²¹²	\$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.

²¹⁰ 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 or special electricity rates offered by utility providers.

²¹¹ Cost = 10 to 13 gallon/h x 1561 h/year x \$3.00 to \$4.13/gallon = \$46,830 to \$83,810 per year. (Fuel efficiency values are from, 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/>.)

²¹² Pacific Maritime Magazine, "Port of San Diego Purchases All-Electric Mobile Harbor Cranes, First in North America," n.d. Accessed October 4, 2024. <https://pacmar.com/article/port-of-san-diego-purchases-all-electric-mobile-harbor-cranes-first-in-north-america/>.

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 \$2,500,000 ²¹³	\$1,200,000 to \$1,300,000 ²¹⁴
Capital - Infrastructure	[Staff is seeking information]	N/A
Op. - Fuel	\$144,600 per year ²¹⁵	\$74,400 to \$122,900 per year ²¹⁶
Op. - Maintenance	\$85,005 per year ²¹⁷	\$63,754 per year ²¹⁸

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 \$2,322,934.²¹⁹

²¹³ 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," Sol Price School of Public Policy, University of Southern California, prepared for the U.S. Department of Transportation, Office of the Assistant Secretary for Research and Technology, August 2021. <https://doi.org/10.25554/8drs-9j23>.

²¹⁴ Ibid.

²¹⁵ 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 or special electricity rates offered by utility providers.

²¹⁶ Cost = 10 to 12 gallon/h x 2479 h/year x \$3.00 to \$4.13/gallon = \$74,370 to \$122,859 per year. (Fuel efficiency values are from, 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>.)

²¹⁷ 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," Sol Price School of Public Policy, University of Southern California, prepared for the U.S. Department of Transportation, Office of the Assistant Secretary for Research and Technology, August 2021. <https://doi.org/10.25554/8drs-9j23>.

²¹⁸ Ibid.

²¹⁹ 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 \$2,840,000.²²⁰ • Trenching, conduit and cables for 20 RTGs cost \$8,000,000.²²¹ • Project contingency is 30% of total system installation costs.²²²
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.²²³

Technology Outlook

Of the 13 types of grid-electric CHE assessed for technology readiness, 7 have commercially available models, including all 4 bulk material CHE types. Also, RMGs and ship-to-shore cranes achieve a Technology Readiness Grade of Equivalence and all these CHE at California seaports are grid-electric.²²⁴ Table 34 summarizes the outlook to achieve a Technology Readiness Grade of Equivalence within the next 10 years for the 11 grid-electric CHE types that do not achieve Equivalence.

²²⁰ Ibid.

²²¹ Grant Farm, "Charging Ahead: The Port Community Electric Vehicle Blueprint," Port of Long Beach, May 2019. <https://thehelm.polb.com/download/379/zero-emissions/6769/port-community-electric-vehicle-blueprint-042919.pdf>.

²²² Ibid.

²²³ Mia Reback, et al., "The Time Is Now for Zero-Emissions Cargo Handling Equipment at America's Busiest Cargo Ports," Rocky Mountain Institute, 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/>.

²²⁴ 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>.

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

Type of CHE	Outlook for Achieving Equivalence Within 10 Years
AGV, Reach Stacker, Shuttle and Straddle Carrier, Side Handler, Top Handler, Yard Truck	Conductive or inductive dynamic powering has not yet been tested for these container CHE. However, there are demonstrations on the way to test these technologies for reach stackers and yard trucks. Implementing this infrastructure would be expensive and potentially disruptive. However, these two technologies could solve many charging logistics challenges for these types of container CHE. These improvements may enhance terminal layout and productivity, increasing land value. ²²⁵ Regardless of these benefits, battery and/or fuel cell technology have been successfully demonstrated for these CHE, offering a clearer path to zero-emissions. Therefore, grid-electric technology for these CHE will likely not achieve Equivalence within 10 years.
Crane (Material Handling and Off-Road), Excavator	These grid-electric 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.

²²⁵ Grant Farm, "Charging Ahead: The Port Community Electric Vehicle Blueprint," Port of Long Beach, May 2019. <https://thehelm.polb.com/download/379/zero-emissions/6769/port-community-electric-vehicle-blueprint-042919.pdf>.

Type of CHE	Outlook for Achieving 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,²²⁶ 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.
Rubber-Tired Gantry Crane	Several grid-electric options are available for RTGs: six 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.²²⁷ Despite these deployment challenges, grid-electric RTGs achieve a Technology Readiness Grade of Limited. 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.

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 address.²²⁸ One example is the Middle Harbor at the Port of Long Beach. The port added

²²⁶ 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.

²²⁷ 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>.

²²⁸ Rose Szoke and Morgan Caswell, "Port of Long Beach Zero-Emission Terminal Equipment Transition Project," CEC, April 2024. <https://www.energy.ca.gov/sites/default/files/2024-04/CEC-600-2024-042.pdf>.

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.²²⁹

As with battery-electric CHE, facilities will continue to move forward and acquire the equipment as incentive programs become available. Execution of infrastructure plans cohesively and effectively is needed to support 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, molten carbonate fuel cells, and reversible fuel cells.²³⁰ 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.

²²⁹ Grant Farm, "Charging Ahead: The Port Community Electric Vehicle Blueprint," Port of Long Beach, May 2019. <https://thehelm.polb.com/download/379/zero-emissions/6769/port-community-electric-vehicle-blueprint-042919.pdf>.

²³⁰ U.S. DOE, "Types of Fuel Cells," n.d. Accessed January 31, 2025. <https://www.energy.gov/eere/fuelcells/types-fuel-cells>.

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.²³¹ 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.²³² 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.²³³

PEM fuel cells are practical for CHE due to their high efficiency, power density, low weight, compact size, low operating temperature, and high durability.²³⁴ 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.²³⁵ In this section, both *hydrogen fuel cell* and *fuel cell* refer to a hydrogen-powered PEM fuel cell.

²³¹ Office of Energy Efficiency & Renewable Energy, "Fuel Cells for Stationary Power Applications," U.S DOE, n.d. Accessed January 7, 2025. <https://www.energy.gov/eere/fuelcells/articles/fuel-cells-stationary-power-applications>.

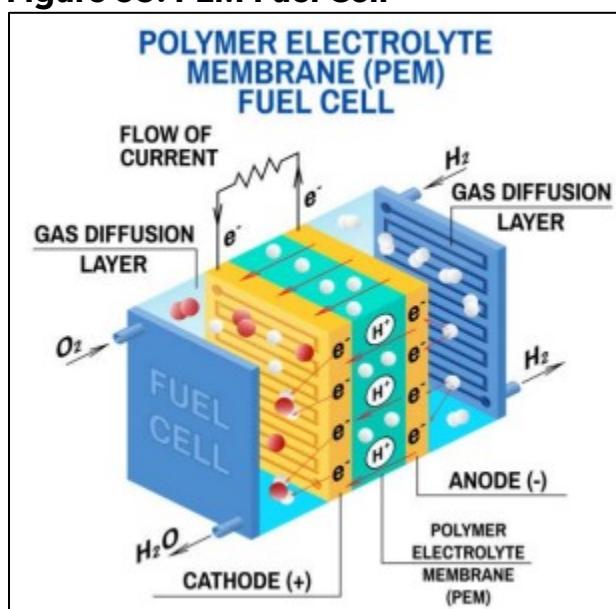
²³² U.S. DOE, "Fuel Cell Animation (Text Version)," n.d. Accessed January 31, 2025. <https://www.energy.gov/eere/fuelcells/fuel-cell-animation-text-version>.

²³³ Ibid.

²³⁴ Miriam M. Tellez-Cruz, et al., "Proton Exchange Membrane Fuel Cells (PEMFCs): Advances and Challenges," *Polymers* (2021), vol. 13(18). <https://doi.org/10.3390/polym13183064>.

²³⁵ Simone, Lombardi, et al., "Optimal Design of an Adaptative Energy Management Strategy for a Fuel Cell Tractor Operating in Ports," *Applied Energy* (2023), vol. 352, December 15, 2023. <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 lead-acid battery-charging infrastructure.²³⁶ When combined with batteries, fuel cells provide consistent power throughout shifts, unlike lead-acid 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.²³⁷

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

²³⁶ Energy Efficiency & Renewable, "Fuel Cell Technologies Office Early Market: Fuel Cells for Material Handling Equipment," U.S. DOE, n.d. Accessed January 31, 2025. <https://www.energy.gov/eere/fuelcells/articles/early-markets-fuel-cells-material-handling-equipment>.

²³⁷ 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.²³⁸ The battery can capture and store energy from regenerative braking or when lowering cargo, 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 never developed.²³⁹ Six types of hydrogen fuel cell CHE are now 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. Table 35 provides the technology readiness data summary for hydrogen fuel cell bulk material CHE.

²³⁸ 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?Dockkey=P1015AQX.pdf>.

²³⁹ After the acquisition, grant funds from CEC were used by Cummins to develop a class 8 drayage truck. See, Jean-Baptiste Gallo, "Final Project Report: Hydrogenics Advanced Fuel Cell Vehicle Technology Demonstration for Drayage Truck," Prepared by Cummins Electrified Power NA Inc. for the CEC, 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	Demonstration
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	Demonstration
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.²⁴⁰ Although these forklifts are commercially available, staff found little available data regarding demonstrations or pilot projects. 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.²⁴¹ In 2024, the Nagoya Port Authority in Japan launched a fleet of 20 fuel cell forklifts at five different terminals.²⁴² However, reports do not specify who manufactured the

²⁴⁰ 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.

²⁴¹ 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>.

²⁴² 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.²⁴³ Although little 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.

Hydrogen Fuel Cell Loaders

In 2023, XCMG put into operation the first commercially available hydrogen fuel cell loader, the XC968-FCEV. It is built on XCMG's third-generation electric loader platform and uses high-rate batteries. It started operations in March 2023, and by June 2023, it had accumulated over 1,000 hours of operation.²⁴⁴ It received positive feedback for reliability and zero pollution.²⁴⁵ Due to this report and commercial availability, hydrogen fuel cell loaders achieve a Technology Readiness Grade of Demonstration.

Other Hydrogen Fuel Cell Bulk Material CHE

There are no commercially available hydrogen fuel cell material handling cranes, mobile cranes, dozers, or log stackers. Staff did not find any demonstrations of these CHE. These CHE achieve a Technology Readiness Grade of Development.

Several projects have tested pre-commercial models of other hydrogen fuel cell bulk material CHE including a mobile harbor crane, an off-road crane, four haul trucks, and a telehandler. Most of these demonstrations are focused on construction or mining and were not carried out at seaports or intermodal railyards. These hydrogen fuel cell bulk material CHE achieve a Technology Readiness Grade of Development due to no commercially available models and lack of performance data for these pre-commercial CHE.

There are several product launch announcements, prototypes, and demonstrations of hydrogen fuel cell excavators. One report on a hydrogen fuel cell-powered excavator said that the equipment performed reliably and "as expected" during a six-month demonstration period,²⁴⁶ helping fuel cell excavators achieve a Technology Readiness Grade of Demonstration. See [Appendix E](#) for more information on this project and other hydrogen fuel cell bulk material CHE demonstrations.

²⁴³ 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/>.

²⁴⁴ 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>.

²⁴⁵ Machmall.com, "XCMG 6-ton Hydrogen Energy Loader Lands in Shanxi, China," June 15, 2023, Accessed March 4, 2026. <https://www.machmall.com/content-info/xcmg-six-ton-hydrogen-energy-loader-lands-in-shanxi-china/965>.

²⁴⁶ Electrive, "Zepp.solutions converts two diesel excavators to hydrogen," October 12, 2023. Accessed June 10, 2025. <https://www.electrive.com/2023/01/03/zepp-solutions-converts-two-diesel-excavators-to-hydrogen/>.

Hydrogen Fuel Cell Container CHE

The only commercially available hydrogen fuel cell container CHE is a hydrogen fuel cell yard truck from Capacity. However, there are demonstration projects testing and showcasing this technology for reach stackers, RTGs, shuttle and straddle carriers, side handlers, and top handlers. 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
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	3	Demonstration
Yard Truck	1	0	5	Limited

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.²⁴⁷ 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 power output of 60 kW, a storage capacity of 32 kg at a pressure of 700 bar and

²⁴⁷ 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/>.

can function for up to 16 hours.²⁴⁸ 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 from 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.

²⁴⁸ David Blekman, "Hydrogen Crane Deployment at the Port of Los Angeles," *Forbes*, June 11, 2024. Accessed February 27, 2025. <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)



Hydrogen Fuel Cell Yard Trucks

While involved with the Zero Emissions for California Ports (ZECAP) demonstration at the Port of Los Angeles, Capacity, in conjunction with Hyster-Yale and Nuvera, announced the production of a hydrogen fuel cell yard truck in 2023.²⁴⁹ It has a gross combined vehicle weight rating of 180,000 lb.²⁵⁰ Additionally, there are several demonstrations of hydrogen fuel cell yard trucks underway. Based on one commercially available model, continuing development efforts by several OEMs, and positive feedback from the ZECAP demonstration, hydrogen fuel cell yard trucks achieve a Technology Readiness Grade of Limited.²⁵¹

Other Hydrogen Fuel Cell Container Cargo Handling Equipment

There are no commercially available hydrogen fuel cell AGVs. 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 2024.²⁵² Due to no commercially available models and no demonstrations, hydrogen fuel cell AGVs achieve a Technology Readiness Grade of Development.

Due to the success of grid-electric RMGs, there has been no publicly announced development or demonstrations of hydrogen fuel cell RMGs. For this reason, they achieve a Technology Readiness Grade of Development.

There are no commercially available hydrogen fuel cell reach stackers, shuttle and straddle carriers, side handlers, or top handlers. However, there have been several demonstrations of this CHE as discussed in [Appendix E](#). Some of these demonstrations outline challenges with hydrogen fuel cell CHE. Because of this and no commercially available models, reach stackers, shuttle and straddle carriers, and side handlers achieve a Technology Readiness Grade of Development. With positive feedback from demonstrations, hydrogen fuel cell top handlers achieve a Technology Readiness Grade of Demonstration.

²⁴⁹ GTI Energy, "Final Report: GTI Energy Project Number 22519," May 1, 2023. <https://www.gti.energy/wp-content/uploads/2023/10/ZECAP-Final-Report-GTI-Energy-Rev2.pdf>; Rev Group, "Capacity Trucks to Launch Zero Emissions Hydrogen Fuel Cell Electric Terminal Truck at TMC Annual Meeting," February 22, 2023. Accessed January 22, 2026. <https://revgroup.com/capacity-trucks-to-launch-zero-emissions-hydrogen-fuel-cell-electric-terminal-truck-at-tmc-annual-meeting/>; Rafael Granato, "Top OEM Manufacturing Electric Yard Trucks Or Yard Tractors in the US for Logistics Purposes" YMX Logistics, October 31, 2024. Accessed January 22, 2026. <https://ymxlogistics.com/blog/top-oem-manufacturing-electric-yard-trucks-or-yard-tractors-in-the-us-for-logistics-purposes>.

²⁵⁰ Capacity Trucks, "Capacity Trucks Zero Emissions H2 and EV," YouTube video, published on May 10, 2024, 2:45. Accessed January 22, 2026. <https://youtu.be/YxGoUIT0DUU?si=TxTeY1ziNKm9TA7R>.

²⁵¹ See *ibid.*, GTI Energy, "Final Report: GTI Energy Project Number 22519"; Also, a video presentation report of the project can be seen on CARB's ZECAP website: ww2.arb.ca.gov/lcti-zero-emissions-california-ports-zecap.

²⁵² Avery, Paul, "End of the road for Gaussin," WorldCargo News, December 3, 2024. Accessed July 30, 2025. <https://www.worldcargonews.com/news/2024/12/end-of-the-road-for-gaussin>.

Hydrogen Fuel Cell Facility Support CHE

Three types of hydrogen fuel cell facility support CHE are commercially available: aerial lifts, general-purpose utility trucks, 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	1	7	Demonstration
Utility Truck, Sweeper	1	1	1	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.²⁵³ Aerial lifts achieve a Technology Readiness Grade of Demonstration due to lack of real-world operational data.

Hydrogen Fuel Cell Cone Vehicles and Railcar Movers

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

Hydrogen Fuel Cell Utility Truck

Utility Truck, General

Hyundai offers a hydrogen fuel cell utility truck in Europe that may be converted for facility support at seaports and intermodal railyards. In addition, 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

²⁵³ 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>.

cell models of the Dodge Ram 5500 in Mexico for North America.²⁵⁴ 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.²⁵⁵ 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 (U.S. DOE) SuperTruck 3 program.²⁵⁶ 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.²⁵⁷ General-purpose trucks that can be converted for use as facility support CHE achieve a Technology Readiness Grade of Demonstration as there are no reports of use at a seaports or intermodal railyards.

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.²⁵⁸ 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. Given commercial availability and the promising data provided by this report, hydrogen fuel cell sweepers achieve a Technology Readiness 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

²⁵⁴ 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.

²⁵⁵ 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>.

²⁵⁶ 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/>.

²⁵⁷ 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>.

²⁵⁸ Global Environmental Products, "M4/M4HSD Hydrogen Fuel Cell," n.d. Accessed December 9, 2024. <https://globalsweeper.com/products/mechanical/m4hsd-fuel-cell>.

reduced overall life-cycle emissions and e-waste from spent batteries. They also do 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).²⁵⁹ 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 uncertainties in terms of capital expenditures and long-term carbon storage viability. Hydrogen from renewable methane sources can significantly reduce life-cycle GHG emissions. In November 2024, CARB approved amendments to LCFS to encourage the production and use of low-carbon and renewable fuels, including renewable hydrogen.²⁶⁰

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*.²⁶¹

Transporting hydrogen using fossil fuel-powered 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 and transporting 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 reduce climate benefits.²⁶² Hydrogen's warming potency strongly depends on the time horizon. A recent study found that the estimated 100-year horizon global warming potential of hydrogen to

²⁵⁹ U.S. DOE, "Hydrogen Resources," n.d. Accessed April 10, 2025.
<https://www.energy.gov/eere/fuelcells/hydrogen-resources>.

²⁶⁰ CARB, "Low Carbon Fuel Standard," n.d. Accessed January 16, 2026.
<https://www2.arb.ca.gov/rulemaking/2024/lcfs2024>.

²⁶¹ 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>.

²⁶² 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>.

be almost 12 times that of CO₂.²⁶³ 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%.²⁶⁴ The total hydrogen leakage rate from hydrogen infrastructure remains uncertain as data is limited.

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

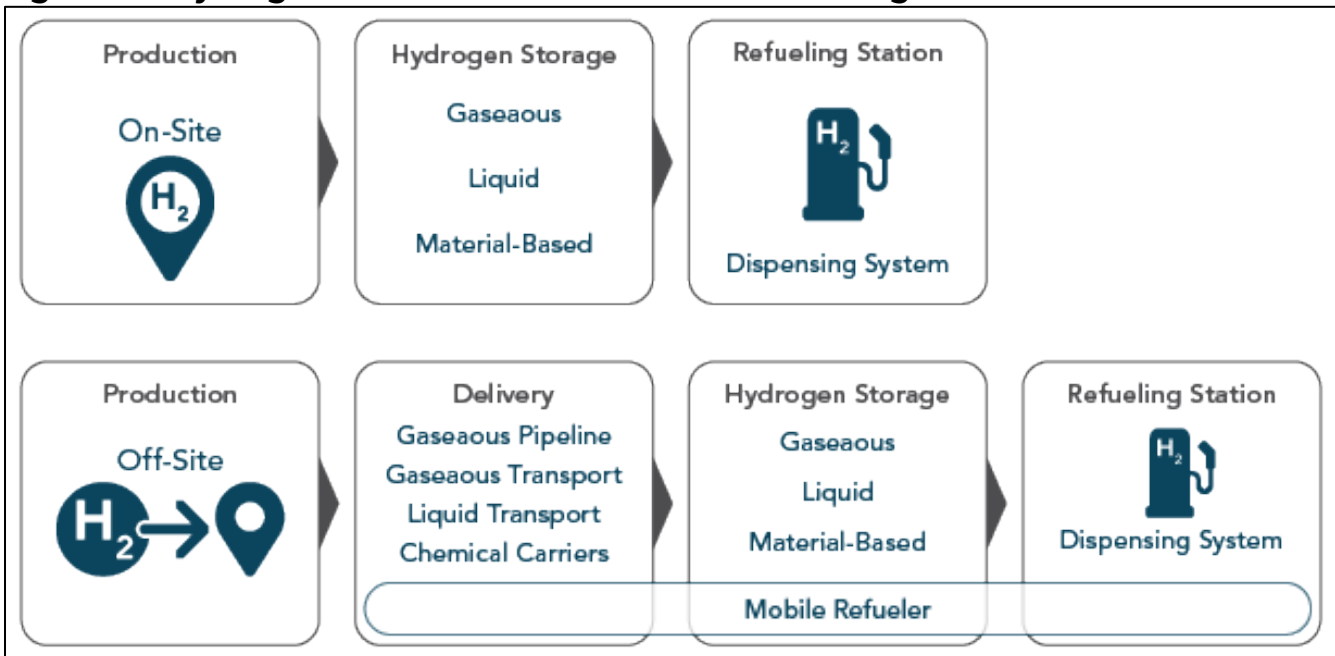
California has made investments in hydrogen as part of its efforts to reduce emissions, particularly in the transportation and industrial sectors. Hydrogen infrastructure, including hydrogen production, storage, distribution, and refueling stations, is designed to support the growing demand for hydrogen 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 these aspects of hydrogen infrastructure:

- 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.

²⁶³ Maria Sand, et al., "A Multi-model Assessment of the Global Warming Potential of Hydrogen," *Communications Earth & Environment* (2023), vol. 4(203), June 7, 2023. <https://doi.org/10.1038/s43247-023-00857-8>.

²⁶⁴ Iris M. Westra, et al., "First Detection of Industrial Hydrogen Emissions Using High Precision Mobile Measurements in Ambient Air," *Scientific Reports* (2024), vol. 14(24147). October 15, 2024. <https://doi.org/10.1038/s41598-024-76373-2>.

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.²⁶⁵ In 2025, SMR was the leading hydrogen production method in the U.S.²⁶⁶

Each method of hydrogen production has an associated GHG emissions output.²⁶⁷ 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

²⁶⁵ 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?Dockkey=P1015AQX.pdf>.

²⁶⁶ 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>.

²⁶⁷ Centre for Innovation and Clean Energy, "Carbon Intensity of Hydrogen Production Methods Supporting the BC Hydrogen Strategy," March 2023. https://www2.gov.bc.ca/assets/gov/business/natural-resource-industries/reports/carbon_intensity_of_hydrogen_production_methods.pdf.

million metric tons by 2050.²⁶⁸ Many projects in California are underway to develop and enhance future hydrogen supply. In July 2024, the U.S. DOE and the Alliance for Renewable Clean Hydrogen Energy Systems (ARCHES) signed a \$12.6 billion agreement to establish the California Hydrogen Hub.²⁶⁹ ARCHES projects will cover the entire hydrogen lifecycle, from production and transportation to usage. ARCHES aims to achieve the major initiatives listed below.²⁷⁰

- Replace diesel-powered equipment at major seaports with hydrogen fuel cell alternatives.
- Construct over 60 hydrogen fueling stations.
- 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.²⁷¹ In August 2024, ARCHES launched its first hydrogen hub to accelerate the development and deployment of renewable hydrogen.²⁷² Several individual projects are also boosting hydrogen supply in California. See [Appendix I](#) for more information on these projects.

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 obtaining 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.²⁷³ 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

²⁶⁸ 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?Dockkey=P1015AQX.pdf>.

²⁶⁹ Arches H2, "California's Renewable Hydrogen Hub Officially Launches," July 17, 2024. Accessed December 6, 2024. <https://archesh2.org/arches-officially-launches/>.

²⁷⁰ Pipeline & Gas Journal, "California Secures \$12.6 Billion for Hydrogen Hub Development," July 23, 2024. Accessed December 6, 2024. <https://pgjonline.com/news/2024/july/california-secures-126-billion-for-hydrogen-hub-development>.

²⁷¹ CARB, "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.

²⁷² Container News, "Port of Oakland Unveils US First ARCHES Hydrogen Hub," September 4, 2024. Accessed December 6, 2024. <https://container-news.com/port-of-oakland-unveils-us-first-arches-hydrogen-hub/>.

²⁷³ Air Products, "Hydrogen Onsite Generators," n.d. Accessed February 18, 2025. <https://www.airproducts.com/equipment/hydrogen-onsite-generators>.

produce up to 400 kg/day of gaseous hydrogen. The unit takes approximately one week to install and takes up a footprint of about 630 square feet.²⁷⁴

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. Seaports and intermodal railyards can potentially seek opportunities to combine hydrogen supply chains with other industries such as drayage, rail, and agriculture operations. For example, in 2023, SCAQMD awarded \$76 million for a hydrogen fuel cell locomotive and infrastructure that will be used for goods movement around the San Pedro Bay port corridor.²⁷⁵

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 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.²⁷⁶ The high initial capital investment required for new pipeline construction creates a challenge for 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 2026.²⁷⁷

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

²⁷⁴ One H2, "ON-SITE GENERATION," n.d. Accessed February 18, 2025. <https://oneh2.com/solutions/on-site-generation/>.

²⁷⁵ South Coast Air Quality Management District, "South Coast AQMD Awarded \$76 Million for a first-of-its-kind Zero-Emission Fuel Cell Train and Infrastructure that will Transform Goods Movement in San Pedro Bay Port Corridor," Press Release, July 6, 2023. <https://www.scaqmd.gov/home/research/pubs-docs-reports/newsletters/october-november-december-2023/ze-fuel-cell-train>.

²⁷⁶ 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?Dockkey=P1015AQX.pdf>.

²⁷⁷ 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>.

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.

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.²⁷⁸ 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).

²⁷⁸ 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* (2023), vol. 3(3), September 2023: 100112. <https://doi.org/10.1016/j.jpse.2023.100112>.

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 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: Liquefied 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 CHE operators.²⁷⁹ 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.²⁸⁰

Figure 58: One H2's Mobile Hydrogen Refueler²⁸¹



The BayoTech GTM1500 mobile refueler has a storage capacity of 146.6 kg, with operating temperatures ranging from -40 °C to 65 °C.²⁸² 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.²⁸³ 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

²⁷⁹ CEC, "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>.

²⁸⁰ WorldCargo 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/>.

²⁸¹ 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.

²⁸² CARB, "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>.

²⁸³ Ibid.

Nikola/HYLA mobile refueler.²⁸⁴ 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.²⁸⁵ 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.²⁸⁶ Plug Power designed a portable hydrogen refueling station that supports 350-bar and 700-bar fleet vehicle fueling, requires minimal site preparation, and uses a single electrical connection. It is designed to reduce infrastructure costs and deployment time for medium- and heavy-duty hydrogen vehicles.²⁸⁷ Exolum placed the first of two publicly accessible mobile hydrogen refueling stations for fuel cell vehicles into service. The stations are containerized, transportable, and capable of dispensing hydrogen at both 350-bar and 700-bar pressures to meet varying customer needs.²⁸⁸

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.

²⁸⁴ 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.

²⁸⁵ Hylium Industries Inc., "H2 Refueling Station HYMS350B (Mobile Hydrogen Refueling Station)," July 24, 2024. Accessed March 11, 2025. <https://hylium-industries.com/products/?q=YToxOntzOjEyOiJrZXI3b3JkX3R5cGUiO3M6MzoiYWxsJt9&bmode=view&idx=50363415&t=board&category=1R4X072134>.

²⁸⁶ Hexagon Purus, "Refueling Systems," April 11, 2024. Accessed March 11, 2025. <https://hexagonpurus.com/our-solutions/refueling-systems>.

²⁸⁷ Plug Power, "Plug's Portable Hydrogen Refuelers," July 2024. Accessed December 18, 2025. <https://resources.plugpower.com/youtube-hydrogen-liquefaction/plugs-portable-hydrogen-refuelers-4>.

²⁸⁸ Exolum, "Exolum launches its first publicly accessible mobile hydrogen refuelling station for fuel cell vehicles," January 8, 2025. Accessed January 14, 2026. <https://exolum.com/en/noticia/exolum-launches-its-first-publicly-accessible-mobile-hydrogen-refuelling-station-for-fuel-cell-vehicles/>.

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.²⁸⁹

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 • Higher cost per delivery trip than compressed gas hydrogen • Contains more hydrogen mass per trip than tube trailer • Can be used for short or long-distance transport/large needs
Mobile Refueler	• Stored at ambient temperature or -253 °C 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.

²⁸⁹ U.S. DOE, "Novel Hydrogen Carriers," n.d. Accessed March 6, 2025.
<https://www.energy.gov/eere/fuelcells/novel-hydrogen-carriers>.

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 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.²⁹⁰ 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 embrittlement in metallic components such as valves and pipelines.²⁹¹ 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/m³. Gaseous hydrogen has a density of around 20 to 40 kg/m³ depending on the pressure.²⁹² 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.²⁹³ 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

²⁹⁰ 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>.

²⁹¹ Xiang Li, et al., "Review of the Hydrogen Permeation Test of the Polymer Liner Material of Type IV On-Board Hydrogen Storage Cylinders," *Materials* (2023), vol. 16(15), July 31, 2023: 5366. <https://doi.org/10.3390/ma16155366>.

²⁹² 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* (2023), vol. 7(2), March 2024: 269-84. <https://doi.org/10.1016/j.ijlmm.2023.08.002>.

²⁹³ Andrew Burke, et al., "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.

hydrogen vapor. Storage of hydrogen as a liquid requires about 1 bar of pressure which is far less pressure than gaseous hydrogen.²⁹⁴

Materials-Based Storage

Hydrogen can also be stored on the surfaces of solids by adsorption, or within solids by absorption.²⁹⁵ 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.

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 • 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 trained in emergency response procedures. Adhering to

²⁹⁴ Ibid.

²⁹⁵ U.S. DOE, "Hydrogen Storage," n.d. Accessed December 9, 2024.
<https://www.energy.gov/eere/fuelcells/hydrogen-storage>.

safety codes and regulations, such as those from the National Fire Protection Association²⁹⁶ and the California Fire Code,²⁹⁷ 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.²⁹⁸

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.²⁹⁹

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.

Several documents 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

²⁹⁶ The National Fire Protection Association, "NFPA 2: Hydrogen Technologies Code (2023)," 2023. <https://www.nfpa.org/>.

²⁹⁷ 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>.

²⁹⁸ Hydrogen Safety Codes & Standards Applicability Navigator. Accessed September 9, 2025. <https://h2tools.org/hyscan/>.

²⁹⁹ 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>.

practices, and operating requirements for hydrogen fueling stations.³⁰⁰ 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* discusses minimum technical requirements for hydrogen fueling station to be eligible for fund applications.³⁰¹

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.³⁰² 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.

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 ○ CHE ○ Mobile refueler (optional) • Infrastructure installation ○ On-site hydrogen production system (optional) ○ Fueling station (optional)	• Equipment fuel • Equipment maintenance • Infrastructure maintenance • Infrastructure operation • Mobile refueler service (optional) • Potential midlife battery replacement

³⁰⁰ 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.

³⁰¹ CARB, “Appendix C: Hydrogen Refueling Station Requirements,” July 2023. https://ww2.arb.ca.gov/sites/default/files/2023-07/fy21-23demoandpilot_appc.pdf.

³⁰² Kate Forrest, et. al, “A Replicable Infrastructure Blueprint for Zero-Emission Medium- and Heavy-Duty Vehicles in the South Coast Air Basin,” CEC, August 2023. https://cleanenergy.uci.edu/PDF_White_Papers/ARV-21-018_Blueprint.pdf.

Equipment Capital Costs

The capital cost of fuel cell CHE is typically 2.5 to 3 times higher than diesel CHE.³⁰³ 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 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.³⁰⁴ 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. However, a midlife battery replacement may not be necessary. The fuel cell usually supplies most of the power, so the batteries experience less stress and maintain a steady charge, unlike battery-electric equipment whose batteries are frequently depleted and recharged. This steady energy flow in fuel cell battery systems may prolong battery life.³⁰⁵

Fuel Costs

Hydrogen fuel costs vary 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.³⁰⁶ In some areas of California, the price of hydrogen at the pump can be over \$36/kg.³⁰⁷ 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

³⁰³ Claimed confidential data obtained from an industry source that requested non-attribution.

³⁰⁴ U.S. DOE, "Hydrogen and Fuel Cell Program Overview," May 13, 2018.

https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review18/01_satyapal_plenary_2018_amr.pdf?Status=Master.

³⁰⁵ Chuanxu Luo, et al., "Towards enhanced durability: A review of fuel cell electric vehicle development," *Next Energy* (2025), vol. 9. October 2025.

<https://www.sciencedirect.com/science/article/pii/S2949821X25001620#bbib112>.

³⁰⁶ U.S. DOE, "Hydrogen's Role in Transportation," February 25, 2022. Accessed November 25, 2024.

<https://www.energy.gov/eere/vehicles/articles/hydrogens-role-transportation>.

³⁰⁷ 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/>.

price of hydrogen fuel. Future hydrogen prices remain uncertain. Economies of scale for hydrogen production may bring down the price. ARCHES has a goal of achieving a \$5 to \$6 refueling cost (outside of any taxes and subsidies) for hydrogen dispensed at 700 bar by the year 2030, making it competitive with diesel.³⁰⁸

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. All costs reflect reported values and do not account for any incentives. 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
Capital - CHE	\$450,000 to \$950,000	\$240,000 to \$420,000
Op. - Fuel	\$32,800 per year ³⁰⁹	\$1,600 to \$2,900 per year ³¹⁰
Op. - Maintenance	[Staff is seeking information]	\$25,000 per year ³¹¹

³⁰⁸ 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.

³⁰⁹ 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 or special electricity rates offered by utility providers. Staff assumes 1 kg of hydrogen provides 33.6 kWh of usable energy. (Values are from, Patrick Molloy, "Run on Less with Hydrogen Fuel Cells," Rocky Mountain Institute, March 2, 2022. <https://rmi.org/run-on-less-with-hydrogen-fuel-cells/>.)

³¹⁰ Cost = 0.71 to 0.95 gallon/h x 733 h/year x \$3.00 to \$4.13/gallon = \$1,561 to \$2,876 per year. (Values are from, 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>.)

³¹¹ 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," Sol Price School of Public Policy, University of Southern California, prepared for the U.S. Department of Transportation, Office of the Assistant Secretary for Research and Technology, August 2021. <https://doi.org/10.25554/8drs-9j23>.

Cost Component	Hydrogen Fuel Cell	Diesel
Op. – Potential Battery Replacement	\$6,000 to \$13,000 ³¹²	N/A

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

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

Cost Component	Hydrogen Fuel Cell	Diesel
Capital – CHE	\$727,078 ³¹³	\$584,500 ³¹⁴
Op. – Fuel	\$124,767 per year ³¹⁵	\$72,594 per year ³¹⁶
Op. – Maintenance	\$6,767 per year ³¹⁷	\$5,123 per year ³¹⁸
Op. – Potential Battery Replacement	[Staff is seeking information]	N/A

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

Cost Component	Hydrogen Fuel Cell	Diesel
Capital – CHE	\$225,000 ³¹⁹	\$110,000 ³²⁰
Op. – Fuel	\$32,966 per year ³²¹	\$19,181 per year ³²²
Op. – Maintenance	\$5,498 per year ³²³	\$3,800 per year ³²⁴
Op. – Potential Battery Replacement	[Staff is seeking information]	N/A

³¹² According to one study, the battery of a hydrogen fuel cell truck could be “around one-tenth the size” of a battery-electric truck battery. Staff estimated the battery replacement cost for hydrogen fuel cell large-capacity forklifts based on an assumption that the cost scales proportionally with battery size. See, Sam Wilson, “A review of the environmental and economic implications of hydrogen fuel for on-road freight,” Union of Concerned Scientists, November 2023. Accessed January 14, 2026.

<https://www.ucs.org/sites/default/files/2023-11/hydrogen-powered-heavy-duty-trucks.pdf>.

³¹³ 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?Dockkey=P1015AQX.pdf>.

³¹⁴ Ibid.

³¹⁵ Ibid.

³¹⁶ Ibid.

³¹⁷ According to a U.S. EPA assessment, this maintenance cost includes a “onetime lifetime replacement of the fuel cell and battery pack (compared with one engine repower with the diesel unit).” (U.S. EPA, “Assessment of Fuel Cell Technologies at Ports,” Office of Transportation and Air Quality, EPA-420-R-22-013, July 2022. <https://downloads.regulations.gov/EPA-HQ-OAR-2022-0985-0805/content.pdf>.)

³¹⁸ 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?Dockkey=P1015AQX.pdf>.

³¹⁹ Ibid.

³²⁰ Ibid.

³²¹ Ibid.

³²² Ibid.

³²³ See *ibid.*, U.S. EPA, “Assessment of Fuel Cell Technologies at Ports.”

³²⁴ See *ibid.*, Eastern Research Group, Inc. “Assessment of Fuel Cell Technologies at Ports.”

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, and space required for hydrogen storage 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.³²⁵

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

³²⁵ Mariya Koleva and Marc Melaina, "DOE Hydrogen Program Record," U.S. DOE, 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 (still available for forklifts).³²⁶ 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.³²⁷ 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.³²⁸ 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. ³²⁹
Hydrogen Mobile Refueler	\$875,432 ³³⁰

³²⁶ Mia Reback, et al., “The Time Is Now for Zero-Emissions Cargo Handling Equipment at America’s Busiest Cargo Ports,” Rocky Mountain Institute, 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/>.

³²⁷ 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.

³²⁸ Argonne National Laboratory, “Hydrogen Delivery Scenario Analysis Model (HDSAM),” n.d. Accessed November 25, 2024. <https://hdsam.es.anl.gov/index.php?content=hdsam>.

³²⁹ Hydrogen Fuel Cell Partnership, “Costs and Financing,” n.d. Accessed January 10, 2025. <https://h2stationmaps.com/costs-and-financing#retail-station-costs>.

³³⁰ 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>.

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.³³¹ • 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 \$4,430,000.³³² Cost information from HDSAM v4.5:³³³ • \$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.³³⁴ • Annual electricity costs range from \$3,139 to \$9,417 for hydrogen fueling stations with off-site production.³³⁵ • Annual electricity costs range from \$7,734 to \$415,855 for hydrogen fueling stations with on-site production.³³⁶

³³¹ Hydrogen Fuel Cell Partnership, "Costs and Financing," n.d. Accessed January 10, 2025. <https://h2stationmaps.com/costs-and-financing#retail-station-costs>.

³³² 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?Dockkey=P1015AQX.pdf>.

³³³ 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>.

³³⁴ Jacob Goldberg, et al., "Final Project Report: The Port of Los Angeles Zero- and Near-Zero-Emission Freight Facilities 'Shore to Store' Project," CARB, May 10, 2023. <https://ww2.arb.ca.gov/sites/default/files/2023-05/POLA-Final%20Report.pdf>.

³³⁵ 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?Dockkey=P1015AQX.pdf>.

³³⁶ Ibid.

Cost Component	Cost
Infrastructure Maintenance	- Annual maintenance costs range from \$19,530 to \$35,620 for hydrogen fueling stations with off-site production.³³⁷ - Annual maintenance costs range from \$35,620 to \$57,590 for hydrogen fueling stations with on-site production.³³⁸

Technology Outlook

In general, battery-electric and grid-electric CHE have advanced further than hydrogen fuel cell CHE. Of the 24 types of hydrogen fuel cell CHE assessed for technology readiness, only 6 are commercially available. Of these 6, none achieve a Technology Readiness Grade of Equivalence. While hydrogen fuel cell technology has the potential to perform equivalently to diesel, has progressed significantly in the last decade, and is being tested in many forms of on- and off-road equipment, it remains in the early stages for CHE. Therefore, hydrogen fuel cell technology is a medium- to long-term option for most types of 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, Log Stacker	Zero-emission options for these types of CHE closely follow the construction industry and little progress has been made in the development of hydrogen fuel cell versions of this equipment. They achieve a Technology Readiness Grade of Development. 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.

³³⁷ Ibid.

³³⁸ Ibid.

CHE Type	Outlook for Achieving Equivalence Within 10 Years
Crane, Mobile	At a high level, mobile cranes can be viewed as heavy-duty trucks engineered to support crane operations. 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. 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.
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.

CHE Type	Outlook for Achieving 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 2024.³³⁹ Incentive programs such as CARB's CORE program are helping deploy this CHE.³⁴⁰ 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.
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.³⁴¹ 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.

³³⁹ H2 News, "Nagoya Pot Implements Hydrogen Forklift," December 2024. Accessed March 2, 2025. <https://h2-news.com/hydrogen/news/nagoya-port-implements-hydrogen-forklifts/>.

³⁴⁰ All nine commercially available models of hydrogen fuel cell forklifts are eligible for CARB's CORE program. See www.californiacore.org for details.

³⁴¹ See [Appendix B](#) for commercially available zero-emission CHE.

CHE Type	Outlook for Achieving Equivalence Within 10 Years
Loader or Loader-Excavator	There is one commercially available hydrogen fuel cell wheeled loader available in China from XCMG which has reportedly accumulated over 1,000 hours of use without any breakdowns. There are also two prototype models being tested. For these reasons, loaders achieve a Technology Readiness Grade of Demonstration. Given this momentum, with additional emission reduction strategies and incentive programs in place for both the CHE and hydrogen infrastructure, hydrogen fuel cell loaders or loader-excavators 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 likely 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, which achieve a Technology Readiness Grade of Equivalence, are already the industry standard. Therefore, hydrogen fuel cell RMGs will likely not achieve 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 achieve Equivalence within 10 years.

CHE Type	Outlook for Achieving 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.³⁴² 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.³⁴³ 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.
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 achieve Equivalence within 10 years.

³⁴² See [Appendix E](#) for demonstrations of zero-emission CHE.

³⁴³ 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
Yard Truck	There is one commercially available hydrogen fuel cell yard truck and there have been several demonstrations. CARB's ZECAP website has links to a video presentation and a final report that provide 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. Feedback was positive regarding the performance of the trucks, helping this CHE to achieve a Technology Readiness Grade of Limited. But the reports did highlight some of the challenges faced in producing the trucks and getting permits for the hydrogen. ³⁴⁴ 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.

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. ³⁴⁵ These have not yet been tested at seaports or intermodal railyards, and achieve 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 cargo-focused hydrogen fuel cell CHE, this CHE can achieve Equivalence within 10 years.

³⁴⁴ CARB, "LCTI: Zero Emissions for California Ports (ZECAP)," n.d. Accessed April 1, 2025. <https://ww2.arb.ca.gov/lcti-zero-emissions-california-ports-zecap>. Also see [Appendix E](#) for more information about this demonstration.

³⁴⁵ 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>.

CHE Type	Outlook for Achieving 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, ³⁴⁶ 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. ³⁴⁷ Because of the high availability of an alternative zero-emission technology, this CHE will likely not achieve 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 achieve Equivalence within 10 years.

³⁴⁶ There are 8 battery-electric Motrek brand cone vehicles at the Port of Long Beach. (Port of Long Beach, "2023 Air Emissions Inventory," August 2024. <https://polb.com/download/14/emissions-inventory/20586/2023-air-emissions-inventory.pdf>.)

³⁴⁷ 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" Zephyr Electric.

CHE Type	Outlook for Achieving Equivalence Within 10 Years
Utility Truck, 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 battery-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, ³⁴⁸ the fuel cell version only became available in 2018. ³⁴⁹ 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 hydrogen fuel cell cargo-focused CHE, this 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 – higher cost compared to diesel, especially for renewable hydrogen, which is essential for achieving true zero-emission benefits. Transportation and storage add to the overall costs.
- Infrastructure costs – 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.

Availability of renewable hydrogen also poses a potential 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 may 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.

³⁴⁸ 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>.

³⁴⁹ GlobalSweeper, "Global M4HSD ZE Zero Emissions," YouTube video, published on November 30, 2018, 2:59. Accessed April 11, 2025. <https://youtu.be/2Rfo3i6gkUk?si=KjKZJvY1Sp3nkCbx>.

- 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.³⁵⁰ 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%), require market intervention – including incentives and additional emission reduction strategies – to achieve Equivalence 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.

Figure 59 through Figure 61 provide a summary for the 75 zero-emission CHE-technology combinations, including commercial availability, the Technology Readiness Grade, and the outlook to achieve a Technology Readiness Grade of Equivalence within the next 10 years.³⁵¹

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.

³⁵⁰ The 400 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](https://oakland-seaport-map-0624-web.pdf).

³⁵¹ Equipment-technology combinations with an "x" for all three items scored a zero for Technology Applicability (e.g., grid-electric dozer). See the [Technology Applicability](#) section for details.

Figure 59: Bulk Material CHE Technology Assessment Summary

COMMERCIAL AVAILABILITY				
Equipment Type	Battery-Electric	Grid-Electric	Hydrogen Fuel Cell	
Crane, Material Handling	●	●	×	● 2 or more U.S. models
Crane, Mobile	●	×	×	■ 1 U.S. model
Crane, Mobile Harbor	×	●	▼	▲ Only non-U.S. model(s)
Crane, Off-Road	●	●	▼	▼ Only non-commercial model(s) available (prototypes, etc.)
Dozer	▲	×	×	×
Excavator	●	■	▼	
Forklift, Heavy Lift	●	×	●	
Forklift, Telehandler	●	×	▼	
Haul Truck	■	×	▼	
Loader or Loader-Excavator	●	×	▲	
Log Stacker	×	×	×	

TECHNOLOGY READINESS GRADE				
Equipment Type	Battery-Electric	Grid-Electric	Hydrogen Fuel Cell	
Crane, Material Handling	▲	▲	▼	● Equivalence
Crane, Mobile	▲	×	▼	■ Limited
Crane, Mobile Harbor	×	▲	▼	▲ Demonstration
Crane, Off-Road	▲	▲	▼	▼ Development
Dozer	▲	×	▼	×
Excavator	▲	▲	▲	
Forklift, Heavy Lift	■	×	▲	
Forklift, Telehandler	▲	×	▼	
Haul Truck	▲	×	▼	
Loader or Loader-Excavator	▲	×	▲	
Log Stacker	▼	×	▼	

OUTLOOK TO ACHIEVE EQUIVALENCE BY 2035				
Equipment Type	Battery-Electric	Grid-Electric	Hydrogen Fuel Cell	
Crane, Material Handling	▲	▲	×	● Already meets equivalence
Crane, Mobile	▲	×	▼	■ Likely
Crane, Mobile Harbor	×	▲	×	▲ With additional emissions reduction strategies and incentives
Crane, Off-Road	▲	▲	×	▼ Dependent on other cargo handling equipment or heavy-duty equipment
Dozer	▲	×	×	×
Excavator	▲	▲	▲	
Forklift, Heavy Lift	■	×	▲	
Forklift, Telehandler	▼	×	▼	
Haul Truck	▲	×	▲	
Loader or Loader-Excavator	▲	×	▲	
Log Stacker	▲	×	×	

Figure 60: Container CHE Technology Assessment Summary

COMMERCIAL AVAILABILITY				
Equipment Type	Battery-Electric	Grid-Electric	Hydrogen Fuel Cell	
AGV	●	×	×	● 2 or more U.S. models
Rail-Mounted Gantry Crane	×	●	×	■ 1 U.S. model
Reach Stacker	●	▼	▼	▲ Only non-U.S. model(s)
Rubber-Tired Gantry Crane	●	●	▼	▼ Only non-commercial model(s) available (prototypes, etc.)
Ship-to-Shore Crane	×	●	×	×
Shuttle and Straddle Carrier	●	×	×	No models
Side Handler	●	×	▼	
Top Handler	●	×	▼	
Yard Truck	●	▼	■	

TECHNOLOGY READINESS GRADE				
Equipment Type	Battery-Electric	Grid-Electric	Hydrogen Fuel Cell	
AGV	●	▼	▼	● Equivalence
Rail-Mounted Gantry Crane	▼	●	▼	■ Limited
Reach Stacker	■	▼	▼	▲ Demonstration
Rubber-Tired Gantry Crane	▲	■	▲	▼ Development
Ship-to-Shore Crane	×	●	×	×
Shuttle and Straddle Carrier	▲	▼	▼	Not graded
Side Handler	■	▼	▼	
Top Handler	■	▼	▲	
Yard Truck	■	▼	■	

OUTLOOK TO ACHIEVE EQUIVALENCE BY 2035				
Equipment Type	Battery-Electric	Grid-Electric	Hydrogen Fuel Cell	
AGV	●	×	×	● Already meets equivalence
Rail-Mounted Gantry Crane	×	●	×	■ Likely
Reach Stacker	▲	×	▼	▲ With additional emissions reduction strategies and incentives
Rubber-Tired Gantry Crane	▲	▲	▲	▼ Dependent on other cargo handling equipment or heavy-duty equipment
Ship-to-Shore Crane	×	●	×	×
Shuttle and Straddle Carrier	▲	×	▼	Not likely
Side Handler	▲	×	▼	
Top Handler	▲	×	▼	
Yard Truck	■	×	▲	

Figure 61: Facility Support CHE Technology Assessment Summary

COMMERCIAL AVAILABILITY				
Equipment Type	Battery-Electric	Grid-Electric	Hydrogen Fuel Cell	
Aerial Lift	●	×	●	● 2 or more U.S. models
Cone Vehicle	●	×	×	■ 1 U.S. model
Railcar Mover	●	×	×	▲ Only non-U.S. model(s)
Utility Trucks, Other	●	×	▲	▼ Only non-commercial model(s) available (prototypes, etc.)
Utility Truck, Sweepers	●	×	■	×
				No models
TECHNOLOGY READINESS GRADE				
Equipment Type	Battery-Electric	Grid-Electric	Hydrogen Fuel Cell	
Aerial Lift	▲	×	▲	● Equivalence
Cone Vehicle	▲	×	▼	■ Limited
Railcar Mover	▲	×	▼	▲ Demonstration
Utility Trucks, Other	▲	×	▲	▼ Development
Utility Truck, Sweepers	■	×	■	×
				Not graded
OUTLOOK TO ACHIEVE EQUIVALENCE BY 2035				
Equipment Type	Battery-Electric	Grid-Electric	Hydrogen Fuel Cell	
Aerial Lift	▼	×	▼	● Already meets equivalence
Cone Vehicle	▼	×	×	■ Likely
Railcar Mover	▼	×	×	▲ With additional emissions reduction strategies and incentives
Utility Trucks, Other	▼	×	▼	▼ Dependent on other cargo handling equipment or heavy-duty equipment
Utility Truck, Sweepers	▼	×	▼	×
				Not likely