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CLEAN AIR ACTION PLAN

2021 UPDATE: FEASIBILITY ASSESSMENT for CARGO-HANDLING EQUIPMENT

July 2022

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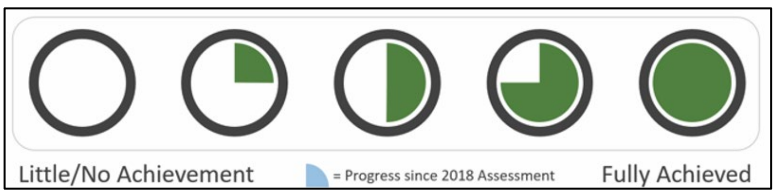
Important Notes: 2021 Feasibility Assessment for Cargo-Handling Equipment (CHE)

The San Pedro Bay Ports Clean Air Action Plan (CAAP) 2017 Update established the need to prepare feasibility assessments to evaluate the status of technology and supporting infrastructure that will be required to achieve the various CAAP strategies. This 2021 Feasibility Assessment for CHE follows on and updates the initial Assessment performed in 2018. As with the 2018 version, this 2021 Feasibility Assessment for CHE is intended to evaluate the current state of zero-emission (ZE) and near-zero-emission (NZE) fuel-technology platforms suitable for four key types of CHE – including infrastructure readiness to fuel and service them. The Assessment's overarching objective is to characterize feasibility for near-term (2021 to 2024), large-scale deployments of CHE using such platforms.

This Assessment is not meant to be a policy document, nor to inventory emission reductions that could be realized through the use of ZE and/or NZE CHE, nor to characterize the associated health benefits. It is not meant to establish timelines for meeting various CAAP goals, or forecast commercialization (especially beyond 2024). It provides a snapshot about which ZE and/or NZE CHE platforms are feasible today, or will likely be feasible by 2024 – for widespread deployment across the San Pedro Bay Ports (SPBP) complex. Please refer to the Framework for Clean Air Action Plan Feasibility Assessments (2017) document (see report text) for the overall process and intent as laid forth in the CAAP.

Using the same basic methodology as the inaugural 2018 report, this 2021 Assessment uses tables to summarize ratings about the relative degree to which various CHE fuel-technology platforms are deemed to be "feasible" today. Tables with "pie" ratings are used to quantify rough degrees of achievement for four of the five feasibility parameters: Commercial Availability, Operational Feasibility, Infrastructure Availability, and Economic Workability. (Technical Viability was evaluated using Technology Readiness Levels; see Section 6.) For each main feasibility parameter and the individual criteria that define it, these tables show pie-wedge ratings in quarter increments. As the above figure shows, ratings range from "little/no achievement" for a given feasibility criteria, to "fully achieved" today. Note that the rating system for this 2021 Assessment has been updated to include blue wedges, which highlight changes (improvements) in feasibility ratings (if any) *since the 2018 Assessment*.



The use of pie ratings is not meant to represent precise percentages of achievement for a given feasibility criteria. Rather, these ratings summarize the relative degrees of progress towards full or near-full achievement.

This Assessment does not include end user monetary incentives when calculating feasibility for every parameter. Incentive sums fluctuate, have uncertain long-term availability, and are not necessarily available to all end users. Thus, certain costs calculations presented in this Assessment (as noted where applicable) were calculated based on non-incentivized totals.

The Ports intend to continue preparing updated CHE feasibility assessments at least every three years. This will be done more frequently if warranted by new, relevant information. For example, the ports may decide to annually update portions of this Assessment if new ZE and/or NZE technologies become truly commercially available, and/or if there is a breakthrough development with infrastructure. Please refer to the Framework for Clean Air Action Plan Feasibility Assessments (2017) document[1] (http://www.cleanairactionplan.org/documents/feasibility-assessment-framework.pdf/) for the overall process and intent, as laid forth in the CAAP.

This document was developed over many months based on significant outreach, research and stakeholder feedback. The final 2021 Feasibility Assessment for Cargo-Handling Equipment – as well as any public comments received – will be reported to the respective Boards of Harbor Commissioners and posted at www.cleanairactionplan.org.

[1] San Pedro Bay Ports, "Framework for Developing Feasibility Assessments", November 2017, http://www.cleanairactionplan.org/documents/feasibility-assessment-framework.pdf/.

Authorship and Uses

This report was prepared by a consulting team consisting of individuals from Tetra Tech and its subcontractor, Gladstein, Neandross & Associates (GNA). Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply endorsement, recommendation, and/or favoring by the Ports or the report authors.

Acknowledgements

Front cover photos – Top Left: NZE natural gas yard demo tractor (Port of Los Angeles) being emissions tested at UC Riverside (photo by Jon Leonard, GNA); Bottom Left: ZE hydrogen fuel cell yard tractor moving cargo at Port of Los Angeles (photo provided by Port of Los Angeles); Middle: ZE battery-electric top handler at the Port of Long Beach (photo provided by Port of Long Beach); Right: ZE grid-electric rubber-tired gantry crane at Port of Long Beach (photo provided by SSA Terminals).

Back cover photo – provided by SSA Terminals

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Individuals from many organizations provided important inputs for this report, and/or generally assisted to gather information. These organizations included, but were not limited to, the Port of Long Beach, the Port of Los Angeles, the California Air Resources Board, the California Energy Commission, the South Coast Air Quality Management District, Southern California Edison, and the Los Angeles Department of Water & Power.

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List of Terms

ACRONYM	DEFINITION
ASC	Automated stacking crane
AQMP	Air quality management plan
BE	Battery electric
CARB	California Air Resources Board
CO_2	Carbon dioxide
CEC	California Energy Commission
CHE	Cargo-handling equipment
CNG	Compressed natural gas
CORE	Clean Off Road Equipment (voucher incentive program)
CWI	Cummins Westport Inc.
DCFC	Direct current fast charge
DGE	Diesel gallons equivalent
EER	Energy economy ratio
EPA	U.S. Environmental Protection Agency
EVSE	Electric vehicle supply equipment
FC	Fuel cell
FEL	Front end loader
g/bhp-hr	Grams per brake horsepower-hour
g/hr	Grams per hour
gCO2e/MJ	Grams of carbon dioxide equivalent per mega Joule
g/mi	Grams per mile
GHGs	Greenhouse gases
HDE	Heavy-duty engine
HDV	Heavy-duty vehicle
KWh	kilowatt hour
LADWP	Los Angeles Department of Water & Power
LCFS	Low Carbon Fuel Standard
LNG	Liquefied natural gas
MT	Metric ton
MWh	Megawatt hour
NAAQS	National Ambient Air Quality Standard
NG	Natural gas
NOx	Oxides of nitrogen
NZE	Near-zero emission
OEM	Original equipment manufacturer
OLNS	Optional Low NOx Standard
PM	Particulate matter
$PM_{2.5}$	Fine PM (diameter equal to or smaller than 2.5 micrometers)
PEMFC	Proton exchange membrane fuel cell
RNG	Renewable natural gas
ROI	Return on investment
ROG	Reactive organic gases
RTG	Rubber tired gantry (crane)
SCAQMD	South Coast Air Quality Management District
SCAB	South Coast Air Basin
SCE	Southern California Edison
SCR	Selective catalytic reduction
SPBP	San Pedro Bay Ports
TCO	Total cost of ownership
TOU	Time of use
UTR	Utility tractor rig (aka: yard tractor)
ZE	Zero emission

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Executive Summary

Background and Methodology

This 2021 Feasibility Assessment for Cargo-Handling Equipment (2021 Assessment) builds upon and updates the inaugural 2018 Assessment that was released by the San Pedro Bay Ports (the Ports, or SPBP) in mid-2019. It applies five key parameters to examine which (if any) emerging zero-emission (**ZE**) and/or near-zero-emission (**NZE**) CHE platforms[2] are demonstrably capable of, and ready for, broad deployment in revenue service at marine terminals operating at the Ports. The focus is on assessing current-day feasibility to widely deploy various ZE and NZE CHE types, although prospects over the next few years are also evaluated. The Ports conducts feasibility assessments to help *continue making sufficient, timely progress to meet the goals of the Ports' joint Clean Air Action Plan (CAAP)*. Thus, this 2021 Assessment is not meant to establish or set CAAP policy. Rather, the Ports will use the assessment findings to inform new policies, demonstration projects, and advocacy that can help realize the 2017 CAAP goal to achieve a 100-percent ZE CHE fleet by 2030. The Ports remain committed to this goal.

However, it is important to note that the largest determinant of pace and scope for this transition will be statewide CHE regulatory amendment(s) from the California Air Resources Board (CARB), which CARB staff currently anticipates presenting for Board consideration in 2025. To complement CARB's regulatory roadmap as it further emerges, the Ports expect to use a combination of mechanisms (e.g., lease renewals, environmental mitigation measures, funding incentives, and infrastructure planning) to support and advance the transition to an all-ZE CHE fleet, *as rapidly as is practicable.* However, transitioning to an all-ZE CHE fleet is not expected to occur in a linear fashion over time. Five complex, inter-related feasibility parameters – as detailed in this report and summarized below – must progress accordingly to make manually operated, ZE terminal operations fully viable. Once all five parameters have been fully achieved (or have approached full achievement), the Ports anticipate that the pace of transition to ZE CHE *will become much more rapid*.

Collectively there are approximately 3,368 individual CHE serving the SPBP. Approximately 70 percent (2,381 CHE units) fall within four CHE categories: 1) yard tractors, 2) top handlers, 3) rubber tired gantry cranes, and 4) large-capacity forklifts.[3] These CHE types continue to be dominated by heavy-duty diesel-fueled internal combustion engines (ICEs), which in general emit high levels of key air pollutants. Consequently, the Ports have prioritized these CHE types for systematic, expeditious "fleet modernization" with ZE CHE where feasible, and NZE CHE for applications that are not yet ready or conducive for ZE fuel-technology platforms.[4]

As with the 2018 Assessment, the following five parameters were applied to collectively assess overall feasibility for each of the four key CHE types, per a specific framework previously prepared by the Ports[5]:

- Commercial Availability
- Technical Viability
- Operational Feasibility
- Availability of infrastructure and Fuel
- Economic Workability (Key Economic Considerations and Issues)

Importantly – as described in this Assessment – marine terminals rely on a complex goods movement system, with many types of heavy-duty equipment and vehicles combining to move cargo efficiently and safely between ships, trucks, and rail cars. Each piece of CHE is responsible for executing a portion of a cargo move. Delays caused by any single CHE unit have the potential to affect the utilization of many other CHE in the chain. Increasing the number of equipment deployed to offset

[2] Please see the "Definitions" call-out box on page 7 for how **ZE** and **NZE** are defined and applied, for purposes of this Assessment.

[3] Other types of diesel-fueled CHE (e.g., side handlers, reach stackers) also contribute to the Ports' collective emissions inventories, in relatively small numbers. Most are similar (in form and function) to one of the four CHE types listed above. These "other diesel" CHE are not specifically addressed in this 2021 Assessment, but they face similar opportunities and challenges for transitioning to ZE and/or NZE platforms.

[4] Smaller types of CHE – typically powered by non-diesel engines – are also targeted for emissions reductions under the CAAP. Prominent examples include small-capacity forklifts powered by gasoline or propane engines. Those types of CHE are addressed under the CAAP separately from this 2021 Assessment.

[5] San Pedro Bay Ports, "Framework for Developing Feasibility Assessments," July 2017, http://www.cleanairactionplan.org/documents/feasibility-assessment-framework.pdf/.

efficiency losses can create other challenges, lead to higher costs, and require major new resources. In sum, overall feasibility for emerging new types of CHE must be evaluated within the context of a typical SPBP MTO goods movement "ecosystem" that includes CHE, other heavy-duty equipment, and on-road drayage trucks.

For each of the four CHE types, five core ZE or NZE fuel-technology platforms were assessed; these were selected because they are generally cited (by knowledgeable industry, government and academic representatives) as being the most promising platforms for near-term incorporation into heavy-duty CHE. Moreover, these five core technology platforms are the subject of ongoing technology development and demonstration programs at the two Ports, in all four types of CHE focused upon in this Assessment.

Specifically, the five assessed core fuel-technology platforms were:

1. **ZE** battery electric (charged via manual plugs or inductively) or grid electric (electricity provided directly from the grid via a trench or cable connection)
2. **ZE** hydrogen fuel cell electric (electricity generated onboard by reacting hydrogen and oxygen from air; typically hybridized with a battery pack for peak power and regenerative braking)
3. **NZE** advanced diesel internal combustion engine (ICE)
4. **NZE** advanced natural gas (or propane) ICE
5. **NZE** hybrid-electric (electric drive hybridized with an ICE using any fuel; may or may not include plug-in capability)

Two parameters – Commercial Availability and Technical Viability – were used to initially screen the above five core **ZE** and **NZE** fuel-technology platforms for their estimated feasibility to power large numbers of CHE within the three-year time-frame of this 2021 Assessment. Commercial Availability was evaluated using four major parameters that collectively gauge the intent and capability of original equipment manufacturers (OEMs) to successfully manufacture, sell and service CHE for use by SPBP marine terminal operators (MTOs). Technical Viability was evaluated using a Technology Readiness Level (TRL) scale commonly applied by the U.S. government. A score at (or approaching) TRL 8 (with 9 being the highest) was required for a given fuel-technology platform to achieve this feasibility parameter.

Summary of Findings: Screening for Commercial Availability and Technical Viability

Two of the four evaluated CHE types – yard tractors and RTG cranes – offer ZE and/or NZE fuel-technology platforms that simultaneously achieve the basic parameters and criteria to be deemed (or approaching) "commercially available" and "technically viable."

While these overarching findings are unchanged from the 2018 Assessment, this Assessment highlights significant OEM progress since 2018 to advance commercial readiness and technical robustness, for both CHE applications. Specific findings are summarized below, including highlighted *examples of progress since 2018*:

Yard tractors:

- **ZE** battery-electric technology is commercially offered for yard tractors by multiple OEMs (*increased from one OEM in 2018*). These are effectively "early commercial" launches of products that currently achieve TRL 7 to 8 for technical viability (*a half step higher than 2018*). ZE battery-electric yard tractors offered by OEMs continue to progress, but have not yet reached full commercial or technological maturity (especially for SPBP marine terminal operation). Overall, however, they meet the basic criteria and considerations to be deemed commercially available and technically viable in late-2021.

- **NZE** natural gas ICE technology is commercially offered for yard tractors by multiple OEMs (*increased from one OEM in 2018*). These are effectively "early commercial" launches of products that currently achieve TRL 7 to 8 for technical viability (*a half step higher than 2018*). NZE natural gas ICE yard tractors offered by OEMs continue to progress, but have not yet reached full commercial or technological maturity (especially for SPBP marine terminal operation). Overall, however, they meet the basic criteria and considerations to be deemed commercially available and technically viable in late-2021.

- The other three core fuel-technology platforms that were evaluated for yard tractors – **ZE** fuel cell, **NZE** hybrid electric, and **NZE** diesel ICE – do not meet the basic criteria and considerations for commercially availability or technical viability. However, it is important to highlight that *at least two yard tractor OEMs have made significant overall progress since 2018 to advance proof-of-concept hydrogen fuel cell yard tractors*; this fuel-technology platform shows potential for low-volume, early commercial launches within the next few years.

RTG cranes:

- **ZE** grid-electric RTG cranes (new built and conversion packages) are fully commercial products with a technical viability measured at TRL 9; all four parameters that collectively define commercial availability appear to be fully achieved. *This is essentially unchanged since 2018, although significant progress has been made to increase deployments and testing at SPBP marine terminals.*

- **NZE** hybrid-electric RTG cranes (new built and conversion packages) are fully commercial products with a technical viability measured at TRL 9; all four parameters that collectively define commercial availability appear to be fully achieved. *This is essentially unchanged since 2018, although significant progress has been made to increase deployments and testing at SPBP marine terminals.* Notably, OEMs continue to reduce emissions through application of Tier 4-certified diesel gen-set engines, but emissions could be further reduced by replacing the diesel gen-set with one powered by an on-road natural gas or propane engine certified to the lowest-tier Optional Low-NOx Standard promulgated by the California Air Resources Board (CARB).

- **ZE** fuel cell RTG cranes are not being manufactured nor sold today by any CHE OEM. This platform does not meet the basic criteria and considerations to be deemed commercially available or technically viable in late 2021. *This is essentially unchanged since 2018.* It is difficult to assess at this time if this fuel-technology approach to RTG cranes is likely to be commercially and technically viable by 2024.

The other two assessed CHE types – top handlers and large-capacity forklifts – do not currently exist with ZE or NZE architectures that have achieved the basic metrics for Commercially Availability and Technically Viability. *This overarching finding is unchanged from the 2018 Assessment.* However, multiple CHE OEMs have demonstrated significant progress to advance the commercial and technological maturity of ZE battery-electric top handlers and large-capacity forklifts. OEMs are also making important progress with hydrogen fuel cell architectures for these CHE applications.

Summary of Findings: Operational Feasibility, Infrastructure Availability, Economic Workability

Yard tractor and RTG crane ZE and/or NZE fuel-technology platforms found to meet basic criteria and considerations under Commercial Availability and Technical Viability were further characterized for overall feasibility. This was done by systematically assessing the remaining three parameters: 1) Operational Feasibility, 2) Infrastructure Availability, and 3) Economic Workability. The table that follows summarizes "rolled-up" feasibility ratings for these remaining three parameters as applied to the four **ZE** and **NZE** fuel-technology platforms.

Important considerations for reviewing and understanding the "pie" ratings in each table

- Pie ratings are not meant to represent precise percentages of achievement for a given feasibility criteria. They summarize relative degrees of progress towards full or near-full achievement.
- Each rolled-up rating reflects multiple feasibility criteria within that particular parameter (e.g., Operational Feasibility). Achievement of each criterion within a parameter is important for the success of a given fuel-technology platform in CHE operations. Thus, the rolled-up achievement rating for each CHE fuel-technology platform is based on the lowest criterion rating for the feasibility parameter identified in each table.
- **Blue** wedges in pie ratings (which are additive to the **green** wedges) specifically highlight progress since the 2018 Assessment.

Roll-up of ratings for remaining three feasibility parameters in 2021

Feasibility Parameter	Yard Tractors		RTG Cranes	
	ZE Battery-Electric	NZE NG ICE	ZE Grid-Electric	NZE Diesel Hybrid-Electric
Operational Feasibility				
Infrastructure Availability				
Economic Workability				

Legend: **Achievement of Each Noted Parameter / Criteria (2021)**

Little/No Achievement = Progress since 2018 Assessment Fully Achieved

*These ratings for are based on the analysis of several criteria within each feasibility parameter. Because each criterion is important for the success of a given fuel-technology platform in CHE operations, the achievement ratings shown reflect the lowest criterion rating for each feasibility parameter.

Overarching Conclusion: 2021 Feasibility Applying All Five Key Parameters

Table 43 below summarizes the relative degree to which the two fully screened CHE types (yard tractors and RTG cranes, each for two fuel-technology platforms) are estimated to currently (late-2021) achieve the five key feasibility parameters, or are likely to achieve them by 2024. These estimated ratings are made in the specific context of CHE operated at marine terminals serving the SPBP.

Recall that **blue** wedges in the pie ratings are additive to the **green** wedges and specifically highlight progress since the 2018 Assessment.

Summary of overall "Feasibility" in 2021 according to five key parameters

Feasibility Parameter	Yard Tractors		RTG Cranes	
	ZE Battery-Electric	NZE NG ICE	ZE Grid-Electric	NZE Diesel Hybrid-Electric
Commercial Availability	◕	◑	●	●
Technical Viability (TRL Rating out of 9)	TRL 7 to 8 (2024: TRL 9)	TRL 7 to 8 (2024: TRL 9)	TRL 9	TRL 9
Operational Feasibility	◔	◕	◕	●
Infrastructure Availability	◔	◕	◑	●
Economic Workability	◔	◑	◑	●

Legend: **Achievement of Each Noted Parameter / Criteria (2021)**

○ ◔ ◑ ◕ ●

Little/No Achievement = Progress since 2018 Assessment Fully Achieved

*These ratings for overall achievement of each five feasibility parameter are based on the analysis of several criteria within that parameter. Because each criterion is important for the success of a given fuel-technology platform in CHE operations, the overall achievement ratings are based on the lowest criterion rating for each feasibility parameter.

Looking Forward: Commercial and Technological Outlook

As first described in 2018 and further documented with this 2021 Assessment, most (if not all) CHE OEMs doing business with SPBP MTOs are now developing ZE and/or NZE fuel-technology platforms for their products. It is important to reiterate that the end goal of the CAAP is to widely deploy ZE CHE by 2030. It is particularly noteworthy that CHE OEMs have accelerated progress over the last three years to further develop, demonstrate, and commercialize ZE battery-electric yard tractors, and parallel (albeit less mature) efforts are underway with ZE fuel cell yard tractors. CHE OEMs are also making important progress to advance ZE battery-electric and fuel cell architectures for top handlers and large-capacity forklifts. OEM-backed demonstrations of first-generation technology are resulting in important lessons learned, driving towards more-advanced pre-commercial products that can better meet the needs of their end-user MTOs. ZE RTG cranes are not newly commercialized products; a key advancement since 2018 is that they are beginning to make significant penetration into the joint SPBP CHE inventory.

This improving commercial maturity and technical viability of pre- and early commercial ZE and NZE CHE has enabled planning and initiation of larger-scale, integrated deployments. Through growing public-private partnerships (involving the Ports, key government agencies, CHE OEMs and host-site MTOs), these newest collaborations are focused on complete "ecosystems" of ZE and NZE CHE, working in unison with ZE and NZE on-road drayage trucks. Such projects address all five feasibility parameters addressed in this 2021 Assessment. It is essential to continue testing the various emerging types of ZE and NZE CHE platforms in revenue service as combined systems at multiple SPBP marine terminals, analogous to how all MTOs currently operate baseline diesel CHE. In particular, OEMs and MTOs need experience to improve ZE battery-electric and fuel cell platforms for top handlers and large-capacity forklifts. Compared to yard tractors, these larger "vertical" CHE entail new opportunities as well as additional challenges for transitioning to ZE architectures.

Although ZE CHE demonstrations are in their early stages of implementation, they reflect important technological advancements made by CHE OEMs and their partners. Thus, the key progress highlighted in the 2021 Assessment relative to 2018 is the growing amount of new information about – and stakeholder experience with – battery-electric CHE (and to a lesser extent, fuel cell CHE). This makes it possible to look more deeply at their feasibility for near-term use at the Ports as replacements for large numbers of diesel equipment.

Since 2018, it is clear that OEM commitments to ZE CHE markets have been growing and strengthening. For even the most-challenging CHE applications like top handlers, CHE OEMs are developing ZE architectures for their products. As of late-2021, multiple major CHE OEMs have publicly stated that they plan to transition all their CHE products to battery-electric and/or fuel cell architectures. Ultimately, these products will achieve true commercialization on timelines that are commensurate with what makes good business sense for each OEM and achieves market acceptance by their customers.

Even after commercially viable ZE platforms become available in a given CHE application, it will be an iterative, gradual process to widely transition the applicable SPBP fleet to ZE technologies. In particular, it is difficult to understate the necessity and importance of timing commercial launches of ZE CHE with build-out of sufficient infrastructure to charge or fuel them. A key initial challenge is the development of sufficient charging infrastructure to support gradually growing roll-outs of battery-electric yard tractors. Before infrastructure can be designed and installed by the MTOs and/or their respective utility, a clear understanding of the performance and charging requirements for battery-electric yard tractors must be developed. The landscape for heavy-duty EV charging infrastructure is rapidly maturing, but a single standard has yet to emerge as the clear winner. This existing barrier will need resolution before any large-scale roll out of heavy-duty battery-electric vehicles (including on-road trucks and off-road CHE) is likely to occur. While current demonstrations are expected to provide significantly more important information for all stakeholders, most will not be completed (including their final reports) for several years.

In sum, over the next three years, it will be very important for OEMs and MTOs – through the many ongoing SPBP demonstrations – to validate marketing statements and prove that ZE CHE platforms can meet MTO needs for performance, safety and cost metrics. In tandem, critical infrastructure build-outs will need to move forward, in proportion to vehicle rollouts. If these things come to fruition, the commercial availability and broad feasibility of ZE platforms for CHE applications will be realized at the SPBP.

1. Introduction

1.1. Background: Clean Air Action Plan

In 2006, the Port of Los Angeles and the Port of Long Beach jointly adopted the San Pedro Bay Ports (SPBP, or the Ports) Clean Air Action Plan (CAAP). The CAAP presents an overall strategy to systematically reduce harmful emissions from five key goods movement sectors – ships, trucks, trains, cargo-handling equipment and harbor craft. In November 2017, the Ports jointly adopted the 2017 Clean Air Action Plan (CAAP) Update. The CAAP Update further defined and clarified emissions reduction targets, and the strategies that will achieve those reductions. Oxides of nitrogen (NOx) is an especially important pollutant to control; it combines with volatile organic compounds (VOCs) in the atmosphere to form ground-level ozone (photochemical smog). This current CAAP specifies incremental reduction targets for all key pollutants between 2020 and 2050, and outlines fourteen source-specific strategies to achieve these targets.

The updated CAAP includes a call to accelerate the timeline for SPBP marine terminals to adopt and deploy zero- or near-zero-emission CHE (see below), where feasible. The ultimate goal is to achieve zero-emission terminal operations by 2030. Extensive details about the overarching CAAP and strategies to phase in progressively lower-emitting CHE over time are available on the CAAP website (http://www.cleanairactionplan.org/strategies/cargo-handling-equipment/).

1.2. Origin and Framework for CAAP Feasibility Assessments

The 2017 CAAP Update includes a provision for the Ports to conduct "feasibility assessments" for CHE as well as drayage trucks. Each assessment is intended to evaluate the status of zero-emission (ZE) and near-zero-emission (NZE) fuel-technology platforms (see **Definitions** callout box below) – including supporting fueling infrastructures – for their feasibility and timeline to replace conventional, higher-emitting diesel-fueled platforms that currently dominate goods movement activities. For additional information, please see the Ports' joint document titled "Framework for Developing Feasibility Assessments"[6] available online at http://www.cleanairactionplan.org/documents/feasibility-assessment-framework.pdf/

Definitions: Zero-Emission (ZE) and Near-Zero-Emission (NZE)

When the Ports prepared the 2018 CHE Feasibility Assessment, CARB had not yet defined the terms "zero emission" (ZE) or "near-zero emission" (NZE) for CHE (or other off-road) applications. As of late-2021, CARB has still not defined these terms for CHE applications. Importantly, CARB staff has initiated work on a new CHE regulation for future rulemaking (https://ww2.arb.ca.gov/resources/documents/cargo-handling-equipment-regulation-transition-zero-emissions). CARB indicates that the new CHE regulation is a "transition to zero emissions" and will undergo "Board consideration in 2024, with effective dates beginning in 2026." The Ports will actively participate in the CHE rulemaking, and encourage stakeholders to do so as well.

To remain consistent with the Ports' original stated intent to conduct feasibility assessments of zero- and lower-emission technologies – and to better facilitate comparisons between the 2018 and 2021 Assessments by maintaining the same terminology – the Ports have carried over the ZE and NZE definitions used in the 2018 Feasibility Assessment for CHE. The Ports do not yet know CARB's intentions regarding CHE-specific definitions for ZE and NZE under its future CHE regulation. Therefore, the ZE and NZE definitions (below) used when discussing CHE in this report should be limited to serving the purpose of general classifications that enable the Ports to provide "snapshots" of CHE readiness, as of late-2021.

In summary, for purposes of this 2021 Assessment:

1. **ZE** refers to any fuel-technology combination for CHE that *does not directly emit any regulated pollutants (including precursors and greenhouse gases)*. Effectively, this eliminates any platform that utilizes onboard fuel combustion.
2. **NZE** refers to any fuel-technology combination for CHE that *is significantly lower emitting on oxides of nitrogen (NOx) than the federal 2010 emissions standards for on-road heavy-duty engines, or the federal Tier 4 Final non-road standards (whichever is applicable)*.

[6] San Pedro Bay Ports, "Framework for Developing Feasibility Assessments", November 2017, http://www.cleanairactionplan.org/documents/feasibility-assessment-framework.pdf/.

Following up on the initial 2018 Assessment, the ultimate objective of this 2021 Assessment is to ascertain which (if any) emerging ZE and/or NZE CHE fuel-technology platforms are now "feasible" (see **Evaluating "Feasibility"** below) to replace baseline diesel CHE at the Ports. Because market conditions and technology landscapes can change rapidly, the Ports intend to continue preparing an updated CHE feasibility assessment every three years, or more frequently if warranted by relevant new information. For example, the ports may decide to annually update portions of this 2021 Assessment if new ZE and/or NZE technologies become commercially available, and/or if there is a breakthrough development with infrastructure.

Evaluating "Feasibility"

For purposes of this Assessment, "feasibility" refers to the ability of any fuel-technology CHE platform to provide similar or better performance and achievement across five key parameters, as compared to the baseline CHE type (assumed to be powered by diesel-fueled internal combustion engines). Specifically, per the Ports' "Framework for Clean Air Action Plan Feasibility Assessments," the following five parameters have been applied to collectively assess and evaluate overall feasibility: 1) commercial availability, 2) technical viability, 3) operational feasibility, 4) infrastructure/fuel availability, and 5) economic workability. For each of these parameters, feasibility has been evaluated within the context of *widespread deployment* for each type of CHE at both San Pedro Bay Ports. See Section 4 for additional discussion.

2. Report Overview

2.1. Overall Methodology and Anticipated Outcomes

This 2021 Feasibility Assessment for Cargo-Handling Equipment (2021 Assessment) builds upon and updates the 2018 inaugural effort (2018 Assessment). It characterizes the 2021 status of ZE and NZE fuel-technology platforms that are (or may be by 2024) suitable to power four key CHE types operated at the San Pedro Bay Ports. As with each of the Ports' joint assessments, its fundamental purpose is to help the Ports continue making sufficient and timely progress to meet CAAP goals.

To prepare this 2021 Assessment, the authors reviewed and analyzed available information deemed to be relevant and credible (see further discussion below), while applying feasibility parameters and boundaries as defined by the "Framework" document.[7] This was used to derive a near-term feasibility "snapshot" (2021 to 2024) about the ability for emerging ZE and/or NZE CHE platforms to replace conventional, higher-emission diesel CHE. Where emerging platforms currently fall short of this bar, this report focuses on progress by OEMs and end users to make them more feasible, and the known challenges that remain before feasibility is likely to be achieved.

With all of this information gathered and assessed, the Ports can best 1) focus attention, resources and support on specific areas that need the most attention, and 2) determine if the CAAP's initial timelines for CHE will need to be adjusted. Examples of specific potential outcomes from this 2021 Feasibility Assessment for Cargo-Handling Equipment include the following actions the Ports could take:

- Further develop strategies needed to enable large-scale deployment of ZE and/or NZE CHE; these could include expansion of technology demonstrations, funding programs, and infrastructure installation.
- Issue advisories and/or guidance documents to marine terminal operators (MTOs), including potential ways to provide additional flexibility while still meeting CAAP deadlines.

2.2. Timeline, Applicability, Scope and Limitations

The following provides important information about the timeline, scope and applicability of this Assessment:

Relevant Timeline – This report represents a snapshot in time. It seeks to characterize the current (late-2021) and expected near-term (by or before 2024) overall feasibility of emerging CHE fuel-technology platforms. This report will be updated by late 2024, or sooner if important new information becomes available.[8] Through the public process to engage stakeholders, and ongoing efforts to work with technical experts, the Ports will continue to refine the scope and content of each feasibility assessment.

Breadth of Application – This report evaluates the feasibility of emerging CHE platforms in terms of their potential for *widespread deployment* (within approximately three years) by all MTOs that serve the SPBP complex. The Ports recognize that some emerging platforms may be feasible solely in select circumstances (e.g., where unique operational, infrastructure, and/or financial conditions exist), compared to the overall SPBP complex. Such situations are recognized and discussed, particularly as they pertain to potential for broader application.

Assessed Types of CHE – Approximately 70 percent of the SPBP CHE fleet consists of four types of equipment that move cargo at marine terminals within the twin port complex: 1) yard tractors (also called yard hostlers and utility tractor rigs, or UTRs), 2) top handlers[9] (also called top picks and front-end loaders), 3) rubber-tired gantry (RTG) cranes, and 4) large-capacity forklifts (generally diesel-fueled forklifts with a payload capacity of at least 36,000 pounds). The energy and power requirements for a given CHE type depends on its specific application and duty cycle. To the extent that it is relevant, this report attempts to account for these differences, and to characterize important nuances that impact the overall feasibility of

[7] San Pedro Bay Ports, "Framework for Developing Feasibility Assessments", November 2017, http://www.cleanairactionplan.org/documents/feasibility-assessment-framework.pdf/.

[8] San Pedro Bay Ports, "2017 Clean Air Action Plan Update," November 2017, http://www.cleanairactionplan.org/documents/final-2017-clean-air-action-plan-update.pdf.

[9] Nearly 400 top handlers are currently in use at the San Pedro Bay Ports. According to the Pacific Merchant Shipping Association (PMSA), these "front-end loaders" (FELs) dominate the collective container moves performed at San Pedro Bay Port marine terminals. Two other types of FELs – side picks and reach stackers – are similar to top handlers in basic form and function. However, both are used sparingly. Consequently, this study focuses on top handlers when assessing the feasibility of potential ZE and/or NZE platforms, which are likely to be transferable to side pick and reach stacker FELs.

each CHE type and the various fuel-technology platforms being assessed for potential to broadly replace baseline diesel CHE. However, it is important to recognize that MTOs currently do not have dedicated CHE fleets to focus on a specific type of operation. In today's system, the same CHE may be used in a variety of applications that have varying duty cycles.

Assessed Fuel-Technology Platforms – This 2021 report uses the same basic parameters and criteria as the 2018 report to assess and compare the following five basic emerging ZE and NZE fuel-technology platforms:

6. **ZE** battery-electric (charged via plugs or inductive systems) or grid electric (electricity provided directly from the grid via a trench or cable connection)
7. **ZE** hydrogen fuel cell electric (electricity generated onboard by reacting hydrogen and oxygen from air; typically hybridized with a battery pack for peak power and regenerative braking)
8. **NZE** advanced diesel[10] internal combustion engine (ICE)
9. **NZE** advanced natural gas (or propane) ICE
10. **NZE** hybrid-electric (electric drive hybridized with an ICE using any fuel; may or may not include plug-in capability)

Note: As of late-2021, the five basic architectures noted above (with possible variations, depending on the specific CHE type) currently exhibit the best potential to be widely and commercially deployed in CHE serving San Pedro Bay Port marine terminals *within the timeframe of this assessment* (2021 to 2024).

Uncertainties and Inherent Challenges – Over the last few years, heavy-duty ZE and NZE fuel-technology platforms with proven or potential use in CHE have been undergoing an accelerated pace of development. This presents a dynamic situation in which information from available and acceptable sources can suddenly become outdated. To the extent possible, such factors have been considered in this Assessment, and reasonable attempts have been made to incorporate emerging developments as they occur. It is possible (although unlikely) that one or more fuel-technology CHE platforms that *are not yet demonstrated in CHE applications* could emerge as "feasible" within this Assessment's relatively near-term timeframe.

2.3. Selection of Credible Information Sources

To accurately assess feasibility of emerging ZE and NZE CHE platforms, it is imperative to obtain and apply credible information across all input parameters. The Ports provide guidance for this process by giving specific examples of credible information sources, while noting that such an approach "ensures consistency with previous studies that have already been publicly vetted and reviewed by technical experts."[11]

Following this template, the authors used an array of credible and relevant information sources to prepare this 2021 Assessment. These include existing reports prepared by the two Ports under their joint Technology Advancement Program (TAP), as well as outside technical reports prepared by (or for) appropriate agencies, such as the U.S. Environmental Protection Agency (EPA), the U.S. Department of Energy (DOE), the California Air Resources Board (CARB), the California Energy Commission (CEC), and the South Coast Air Quality Management District (SCAQMD). Where appropriate, reports from industry stakeholders such as CHE original equipment manufacturers (OEMs), fuel providers, and end users (MTOs and/or their associations) were also utilized. In addition, the authors gathered direct, real-time inputs by 1) interviewing or meeting with CARB, SCAQMD and/or CEC staff; 2) using survey instruments to query CHE OEMs and technology providers; and 3) interviewing and/or visiting a cross-section of SPBP MTOs (in conjunction with their trade association). More details about the specific sources of information that have been utilized are provided throughout this report, including references found in tables, figures and footnotes.

In the preparation of this report, it was equally important to define boundaries for unacceptable information and data sources. Table 1 presents the general types of information sources that were deemed unacceptable as references for citation in this Assessment.

[10] For purposes of this Assessment, "advanced diesel" refers to diesel-fueled internal combustion engines that incorporate advanced emission control systems and/or engine technologies (beyond those used with today's baseline diesel engines), enabling them to achieve significantly lower emissions relative to current prevailing federal emissions standards for heavy-duty engines.

[11] San Pedro Bay Ports, "Framework for Developing Feasibility Assessments", November 2017, page 3.

Table 1. General types of unacceptable information / data sources for feasibility assessments

Unacceptable Types of Information/Data Sources for Feasibility Assessments
• Unsourced reports • Personal accounts or anecdotes (unless provided by individuals verified to be involved in an official capacity with at least one "Information Source" identified in Appendix A: Acceptable Data Sources) • Policy advocacy documents without verifiable data/sources to support claims • Material lacking sufficient information to be judged credible, verifiable, and/or relevant by Port CAAP representatives and/or TAP advisors

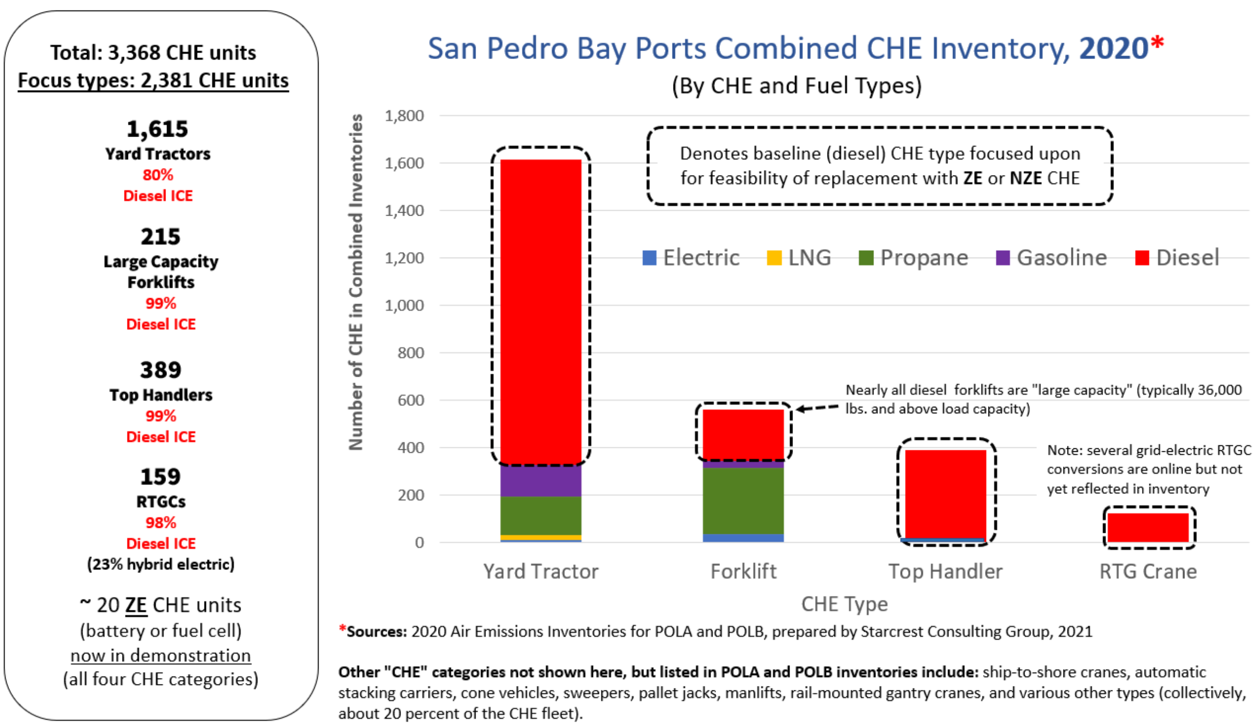
3. Overview of SPBP CHE Fleet

3.1. 2020 Inventory by Key Fuel-Technology Types

As reported in the Ports' respective most-current Emission Inventories (2020), there are approximately 3,368 individual CHE in the collective SPBP fleet. Approximately 70 percent (2,381 CHE units) fall within the four CHE categories that are focused upon for this feasibility assessment. Figure 1 breaks out the collective fleet by CHE and fuel type.

As can be seen, the four key CHE categories continue to be dominated by heavy-duty diesel-fueled ICE technology. Specifically, there are:

- 1,615 yard tractors, of which 80 percent are powered by diesel ICE technology
- 560 forklifts, of which 215 are "large capacity" units powered by diesel ICE technology
- 389 top handlers, of which 99 percent are powered by diesel ICE technology
- 159 RTG cranes, of which 98 percent are powered by diesel ICE technology; about 23 percent of those use advanced ICE/hybrid-electric technology that achieves higher efficiency and lower emissions (**NOTE:** seven conventional RTGs are in the process of being converted and commissioned as ZE grid-electric RTGs, as of late-2021. A total of nine will be converted.)



***Sources:** 2020 Air Emissions Inventories for POLA and POLB, prepared by Starcrest Consulting Group, 2021

Other "CHE" categories not shown here, but listed in POLA and POLB inventories include: ship-to-shore cranes, automatic stacking carriers, cone vehicles, sweepers, pallet jacks, manlifts, rail-mounted gantry cranes, and various other types (collectively, about 20 percent of the CHE fleet).

3.2. Notable Inventory Changes Since 2018 Reflecting Significant ZE and NZE Advancements

In the three years since the 2018 Assessment was prepared (using the 2017 CHE inventories), important changes relevant to the 2021 Assessment can be seen in the Ports' collective CHE fleet (using the 2020 CHE inventories). Specifically – as also highlighted in Figure 1 above – at least 20 ZE CHE units (various types) are now in active deployment and demonstration; most of these units are in pre-production stages of development. ZE CHE units now in demonstration (but not necessarily with oversight by either Port) include battery-electric and/or hydrogen fuel cell yard tractors, top handlers, and large-capacity forklifts. Not yet reflected in this inventory are the above-noted Pier J (Port of Long Beach) conversions of multiple conventional RTG cranes to ZE grid-electric architecture; by the end of 2021, it is expected that eight will be commissioned and in revenue service.[12]

While these demonstrations are in their early stages of implementation, they reflect important technological advancements made by CHE OEMs (and their partners) with ZE platforms for heavy-duty CHE. Thus, key progress highlighted in the 2021 Assessment relative to 2018 is the growing amount of new information about – and stakeholder experience with – battery-electric CHE (and to a lesser extent, fuel cell CHE). This makes it possible to look more deeply at their feasibility for near-term use at the Ports as replacements for large numbers of baseline diesel equipment.

Also notable are the 22 yard tractors powered by NZE natural gas engines that have now been demonstrated for more than two years at a major MTO. All of these advancements toward "feasible" ZE and NZE CHE types (relative to the 2018 Assessment) are further discussed in detail.

3.3. The Importance of Integrated CHE Operations at Marine Terminals

SPBP MTOs stress that they utilize CHE in complex, interactive systems. Widely used CHE like yard tractors, top handlers, and RTG cranes must be operated in careful coordination to move cargo optimally, economically and safely between ships, trucks, and rail cars. Each piece of equipment is responsible for executing one or more specific portion(s) of a cargo move. If there are any delays caused by any single piece of equipment, this has potential to reduce utilization and effectiveness of other CHE in the chain. Section 7.3 further describes the importance of individual CHE optimally operating within the larger system of multiple interacting CHE types, to maximize efficiency, safety and expediency during cargo moves at SPBP marine terminals.

3.4. Rationale for Focusing on Diesel-Fueled CHE

The CAAP is primarily focused on reducing or eliminating emissions from high-horse-power diesel-fueled goods movement vehicles and equipment, which contribute disproportionately to local air quality problems and the associated adverse impacts on public health,[13] as well as to greenhouse gases (GHGs) that cause climate change. Hence, this 2021 Assessment continues the Ports' focus on near-term feasibility to replace (or convert) conventional diesel-engine CHE to versions that incorporate ZE or NZE fuel-technology platforms.

Notably, the Ports' collective emissions inventory still includes hundreds of CHE fueled by propane and gasoline using spark-ignition engines. These non-diesel fueled CHE (represented by bars with green or purple shading in Figure 1 above) primarily consist of small forklifts (16,500-pound or lower lifting capacity) and yard tractors. In the case of small forklifts, battery-electric versions have long been commercially available, and some of them could be used in marine terminal applications. Additionally, hydrogen fuel cell powered forklifts are now being used in industrial applications. While these smaller-horsepower non-diesel equipment types are listed in the CHE inventory, they are significantly different than the high-horsepower diesel-fueled CHE focused upon in this report. Because the Ports believe it is important to include separate discussion about the feasibility of ZE and/or NZE replacements for smaller forklifts that do not use diesel engines, a separate analysis about their use at both Ports was prepared in 2018. These dynamics specific to small forklifts remain essentially unchanged; interested readers can find details in the 2018 Assessment.[14]

[12] Port of Long Beach, personal communication to GNA, December 2021.

[13] For extensive discussion about the adverse impacts of high-horsepower diesel engines and their emissions on air pollution and public health, see CARB's webpage at https://ww2.arb.ca.gov/resources/overview-diesel-exhaust-and-health.

[14] The 2018 Assessment is downloadable at https://cleanairactionplan.org/2019/09/20/cargo-handling-equipment-assessment-released/; see Section 13, Appendix C.

4. Applied Parameters and Initial Screening

This 2021 Assessment for CHE continues the 2018 Assessment's approach to apply five key parameters that examine which (if any) emerging ZE and/or NZE fuel-technology platforms for CHE are demonstrably capable of and ready for broad deployment at the Ports. The five feasibility parameters, which were originally outlined by the Ports in the previously described "Framework" document,[15] are as follows:

- Commercial Availability
- Technical Viability
- Operational Feasibility
- Infrastructure Availability
- Economic Workability (Key Economic Considerations and Issues)

All five of these parameters interact to collectively define feasibility. Failure to meet any one parameter could present a significant barrier to wide-scale deployment at the Ports. However, until a technology has made substantial progress in achieving the first two parameters – Commercial Availability and Technical Viability – it is not possible to conduct a detailed and accurate assessment of the three remaining parameters. This is due to the lack of basic, verifiable cost information and equipment design data that have been corroborated on technologically maturing products in real-world (revenue) service.

Thus, the two feasibility parameters of Commercial Availability and Technical Viability were used to initially screen leading ZE and NZE fuel-technology platforms that appear capable of powering one or more of the four basic CHE types. All fuel-technology platforms shown to meet basic considerations for these two parameters (while applying noted guidelines, and within a three-year timeframe) were then further assessed, according to the three remaining feasibility parameters (Operational Feasibility, Infrastructure Availability and Economic Workability). The schematic in Figure 2 depicts this general screening procedure.

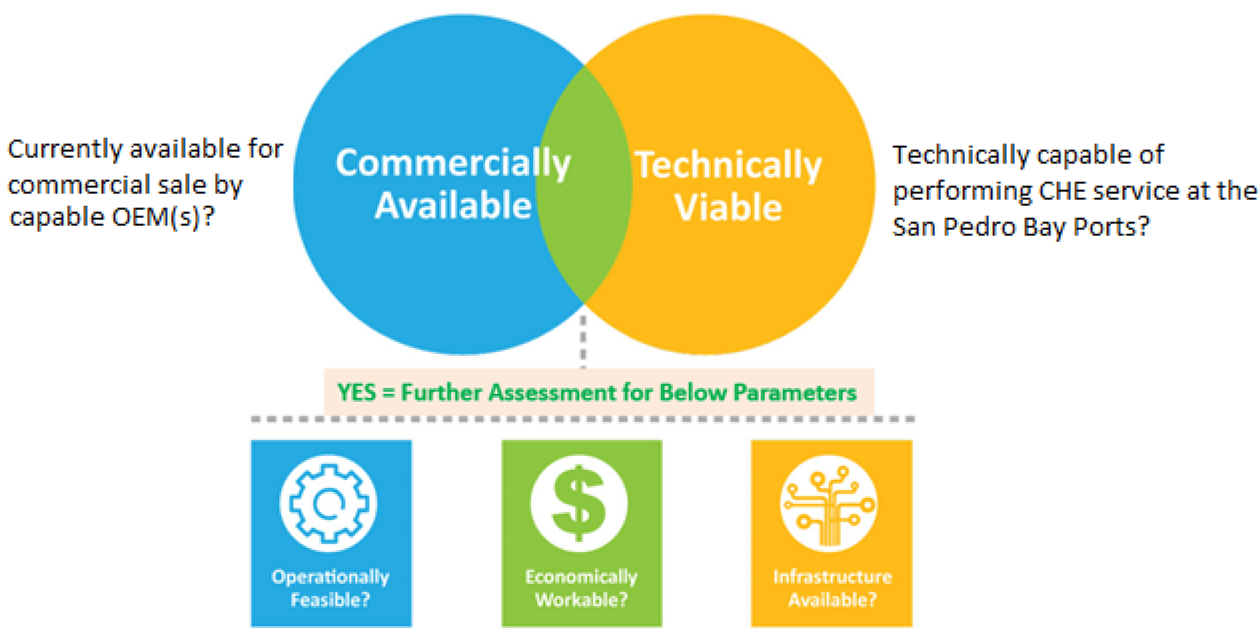


Figure 2. General screening procedure for applying feasibility parameters to assess fuel-technology platforms

[15] San Pedro Bay Ports, "Framework for Developing Feasibility Assessments", November 2017, http://www.cleanairactionplan.org/documents/feasibility-assessment-framework.pdf/.

Note: It is important to repeatedly stress that this 2021 Feasibility Assessment for CHE represents a snapshot in time (late-2021, with potential for feasibility by 2024). The technology and economic landscapes for clean heavy-duty goods movement technologies (including CHE) can change rapidly. ZE and/or NZE CHE platforms that do not yet warrant deeper analysis (as of late-2021) could still exhibit rapid development and advancement. Recognizing this potential, the Ports intend to prepare a revised / updated feasibility assessment for CHE every three years, or more frequently if warranted (e.g., accelerated technological progress, significant expansion in commercial platforms, improving economics).

5. Assessment of Commercial Availability

5.1. Background: Criteria and Methodology

An emerging ZE or NZE fuel-technology CHE platform is deemed to be "commercially available" when (1) it is being manufactured in similar quantities[16] and timeframes as the baseline equipment (usually powered by diesel ICE technology), and (2) it has achieved (or is approaching) baseline-equivalent customer support systems for vehicle warranty, maintenance, and parts. The Ports have identified specific criteria to collectively define if these two basic tests are met.[17] Table 2 summarizes these commercial availability criteria and their base considerations.

Table 2: Criteria and base considerations used to evaluate Commercial Availability

Commercialization Criteria/Issue	Base Considerations for Assessing Commercial Availability
Production and Sales with Major OEM Involvement	Production and full certification as applicable, by either a major CHE OEM or by a proven technology provider that has partnered with the major OEM.
Proven Network / Capabilities for Sales, Support and Warranty	Demonstrated existing (or near-term planned) network of sufficient dealerships to sell and service existing or expected CHE demand.
	Demonstrated ability to sell ZE and/or NZE CHE platforms that are equivalent to baseline diesel CHE (full warranty provisions, long-term support for maintenance and parts replacement).
Sufficient Means and Timeline for Production	Demonstrated capability to manufacture sufficient numbers of CHE within a timeline to meet existing or expected demand.
Existence of Current and/or Near-Term Equipment Orders	Demonstrated backlog of CHE orders, or credible expression of interest from prospective customers to submit near-term orders.
Source: Based on criteria in San Pedro Bay Ports' "Framework for Developing Feasibility Assessments," November 2017.	

5.1.1. Objectives and Methodology for Obtaining OEM Inputs

A common denominator among the above criteria is emphasis on the essential role that capable CHE OEMs must play to develop, fully certify, sell and support large deployments of ZE and/or NZE CHE. To gather and summarize the current status of major OEM involvement in these markets for the four CHE types, the authors used two key sources of information: 1) interviews of (or surveys completed by) senior OEM representatives; and 2) public statements and product information released by the OEMs. The specific objective of direct outreach (interviews and surveys) was to obtain anonymous[18] feedback from the CHE OEMs (and their drivetrain partners[19]) in two basic areas: 1) their existing or near-term-planned product offerings for ZE and/or NZE CHE (as previously defined); and 2) their perceived opportunities, challenges, and timelines associated with new or expanded CHE markets at the SPBP.

To gather this input, the authors contacted senior-level representatives from 1) existing CHE OEMs and 2) key "emerging" CHE OEMs, i.e., those that have recently entered North American CHE markets. OEM representatives were asked to provide relevant inputs via telephone interviews and/or written questionnaires. In addition, the authors contacted four OEMs of drivetrain systems currently being installed in OEM CHE with ZE and/or NZE architectures. This type of "off-the-record" OEM input was combined with relevant OEM information in the public domain (e.g., websites, press releases, corporate reports, government grants, public reports on CHE demonstrations, etc.) to build a current, verifiable snapshot of overall CHE

[16] "Similar quantities" is not meant to indicate that ZE and/or LE truck types cannot be considered "commercially feasible" unless/until they are sold in equal quantities as diesel trucks. Rather, it means they must be sold in the same order of magnitude as diesel trucks (hundreds to thousands per year).
[17] San Pedro Bay Ports, "Framework for Developing Feasibility Assessments", November 2017, http://www.cleanairactionplan.org/documents/feasibility-assessment-framework.pdf/.
[18] These existing and emerging OEMs were asked to provide non-proprietary answers and information. To help encourage a high rate of response and facilitate frank inputs, it was communicated to the OEMs that their information and inputs would be treated as anonymous, i.e., without attribution to any specific OEM or company representative. It was made clear that public statements by OEMs might be cited.
[19] Some CHE OEMs continue to work with, and rely upon, smaller-volume start-up* OEMs, technology providers and qualified upfitters to help accelerate technological progress and incorporate alternative fuel systems into various ZE and NZE platforms. These companies have proven histories for developing ZE and/or NZE architectures that can work in numerous on- and off-road heavy-duty vehicle/equipment applications. The important activities of such companies are reflected in the partnerships they have established with OEMs to develop and help commercialize ZE and NZE CHE technologies. *When used, the term "start-up OEM" is within the context of North American sales for heavy-duty vehicles and equipment.

feasibility in 2021, beginning with commercial availability as the initial parameter to evaluate. The authors also helped gauge and corroborate which types of CHE can be purchased today from OEMs by reviewing key grant programs, e.g., California's Clean Off-Road Equipment (CORE) Program (www.californiacore.org) Notably, listing of a given fuel-technology CHE type under CORE (or any incentive program) does not in itself constitute achieving Commercial Availability.

Table 3 summarizes the 15 different companies that were contacted and asked to provide inputs. As shown, they produce and sell a wide range of CHE products – including all four key types assessed in this report. Of the ten existing CHE OEMs that were contacted, six provided inputs via telephone interviews and/or written responses; the other four CHE OEMs declined to participate, or did not respond to requests for input (although public information may have been incorporated). Of the five OEMs for CHE drive systems and components (i.e., enablers of ZE and/or NZE architectures), four provided inputs via telephone discussion and/or email communications. Inputs from OEMs not interviewed were collected (as applicable from public statements, websites, etc. In this way, inputs from all major OEMs supplying CHE to MTOs at the SPBPs were

Table 3: CHE OEMs and component suppliers contacted about ZE/NZE products, opportunities and challenges

Category of OEM	Name of OEM	Most-Relevant CHE Product(s) or Subsystems
Existing CHE OEM	Capacity Trucks	• Yard/Terminal Tractors
	Kalmar (Cargotec)	• Yard/Terminal Tractors, Top Handlers, Side Picks/Reach Stackers, Rubber Tired Gantry Cranes, Straddle Carriers
	TICO	• Yard/Terminal Tractors
	Autocar	• Yard/Terminal Tractors
	BYD	• Yard/Terminal Tractors
	Orange EV	• Yard/Terminal Tractors
	Taylor Machine Works	• Top Handlers, Side Picks/Reach Stackers, Large Capacity Forklifts
	Hyster-Yale	• Top Handlers, Side Picks/Reach Stackers, Large Capacity Forklifts
	Hoist Lift Trucks	• Top Handlers, Side Picks/Reach Stackers, Large Capacity Forklifts
	Konecranes	• Yard/Terminal Tractors (Automated), Rubber Tired Gantry Cranes, Straddle Carriers
OEM for CHE Drive Systems / Components	Conductix-Wampfler	• Rubber Tired Gantry Crane Electrification Systems/Solutions
	Cavotec	• Rubber Tired Gantry Crane Electrification Systems/Solutions
	Toyota Motor Co.	• Yard Tractor Hydrogen Fuel Cell Engines (development stage)
	Cummins Corporation	• Yard Tractor Natural Gas Engines/Fuel Cell and Battery Powertrains (development stage)
	Meritor/Transpower	• Yard Tractor / Other CHE Electric Powertrains (development stage)

incorporated.

5.1.2. "Pre-Commercial" vs. "Early Commercial," and the Importance of Fully Demonstrating Technology

This Assessment frequently uses the terms "pre-commercial" and "early commercial" when summarizing the commercialization status of various fuel-technology CHE platforms. Per CARB's use,[20] early commercial refers to emerging-technology CHE that are relatively new to the market, but "have been demonstrated, are certified by CARB, come with a warranty, and are purchased or leased by the end user." Typically, these are made available to end users in small numbers and have not yet been commonly deployed in CHE service by MTOs at the Ports. By CARB's terminology, a pre-commercial CHE fuel-technology platform does not yet meet all of the above tests (e.g., it may not be CARB certified), and is generally "focused on first-time demonstrations of advanced technologies in new applications." Most of the ZE and NZE CHE fuel-technology platforms discussed in this Assessment fall somewhere between these two definitions, especially when considered in the specific context of use by SPBP MTOs.

Like the 2018 report, this 2021 Assessment emphasizes the critical importance of fully demonstrating pre-commercial and early commercial CHE in revenue service at SPBP marine terminals. Demonstrations of OEM-built products are essential for all parties (OEMs, MTOs, the Ports, fuel/infrastructure providers, permitting officials, etc.) to collectively establish and corroborate the feasibility of ZE and NZE CHE platforms *before attempting broad deployments*. Notably, a number of pre-commercial or early commercial CHE units were scheduled to receive significant revenue service operation at the Ports in the 2019-2020 timeframe. Nearly all were expected to be completed by 2021, for incorporation of full results into this 2021 Assessment. However, most demonstrations – involving all four types of CHE (yard tractors, RTG cranes, top handlers, and

[20] See https://www.arb.ca.gov/msprog/aqip/fundplan/proposed_fy16-17_fundingplan_appb.pdf.

large-capacity forklifts) – were delayed in getting started and/or completed (for a wide array of reasons, including safety and mechanical design issues, permitting issues, COVID-19, and other challenges that have arisen). Thus, few of those demonstrations have been fully completed including provision of peer-reviewed final reports presenting critical information that fall within the five feasibility parameters addressed in this report. Finally, it is important to note that entirely new demonstrations are now getting underway, at both Ports.

Section 5.6 contains details about the many CHE demonstrations that are now underway or planned at the Ports, and the essential role they will play to provide MTOs with first-hand operational experience on various emerging ZE and NZE fuel-technology platforms. As described, the next 12 to 24 months will be critical for OEMs and MTOs to jointly corroborate overall feasibility for the leading ZE and NZE CHE platforms as they are fully demonstrated in revenue service at the Ports.

5.1.3. Baseline for Measuring Commercial Availability Progress Since 2018 Assessment

As a frame of reference, the 2018 Feasibility Assessment reported that:

1) ZE grid-electric and NZE hybrid-electric RTG cranes had already achieved full commercial availability, although they were not widely deployed at either Port
2) ZE battery-electric and NZE natural gas yard tractors were in "early commercialization" stages
3) ZE top handlers and large-capacity forklifts were entering pre-commercial stages of development and demonstration

Over the last few years (mid-2018 to late-2021), CHE OEMs (along with their technology partners) have made significant new progress to commercialize ZE and NZE CHE. The next section describes specific ways that OEMs have further advanced ZE and/or NZE CHE types and architectures toward sufficient commercial availability to achieve widescale deployment at the SPBP, when combined with successful achievement of the four other feasibility parameters.

5.2. 2021 Status of OEM Commercialization Efforts for CHE, by Type and Application

5.2.1. ZE and NZE Yard Tractors

According to the most-current (2020) combined CHE inventory,approximately 1,600 yard tractors currently serve the two SPBP. Of these, 80 percent are powered by conventional diesel engines. The other 20 percent consist of units powered by a mix of natural gas, propane, and gasoline engines. Less than one percent (11 units) are powered by ZE battery electric technology. The two most prevalent brands of yard tractors in use at the Ports are Kalmar and Capacity, holding 38 and 48 percent of the market-share, respectively.

Yard tractors are very similar to on-road heavy-duty trucks. Their design, use and duty cycle characteristics are generally conducive to zero-emission propulsion systems. As of late-2021, three CHE OEMs indicate they commercially offer at least one yard tractor model powered by a ZE technology; three other CHE OEMs have demonstrated proven capability to commercially offer yard tractors with NZE technology (see Table 4). Essentially, all of these constitute pre- or early commercial products . It is important to note that some commercially offered CHE types have not yet been deployed at the SPBP in typical MTO service. Further discussion is provided below.

The following provides a snapshot of key EM commercialization and/or demonstration efforts involving **ZE** yard tractors; again, the focus is on relevancy to existing or potential use by MTOs at the SPBP.

- Three CHE OEMs, Kalmar Ottawa, BYD and Orange EV[21] are selling battery-electric yard tractors that are certified and listed by CARB (see Figure 3 below) as eligible for incentive funds (up to $200,000 per unit) under the California Clean Off-Road Equipment Project (CORE). To date, CORE has funded approximately 306 low- or zero-emission CHE units, of which approximately 46 percent has been yard tractors.[22] Importantly, eligibility of these emerging-technology yard tractors for funding incentives does not require prior demonstration in revenue service by a SPBP MTO to corroborate

[21]The battery-electric yard tractor model currently offered by Orange EV (and listed as CORE eligible) is not intended for operation in typical MTO duty cycles at the San Pedro Bay Ports. However, Orange EV has announced intent to commercialize a yard tractor model that specifically designed for use in marine terminal operations; production is scheduled to begin in 2022.

[22] CORE Update Webinar, July 2021, Power Point presentation, CORE-Update-Webinar-07212021-Final_Draft.pdf (californiacore.org).

Battery Electric Yard Tractors Eligible for CORE Incentive Funding (up to $174,000/unit), Mid-2021

Source and Photos: CORE, Terminal Tractors - Clean Off-Road Equipment Voucher Incentive Project (californiacore.org)

Figure 3. Mid-2021 snapshot of ZE battery-electric yard tractors eligible for incentives under CORE program

ability to meet technical and operational needs (see Sections 6 and7).

- A fourth yard tractor OEM, TICO, has entered into "strategic partnerships" with Volvo Penta and Cummins to bring early commercial electric yard tractors to the North American market by 2022.[23] A fifth OEM, Autocar, is also commercially introducing a battery-electric yard tractor; sales are expected to begin in late-2021 or early-2022.[24]

- Roughly 10 battery-electric yard tractors are currently being tested in revenue-service deployments at various SPBP MTOs.[25] Most of these are first- or second-generation OEM units designed and manufactured by BYD. SPBP MTO deployments of pre- and early commercial battery-electric yard tractors are expected to increase significantly over the next two years. For example, under California's Sustainable Terminals Accelerating Regional Transportation (START) Program, yard tractor OEM DINA is teaming with electric-drive provider Meritor (and its subsidiary TransPower) to provide as many as 33 battery-electric units for testing at SSA Terminals (Port of Long Beach).[26]

- Capacity Trucks has entered into a partnership with the Hyster-Yale Group "to co-develop electric and hydrogen-powered terminal tractors with automation-ready capabilities." As of late 2020, the two companies were targeting "initial prototypes" to "be available in 2021 for market testing."[27] One prototype was displayed at the August 2021 ACT Expo show in Long Beach (see Figure 4), which included "ride and drive" opportunities for attendees. Nuvera (a Hyster-Yale subsidiary) is providing the fuel cell engine technology for these ZE hydrogen yard tractors.

- Light-duty car and forklift OEM Toyota is building fuel cell electric drivetrains specifically for incorporation into yard tractors. Toyota is applying the same fuel cell system that powers its commercially proven "Mirai" model fuel cell passenger car. The company's intent is to commercialize ZE fuel cell powerplants (starting in 2022) that yard tractor (and Class 8 truck) OEMs can purchase and incorporate into their model lineups. Figure 4 shows a prototype yard tractor with Toyota's fuel cell system powering an unspecified OEM's chassis. This fuel-technology platform for yard tractors has undergone "trial testing" by SPBP MTOs (e.g., Fenix Marine Services at POLA).[28]

[23] TICO, "TICO Announces Two Strategic Electric Vehicle Partnerships," press release, March 25, 2021, https://ticotractors.com/press-releases/#foobox-1/0.
[24] Truckinginfo.com, "Autocar Launches Electric Terminal Tractor," May 18, 2021, https://www.truckinginfo.com/10143717/autocar-launches-electric-terminal-tractor.
[25] This is estimated based on the joint 2020 CHE inventories for the two Ports and anecdotal inputs from Port reps and interviewed MTOs.
[26] California Air Resources Board, "Appendix G: Low Carbon Transportation Investment Project Summaries," Proposed Fiscal Year Funding Plan for Clean Transportation Incentives, October 2021, https://ww2.arb.ca.gov/our-work/programs/low-carbon-transportation-investments-and-air-quality-improvement-program/low-1.
[27] Hyster Company, "Hyster-Yale Group and Capacity Trucks Enter Partnership to Jointly Develop Electric, Hydrogen and Automation-Ready Terminal Tractors, press release, December 14, 2020, HYSTER-YALE GROUP AND CAPACITY TRUCKS ENTER PARTNERSHIP TO JOINTLY DEVELOP ELECTRIC, HYDROGEN AND AUTOMATION-READY TERMINAL TRACTORS.
[28] Fenix Marine Services, "Corporate Social Responsibility," https://fenixmarineservices.com/corporate-social-responsibility/.

Capacity Tractor with Hyster-Yale (Nuvera) Fuel Cell Engine

Unspecified OEM Tractor with Toyota Fuel Cell Engine

Hydrogen Fuel Cell Yard Tractor Prototypes (Development and Demonstration), Mid-2021

Photos: Jon Leonard, Gladstein, Neandross & Associates (ACT Expo 2021)

Figure 4. Mid-2021 snapshot of ZE hydrogen fuel cell yard tractor prototypes with major OEM involvement

- Under the "ZECAP" (Zero Emissions for California Ports) program, Capacity Trucks built and deployed two hydrogen-fueled yard trucks powered by Ballard Power's fuel cell engine. Under a multi-year development and demonstration effort funded by CARB, these proof-of-concept ZE units are currently undergoing testing in revenue service at TraPac Terminal (Port of Los Angeles).[29]

The following provides a snapshot of OEM commercialization and/or demonstration efforts for **NZE** yard tractors:

- At least three major CHE OEMs – Capacity Trucks, TICO and Autocar – have publicly demonstrated the *capability* to commercially produce and sell NZE natural gas yard tractors. In particular, Capacity built and demonstrated 22 liquefied natural gas (LNG) NZE yard tractors at the Port of Los Angeles (Everport Terminals). During more than a year of demonstration in revenue service, Capacity worked with Everport, Cummins and other partners to resolve pre-production issues, increase product robustness and improve operational feasibility.[30] Notably – while those units emerged as near-ready products (and are still in service as of late-2021) – Capacity has not announced any decision to commercialize natural gas fueled NZE yard tractors. TICO partnered with Cummins in 2019 to offer its Pro-Spotter model with a 6.7L NZE compressed natural gas (CNG) engine[31]; although none are currently in use by SPBP MTOs, fleets such as UPS have purchased significant numbers for other applications (e.g., warehouse and distribution). Autocar also can offer NZE natural gas (CNG) options for its diesel yard tractors.[32] One of these CHE OEMs reportedly will announce in early 2022 intent to build NZE yard tractors with propane engines; the specific application will be container movements at marine terminals.[33]

- The 22 Capacity NZE LNG-fueled yard tractors at Everport Terminals are the only NZE units that have accrued operating time in revenue service, at any SPBP MTO. NZE natural gas yard tractors are further discussed and analyzed in Section 7 (Operational Feasibility), specifically with regard to shift endurance between fueling events when moving cargo at SPBP marine terminals. In the recent past, non-NZE versions of LNG tractors have been successfully used to move containers at a yard near POLA. These are older-generation yard tractor models / engines that have been discontinued by their respective manufacturers.

Table 4 summarizes various models of ZE and NZE yard tractors that OEMs offer for sale today. Essentially, these all constitute pre- or early commercialization launches within the context of use at the SPBP, as replacements for baseline diesel tractors.

[29] California Air Resources Board, "Zero Emissions for California Ports (ZECAP)," March 2020, https://ww3.arb.ca.gov/msprog/lct/pdfs/zecap.pdf.

[30] Leonard, Jonathan, Patrick Couch, Kent Johnson, and Thomas Durbin. 2021. *Developing, Demonstrating, and Testing Advanced Ultra-Low-Emission Natural Gas Engines in Port Yard Trucks.* California Energy Commission. Publication Number: CEC-500-2021-037.

[31] TICO, "TICO Teams with Cummins 6.7-Liter Compressed Natural Gas (CNG) Alternative Fuel Engine During the ACT Expo," press release, April 19, 2019, https://ticotractors.com/press-releases/#foobox-3/0.

[32] See Autocar's webpage titled "Considering Going Green? It's Time to Hit the Gas," https://www.autocartruck.com/cng-advantage/.

[33] Personal communication, Propane Education & Research Council to GNA, December 2021.

Additional discussion about these early commercial deployments is provided in Section 5.6, within the context of the many important CHE demonstration programs that are underway at the two Ports, for all four types of CHE addressed in this report.

Table 4. Yard Tractors: Late-2021 snapshot of "commercially offered" ZE and/or NZE platforms, by OEM

Make	Model	ZE Battery-Electric	ZE Fuel Cell	NZE Hybrid Electric	NZE CNG and/or LNG ICE	CORE Status	Status: SPBP Deployment*
BYD	8Y	√	-	-	-	Eligible	~10 units with SPBP MTO(s)
Kalmar Ottawa	T2E 4X2	√	-	-	-	Eligible	~ 1 to 3 units with SPBP MTO(s)
Orange EV	T-Series	√	-	-	-	Eligible	None with SPBP MTO(s)
Capacity Trucks	TJ9000	-	-	-	√*	Not Eligible	22 units with SPBP MTO(s)
TICO	Pro-Spotter	-	-	-	√*	Not Eligible	None with SPBP MTO(s)
Autocar	ACTT XSPOTTER	-	-	-	√*	Not Eligible	None with SPBP MTO(s)

Sources: OEM websites and publicly available literature (e.g., CORE); *SPBP deployment status based on various grant awards for POLA and/or POLB demonstration / deployment projects, and interviews with MTOs (July/August 2021).
*In recent years, these OEMs may have offered a CNG and/or LNG engine option for yard tractors. Based on publicly available information, all have ongoing capability to produce and sell large numbers of NZE units. However, specific plans and timelines for these OEMs to produce NZE yard tractors are proprietary, and subject to unclear customer demand associated with an uncertain regulatory environment. At least one of these OEMs is expected to announce in early 2022 that it will make and sell NZE yard tractors for port applications.

5.2.2. ZE and NZE Top Handlers

According to the most-current (2020) combined CHE inventory, approximately 390 top handlers serve the two Ports. Nearly all (99 percent) use diesel engines, with an average of 350 horsepower. Diesel top handlers are versatile workhorses at both Ports; some are operated for 4,600 annual hours (equivalent to two daily shifts, five-to-six days per week). These large CHE are operated under energy-intensive duty cycles – they move, lift and re-stack fully loaded containers with a vertical lift as high as 60 feet. Consequently, CHE OEMs face greater challenges to design operationally feasible ZE top handlers compared to yard tractors. Not surprisingly, OEM efforts to develop, demonstrate and commercialize ZE top handlers have lagged behind corresponding efforts for yard tractors.

Despite the challenges, top handler OEMs have made major progess since 2018 to accelerate commercialization of battery-electric technology. Taylor Machine Works – the OEM for 80 percent of the top handlers listed in the joint SPBP CHE inventory – has been a leader in developing proof-of-concept ZE battery-electric top handlers. Beginning in 2018, with monetary support from the Ports and three key California agencies (CARB, CEC, and the SCAQMD), Taylor began building four prototype battery-electric top handlers. Each yard tractor was designed to the same basic specification. The chosen design centers on a very large (1 megawatt-hour) battery pack to provide the necessary power, shift endurance and load-ballast weight. Taylor teamed with technology partners to design and incorporate the electric drive sytem. The original schedule called for multipe-MTO demonstrations to commence in 2019, and the demonstration units were delivered in August and September of 2019. However, demonstration timelines were delayed by approximately one year, primarily due to long lead times to obtain certification of the 200 kW charging stations.[34] By mid-to-late 2020, four prototype units were operational.[35] Figure 5 shows a baseline diesel top handler and two different pre-commercial Taylor models being demonstrated in revenue service at separate MTOs serving both Ports. While these two units have different Taylor model designations, they are equivalent regarding the key specifications of load capacity, lift height, and battery capacity. Details regarding demonstration of three

[34]Personal communication to GNA by MTO representative demonstrating Taylor battery-electric top handlers at the Port of Long Beach. Additionally, a September 2020 report about these Taylor battery-electric top handlers (posted by CARB) notes that "deploying charging infrastructure at active terminals requires creative solutions and long lead times to secure UL certification, or equivalent, and sign off by the authority having jurisdiction."
[35] See for example Port of Los Angeles, "World's First Zero-Emissions Top Handlers Performing Well at Port of Los Angeles," August 6, 2020, https://www.portoflosangeles.org/references/news_080520_top_handlers_performing_well.

Taylor battery-electric top handlers at the Port of Long Beach (under the CARB-funded C-PORT project) are available in Taylor's final report of June 2021.[36]

Significantly, the University of California-Riverside (UCR) "data logged" three pre-commercial top handlers while being demonstrated at the Port of Long Beach under the C-PORT project. The UCR team compared the battery-electric top handlers for performance as well as environmental attributes, relative to two baseline diesel top handlers that were also data logged. UCR found that "based on the monitored activity data . . . the battery-electric equipment was able to perform over a work shift comparable to that of the diesel equipment." The test team noted that such in-use performance "will provide important feedback about the effectiveness of battery-electric equipment in different applications, which can be used to improve the designs of future generations of battery-electric equipment."[37] In sum, these tests clearly demonstrated that pre-commercial battery-electric top handlers can complete one or more shifts of operation between charging events. UCR also noted that "deployment of battery-electric equipment in port cargo handling operations could provide considerable benefits in terms of emissions reductions and energy consumption."

Taylor **Baseline Diesel** Top Handler (POLA) | Taylor ZLC976 **Battery-Electric** Top Handler (POLA) | Taylor ZLC906 **Battery-Electric** Top Handlers (POLB)

Photos: (Left) Jon Leonard, GNA, **(Middle)** Port of Los Angeles, and **(Right)** Port of Long Beach

Figure 5. Taylor Machine Works baseline diesel (left), and prototype ZE top handlers built by Taylor Machine Works

In addition to Taylor efforts to design, build and demonstrate battery-electric top handlers, Hyster-Yale (about 10 percent of the top handlers in the Ports' joint CHE inventory) is also working on ZE top handler technology. Section 5.6 further describes how ZE top handlers with battery-electric (and hydrogen fuel cell) architectures are now entering into demonstrations at the SPBP.

While OEM involvement in these efforts is strong, and major progress has been achieved, ZE top handlers are not yet technologically or commercially mature products for wide-scale application at the SPBP. No OEMs are selling them commercially, and (unlike yard tractors) ZE top handlers are not yet certified, nor are they available/eligible for incentives under California's CORE incentive program.

Notably, as further described in Section 5.2.4, top handlers share key attributes with large-capacity forklifts (basic size and type of duty cycle). CARB has listed two ZE battery-electric large-capacity forklift models as pre-commercial products that are eligible to receive incentive funds under the CORE program (see Section 5.2.4).

5.2.3. ZE / NZE RTG Cranes

Conventional RTG cranes use diesel engines as their baseline technology. Similar to locomotives, a diesel-powered generator ("gen-set") produces electricity for an electric-drive system that provides smooth, high-torque motive power. To reduce (or

[36]Taylor Machine Works, Inc., "Final Equipment Summary Report for Taylor Machine Works, Inc.: Taylor Zero Emission Vehicles ZLC-906 Loaded Container Handlers," Final Report G16-DEMO-003 for the California Air Resources Board, June 15, 2021.

[37]Frederickson, C., Durbin, T., Li, C., Ma, T. et al., "Performance and Activity Characteristics of Zero Emission Battery-Electric Cargo Handling Equipment at a Port Terminal," SAE Technical Paper 2022-01-0576, 2022, doi:10.4271/2022-01-0576.

eliminate) diesel engine emissions and improve system efficiency, conventional RTG cranes can be replaced with (or converted to) two basic architecture types. These are:

1) **ZE** grid electric, which eliminates the need for a diesel gen-set by tying the RTG crane's electric drive directly into the electricity grid, using trenching or cabling systems for the necessary high-voltage wires. This architecture provides the advantage of zero direct-CHE emissions (under normal operational conditions); the tradeoff is that safely connecting existing or new RTG cranes for full-electric power can require costly, complex and/or disruptive wire connections to the grid.
2) **NZE** advanced hybrid electric, which incorporates battery power to enable significant downsizing of the diesel engine. A baseline RTG crane may have a very large diesel engine (up to ~1,000 horsepower); sometimes these are equipped with little (or no) controls for emissions. Replacing the baseline diesel engine with a much smaller engine (~150 horsepower) certified to EPA's lowest existing emissions standard for heavy-duty diesel off-road engines (Tier 4 final) – and combined with a more-advanced battery-electric drive system – can provide major air quality benefits. The net effect is that hybrid-electric RTGs operate at higher efficiency and burn much less diesel than conventional RTG cranes. Multiple OEMs of new-build RTG cranes and conversion packages cite diesel-use reductions ranging from 56 percent to 60 percent, which directly result in major reductions for criteria pollutant (e.g., NOx and PM) and GHG emissions. Thus, while hybrid RTG cranes are not ZE CHE, they deliver major air quality (and climate-change) benefits via their NZE-level emissions (further discussed below).

ZE and NZE RTG crane technologies are commercially available today from multiple CHE OEMs; this has been recognized for several years by the Ports, the marine terminal industry[38] and regulatory agencies in California.[39] Examples of North American CHE OEMs that are well engaged in this market include Kalmar, Konecranes, ZPMC, Mi-Jack/Kůnz[40] and Mitsui/Paceco.[41] Many (if not all) OEMs team with companies specializing in advanced RTG crane drive systems such as Conductix Wampfler or Cavotec; these work with OEMs to enable ZE or NZE drivetrain technology and electrification for RTG cranes. MTOs can purchase new ZE or NZE RTG cranes from the OEMs, but they can also purchase complete packages (hardware, software, installation) to convert existing conventional RTG cranes at the terminal.

Fully electric RTG (grid-connected) cranes and hybrid-electric RTG cranes are gaining significant market share at major world seaports. Europe and Asia are showing the strongest adoption rates, but North American sales are accelerating. Over the next two decades, ZE and NZE RTG cranes are expected to be the fastest growing segment of RTG sales at the world's large seaports. [42] Specific examples of commercially available ZE and NZE platforms for RTG cranes sold in North America are summarized below.

- Kalmar, Konecranes and Shanghai Zhenhua Port Machinery (ZPMC) sell new-build ZE RTG cranes, typically using electric-enabling systems by other companies (see below). Grid power can be supplied either by a motorized cable reel or a conductor bar/rail system. These units are equipped with relatively small battery packs that store and manage regenerative electricity from the down-stroke of each RTG crane lift. Worldwide, these types of new-build ZE RTG cranes have been commercially sold and deployed in significant numbers, beginning in 2008. These companies can also convert existing conventional RTG cranes to ZE grid-electric configurations.
- The above OEMs also sell new-build NZE hybrid-electric RTG cranes, and some also commercially offer NZE hybrid-electric conversion kits for existing RTG cranes. For example, in April 2021 Konecranes' received EPA approval for its "EcoLifting Hybrid" retrofit system for RTG cranes as a "Verified Clean Diesel Technology." According to the EPA verification letter, "EcoLifting demonstrated a 30 percent or greater fuel economy improvement depending on the operating conditions," and has been shown to reduce major criteria pollutant emissions by 90 percent (if operated and maintained properly).[43]

[38] Pacific Merchant Shipping Association, "Technical Memorandum: Sustainable Freight Strategy Impact Study," December 4, 2015, http://www.pmsaship.com/pdfs/PMSA%20Sustainable%20Freight%20Strategy%20Impact%20Study%20Tech%20Memo%208918%20Final.pdf.
[39] California Air Resources Board, "Proposed Fiscal Year 2018-19 Funding Plan for Clean Transportation Incentives," September 21, 2018, https://www.arb.ca.gov/msprog/aqip/fundplan/proposed_1819_funding_plan.pdf.
[40] Mi-Jack is the OEM in the hybrid RTG crane market; Kůnz is the OEM for ZE RTG cranes, with Mi-Jack as the dealer.
[41] Mitsui E&S Machinery and its subsidiary Paceco Corp. have sold hundreds of NZE and ZE RTG cranes worldwide. See https://pacecocorp.com/.
[42] Grand View Research, "Rubber Tired Gantry (RTG) Crane Market Analysis," published May 2017, https://www.grandviewresearch.com/industry-analysis/rubber-tired-gantry-rtg-crane-market.
[43] U.S. Environmental Protection Agency, "Konecranes PLC —Tier 4F EcoLifting Hybrid System, https://www.epa.gov/verified-diesel-tech/konecranes-plc-tier-4f-ecolifting-hybrid-system.

To date, no North American port has yet deployed this NZE Konecranes RTG crane retrofit system. The Port of Charleston (South Carolina) will be the first case; EPA-verified kits will be retrofitted on 12 in-use RTG cranes (all 20+ years old) beginning in January 2022.[44]

- Conductix Wampfler is one of the major technology enablers for these advanced electric-drive RTG cranes. With major OEMs like Konecranes (the EcoLift system) and Kalmar as their customers, Conductix Wampfler manufactures and sells aftermarket systems that convert conventional RTG cranes into either ZE grid-electric or NZE hybrid-electric versions. Since 2006, Conductix Wampfler has installed its "E-RTG Solutions" (of various architectures and electrification strategies) into hundreds of new-build or in-use RTG cranes throughout the world (mostly in Asia). Since 2012, multiple Conductix Wampfler e-RTG systems have been installed at U.S. ports that include the Port of Savanah, the Port of Los Angeles, the Port of Everglades, and the Port of Miami. As of mid-2021, all installations have entailed fully commercial e-RTG systems. Conductix Wampler is also working on "concept design" configurations that are being designed to achieve ZE operation with 1) a grid-charged "extra-large battery pack," or 2) a grid-free fuel cell/battery pack combination that generates electricity using a hydrogen fuel cell.[45] Photos of Conductix Wampfler's commercially deployed hybrid-electric and grid-electric e-RTG crane systems are provided in Figure 6 and Figure 7, respectively.

[44] Konecranes, "Konecranes wins first customer for EPA-approved new diesel-to-hybrid conversion technology," press release, July 29, 2021, https://www.konecranes.com/press/releases/2021/konecranes-wins-first-customer-for-epa-approved-new-diesel-to-hybrid-conversion-technology.

[45] Conductix Wampfler, "E-RTG Solutions," sales brochure provided directly to GNA, September 2021. Augmented with personal communications from Conductix Wampler to GNA, September 2021.

Figure 6. Conductix-Wampfler NZE hybrid-electric conversion system for RTG cranes (courtesy of Conductix-Wampfler)

Figure 7. Conductix Wampfler ZE grid-electric conversion system for RTG cranes (courtesy of Conductix Wampfler)

- Similarly, Cavotec designs and manufactures advanced electrification solutions for in-use or new-build RTG cranes that include motorized cable reels, cable protection and power connection systems (see Figure 8). In early 2021, the company announced that it plans to specifically focus resources and investments on electrification-based "sustainability solutions for ports and the maritime industry."[46]

Figure 8. Cavotec ZE grid-electric conversion system for RTG cranes (courtesy of Cavotec)

Worldwide, more than one hundred ZE (fully electric) and NZE (hybrid-electric) RTG cranes are in revenue service at major seaports. To date, most deployments are in Europe and Asia; for example, the Port of Shanghai operates more than 30 all-electric RTG cranes.[47] A slower rate of adoption has occurred at North American seaports, but deployments of all-electric RTG cranes and hybrid RTG cranes (new-build and conversions) have been steadily increasing. Most recently, the Port of Savannah (Georgia Ports Authority) began testing and demonstrating grid-electric RTG cranes in 2021. The initial project entailed converting four conventional Konecranes RTG cranes to grid-connected RTG cranes using Conductix-Wampfler conductor rail systems. In April 2021, the Georgia Ports Authority ordered 20 additional electric RTG cranes from Konecranes that use Conductix-Wampfler technology, for delivery in 2021 and 2022.

At the SPBP, the earliest ZE and/or NZE RTG crane deployments began in 2012. Short-term trial efforts were conducted on these older-technology units at APM Terminals (Pier 400, POLA)[48] and West Basin Container Terminal (POLA).[49] Although the Ports' most-recent (2020) combined emissions inventories do not show any grid-electric RTG cranes in use at either port, SSA Terminals has recently started retrofitting nine existing RTG cranes to grid-electric units (see below). The collective inventory also indicates that MTOs are operating at least 36 hybrid RTG cranes (out of 123 total) at the two Ports (about 30 percent). The specific technology providers and architectures vary, but all 36 hybrid RTG cranes feature significantly smaller diesel engines (an average horsepower reduction of about 65 percent, per specifications listed in the inventories). As noted, downsizing the diesel genset results in significantly reduced fuel combustion and concomitant reductions of harmful criteria pollutants.

Examples of the most-recent SPBP MTO deployments of ZE and NZE RTG cranes that are now underway (or planned for the near-term) include the following:

- SSA Terminals has joined with the Port of Long Beach to repower nine conventional RTGs at Pier J into ZE grid-connected E-RTGs. This is part of the Zero-Emissions Terminal Equipment Transition Project, which is a state/federally funded grant

[46] Cavotec, "Cavotec to Focus on Growing Markets for Sustainability Solutions in Ports & Maritime and Industry – Initiates Process to Divest Airport Business," Press Release, March 5, 2021, https://press.cavotec.com/pressreleases/cavotec-to-focus-on-growing-markets-for-sustainability-solutions-in-ports-and-maritime-and-industry-initiates-process-to-divest-the-airports-business-3078878.
[47] ZPMC, "Energy Saving Technologies: Lithium Battery RTG," product brochure, provided by the Port of Long Beach, January 2019.
[48]Ibid.
[49]Ibid.

program. Reportedly, this will be "the nation's largest deployment of fully electric RTGs at a single terminal."[50] The conversion process entails completely eliminating 1,000 horsepower diesel engines with "100% electric grid-tied" systems. As of late-2021, six units were in operation. SSA has noted that "long lead times" for the full process to convert RTGs and make infrastructure upgrades have delayed deployment timelines somewhat, but all infrastructure installations were completed in 2020. The delay was further exacerbated by the surge in goods movement activity in late 2020 and during most of 2021, which prevented SSA from pulling a diesel RTG crane offline to start the conversion process.[51] SSA has also converted a large portion of its diesel RTG cranes in Mexico and Panama to all-electric using Conductix-Wampfler technology.[52] Additionally, SSA has purchased multiple new-build E-RTG cranes from ZPMC for deployment in these countries.[53]

- SSA Terminals has also converted parts of its RTG crane fleet at the Port of Long Beach (and the Port of Oakland) to NZE hybrid-electric configurations. For these state-funded conversions, SSA used a Mi-Jack system that includes capability to operate in a zero-emissions (ZE) mode using their battery packs.[54]
- Total Terminals International (Port of Long Beach) is receiving six new-build hybrid RTG cranes from Kalmar (part of Cargotec); delivery are expected to begin by early-2022.[55] Kalmar will supply two additional hybrid RTG cranes at a later date. To support these deployments, the Port of Long Beach secured federal funds under the Diesel Emissions Reduction Act.[56]
- Fenix Marine at the Port of Los Angeles has purchased and received nine new-build hybrid RTG cranes from Mitsui E&S Holdings and its subsidiary, Paceco Corporation. Installation of the first units began in 2020;[57] all nine hybrid RTG cranes are operational as of late-2021. In addition to deploying new-build hybrid RTG cranes, Fenix Marine is upgrading four older conventional RTG cranes to a hybrid configuration. These converted hybrid RTG units are expected to be in operation by February 2022.[58]

For an MTO seeking to reduce diesel emissions from RTG cranes, the choice to select a ZE grid-electric versus NZE hybrid-electric architecture depends on numerous factors. Many of these are specific to the MTO (e.g., size and physical layout of the site, access to electricity / power, specific type of yard operation). The key advantage of grid-electric RTG cranes is that they deliver zero direct emissions by eliminating use of diesel engines (although, a diesel gen-set may be retained for infrequent use). The tradeoff is that MTOs installing grid-electric RTG cranes can face higher capital costs and significant challenges associated with site modifications needed to enable grid connections. For MTO's not well suited for deploying grid-electric RTG cranes, NZE hybrid architectures offer very low (but not zero) emissions relative to baseline RTG cranes (see Section 9.7), at lower total capital cost and reduced negative impacts on operational efficiency. These types of tradeoffs and related issues are further discussed in Section 0 titled "

[50] The Port of Long Beach, "Fact Sheet: Zero-Emissions Terminal Equipment Transition Project," https://polb.com/environment/our-zero-emissions-future/#program-details.
[51] Personal communication to GNA from the Port of Long Beach, December 2021.
[52] SSAMarine.com, "Carrix Sustainability Report" for fiscal year ending January 2021,
[53] Container Management, "SSA Mexico Becomes First Fully Electrified Container Terminal in the Americas," July 31, 2015, https://container-mag.com/2015/07/31/ssa-mexico-becomes-first-fully-electrified-container-terminal-americas/.
[54] Port of Oakland, comments on "Draft 2018 Feasibility Assessment for Cargo-Handling Equipment," May 2019.
[55] Cargotec Corporation, press release, January 7, 2021, Kalmar's hybrid RTGs to support sustainable growth for Total Terminals International at the Port of Long Beach, California | Kalmarglobal.
[56] U.S. Environmental Protection Agency, "Overview of DERA Grants Awarded for Port Projects: 2008 – 2020," accessed on December 7, 2021 at https://www.epa.gov/ports-initiative/overview-dera-grants-awarded-port-projects.
[57] PACECP Corporation, "Recent TRG Delivery in LA," September 15, 2020, https://pacecocorp.com/.
[58] Personal Communication to GNA from Scott Schoenfeld, Fenix Marine Corporation, January 2022.

Assessment of Operational Feasibility."

5.2.4. ZE and NZE Large-Capacity Forklifts

There are approximately 215 diesel-fueled forklifts operating at the two Ports; most of these can be categorized as large-capacity units (36,000 lbs and above). Because these CHE are similar to top handlers in size, structure and operational use, they present similar opportunities and challenges for building feasible ZE platforms. Not surprisingly, several CHE OEMs working on ZE top handlers are also engaged in similar efforts to develop, demonstrate and commercialize large-capacity forklifts with the same basic ZE architectures (battery-electric or fuel cell electric). In some cases, OEMs have joined with third-party technology providers, MTOs and the Ports to covert in-use diesel forklifts to ZE battery-electric configurations (for example, POLA's "Green Omni" program at Pasha Terminal[59]).

Multiple CHE OEMs have made signficant recent progress to develop and demonstrate ZE large-capacity forklifts as additions to their commercial product lineups. Kalmar's battery-electric model DCE160-12 (lift capacity of 36,000 pounds) has achieved sufficient technological maturity that CARB listed it as "eligible equipment" for CORE incentive funding; at least one Southern California dealer will quote a price and timeframe for purchasing them (see https://californiacore.org/equipment-category/forklifts/). Three ZE battery-electric Kalmar units – essentially pre-commercial prototypes – are listed in the most-current (2020) CHE inventory for the Port of Los Angeles. Based on the inventory, these units are just beginning to accrue significant operational hours.[60] California-based OEM Wiggins Lift Company is currently manufacturing and selling its 36,000-pound lift capacity "Yard eBull," which uses a battery-electric drivetrain designed and built by Thor Trucks.[61] MTOs can purchase the Wiggins eBull by special order today. Under a State of California grant, the Port of Stockton has teamed with SSA Terminal to order eighteen (18) ZE eBulls, and twelve have already been delivered. According to a Wiggins company representative, these units are able to "run a full shift on a single charge," although this has not necessarily been independently tested in service. SSA Marine's representative has noted that the Port of Stockton cargo throughput is lower than "larger container ports like Long Beach or Los Angeles," and Stockton handles non-containerized cargo. At the Port of Stockton, this provides "opportunities for mid-shift charging" for the SSA deployments. The SSA representative also notes that cargo moved at this site is "relatively light;" it is likely that typical container movements by a San Pedro Bay Ports MTO would "drain the battery quicker."[62]

As of late-2021, neither the Kalmar nor the Wiggins battery-electric forklift models have been fully proven in the duty cycles encounterd by MTOs at large container ports like the SPBP. Still, emergence of these products is very positive for the future of ZE large-capacity forklifts with a battery-electric architecture. These and other CHE OEMs continue to improve proof-of-concept large-capacity forklifts with ZE architectures, and work with the Ports and MTOs to demonstrate increasing numbers of units. At least 12 battery-electric large-capacity forklifts are being (or will soon be) demonstrated. Some will be deployed using CARB funding from California's Zero and Near Zero Emission Freight Facilities (ZANZEFF) program. (This is the same award that is funding SSA's deployment of ZE large-capacity forklifts at the Port of Stockton, and various ZE-related demonstrations at the Port of Hueneme.)[63] Results will be tabulated on behalf of MTOs and/or funding agencies over the next several years.

5.3. Proven Network and Capability for Sales, Service, Parts and Warranty

As with the 2018 Assessment, this report assumes that commercially available ZE and/or NZE CHE must be sold by OEMs that have the demonstrated capability to provide essential support (i.e., equivalent to baseline diesel CHE) for such emerging products. Specifically, the necessary pre- and post-sales support includes existence of a proven network for selling and servicing the CHE; providing replacement parts; training fleet personnel for new procedures and equipment (including safety related); and providing diesel-equivalent warranty coverage.

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[59] See https://www.portoflosangeles.org/business/terminals/breakbulk/pasha.

[60] Port of Los Angeles, 2020 Air Emissions Inventories prepared by Starcrest Consulting Group, provided to GNA in 2021.

[61] Wiggins Lift Co., https://wigginslift.com/products/ebull/).

[62] Association of Pacific Ports, "Port of Stockton Moves Toward Zero-Emissions Goals," May 20, 21, https://www.pacificports.org/port-of-stockton-moves-toward-zero-emissions-goal/.

[63] CARB, "CARB announces more than $200 million in new funding for clean freight transportation," September 26, 2018, https://ww2.arb.ca.gov/news/carb-announces-more-200-million-new-funding-clean-freight-transportation.

Major long-established OEMs that now commercially offer CHE types with ZE and/or NZE platforms have generally demonstrated capability to meet this basic requirement. They stress that new products of any kind will not be sold before establishment of full support, service, and warranty packages. As ZE and/or NZE platforms become fully developed and ready for wider sale, existing major CHE OEMs can provide these support systems by augmenting or replicating existing systems. Having provided similar support for diesel CHE over decades, this is likely to be relatively routine. [64]

Notably, even for existing major OEMs it can be a resource-intensive, costly endeavor to establish strong pre- and post-sale customer support for new-technology products that use alternative fuel/energy sources. Ability to meet this need must be continually proven. Thus, it still remains to be seen if this can be done on the scale that would be needed for wide deployment of ZE and/or NZE CHE at SPBP MTOs. Past performance indicates that the major OEMs should be able to meet the basic requirements outlined for this criterion. Larger-scale demonstrations that are now underway at both Ports (for multiple CHE types) will help OEMs and their MTO customers work together to improve all facets of pre- and post-sales support.

Notably, for start-up OEMs, it can be complex and costly to establish such support systems from scratch. It is possible that start-up OEMs will find it most cost-effective to use established third-party services to provide fleet customers with all service and support, including dealer and mechanic training. Sections 7 (Operational Feasibility), 8 (Infrastructure Availability) and 9 (Economic Workability) provide additional discussion about these important peripheral systems (e.g., workforce training), particularly from MTOs' perspectives.

5.4. Sufficient Means and Timeline for Production

This parameter refers to the ability of CHE OEMs to collectively produce sufficient numbers of ZE and/or NZE CHE to enable systematic replacement of the entire SPBP fleet, for a given CHE category. This does not mean all units would need to be replaced in a single year; in fact, such a process would likely occur over many years while considering normal replacement cycles for the particular CHE type.

As described above, OEMs are selling <u>two types of CHE (yard tractors and RTG cranes) with ZE and/or NZE platforms</u> for use by San Pedro Bay Port MTOs. (ZE large-capacity forklifts are nearing the threshold of becoming commercial products, but this is not yet the case for use by MTOs under rigorous duty cycles required of CHE by MTOs at the SPBP.) These two specific cases are further discussed below:

- <u>Yard tractors</u>: To fully replace the existing SPBP fleet, approximately 1,600 in-use yard tractors would need to be systematically replaced with (or converted to) a ZE or NZE architecture. (This would likely occur gradually over many years, based on the useful lives and normal MTO replacement schedules for yard tractors.) None of the yard tractor OEMs have yet mass-manufactured hundreds (or thousands) of units with either of the two commercially offered options, battery-electric (ZE) or natural gas ICE (NZE). However, existing major OEMs such as Kalmar and Capacity have been selling and supporting yard tractors at the two Ports for decades. Notably – especially in the case of ZE battery-electric yard tractors – it will be important for the OEMs and their customers (the MTOs) to complete ongoing or emerging demonstration programs (see Section 5.6) prior to full-scale manufacturing.
- <u>RTG Cranes</u>: To fully replace the existing SPBP fleet, nearly 130 in-use conventional diesel RTG cranes would need to be replaced with (or converted to) a ZE or NZE architecture. In the case of NZE hybrid-electric RTG cranes, the current CHE inventory for both Ports indicates that 36 units are now in service, and many more are in commercial service today across the world. In general, the OEMs (and conversion companies) engaged in this market appear capable of providing sufficient quantities to gradually convert the SPBP total fleet. This does not discount the importance for RTG crane OEMs and their customers to gain additional revenue-service experience with both hybrid-electric and grid-electric architectures. This is especially the case for the latest ZE grid-electric architectures and products, which have not yet received significant operational time at the two Ports. In addition – depending on specifics at a given marine terminal – switching from a conventional RTG crane to a grid-connected E-RTG crane can significantly reduce the terminal's operational flexibility (see Section 5.6 and Section 6).

In sum, for both yard tractors and RTG cranes, it is likely that additional numbers of ZE and/or NZE units could be manufactured and available for deployment by 2024, assuming orders are placed. With the possible exception of NZE hybrid

[64]These conclusions are based on GNA's telephone interviews with CHE OEMs, combined with OEM public literature (websites, press releases, etc.).

RTG cranes, future availability for large orders of commercial products remains unknown at this time. Moreover, additional time is needed for MTOs to gain operational experience on pre-commercial or early commercial deployments, to help OEMs make improvements for production-intent versions. A key intent of already-underway demonstration is to help this process and further define if and how these technologies can be manufactured and deployed at larger scale.

5.5. Existence of Current and/or Near-Term Equipment Orders

The SPBP and various MTOs continue to work with key government agencies (CARB, CEC and SCAQMD) to purchase and demonstrate approximately 160 individual CHE of various types that utilize ZE or NZE architectures (see the next section). These current and near-term CHE orders involve fully commercial products in some cases (RTG cranes), while in others they involve early commercial or pre-commercial products (yard tractors). In the specific context of the SPBP (or equivalent large port operations), this parameter for commercial availability is essentially met for yard tractors and RTG cranes, but not for top handlers and large-capacity forklifts.

CHE Demonstrations: Role of the Ports' Joint Technology Advancement Program

The Ports' joint Technology Advancement Program (TAP) facilitates development and demonstration of clean goods movement technologies needed to meet CAAP goals. Since 2007, the TAP has undertaken numerous projects to help develop, test and/or commercialize CHE that incorporate ZE or NZE architectures. TAP projects have resulted in successful deployments for many pre-commercial or early commercial CHE platforms discussed in this 2021 Assessment (of all four CHE types). Please see the 2020 TAP Annual Report,* which is currently available online.

***Source:** San Pedro Bay Ports, "2020 Annual Report and 2021 Priorities: Technology Advancement Program," April 2021, https://cleanairactionplan.org/2021/04/14/2018-tap-annual-report-now-availalble-2/.

5.6. Essential Role of Demonstrations in Revenue Service to Advance Commercialization

As first described in the 2018 Feasibility Assessment – and stressed again in this 2021 update – it is critically important for all San Pedro Bay stakeholders (OEMs, MTOs and the Ports) to gain hands-on experience with emerging ZE and NZE CHE platforms. This needs to occur well before wide-scale deployments are initiated. Demonstrations are the key to enable OEMs and their MTO customers to gain site-specific revenue-service experience in rigorous duty cycles that typify San Pedro Bay CHE applications. For example, before a CHE (or on-road truck) OEM commercializes a battery-electric product, it needs to work closely with its customers for both parties to gain detailed understanding about operating time between charging events, battery life, vehicle or equipment residual value, infrastructure requirements and station footprint, and total cost of ownership.[65] Gathering this information requires sufficient demonstration and testing time – in a site-specific context – for multiple pre-commercial units during typical daily CHE operation.

Towards these ends, OEMs have joined with MTOs at both Ports to complete multiple demonstrations involving pre-commercial and early commercial CHE. Most of these were completed over the last three years (i.e., since the 2018 Assessment was prepared). As summarized in Table 5, these completed demonstrations have involved 25 yard tractors and five top handlers, using a ZE battery-electric or NZE natural gas ICE architecture. Notably, in some cases MTOs continue to operate these CHE in revenue service operation.

[65] Trucking Info.com, "Daimler Deals with Booming Market, Preps Electric Trucks," October 29, 2018, https://www.truckinginfo.com.

As Table 5 indicates, no demonstrations of RTG cranes or large-capacity forklifts have been completed, although some are now underway (further described).

Table 5. Completed ZE and NZE CHE demonstrations by CHE type, Port, # of units, MTO host site and architecture

CHE Type	Completed CHE Demonstrations: # of Units by OEM and Architecture *(with Host Site Marine Terminal)*		Total Number of Units Completing Demonstration
	Port of Los Angeles	**Port of Long Beach**	
Yard Tractors	• 5 ZE BYD Battery-Electric *(Everport)* • 22* NZE Capacity Natural Gas *(Everport)*	• 1 ZE Kalmar Battery-Electric *(LBCT)* • 6 ZE BYD Battery-Electric *(ITS)* • 1 ZE BYD Battery-Electric w/ Cavotec Smart Charge *(ITS)*	25
RTG cranes	(None to date)	(None to date)	(None to date)
Top Handlers	• 2 Battery-Electric *(Everport)*	• 3 Battery-Electric *(SSA Pier J, LBCT)*	5
Large-Capacity Forklifts	(None to date)	(None to date)	(None to date)
		Total Number of CHE Units Completing Demonstrations (September 2021)	**30**

Sources: Rose Szoke (POLB) and Teresa Pisano (POLA), "Overview of CHE Demonstrations at the Ports," presentation to the Sustainable Supply Chain Action Committee, September 15, 2021. *This includes 20 NZE natural gas yard tractors with 9-liter Cummins Westport (CWI) engines in a CEC-funded demonstration led by the Port of Los Angeles, and two additional units with 7-liter CWI engines in a separate CEC-funded demonstration at the same host site.

However, many more CHE demonstrations – involving all four CHE types and various ZE or NZE architectures – are currently underway (or near start-up) at both Ports. Joining with government agencies like CARB, CEC and SCAQMD, the Ports have collaborated with various MTOs to initiate new, larger-scale demonstrations intended to gain much-needed revenue-service operational data on CHE with ZE and NZE architectures. These demonstration projects involve major existing and startup CHE OEMs, partnered in some cases with CHE technology providers. Additionally, similar demonstrations are underway at the Port of Oakland and the Port of Stockton. Over the next two to three years, more than 150 individual CHE (mostly early commercial or pre-commercial units) are expected to under demonstration at California seaports. Table 6 provides a breakout of these CHE by type and ZE or NZE architecture (the information continues to evolve, and is not meant to be definitive).

Table 6. Break out of demonstrations at California seaport marine terminals, by CHE type

Yard Tractors	Top Handlers*	RTG Cranes	Large-Capacity Forklifts
• **111 ZE battery-electric**	• 10 **ZE** battery electric	• 9 **ZE** grid electric	• 12 **ZE** battery electric
• **2 ZE fuel cell**	• 1 **ZE** fuel cell	•	•
• **22 NZE natural gas ICE****	•	•	•

*The top handler category includes one battery-electric reach stacker.
**These 22 NZE natural gas ICE yard tractors are also shown in the table above; they have formally completed their government-funded demonstration requirements. However, the MTO continues to operate them – in essentially a pre-commercial demonstration mode.
Sources: Grant announcements from the San Pedro Bay Ports, the Port of Oakland, the Port of Stockton and various government agencies
Note: this information continues to evolve, and is not meant to be definitive.

Figure 9 summarizes key SPBP demonstrations; these are being conducted at eleven different MTO host sites located across the twin Ports complex. The map refers to host site locations, specific CHE types, fuel-technology architectures, and charging infrastructure build-outs (if applicable). **Note:** the actual number of demonstrated CHE fluctuates; the numbers shown are estimated and not meant to be definitive. The photographs that follow Figure 9 (Figures 10-14) show ZE and NZE CHE units in actual revenue demonstration, at some of these various SPBP MTO sites.

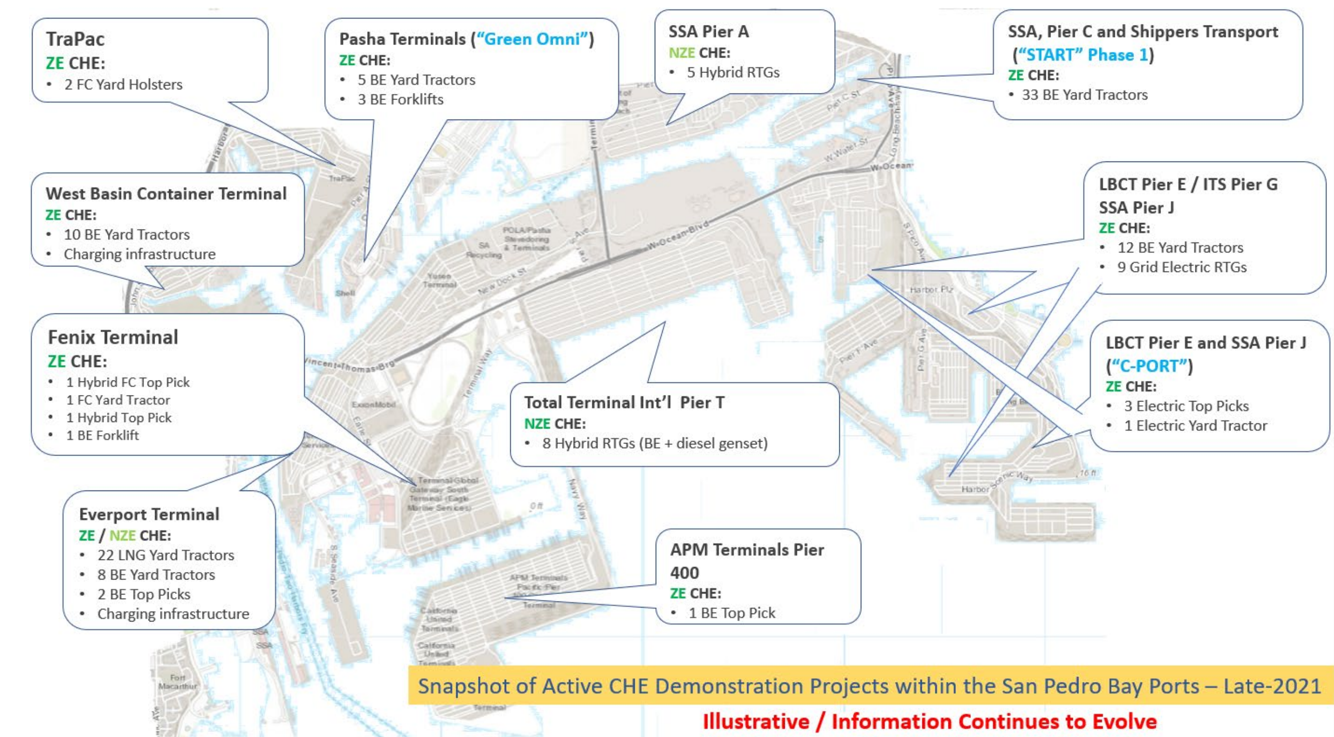


Figure 9. Snapshot of key ZE and NZE CHE demonstrations at the San Pedro Bay Ports, by Location and MTO

Kalmar **Battery-Electric** Yard Tractor with Cavotec Charger System at ITS **(POLB photo)**

BYD **Battery-Electric** Yard Tractor at Everport Terminal **(POLA photo)**

Hydrogen Fuel Cell Yard Tractor (Toyota System) at Fenix Marine Services **(POLA photo)**

Figure 10. Three different ZE yard tractor demonstrations underway at multiple San Pedro Bay marine terminals

Left: **NZE LNG-ICE** yard tractor moving cargo at Everport (POLA); **Center:** Onsite LNG fueling station; **Right:** Emissions testing at UCR **(photos by GNA)**

Figure 11. NZE LNG-ICE yard tractor at Everport (POLA); LNG fueling station; emissions testing at UC-Riverside

Figure 12. Two NZE LNG (left) and five ZE BE yard tractors undergoing prep for testing at Everport POLA (photo: GNA)

Taylor **Baseline Diesel** Top Handler (POLA) | Taylor ZLC976 **Battery-Electric** Top Handler (POLA) | Taylor ZLC906 **Battery-Electric** Top Handlers (POLB)

Photos: (Left) Jon Leonard, GNA, **(Middle)** Port of Los Angeles **(Right)** and Port of Long Beach (R)

Figure 13. Taylor's baseline diesel (left) and two ZE battery-electric top handlers under demonstration by SPBP MTOs

Kalmar **ZE Battery-Electric** Large Capacity Forklift **(photo: CORE website)**

Figure 14. Kalmar ZE battery-electric large capacity forklift similar to those at POLA (photo from CORE website)

In summary, some key CHE demonstrations have been completed, but many are still underway. Most have been delayed in getting started and/or reaching completion. In addition to COVID-19 shutdowns, reasons have included longer-than-expected lead times for CHE manufacture and delivery, and unanticipated permitting requirements for fueling or charging infrastructure. For example, all equipment operating in the County or City of Los Angeles requires certification to standards promulgated by Underwriter Laboratories (UL). This requirement has resulted in significant project delays to get new charging infrastructure and fueling stations into revenue service operation.[66] The adverse impact on the project schedule of agency permitting requirements for these demonstration projects should not be underestimated.

Nearly all demonstrations that are currently underway are expected to be completed by late 2023. That appears to be the time frame for when the Ports, MTOs and all stakeholders will have an improved body of operational data and information. Collectively, this can be used to help further assess overall feasibility of the various emerging ZE and NZE architectures, for all four types of CHE addressed in the study. Until multiple units have been successfully demonstrated for a given fuel-technology platform – and yielded sufficient data and "lessons learned" – it will be premature to conclude that the five key parameters for determining overall feasibility have been fully achieved. This important issue is further discussed in the section on Operational Feasibility.

[66] California Air Resources Board, "Appendix A: Clean Transportation Investment Project Summaries," Proposed Fiscal Year 2020-21 Funding Plan for Clean Transportation Incentives, November 2020, https://ww2.arb.ca.gov/our-work/programs/low-carbon-transportation-investments-and-air-quality-improvement-program/low-1.

5.7. Overarching MTO Comments on Pre- and Early Commercial ZE/NZE CHE

To accurately characterize all five feasibility parameters discussed in this 2021 Assessment, it is essential to incorporate inputs from MTOs about the various ZE and NZE CHE platforms they have deployed and tested. To gather these inputs, the authors conducted telephone interviews in mid-2021 with representatives from seven different MTOs (three at POLA and four at POLB). Table 7 summarizes MTO comments that broadly address overall commercial maturity, while also touching upon the inter-related parameters of technical reliability, operational feasibility, infrastructure availability, and economic workability. Subsequent sections further evaluate MTO inputs within the specific context of each feasibility parameter.

Table 7. Summary of Comments from SPBP MTOs about NZE and ZE Commercial Availability and Technical Viability

Type of ZE or NZE CHE	Sample of MTO Inputs: Commercial Availability, Technical Viability, and Other Feasibility Parameters
Yard Tractors	**Early Commercial ZE Battery-Electric** • When working, units perform well (power, speed, towing power) • Some problems noted with design or operation of subsystems • Drivers/workers like performance, most ergonomics (some problems noted), and lack of noise/exhaust smell • Capital cost: 2 to 3 times more than baseline diesel • Operational time limited, due to technical issues and repairs (tractors and chargers) • Onsite service to get yard tractors and/or chargers repaired was initially unacceptable, but service did improve • Compliance with some types of government oversight (e.g., OSHA) created challenges • Charger permitting requirements delayed implementation significantly • Charging infrastructure deployment requires creative solutions • Must plan for long lead times to secure permits/certification and sign-off by authority having jurisdiction • Charging standardization is lacking and needed; MTOs prefer better fit with how they "wet fuel" diesel yard tractors **Early Commercial NZE Natural Gas ICE** • Units perform well (power, speed, towing power) • Drivers / workers like performance and ergonomics, lack of noise and diesel exhaust smell • Units capable of two-shift endurance; however, centralized LNG fueling hinder this (need similar fueling process to diesel) • Initial technical and reliability issues were resolved through engine and tractor OEM collaborations • MTO had to design, fabricate and install LNG tank guards (not standard part of LNG fuel system / package) • LNG fueling station permitting requirements delayed implementation significantly **Proof-of-Concept ZE Fuel Cell Electric** • Insufficient demonstration experience, to date • Permitting process for hydrogen station was accomplished without major problems, although each project differs • Early design of fuel cell tractors resulted in failures that required excessive onsite troubleshooting
RTG Cranes	**Commercial ZE Grid-Electric** • Initial deployments (four of nine converted diesel units) work satisfactorily • Infrastructure capital costs (to enable grid-connection / sufficient power at site) can be largest part of investment • Must plan for long lead times to secure permits / certification and sign-off by authority having jurisdiction
Top Handlers and/or Large-Capacity Forklifts	**Proof-of-Concept ZE Battery-Electric** • Units perform well (power, speed, lifting power), after initial problems were addressed • Drivers/workers like performance and ergonomics, lack of noise and diesel exhaust smell • Good shift endurance (up to 13 hours), although MTOs need up to 18 hours (to be 1-to-1 replacement for diesel) • Charger permitting requirements delayed implementation significantly • Charging infrastructure deployment requires creative solutions • Must plan for long lead times to secure permits / certification and sign-off by authority having jurisdiction

Source: Telephone interviews of seven San Pedro Bay Port MTOs, July and August 2021.

5.8. Larger-Scale, Integrated CHE Demonstrations

The number and scope of these various CHE demonstrations – and the strong involvement of major CHE OEMs – are testaments to the important near-term progress made to commercialize ZE and NZE CHE with potential for wide-scale use at the SPBP. However, it is important to stress that in most cases, MTOs are just beginning to gain significant operational experience with early commercial and pre-commercial CHE. As the various MTOs continue to receive and deploy their demonstrations of ZE and NZE CHE units over the next two-to-three years, they will obtain additional operational experience and data in revenue experience; this will be instrumental in more fully assessing overall feasibility.

As reported in the 2018 Assessment, the San Pedro Bay Port CHE demonstrations seek to emphasize and advance *integrated* operation of various CHE types using ZE and/or NZE platforms. Both Ports are doing this by co-sponsoring projects to simultaneously deploy ZE and/or NZE yard tractors, RTG crane, top handlers, and large-capacity forklifts. In fact, these various types of ZE and NZE CHE are being used to load and unload on-road ZE drayage trucks,[67] analagous to how baseline diesel CHE and drayage trucks work in unison within a typical MTO "ecosystem."

Additionally, the Ports have recognized the need to rapidly move into larger-scale pre-commercial and early commercial deployments involving ZE and NZE CHE platforms. This includes the need to continue working with MTOs, and utilities / fuel providers to build-out corresponding types of fueling infrastructure. Thus, the Ports continue to initiate new, larger-scale demonstration programs that are specifically focused on ZE fuel-technology platforms for all four CHE types. Such new efforts are building upon the numerous smaller-scale demonstrations that are now underway or will soon be initiated.

5.9. Summary of Ratings on Commercial Availability

Important Note: The commercialization landscape for these products is dynamic, and subject to unforeseen rapid change. This is one key reason that the Ports plan to prepare updates to these feasibility assessments every three years, or sooner if warranted by major new developments regarding technological maturity and/or expanded commercial offerings. Additionally, if agencies (e.g., CARB and/or EPA) adopt new regulations with potential to expedite ZE CHE deployments at the Ports, this could necessitate re-evaluating the commercial availability and/or potential CAAP role of NZEV CHE. In particular, by 2024 CARB is expected to modify its Cargo Handling Equipment regulation to require that all CHE "transition to zero emissions," beginning with the 2026 model year. Details are available at https://ww2.arb.ca.gov/resources/documents/cargo-handling-equipment-regulation-transition-zero-emissions.

For each of the four major CHE types, Table 8 through Table 11 below summarizes the basic findings and conclusions regarding Commercial Availability, as discussed in this section. The first two columns repeat specific criteria and base considerations that collectively define commercial availability. The final five columns provide ratings about the relative degree to which five core ZE and NZE fuel-technology platforms (specific to each type of CHE) appear to meet these basic considerations as of late-2021, or at least show measurable progress towards meeting them by approximately 2024. Note that a **blue** "wedge" within any pie rating highlights progress that has been made since the 2018 Feasibility Assessment (if applicable).

[67] CARB, "CARB announces more than $200 million in new funding for clean freight transportation," September 26, 2018, https://ww2.arb.ca.gov/news/carb-announces-more-200-million-new-funding-clean-freight-transportation.

5.9.1. Yard Tractors

Table 8. Summary of findings: 2021 Commercial Availability of key ZE / NZE Yard Tractor platforms

"Commercial Availability" Criteria	Base Considerations for Assessing "Commercial Availability"	Yard Tractors: Achievement of Criteria in 2021 by Type of ZE or NZE Fuel-Technology Platform				
		ZE Battery-Electric	ZE Fuel Cell	NZE Hybrid-Electric	NZE NG ICE	NZE Diesel ICE
Production and Sales with Major OEM Involvement	Production and full certification by either a major CHE OEM, or by a proven technology provider that has partnered with the major OEM.	◕	◔	○	◕	○
Proven Network / Capabilities for Sales, Service, Parts and Warranty	Demonstrated existing (or near-term planned) network of sufficient dealerships to sell, service, warranty, and provide parts for all commercially deployed CHE of this type	●	◑	◑	●	●
Sufficient Means and Timeline for Production	Demonstrated capability to manufacture sufficient numbers of CHE (suitable for SPBP MTOs) within timeline to meet existing or expected demand.	◕	◔	◑	◕	◑
Existence of Current and/or Near-Term Equipment Orders	Demonstrated backlog of orders, or credible expression of interest from prospective customers to submit near-term orders.	◕	○	○	◑	○

Legend: Commercial Availability (2021)

○ ◔ ◑ ◕ ●

Little/No Achievement — = Progress since 2018 Assessment — Fully Achieved

Source of Ratings: based on OEM survey responses, OEM product information, various government sources, and consultant's site visits to San Pedro Bay Ports Marine Terminal Operators.

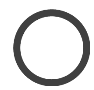
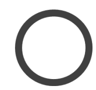
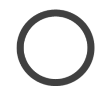
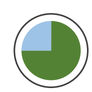
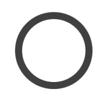
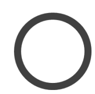
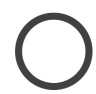
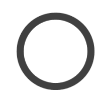
To summarize for yard tractors:

- **ZE** battery-electric technology is commercially offered for yard tractors by multiple OEMs. These are effectively "early commercial" product launches. While these OEM-offered products have not necessarily reached full commercial maturity (especially for SPBP marine terminal operation), two of four parameters that collectively define commercial feasibility are at (or nearing) full achievement. OEM involvement in producing and selling these products reflects some improvement from 2018, as indicated by the ¼ blue pie wedge ("Production and Sales with Major OEM Involvement"). For example, Kalmar has subsequently entered into the market with two different battery-electric yard tractor models (T2e and T2e+), and BYD is working on its third-generation 8Y model. However, two parameters remain at "partial achievement" and show no significant change from 2018, as indicated by the lack of blue pie wedges. **Overall**, ZE battery-electric yard tractors marginally meet the basic criteria and considerations to be deemed commercially available in late-2021.

- **NZE** natural gas ICE technology is commercially offered for yard tractors by multiple OEMs, although only one make/model has been demonstrated in container port operations. These are effectively "early commercial" product launches. While these OEM-offered products have not necessarily reached full commercial maturity (especially for SPBP marine terminal operation), two of four parameters that collectively define commercial feasibility are at (or nearing) full achievement. OEM involvement in producing and selling these products reflects some improvement from 2018, as indicated by the blue pie wedge. However, two parameters remain at "partial achievement" and show no significant change from 2018, as indicated by the lack of blue pie wedges. **Overall**, NZE natural gas ICE yard tractors marginally meet the basic criteria and considerations to be deemed commercially available in late-2021.

- The other three core fuel-technology platforms that were evaluated for yard tractors – **ZE** fuel cell, **NZE** hybrid electric, and **NZE** diesel ICE – do not meet the basic criteria and considerations to be deemed commercially available in late-2021. However, it is noteworthy that ZE hydrogen fuel cell yard tractors have made promising advancements towards commercial availability (reflected in new blue pie wedges). This is evidenced by 1) OEM Capacity Trucks (working with Hyster/Nuvera) demonstrating two fuel cell yard tractors, and 2) OEM Toyota demonstrating fuel cell engines in yard tractors, with intent to commercialize starting in 2022. (See the next section about "Technology Readiness Levels" for additional discussion about the potential for NZE diesel ICE technology to rapidly advance towards full commercial feasibility.)

Table 9. Summary of findings: 2021 Commercial Availability of key ZE / NZE Top Handler platforms

"Commercial Availability" Criteria	Base Considerations for Assessing "Commercial Availability"	Top Handlers: Achievement of Criteria in 2021 by Type of ZE or NZE Fuel-Technology Platform				
		ZE Battery-Electric	ZE Fuel Cell	NZE Hybrid-Electric	NZE NG ICE	NZE Diesel ICE
Production and Sales with Major OEM Involvement	Production and full certification by either a major CHE OEM, or by a proven technology provider that has partnered with the major OEM.					
Proven Network / Capabilities for Sales, Service, Parts and Warranty	Demonstrated existing (or near-term planned) network of sufficient dealerships to sell, service, warranty, and provide parts for all commercially deployed CHE of this type					
Sufficient Means and Timeline for Production	Demonstrated capability to manufacture sufficient numbers of CHE (suitable for SPBP MTOs) within timeline to meet existing or expected demand.					
Existence of Current and/or Near-Term Equipment Orders	Demonstrated backlog of orders, or credible expression of interest from prospective customers to submit near-term orders.					

Legend: Commercial Availability **(2021)**

Little/No Achievement = Progress since 2018 Assessment Fully Achieved

Source of Ratings: based on OEM survey responses, OEM product information, various government sources, and consultant's site visits to San Pedro Bay Ports Marine Terminal Operators.

5.9.2. Top Handlers

To summarize for <u>top handlers</u>:

- None of the five core fuel-technology platforms that were evaluated for top handlers – **ZE** battery-electric, **ZE** fuel cell, **NZE** hybrid electric, **NZE** natural gas ICE, and **NZE** diesel ICE – are currently built and sold by CHE OEMs, although several OEMs are building and demonstrating proof-of-concept ZE vehicles. None meet the basic criteria and considerations to be deemed commercially available in late-2021.

- However, as reflected by the blue wedges in the pie ratings, OEMs have made significant progress to advance the commercial (and technical) viability of battery-electric top handlers. One major OEM, Taylor Machine Works, has worked with MTOs to demonstrate basic capabilities of the ZLC series battery-electric top handler at both Ports, and appears likely to sell an early commercial model by (or before) 2024. Other major CHE OEMs (e.g., Hyster-Yale) are working on their own battery-electric top handler models. Collectively, these established OEMs demonstrate that "sufficient means and timeline" exists to produce battery-electric top handlers by or before 2024; this is the rationale for awarding a full pie rating specific to this capability. The "existence of near-term orders" criterion has been advanced by ¼ pie progress because Taylor has initiated efforts to obtain eligibility for grant funding of one (or more) battery-electric top handler model(s) under California's CORE program. Thus, there is now a ½ pie rating for this commercial availability criterion.

- OEMs are also advancing ZE fuel cell top handlers, although this fuel-technology type lags behind battery-electric for the likely timing of any commercial launches (similar to the case with yard tractors).

5.9.3. RTG Cranes

Table 10. Summary of findings: 2021 Commercial Availability of key ZE / NZE RTG Crane platforms

"Commercial Availability" Criteria	Base Considerations for Assessing "Commercial Availability"	RTG Cranes: Achievement of Criteria in 2021 by Type of ZE or NZE Fuel-Technology Platform				
		ZE Grid-Electric	ZE Fuel Cell	NZE Hybrid-Electric	NZE NG ICE	NZE Diesel ICE
Production and Sales with Major OEM Involvement	Production and full certification by either a major CHE OEM, or by a proven technology provider that has partnered with the major OEM.	●	◑	●	N/A*	N/A*
Proven Network / Capabilities for Sales, Service, Parts and Warranty	Demonstrated existing (or near-term planned) network of sufficient dealerships to sell, service, warranty and provide parts for all commercially deployed CHE of this type	●	◑	●		
Sufficient Means and Timeline for Production	Demonstrated capability to manufacture sufficient numbers of CHE (suitable for SPBP MTOs) within timeline to meet existing or expected demand.	●	◔	●		
Existence of Current and/or Near-Term Equipment Orders	Demonstrated backlog of orders, or credible expression of interest from prospective customers to submit near-term orders.	●	○	●		

Legend: Commercial Availability (2021)

○ ◔ ◑ ◕ ●

Little/No Achievement = Progress since 2018 Assessment Fully Achieved

Source of Ratings: based on OEM survey responses, OEM product information, various government sources, and consultant's site visits to San Pedro Bay Ports Marine Terminal Operators.

*Conventional RTG cranes have diesel-electric hybrid architectures; ICE engines alone are not applicable architectures. Reducing the emissions profiles of an RTG crane's ICE engine can further reduce emissions from either baseline or NZE hybrid-electric RTG cranes.

To summarize for RTG cranes:

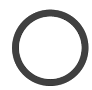
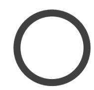
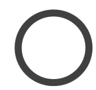
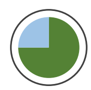
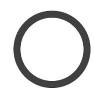
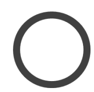
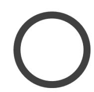
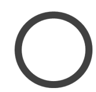
- **ZE** grid-electric RTG cranes (new built and conversion packages) have been sold by multiple OEMs for many years. These are fully commercial products; all four parameters that collectively define commercial availability are fully achieved *(no changes since 2018*). However, San Pedro Bay Port MTO deployments of current-technology ZE grid-electric *RTG crane*s are in their infancy. Successful installation and operation of grid-electric RTG cranes depends in part on region- and site-specific factors (e.g., the utility providing the grid connection and supplying electricity). Demonstrations that are now underway (e.g., SSA at Pier J at POLB) will continue to provide important information and lessons learned, specifically in the context of a San Pedro Bay marine terminal and the utility that serves it. **Note:** battery-electric technology for RTG cranes (not included in the above table) – which can have commonality with grid-electric architectures – appears to be under development by at least one OEM. However, as of late-2021 no evidence or information exists that ZE battery-electric RTG cranes warrant further assessment for commercial availability.

- **NZE** hybrid-electric RTG cranes (new built and conversion packages) have been sold by multiple OEMs for many years. These are fully commercial products; all four parameters that collectively define commercial availability appear to be fully achieved. At least 26 NZE hybrid-electric RTG cranes are now listed in the joint Ports CHE inventory. This fuel-technology platform does not appear to need further demonstration to advance commercial or technological maturity. A potential near-term future improvement for advancement of low-emission hybrid-electric RTG cranes would be substitution of the down-sized diesel ICE with a zero-emission fuel cell, or an ICE certified to CARB's lowest-tier Optional Low-NOx Standard (OLNS) of 0.02 g/bhp-hr (e.g., engines fueled by natural gas or propane).

- **ZE** fuel cell RTG cranes are not currently being manufactured or sold by any CHE OEM. This platform does not meet the basic criteria and considerations to be deemed commercially available in late-2021, nor does they appear (at this time) to be on that path by 2024.

5.9.4. Large-Capacity Forklifts

Table 11. Summary of findings: 2021 Commercial Availability of key ZE / NZE Large-Capacity Forklift platforms

"Commercial Availability" Criteria	Base Considerations for Assessing "Commercial Availability"	Large-Capacity Forklifts: Achievement of Criteria in 2021 by Type of ZE or NZE Fuel-Technology Platform				
		ZE Battery-Electric	ZE Fuel Cell	NZE Hybrid-Electric	NZE NG ICE	NZE Diesel ICE
Production and Sales with Major OEM Involvement	Production and full certification by either a major CHE OEM, or by a proven technology provider that has partnered with the major OEM.					
Proven Network / Capabilities for Sales, Service, Parts and Warranty	Demonstrated existing (or near-term planned) network of sufficient dealerships to sell, service, warranty and provide parts for all commercially deployed CHE of this type					
Sufficient Means and Timeline for Production	Demonstrated capability to manufacture sufficient numbers of CHE (suitable for SPBP MTOs) within timeline to meet existing or expected demand.					
Existence of Current and/or Near-Term Equipment Orders	Demonstrated backlog of orders, or credible expression of interest from prospective customers to submit near-term orders.					

Legend: Commercial Availability **(2021)**

Little/No Achievement = Progress since 2018 Assessment Fully Achieved

Source of Ratings: based on OEM survey responses, OEM product information, various government sources, and consultant's site visits to San Pedro Bay Ports Marine Terminal Operators.

To summarize for large-capacity forklifts:

- Of the five core fuel-technology platforms that were evaluated for large-capacity forklifts – **ZE** battery-electric, **ZE** fuel cell, **NZE** hybrid electric, **NZE** natural gas ICE, and **NZE** diesel ICE – are currently built and sold by CHE OEMs, although several OEMs are building and demonstrating proof-of-concept ZE vehicles. None meet the basic criteria and considerations to be deemed commercially available in late-2021 (for use at the SPBP). However, as reflected by the blue wedges in the pie ratings, OEMs have made significant advancements for battery-electric large-capacity forklifts, and they may be sold as early commercial products by (or before) 2024. The rationale for the ¼ pie increases for each of the four criterion are based on the following factors: 1) major OEM Taylor Machine Works, which is moving to commercialize battery-electric top handlers, is also working to advance battery-electric large capacity forklifts; 2) major OEM Kalmar is also working on commercializing one or more battery-electric models; 3) the Wiggins Yard eBull can be purchased today, and is being demonstrated by SSA at the Port of Stockton (albeit as noted in a less-stringent duty cycle than experienced by CHE at the San Pedro Bay Ports). Collectively, these established OEMs demonstrate the rationale for ¼ pie increases for the first three criterion in the above table. The "existence of near-term orders" criterion has been advanced by ¼ pie because all three OEMs have initiated efforts to obtain eligibility for grant funding of one (or more) battery-electric large-capacity forklift model(s) under California's CORE program. Thus, there is now a ½ pie rating for this commercial availability criterion.

- OEMs are also advancing ZE fuel cell large-capacity forklifts, although any commercial launchings are likely to come after those for behind battery-electric versions. The blue pie rating changes from 2018 are based on the fact that some of the same major OEMs moving to commercialize battery-electric large-capacity forklifts (and/or top handlers) bring the same types of resources and capabilities in their efforts to advance commercialization for fuel cell versions. (See the next section about the potential for NZE diesel ICE technology to rapidly advance and achieve immediate commercial feasibility.)

6. Assessment of Technical Viability

6.1. Background: Criteria and Methodology

The federal government, manufacturers and researchers often assign Technology Readiness Level (TRL) ratings to help track, assess and describe the technological maturity of emerging products, as they progress towards commercialization. Typically, these scales range from TRL 1 (just emerging as a basic principle) to TRL 9 (fully proven for technological maturity in (or near) its final commercial-ready form). TRL ratings can be very useful for tracking progress with new types of heavy-duty transportation technologies. For this 2021 Cargo-Handling Equipment Feasibility Assessment, snapshot TRL ratings have been assigned to emerging ZE and NZE platforms. This provides an objective, standardized means to gauge and compare technical readiness for broad commercial deployment at the SPBP over the next several years.

The U.S. Department of Energy (DOE) published a guidebook[68] designed to help government researchers conduct technology readiness assessments. DOE's guide includes a standardized TRL scale that is useful for tracking and assessing progress for HDV prototypes that are being developed, demonstrated and/or commercialized under government funding. DOE has established definitions for each of nine TRLs, as summarized in Table 12 below. This offers a condensed version of DOE's TRLs in the referenced guidebook.

Technologies achieve a TRL level when they meet defining characteristics of that level. Because some of the technologies discussed in this Assessment are currently at TRL 7 or lower, it is worth emphasizing the difference between a TRL 7 versus a TRL 8 technology. A technology achieves TRL 7 when a full-scale prototype is demonstrated in the relevant environment. This TRL focuses on a prototype being evaluated in a real-world environment, with a key objective to feed that data back into further design revisions. Note that TRL 7 does not require *successful* demonstration of the prototype. By contrast, achieving TRL 8 does require a successful demonstration of a product in its final or near-final form. In many cases, a manufacturer may demonstrate multiple generations of a design in an effort to move from TRL 7 to TRL 8. Therefore, a technology may be considered TRL 7 if it has been demonstrated in a prototype form, even if the demonstration has not yet proven the product to be successful in achieving OEM and/or end user targets, needs and objectives.

What Constitutes a **Successful** Demonstration for ZE/NZE CHE?

The Ports are engaged in demonstrations of multiple technologies because they are essential to advancing "feasibility" across all parameters discussed in this Assessment. In this overarching context, various levels of criteria are used to determine if a "successful" demonstration of ZE/NZE CHE has been achieved:

1) One level of success is defined by whether or not the demonstration resulted in valuable lessons learned that can assist CHE OEMs in development of future generations. At this level of success, the CHE units should be viewed as experimental prototypes, rather than CHE ready for prime-time.
2) Another level of success relates to proving that the demonstrated CHE can routinely complete at least one full shift performing normal UTR duties, in between fueling or charging events.
3) An additional success metric is whether or not the host MTO decides to continue utilizing the CHE type *beyond the demonstration period*.
4) The ultimate level of success is achieved if the ZE or NZE CHE is able to provide an affordable, one-to-one replacement (including two shifts per day) for the comparable (baseline) diesel CHE, while being operated over the same duty cycle; this includes infrastructure requirements for fueling/recharging and performing maintenance.

For purposes of assessing whether or not a given CHE platform warrants (or is approaching) a TRL 8 rating, "successful demonstration" (i.e., "qualified through test and demonstration" in Table 12 below) is defined to be *proven ability of the CHE type to perform diesel-equivalent work moving containers for at least one full shift with sufficient remaining energy and charging/fueling speeds to complete a second shift after refueling or recharging between shifts*. This distinction is further discussed below.

[68] U.S. Department of Energy, "Technology Readiness Assessment Guide", September 15, 2011, https://www.directives.doe.gov/directives-documents/400-series/0413.3-EGuide-04a/@@images/file.

Table 12. Definitions for Technology Readiness Levels (TRLs) adapted from U.S. DOE

Relative Stage of Development	Corresponding TRL #	DOE's TRL Definition / Description (condensed / abbreviated)
Systems Operations	**TRL 9**	**Actual system in its final form** and operated **under full range of operating conditions**.
Systems Conditioning	**TRL 8**	**Actual system completed and qualified through test and demonstration**. The technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the **end of true system development**.
	TRL 7	**Full-scale, similar prototype system demonstrated in relevant environment**. Represents a major step up from TRL 6, requiring demonstration of an actual system prototype in a relevant environment.
Technology Demonstration	**TRL 6**	**Engineering/pilot-scale**, similar (prototypical) system validation in **relevant environment**; represents a **major step up** from TRL 5
Technology Development	**TRL 5**	**Laboratory scale**, similar system validation in **relevant environment**: basic technological components are integrated so that system configuration is similar to (matches) final application in almost all respects.
	TRL 4	**Component and/or system validation in laboratory environment**: basic technological components are integrated to establish that pieces will work together; this is **relatively "low fidelity"** compared with the eventual system.
Research to Prove Feasibility	**TRL 3**	These TRLs range from **Initiation of active research & development (TRL 3)** down to **Basic principles observed and reported** (TRL 1)
	TRL 2	
Basic Research	**TRL 1**	
Source: adapted from U.S. DOE, "Technology Readiness Assessment Guide," Table 1: Technology Readiness Levels, September 2011.		

6.2. Estimated 2021 Technology Readiness Level (TRL) Ratings (with Prognoses for 2024)

DOE's TRL system provides a straightforward, concise and defensible tool to compare the technological maturity of various emerging fuel-technology CHE platforms that have the clearest potential for wide-scale application at the San Pedro Bay Ports over the next several years. Using DOE's system, "snapshot" TRL ratings have been assigned for the core emerging ZE and NZE platforms discussed in this report. These TRL ratings were derived by applying publicly available information (e.g., OEM technical specifications), survey responses directly submitted by the OEMs, and various footnoted technical reports / sources.

The following tables and discussion summarize the estimated TRL rating (late-2021) for each of the four assessed CHE types (by leading fuel-technology platform) and denoted using solid lines. This includes "educated prognoses" about how or if each TRL rating is expected to change by 2024 (denoted using dashed lines).

6.2.1. Yard Tractors

Table 13. Yard Tractors: Technical Viability (late-2021) using TRL values (with 2024 prognoses)

TRL	Relative Stage of Development	Late-2021 TRLs for Leading Fuel-Technology Platforms (Yard Tractors)	~2024: Educated Prognoses (by or before)	Comments / Basis for 2024 Educated Prognosis
TRL 9	**Systems Operations**		ZE Battery NZE NG ICE **(TRL 9)**	**ZE Battery Electric / NZE NG ICE:** strong OEM involvement and roll-outs of early commercial products; both platforms need more OEM development and MTO operational time in revenue CHE service at Ports.
TRL 8	**Systems Conditioning**	ZE Battery NZE NG ICE **(TRL 7 to 8)**		
TRL 7		ZE Fuel Cell or NZE PHEV **(TRL 6 to 7)**	ZE FC or NZE PHEV **(TRL 7 to 8?)** NZE Diesel ICE **(TRL 7, or higher?)**	**ZE Fuel Cell:** technology demos just underway, OEMs need time to address remaining technical hurdles; **NZE Plug-in Hybrid:** prognosis is a wild card; OEM interest is hard to gauge, but plug-in architecture enables valued partial zero-emission modes.
TRL 6	**Technology Demonstration**	NZE Diesel ICE **(TRL 5 to 6)**		
TRL 5	**Technology Development**			**NZE Diesel ICE:** could "**leapfrog**" to TRL 8 or 9, but only if suitable diesel engine(s) get certified to 0.02 g/bhp-hr NOx (or other CARB OLNS)
TRL 4				

Source: TRL methodology adapted from U.S. DOE, "Technology Readiness Assessment Guide, Table 1: Technology Readiness Levels, September 2011 (see footnote). TRL ratings estimated based on input from 1) OEM surveys, 2) various technical reports, 3) demonstration activities, and 4) meetings with agency technical personnel (CARB, CEC, SCAQMD).

Key takeaways and additional discussion for yard tractors are summarized below:

- **ZE** battery-electric and yard tractors are currently at **TRL 7 to 8**; *this is a half step higher from 2018*. OEMs Kalmar and BYD continue to make technological progress through ongoing improvements on early commercial units being demonstrated in revenue service at SPBP marine terminals. Additionally, on-road HDV OEMs have made important progress with early commercial battery-electric trucks that have helped advance the technological maturity of battery-electric yard tractors. As noted, achievement (or near achievement) of TRL 8 requires *successful demonstration* by one or more San Pedro Bay Ports MTO. Several MTOs demonstrating pre- or early commercial battery-electric yard tractors were surveyed specifically to obtain quantitative and/or qualitative information corroborating if this has yet been achieved. In the context of the Technical Viability parameter, a "successful demonstration" is deemed to be proven ability to *perform diesel-equivalent work moving containers for at least one full shift with sufficient remaining energy and charging/fueling speeds to complete a second shift after refueling or recharging between shifts*. Several MTOs reported that their battery-electric demonstration units achieved one full shift of operation in demonstrations. The University of California-Riverside corroborated this under the C-PORT demonstration by testing a pre-commercial Kalmar battery-electric yard tractor at the Port of Long Beach (see Operational Feasibility section for more details). Additionally, analysis of test data from the C-PORT demonstration indicate that the tested yard tractors could marginally meet the requirement to complete a second shift with charging between shifts, albeit with very little remaining state of charge. However, two shift operations of 16 hours or more of operational time per day (with or without charging between shifts) have not been demonstrated in real-world operations and preclude a finding of TRL 8. Newer battery-electric platforms are expected to improve the ability to complete two shifts with charging between shifts, supporting the finding that battery-electric yard tractors are approaching TRL 8. Notwithstanding this important progress, it is important to reiterate that TRL rating is only one of five parameters used to define overall feasibility. As MTOs also described, they experienced issues, challenges and problems while demonstrating pre-production battery-electric yard tractors. Such MTO feedback is captured in the ratings for other feasibility parameters (cost and operational feasibility, in particular). For their next-generation battery-electric yard tractors, OEMs need additional time to make improvements that resolve these issues, and then conduct field tests on multiple pre-production units in revenue-service operation by MTOs.

- **NZE** natural gas ICE yard tractors are currently at **TRL 7 to 8**; *this is a half step higher from 2018.* OEM Capacity has made technological progress through ongoing improvements made to 22 early commercial LNG-fueled units being demonstrated in revenue service at one SPBP marine terminal. Notably, Capacity (and other OEMs like TICO) indicate that fully commercial NZE natural gas ICE yard tractors for this application will likely use CNG (rather than LNG) fuel systems.[69] Consequently, for NZE natural gas ICE yard tractors to achieve TRL 9, at least one capable OEM needs to finalize a production-intent fuel configuration, and collaborate with at least one MTO to test multiple demonstration units in revenue service.
- Both of these emerging yard tractor platforms need additional time and resources for OEMs to make further improvements (e.g., increase endurance, improve reliability, reduce turning radius, improve cab ergonomics, improve fueling/charging speed and dynamics). Equally important, MTOs need opportunity to continue demonstrating improved units in revenue service. If these come to fruition, ZE battery-electric and NZE natural gas ICE yard tractors are likely to achieve **TRL 9 by (or before) 2024.**
- **ZE** fuel cell and **NZE** hybrid-electric yard tractors are currently at **TRL 6 to 7** (technology demonstration and systems conditioning); *this is a full step higher from 2018*. Fuel cell yard tractors in particular have advanced technologically through 1) Capacity Trucks' collaboration with Hyster / Nuvera, and 2) Toyota's development of (and near-term intent to commercialize) fuel cell electric drivetrains specifically for incorporation into yard tractors. Continued technology demonstrations are needed to identify and address remaining technical hurdles, including challenges associated with on-board storage of compressed hydrogen up to 10,000 psi and limited endurance (currently limited by insufficient fuel storage space on protypes). While OEMs have shown capabilities with hybrid ICE-electric architectures (including plug-in capability), current interest by OEMs is hard to gauge. Fuel cell and/or hybrid-electric yard tractors may move up to **TRL 7 to 8 by (or before) 2024**.
- **NZE** diesel ICE yard tractors are currently at **TRL 5 to 6** (technology development and demonstration); *this is slightly higher from 2018*. If a suitable diesel engine is certified to CARB's OLNS, NZE diesel ICE yard tractors could leapfrog to **TRL 8 or 9 by (or before) 2024**. Prospects for this have recently been enhanced by 1) various government-industry diesel-engine technology development efforts; and 2) CARB's adoption of its "Low-NOx Omnibus" regulation, which pushes future emissions standards for on-road heavy-duty diesel engines (certification and in-use) down to NZE levels. Because on-road engines are sometimes used in CHE applications (yard tractors in particular) – and CARB could adopt a similar rule focused on off-road engines – the emission reduction benefits of CARB's Low-NOx Omnibus may also be realized in CHE used by SPBP MTOs.

[69]Leonard, Jonathan, Patrick Couch, Kent Johnson, and Thomas Durbin. 2021. *Developing, Demonstrating, and Testing Advanced Ultra-Low-Emission Natural Gas Engines in Port Yard Trucks.* California Energy Commission. Publication Number: CEC-500-2021-037.
[69] TICO, "TICO Teams with Cummins 6.7-Liter Compressed Natural Gas (CNG) Alternative Fuel Engine During the ACT Expo," press release, April 19, 2019, https://ticotractors.com/press-releases/#foobox-3/0.

6.2.2. Top Handlers

Table 14. Top Handlers: Technical Viability (late-2021) using TRL values (with 2024 prognoses)

TRL	Relative Stage of Development	Late-2021 TRLs for Leading Fuel-Technology Platforms **(Top Handlers)**	~2024: Educated Prognoses (by or before)	Comments / Basis for 2024 Educated Prognosis)
TRL 9	**Systems Operations**			
TRL 8	**Systems Conditioning**		**ZE Battery (TRL 7 to 8)**	**ZE Battery Electric** good OEM involvement in proof-of-concept demonstrations. CORE-listing initiated. MTO: "insufficient range for 2 shifts"
TRL 7				
TRL 6	**Technology Demonstration**	**ZE Battery (TRL 6 to 7)**	**ZE FC or NZE PHEV (TRL 6 to 7?)** **NZE Diesel ICE (TRL 7, or higher?)**	**ZE Fuel Cell:** likely to benefit from yard hostler demonstrations; **NZE Plug-in Hybrid:** OEM interest is hard to gauge
TRL 5	**Technology Development**	**ZE FC or NZE PHEV (TRL 5 to 6)** **NZE Diesel ICE (TRL 5 to 6)**		**NZE Diesel ICE:** could "**leapfrog**" to TRL 8 or 9, but only if suitable diesel engine(s) get certified to 0.02 g/bhp-hr NOx (or other CARB OLNS)
TRL 4				

Source: TRL methodology adapted from U.S. DOE, "Technology Readiness Assessment Guide, Table 1: Technology Readiness Levels, September 2011 (see footnote). TRL ratings estimated based on input from 1) OEM surveys, 2) various technical reports, 3) demonstration activities, and 4) meetings with agency technical personnel (CARB, CEC, SCAQMD).

Key takeaways and additional discussion for top handlers are summarized below:

- **ZE** battery-electric top handlers are currently in the late stage of **TRL 6 to 7** (technology demonstration and systems conditioning); *this is a full step higher from 2018*. Demonstrations of top handlers using first-generation technology have been completed at marine terminals serving both Ports, and one pre-production model has demonstrated capability to achieve one shift between charging events. Technology development has benefitted significantly from OEM / government support and transferable technology development from on-road and yard tractor applications. In sum, they appear likely to attain **TRL 7 to 8 by (or before) 2024**.
- **ZE** fuel cell and **NZE** hybrid-electric top handlers are currently at **TRL 5 to 6** (technology development and demonstration); *this is nearly a full step higher from 2018*. Both platforms show good long-term promise for top handler applications, but significant technical challenges remain that require increased development and demonstration time to address. OEM interest in hybrid-electric architectures (possibly with plug-in capability) that use an NZE ICE is hard to gauge. Based on

existing demonstrations and OEM involvement (including for on-road HDVs), it is estimated that fuel cell and/or hybrid-electric top handlers may move up to **TRL 6 to 7 by (or before) 2024**.

- **NZE** diesel ICE top handlers are currently at **TRL 5 to 6** (technology development and demonstration); *this is slightly higher from 2018*. They have potential to reach **TRL 6 to 7 by 2024**, or possibly leapfrog to **TRL 8 or 9** (see text and other NZE diesel ICE examples).

6.2.3. RTG Cranes

Table 15. RTG Cranes: Technical Viability (late-2021) using TRL values (with 2024 prognoses)

TRL	Relative Stage of Development	Late-2021 TRLs for Leading Fuel-Technology Platforms (RTG Cranes)	~2024: Educated Prognoses (by or before)	Comments / Basis for 2024 Educated Prognosis
TRL 9	**Systems Operations**	-ZE Grid Electric -NZE Diesel Hybrid (TRL 9)	-ZE Grid Electric -NZE Diesel Hybrid (TRL 9)	ZE Grid Electric and NZE Diesel Hybrid* are sold commercially; emerging demonstrations of grid-electric units will provide important MTO experience.
TRL 8	**Systems Conditioning**			***Hybrid:** Emissions continue to be reduced; could be further reduced by replacing diesel gen-set with one using OLNS-certified natural gas or propane engine.
TRL 7				
TRL 6	**Technology Demonstration**		ZE FC (TRL 6)	**ZE Fuel Cell**: One company sells FC option, implying TRL well above 5. However, TRL 6 and above requires working out challenges in an actual demonstration at SPBP.
TRL 5	**Technology Development**	ZE FC (TRL 5)		
TRL 4				

Source: TRL methodology adapted from U.S. DOE, "Technology Readiness Assessment Guide, Table 1: Technology Readiness Levels, September 2011 (see footnote). TRL ratings estimated based on input from 1) OEM surveys, 2) various technical reports, 3) demonstration activities, and 4) meetings with agency technical personnel (CARB, CEC, SCAQMD).

Key takeaways and additional discussion for RTG cranes are summarized below:

- **ZE** grid-electric RTG cranes are at **TRL 9** (actual system in its final form and operated under full range of operating conditions); *this is unchanged from 2018*. At least six ZE grid-electric RTG cranes (converted from baseline diesel) are currently in operation at the Ports (SSA's Pier J program, with three additional units scheduled for conversion). This nine-unit demonstration at SSA (and others that may soon follow at other terminals) will provide important MTO experience (e.g., enabling optimal grid connection under site-specific opportunities and challenges).

- **NZE** hybrid-electric RTG cranes are also at **TRL 9** (actual system in its final form and operated under full range of operating conditions); *this is unchanged from 2018*. Based on the 2020 CHE inventory, dozens of units (new or conversions) are operating at the Ports. OEMs continue to reduce emissions through application of Tier 4-certified diesel gen-set engines, but emissions could be further reduced by using a gen-set with an OLNS-certified natural gas or propane engine.

- **ZE** fuel cell RTG cranes remain at **TRL 5** (technology development); *this is unchanged from 2018*. An aftermarket conversion is available, but there are no known deployments. Moving **to TRL 6 by 2024** will require at least one revenue-service demonstration at an SPBP MTO.

6.2.4. Large-Capacity Forklifts

Table 16. Large-Capacity Forklifts: Technical Viability (late-2021) using TRL values (with 2024 prognoses)

TRL	Relative Stage of Development	Late-2021 TRLs for Leading Fuel-Technology Platforms **(Large-Capacity Forklifts)**	~2024: Educated Prognoses (by or before)	Comments / Basis for 2024 Educated Prognosis
TRL 9	**Systems Operations**			
TRL 8	**Systems Conditioning**			
TRL 7			**ZE Battery (TRL 7 to 8)**; **ZE FC or NZE PHEV (TRL 6 to 7?)**; **NZE Diesel ICE (TRL 6 to 7, or higher?)**	**ZE Battery Electric** good OEM involvement in proof-of-concept demonstrations. Wiggins e-Bull shows higher TRL for Port of Stockton use, but not yet tested in tougher SPBP duty cycles
TRL 6	**Technology Demonstration**	**ZE Battery (TRL 6)**		**ZE Fuel Cell:** likely to benefit from yard hostler and top handler demonstrations; **NZE Plug-in Hybrid:** OEM interest is hard to gauge
TRL 5	**Technology Development**	**ZE FC or NZE PHEV (TRL 5 to 6)**; **NZE Diesel ICE (TRL 5 to 6)**		**NZE Diesel ICE:** could "**leapfrog**" to TRL 8 or 9, but only if suitable diesel engine(s) get certified to 0.02 g/bhp-hr NOx (or other CARB OLNS)
TRL 4				

Source: TRL methodology adapted from U.S. DOE, "Technology Readiness Assessment Guide, Table 1: Technology Readiness Levels, September 2011 (see footnote). TRL ratings estimated based on input from 1) OEM surveys, 2) various technical reports, 3) demonstration activities, and 4) meetings with agency technical personnel (CARB, CEC, SCAQMD).

Key takeaways and additional discussion for large-capacity forklifts are summarized below:

- **ZE** battery-electric large-capacity forklifts are currently at **TRL 6** (technology demonstration); *this is a full step higher from 2018*. Similar to the case with top handlers, this fuel-technology platform is moving towards **TRL 7 to 8 by (or before) 2024.** The Wiggins e-Bull has been deployed for testing in fairly large numbers (>10) by SSA Terminals at the Port of Stockton; they reportedly work well, but the MTO reports that the duty cycle is significantly less rigorous than a typical

SPBP operation. Planned demonstrations at SPBP will provide new information about technology readiness in this specific context.

- **ZE** fuel cell and **NZE** hybrid-electric large-capacity forklifts are currently at **TRL 5 to 6** (technology development and demonstration); *this is slightly higher from 2018*. Both fuel-technology platforms show good long-term promise for this application, but significant technical challenges remain that require demonstration time to address. Also, OEM interest in hybrid-electric architectures (including plug-in capability) is hard to gauge. It is estimated that fuel cell and/or hybrid-electric large-capacity forklifts may move up to **TRL 6 to 7 by (or before) 2024**.
- **NZE** diesel ICE large-capacity forklifts are currently at **TRL 5 to 6** (technology development and demonstration); *this is slightly higher from 2018*. As with top handlers, this could leapfrog to **TRL 8 or 9 by (or before) 2024**.

6.3. Key Comparisons to CARB's Latest CHE "Snapshot" TRL Ratings

In late-2021, CARB staff released its "Proposed FY 2021-22 Funding Plan for Clean Transportation Incentives." Appendix D of the document provides "technology status updates" from CARB staff for various on- and off-road vehicle / equipment types with ZE and NZE architectures. This includes CARB staff's estimated "draft" TRL ratings (using NASA's scale[70]) as of mid-2021, with the following caveat: "CARB recognizes that technology status represents only part of the commercialization story, and that a number of other metrics need to be assessed to also evaluate market readiness." CARB specifically cites the need to account for "issues such as infrastructure, workforce training, the needs of small fleets, total cost of ownership (TCO), and supply chain management."[71]

CARB staff used a series of graphs to summarize draft TRL ratings for on- and off-road heavy-duty vehicles powered by emerging ZE and NZE fuel-technology platforms. These ratings included three (of the four) CHE categories discussed in this 2021 Assessment: yard tractors, top handlers, and large-capacity forklifts. (Elsewhere in the document, CARB staff implies that ZE and NZE RTG cranes are fully commercial products with TRL 9 ratings.) The following summarizes CARB staff's draft TRL ratings for battery-electric versions of yard tractors, top handlers, and large-capacity forklifts[72] as of mid-2021:

- **ZE** battery-electric yard tractors are moving past "advanced technology pilot" demonstrations into becoming "commercial" products, albeit at an "early market entry" stage. CARB staff assigns a TRL 9 rating for battery-electric yard tractors in 2021, while also noting there is a large "readiness range" for different models under development. **Note:** as discussed further below, CARB's TRL rating includes yard tractors used in warehouse applications; it is not specific to yard tractors used in more-rigorous duty cycles by port MTOs.
- **ZE** battery-electric top handlers and large-capacity forklifts have a current TRL 7 rating; they are entering into advanced technology pilot demonstrations.

Within the report's narrative, CARB staff made the following additional relevant comments:

- The technology readiness of battery-electric vehicle technologies has "improved continually" since 2018, especially in "beachhead strategy" platforms that include port-serving yard tractors, top handlers, and large-capacity forklifts.
- Yard tractors "stand out for their technical status as early products and for their high demand in the Clean Off-Road Equipment (CORE) incentive project," which "specifically target(s) zero-emission off-road freight equipment . . .

[70] CARB staff uses the National Aeronautics and Space Administration (NASA) scale for its TRL ratings (https://www.nasa.gov). Like the DOE scale used in this 2021 CHE Assessment, NASA's scale uses TRL 1 through TRL 9. The two scales are very similar for basic definitions applying to each TRL rating. As an example, NASA's TRL 9 rating refers to "Actual system flight proven through successful mission operations;" DOE's TRL 9 refers to "Actual system operated over the full range of expected mission conditions."
[71] California Air Resources Board, "Appendix D: Long-Term Heavy-Duty Investment Strategy Including Fiscal Year 2021-22 Three-Year Recommendations for Low Carbon Transportation Investments," Proposed Fiscal Year Funding Plan for Clean Transportation Incentives, October 2021, https://ww2.arb.ca.gov/our-work/programs/low-carbon-transportation-investments-and-air-quality-improvement-program/low-1.
[72] CARB staff used non-descript terminology in its graphs depicting TRL ratings. For example, top handlers and large-capacity forklifts were lumped together simply as "Cargo-Handling Equipment." To make comparisons, the authors normalized CARB's CHE terminology to that used in this Assessment.

currently in the early stages of commercial deployment."[73] **Author's note:** CORE is a relatively new program. While nearly half of its funding is allocated toward "terminal tractors" (SPBP-deployed yard tractors are included in this category), the program is closed to all applications as of late-2021. It is unclear how many battery-electric yard tractors have been awarded and deployed at any California port through CORE, to date.

- Much of the progress with battery-electric CHE has resulted from OEMs being able to successfully transfer enabling technology (e.g., battery packs, electric drive systems, chargers) over from similar heavy-duty on-road vehicles.

The following summarizes CARB staff's draft TRL ratings for hydrogen fuel cell yard tractors, top handlers, and large-capacity forklifts as of mid-2021:

- **ZE** fuel cell electric yard tractors are moving into "advanced technology pilot" demonstrations; their TRL rating is at the 7 to 8 range.
- **ZE** fuel cell electric top handlers and large-capacity forklifts are also in pilot demonstration phases, there TRL rating of 7 is slightly lower than fuel cell yard tractors.
- **ZE** fuel cell electric material handling forklifts – which are small-capacity units and NOT CHE – are essentially commercial products, at the TRL 9 stage of technological maturity.

Table 17 compares CARB staff's estimated TRL ratings (summarized above) with TRL rating assigned by the authors for this 2021 Assessment. This is done for each of the four CHE types and leading fuel-technology platforms. The next-to-last column notes the degree of difference (if any) between CARB's TRL rating and this Assessment's rating. The last column provides observed reasons for the two cases where the degree of difference is significant.

Table 17. Comparison of CARB Staff's snapshot 2021 TRL ratings, by key CHE and ZE or NZE platform

CHE Type	Fuel-Technology Platform	2021 CARB TRL (Draft)	2021 Feasibility Assessment TRL	Degree of Difference	Observed Reason(s) for Difference (if applicable)
Yard Tractors	**ZE** Battery Electric	9	7 to 8	Significant	CARB's TRL ratings are applicable to all CHE uses (i.e., not specific to use by MTOs in San Pedro Bay Ports duty cycles). This is an *especially important difference in assumptions* for the yard tractor application. CARB's nomenclature for larger CHE is not easily translated into specific vehicle types like top handlers and large-capacity forklifts
	NZE Natural Gas ICE	9*	7 to 8	Significant	
	ZE Hydrogen Fuel Cell	7 to 8	6 to 7	Modest.	
Top Handlers / Large-Capacity Forklifts	**ZE** Battery Electric	~7	6 to 7	Insignificant	
	ZE Hydrogen Fuel Cell	~7	5 to 6	Modest	
RTG Cranes	**ZE** Grid-Electric	9	9	None	
	NZE Hybrid-Electric	9	9	None	
	ZE Hydrogen Fuel Cell	Not Rated	5	(N/A)	

*CARB staff does not specifically call-out natural gas yard tractors, or any other specific type of on-/off-road natural gas vehicle application. Staff assigned a TRL 9 rating to multiple "0.02 g NOx" natural gas (and propane) engines that OEMs commercially offer as NZE options in yard tractors.

To summarize, CARB staff's 2021 TRL ratings and assessments for commercial maturity are generally similar to, and consistent, with those presented in this 2021 Feasibility Assessment for Cargo-Handling Equipment. Notably, CARB's TRL 9

[73] California Air Resources Board, "Clean Off-Road Vehicle Equipment Voucher Incentive Project," https://ww2.arb.ca.gov/our-work/programs/clean-off-road-equipment-voucher-incentive-project.

rating for ZE battery-electric yard tractors is significantly higher than the TRL 7 to 8 assigned in this Assessment). Importantly, CARB's TRL rating appears to be generic for all yard tractors, rather than specific to units operated at SPBP marine terminals. Yard tractors deployed by MTOs at both Ports are used in significantly more energy-intensive duty cycles than those deployed for warehouse and distribution applications.

6.4. Summary of Ratings for Technical Viability

The Technical Viability parameter evaluated under this 2021 Feasibility Assessment for Cargo-Handling Equipment is closely related to the previous parameter (Commercial Availability), as well as the parameter that follows (Operational Feasibility). All three parameters are measures of technological maturity for emerging ZE and NZE CHE platforms, and their ability to meet MTO needs for power, performance, shift endurance (operating time between fueling or charging), fueling time, durability / reliability, safety, and others (see Section 7 on Operational Feasibility).

To specifically gauge technical viability, the study authors assigned TRL ratings (based on the U.S. DOE's scale and definitions) to a mix of ZE and NZE platforms that appear to have the best potential for broad incorporation into the SPBP CHE fleet over the next several years. **TRL 8** is the stage at which a given platform becomes near-final or final, and has adequately exhibited technical viability through test and demonstration. **TRL 9** constitutes DOE's highest rating; this is the stage at which full technical viability has been achieved and definitively documented. [74]

Four different ZE and NZE fuel-technology platforms for two CHE types (yard tractors and RTG cranes) are found to be "technically viable" as of late-2021, based on the observation that they have reached (or are approaching) a **TRL level of 8 or higher.** These are:

- **Yard Tractors:** 1) **ZE** battery-electric and 2) **NZE** natural gas ICE
- **RTG Cranes:** 3) **ZE** grid electric and 4) **NZE** hybrid electric (includes battery with small diesel generator set)

As shown by the solid outlines in the table, yard tractors (green) are currently at **TRL 7 to 8** for both architectures. The green dotted circles in the table indicate that yard tractors are expected to reach TRL 9 by or before 2024, for both architectures. RTG cranes (blue) have already achieved **TRL 9,** for both architectures.

As was the case in 2018, this 2021 Assessment finds that no ZE or NZE platforms for top handlers or large-capacity forklifts have yet reached (or approached) TRL 8. However, it is clear that CHE OEMs have made major advancements since 2018 for battery-electric architectures used on both top handlers and large-capacity forklifts. As of late-2021, these are in the TRL 6 to 7 range. It is anticipated that demonstrations by SPBP MTOs over the next two years will move battery-electric top handlers and large-capacity forklifts a full step higher, into the TRL 7 to 8 range. This will put them at the threshold of being "technically viable" for wide-scale use at the Ports. Combined with sufficient progress by OEMs to commercialize these types of battery-electric CHE, it will warrant deeper evaluation by the Ports (i.e., for Operational Feasibility, Infrastructure Availability, and Economic Workability) by or before the 2024 Feasibility Assessment update.

OEMs are also advancing the technology of fuel cell architectures for top handlers and large-capacity forklifts, although they lag behind battery-electric versions for technical viability. New development and demonstration efforts are reportedly in the works by major existing OEMs (e.g., Hyster Yale and Taylor) to pursue CHE of these types with fuel cell architectures.

6.5. Implications to Remainder of 2021 Feasibility Assessment for Cargo-Handling Equipment

The methodology of this Assessment initially applied two key parameters, Commercial Availability and Technical Viability, to screen leading CHE fuel-technology platforms. Those found to currently meet the basic criteria and considerations for

[74] U.S. Department of Energy, "Technology Readiness Assessment Guide", September 15, 2011, page 9, https://www.directives.doe.gov/directives-documents/400-series/0413.3-EGuide-04a/@@images/file.

Commercial Availability and Technical Viability (or exhibit strong likelihood to achieve them soon) were selected for further assessment, by applying the remaining three parameters (Operational Feasibility, Infrastructure Availability, and Economic Considerations).

The rationale for this is straightforward. Until a particular fuel-technology platform has 1) achieved (or is approaching) the minimum threshold for technical viability, and 2) becomes (or can soon become) a fully certified product offered by a major CHE OEM, it is premature and speculative to evaluate its potential for broad-scale deployment in the SPBP' CHE fleet within the next three years (the timeframe of this 2021 Assessment update).

Consequently, the remainder of this 2021 Assessment focuses on further characterizing the feasibility of the two specific types of CHE, powered by the fuel-technology platforms that currently meet the above tests:

1) Yard tractors: **ZE** battery-electric and **NZE** natural gas ICE
2) RTG cranes: **ZE** battery-electric and **NZE** hybrid-electric

Important Notes / Reminders:

1) A high Technical Viability score (i.e., a TRL rating of 8 or 9) **does not solely constitute "feasibility"** for any given CHE fuel-technology platform. Sufficient degrees of achievement for Commercial Availability, Operational Feasibility, Infrastructure Availability, and Economic Workability are also required. These five inter-related parameters work together to collectively define feasibility for MTOs to successfully operate CHE (of any type and fuel-technology CHE platform) on a wide-scale basis at the San Pedro Bay Ports.

2) Nothing in this 2021 Feasibility Assessment for Cargo-Handling Equipment precludes or discourages expanded development, demonstration, and deployment of pre-commercial ZE and NZE fuel-technology platforms that have not yet reached or approached the technical viability threshold of TRL 8. In fact, both Ports continue to support efforts to test a variety of CHE platforms with TRL ratings in the 5-to-7 range, especially in cases that include major involvement and cost sharing by CHE OEMs (see Section 5.6).

3) This Assessment is a snapshot of CHE fuel-technology platforms as of late-2021. The Ports intend to conduct the next feasibility assessment within three years, or sooner if technological and market conditions warrant an accelerated schedule.

7. Assessment of Operational Feasibility

7.1. Background: Criteria and Methodology

Operational feasibility for a given CHE type refers to its ability to meet the essential needs of SPBP MTOs to move cargo efficiently, affordably, and safely. The fundamental question for any emerging fuel technology platform is: will it be able to move containers (or other cargo) as well (or nearly as well) as the baseline diesel technology that it is intended to replace?

It is difficult to overstate the importance of MTOs gaining real-world experience with – and confidence in – the operational feasibility of any emerging CHE platform before widely deploying it in regular operations. To date, MTOs have participated in numerous ZE and NZE CHE demonstration projects. Many of these projects have been co-funded by the Ports and are documented on the Ports Clean Air Action Plan website.[75] While these demonstrations have been useful in the development of ZE and NZE technologies, they have largely been conducted on pre-commercial platforms over relatively short periods of time. Consequently, MTOs have limited operational experience with the newest early commercial ZE and NZE CHE platforms. This is especially true for the two leading ZE architectures (battery-electric and hydrogen fuel cell). Fortunately, many important demonstration programs are anticipated to conclude over the next 18 months (as were described in Section 5.6) that will provide valuable lessons learned for MTOs.

Table 18 lists the criteria that have been applied (within the scope and timeline of this Assessment) to evaluate if various fuel-technology platforms for CHE can meet base considerations to deem them "operationally feasible" as of late-2021.

Table 18: Criteria for assessing Operational Feasibility of emerging CHE platforms.

Operational Criteria / Issue	Base Considerations for Assessing Operational Feasibility
Basic Performance	Demonstrated capability to meet MTO needs for basic performance parameters including power, torque, speed, operation of accessories, etc.
Fuel Economy and Endurance	Demonstrated capability to achieve per-shift and daily operating time requirements found at SPBP terminals.
Speed and Frequency of Fueling / Charging	Demonstrated capability to meet MTO needs for speed and frequency to fuel/charge such that revenue operation is not significantly reduced relative to diesel baseline.
Operator Comfort, Safety, and Fueling Logistics	Proven ability to satisfy typical MTO needs for comfort, safety, and fueling procedures.
Availability of Replacement Parts and Support for Maintenance / Training	Verifiable existence of and timely access (equivalent to baseline diesel) to all replacement parts needed to conduct scheduled and unscheduled maintenance procedures.
	Verifiable existence of maintenance procedure guidelines and manuals, including OEM-provided training courses upon purchase and deployment of new equipment.
Source: Based on criteria in San Pedro Bay Ports' "Framework for Developing Feasibility Assessments," November 2017.	

As shown, these base considerations focus on post-purchase parameters from the end users' perspective. These include 1) vehicle/equipment-related parameters (e.g., power, torque, acceleration and handling, fuel economy / endurance, driver

[75] http://www.cleanairactionplan.org/technology-advancement-program/final-reports/

comfort, availability of replacement parts, layout and operational ease of accessories); and 2) facility-related parameters (e.g., fueling logistics, required time to fuel, need for facility upgrades).

7.2. MTO Interviews and Data Collection

To assess operational feasibility, data on existing equipment and operations were collected from MTOs through a series of meetings and three site visits to separate marine terminals. Information collected during this process included the following:

- Representative equipment specifications
- Typical fuel consumption by equipment type
- Typical equipment useful life
- Work shift schedules and daily hours of operation requirements
- Parking and fueling logistics

The gathered information is indicative of typical terminal operations, but should not be considered an exhaustive assessment of all possible uses of terminal equipment, or for all terminal operations. Marine terminals are a complex system of inter-related equipment operations. They serve a broad range of daily operational needs that can vary markedly by terminal, and from day-to-day. The focus of this Assessment considers the ability of the four "pre-screened" ZE and/or NZE platforms (two each for yard tractors and RTG cranes) to provide direct replacements for the corresponding baseline diesel equipment that can meet maximum shift lengths and other critical MTO needs for daily operation.

7.2.1. Representative Equipment Specifications

Table 19 and Table 20 summarize the representative equipment specifications for yard tractors and RTG cranes provided by the MTOs. The example baseline equipment types are consistent with equipment reported in both Ports emissions inventories. Revisions to these specifications from the 2018 Assessment are indicated in parentheses, where applicable.

Table 19. Representative specifications for Yard Tractors (with revisions from 2018)

Representative Yard Tractor Specification	
Example Baseline Equipment	Kalmar Ottawa T2, Capacity TJ7000
Fuel Type	Diesel
Axle Config	4x2
Wheel base	116 inches
Engine Power	170 HP *(formerly 200-240 HP)*
GCWR	81,000 lbs.
Top speed	25 mph *(formerly 25-33 mph)*
Fuel Capacity	50 gallons
Estimated Endurance	20 hours

Table 20. Representative specifications for RTG Cranes (with revisions from 2018)

Representative RTG Crane Specification	
Example Baseline Equipment	Konecranes, Kalmar, ZPMC RTG cranes
Lift Capacity	40-50 tons *(formerly 65 tons)*
Spreader Capacity	20, 40, and 45 feet
Wheel Span	77 feet
Hoist Height	1 over 6 high cubes
Hoist Speed	30 meters/minute loaded, 60 meters/minute empty
Trolley Speed	75 meters/minute
Gantry Speed	135 meters/minute, empty spreader
# of Gantry Wheels	8-16
Engine Power	500 - 800 HP *(formerly 600-1,000 HP)*
Fuel Capacity	700 gallons
Estimated Endurance	70+ hours

7.2.2. Typical Fuel Consumption and Equipment Life

MTOs that were surveyed provided composite estimates of hourly fuel consumption for each CHE type, and typical useful lives for their equipment. These values are shown in Table 21. MTO-provided fuel consumption estimates were compared to other data sources, and found to be generally in agreement. Revisions to these specifications from the 2018 Assessment are indicated in parentheses where appropriate.

Table 21. Fuel consumption and useful life estimates (with revisions from 2018)

Equipment Type	Fuel Consumption	Useful Life
Yard Tractors	2.5 gallons/hour	10-12 years *(formerly 7-10 years)*
Conventional RTG Cranes	9.5 gallons/hour	10-20 years *(formerly 15-25 years)*
Advanced Hybrid RTG Cranes	5.5 gallons/hour	10-20 years *(formerly 15-25 years)*

Prior demonstrations of proof-of-concept yard tractors reported fuel consumption rates of 1.7 to 2.6 gal/hour[76], 1.9 gal/hour[77], and 1.1 to 2.9 gal/hour.[78] The MTO-provided estimate of 2.5 gal/hour is on the high end of these fuel consumption rates reported in demonstrations, but it is reasonable for a high-intensity port operation.

Fuel consumption rates for RTG cranes were previously estimated using several approaches in a load factor study commissioned by the Ports in 2009.[79] The fuel consumption rates were estimated at 5.5 to 9.6 gal/hour, including one data point based on measured consumption for a baseline diesel RTG crane of 6.5 gal/hour during a demonstration of a hybrid RTG crane technology. Again, the MTO-provided fuel consumption rate is at the upper end of previously reported ranges but is assumed to be reasonable for a high intensity operation.

In a 2012 demonstration of a Kalmar EcoCrane hybrid RTG crane, the hybrid unit demonstrated roughly a 40 percent reduction in fuel consumption from the diesel baseline.[80] This reduction is consistent with the reductions reported by the MTO for hybrid RTG cranes. Note that the EcoCrane is a battery-electric hybrid system that uses a battery and a downsized engine for power generation. A prior hybrid system demonstrated by Vycon used a flywheel to capture energy from lowering containers, but demonstrated only 15 percent fuel savings when retrofitted to the baseline diesel engine. Fuel savings increased to 35 percent when the flywheel system was combined with a downsized engine, highlighting the value of engine downsizing. For the purposes of this Assessment, it is assumed that hybrid RTG cranes would be of the battery-electric type as they maximize fuel savings relative to a flywheel system.

An analysis of the 2020 CHE inventories for the Ports was conducted to estimate useful life as a comparison point for the values provided by the MTOs. Based on that analysis, the median age of a traditional RTG is 10 years, with some RTG cranes being as old as 22 years. The median age for a yard tractor was 8 years, with 95 percent of units being 13 years old, or newer. These values are consistent with the useful life estimates reported by the MTOs.

7.2.3. Daily and Shift Endurance Requirements

Endurance refers to the time a piece of equipment must operate between fueling/charging events. Endurance requirements are dictated by the physical and operating conditions on the terminal, including shift length, facility size, break periods, and staffing of the equipment. To estimate endurance requirements, MTOs were asked to describe their regular operating conditions, which are largely governed by shift lengths.

[76] Calstart, "Hybrid Yard Hostler Demonstration and Commercialization Project", March 2011. http://www.cleanairactionplan.org/documents/hybrid-yard-hostler-demonstration-and-commercialization-project-revised-final-report-august-2012.pdf/

[77] TIAX, "Pluggable Hybrid Electric Terminal Tractor (PHETT™) Demonstration at the Port of Long Beach", September 2009. http://www.cleanairactionplan.org/documents/capacity-plug-in-hybrid-terminal-tractor-phett-demonstration-polb-final-report.pdf/

[78] Calstart, "Liquefied Natural Gas (LNG) Yard Hostler Demonstration and Commercialization Project", August 2008. http://www.cleanairactionplan.org/documents/sound-energy-solutions-ses-liquefied-natural-gas-lng-yard-hostler-demonstration-and-commercialization-project-1-final-report-august-2008.pdf/

[79] Starcrest LLC, "Rubber Tire Gantry (RTG) Crane Load Factor Study", November 2009. http://www.polb.com/civica/filebank/blobdload.asp?BlobID=6915

[80] Starcrest LLC, "Rubber-Tired Gantry Crane Hybridization Demonstration Project", January 2012, http://www.cleanairactionplan.org/documents/lbct-ecocrane-final-report-january-2012.pdf/

A typical shift lasts eight hours and includes a meal break and 15-minute rest periods. Most terminals regularly operate two shifts, but can add a third shift. This third shift, commonly referred to as a "hoot" shift, is typically five hours long. Hoot shifts are less common because labor costs are significantly higher during these periods. Additionally, adding a hoot shift results in a 23-hour equipment operating period, with the only break being a one-hour period between first and second shift. This complicates fueling/charging logistics and may require fueling/charging during meal hours, or (where feasible) bringing fuel out to an operating piece of equipment.

Examples of three types of shift schedules are shown in Figure 15. **Green** blocks indicate full operation, while **yellow** blocks indicate meal periods where typically half of workers are on meal break. **Grey** blocks indicate periods where cargo-handling operations are dormant.

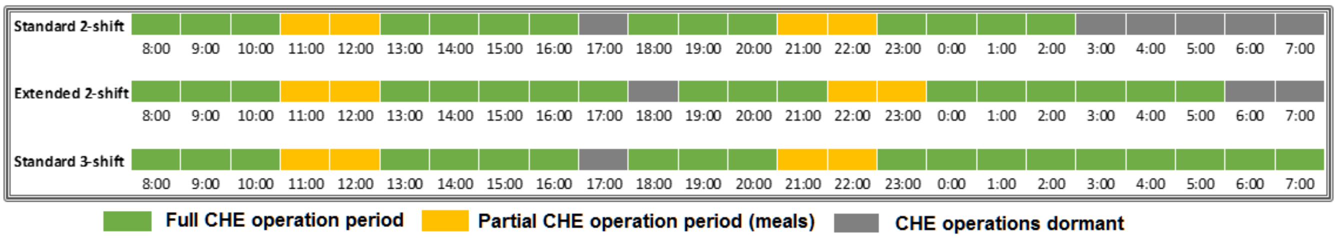


Figure 15. Examples of typical CHE operator shift schedules

The **standard two-shift** schedule is a typical two, 8-hour shift schedule with one hour of downtime between shifts. Fueling equipment typically occurs in the five-hour period between the end of the second shift and start of the first shift. The one-hour period between the first and second shift provides an additional opportunity to fuel.

The **extended two-shift** schedule accounts for the fact that terminals may extend a shift by one hour in the shift prior to a vessel sailing. They may also extend a shift by two hours in the shift the vessel is scheduled to sail. Combined, these extensions result in a total of 21 hours of operation with a single one hour fueling/charging opportunity between shifts.

The **standard three-shift** schedule is a standard two-shift schedule with a hoot shift added. The one-hour periods between shifts provide additional opportunities to fuel/charge.

Under the standard two-shift schedule, CHE must have an endurance of eight (8) hours and be able to complete 16 hours of work with one fueling/charging opportunity between shifts. While there are technically other fueling/charging opportunities during rest periods and meal hours, MTOs have indicated that equipment is not always available for fueling/charging during those periods. For example, some MTOs "hot-seat" yard tractor drivers, meaning that when a driver goes on break, a new driver continues to operate the yard tractor and it remains in service. This practice maximizes the utilization of the equipment, reducing number of yard tractors the terminal must deploy but also reduces the opportunity for fueling/charging. Additionally, yard tractors may not be returned to the fueling/parking areas during rest periods.

MTOs also noted that RTG cranes operate continuously over the course of a shift. Hence, the only fueling/charging opportunities for conventional RTG cranes are between shifts.

When a terminal operates an extended two-shift schedule, the endurance requirement of the equipment increases to 10 hours and must be able to complete 19 hours of service with a one-hour fueling/charging opportunity between shifts.

A standard three-shift schedule results in the most extreme endurance requirement, up to 23 hours of operation between fueling/charging opportunities. In practice, this requirement can exceed existing diesel yard tractor endurance capabilities of approximately 20 hours. Therefore, for the purposes of this analysis, the maximum endurance requirement considered is 20 hours under a three-shift schedule.

7.2.4. Parking and Fueling Logistics

Despite how they may appear to outsiders, marine terminals are highly constrained on space. Annual land lease costs can exceed $200,000 per acre.[81] High-density stacked container operations are intended to maximize terminal capacity, within the space constraints of each facility. Where large, open areas exist, they primarily serve as thoroughfares for equipment and cargo movement. As a result, parking areas for CHE are often compact. During the site visits to marine terminals, three basic parking configurations were observed. The first configuration is a single piece of CHE in a single stall, similar to a standard parking lot for passenger cars. This configuration is common for top handlers due to their large size (Figure 16) but some yard tractors can also be found parked in this configuration depending on the specifics of the terminal layout and parking area.

Figure 16. Top handlers parked in individual stalls

Yard tractors were also found to be parked in two other common configurations, lanes and stacked stalls. Figure 17 illustrates these two configurations. In the lane parking configuration, yard tractors are parked front-to-back up to about 12-15 units deep, and in multiple parallel lanes. In the stacked stall parking configuration, two yard tractors are parked front-to-back or head-to-head in each stall, typically along a fence line.

RTG cranes remain parked at the end of container stacks or moved to empty RTG crane runs, unless they are moved to a maintenance shed for service.

All diesel CHE on the terminals are fueled by wet hosing from fuel delivery trucks. These trucks typically carry between 2,500 and 5,000 gallons of fuel and have long fueling hoses to reach equipment parked in these various configurations. Fueling occurs between shifts and each yard tractor, top handler, and forklift are fueled, regardless of the amount of fuel remaining.

[81] West Coast MTO Agreement (WCMTOA), August 2016, https://wcmtoa.org/tag/port-of-long-beach/.

This ensures that each piece of equipment has a full diesel tank at the end of the fueling period, despite differences in fuel consumption rates over the prior shift. RTG cranes are typically fueled every two to three days.

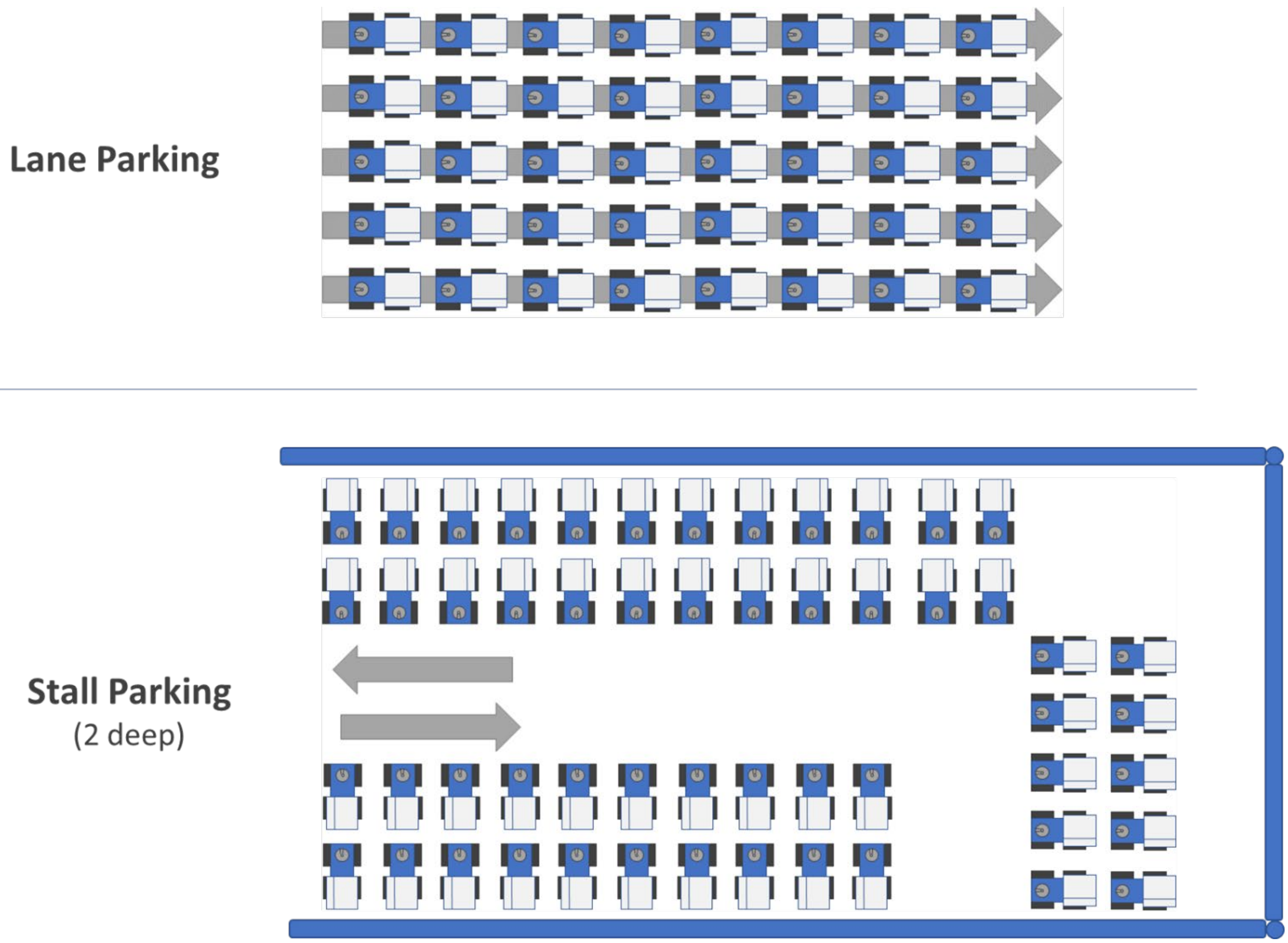


Figure 17. Example parking configurations for yard tractors

7.2.5. Annual usage

An analysis of the 2020 CHE emissions inventories for the Ports was conducted to estimate average annual hours of operation, as well as the distributions of operating hours. The distributions of operating hours are shown in Figure 18 and Figure 19. Summary statistics are provided in Table 22. Revisions to these specifications from the 2018 Assessment are indicated in parentheses where appropriate.

Table 22. Summary statistics for annual operating hours of yard tractors and RTG cranes

Equipment Type	Average Hours Per Year	Median Hours Per Year
Yard Tractors	1,806 *(formerly 1,662)*	1,951 *(formerly 1,644)*
RTG cranes	2,646 *(formerly 2,102)*	2,568 *(formerly 2,047)*

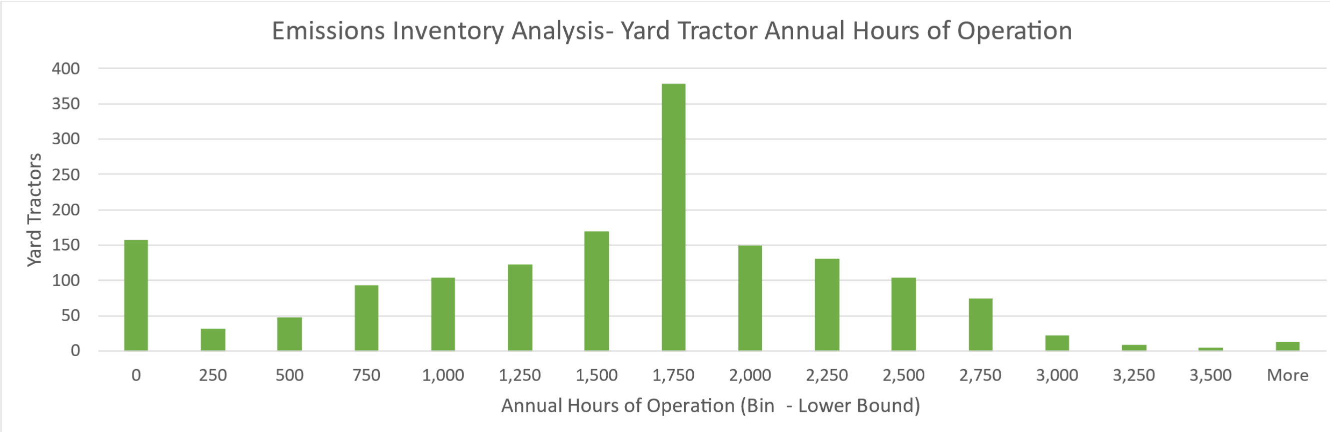


Figure 18. Distribution of annual operating hours for yard tractors at the San Pedro Bay Ports

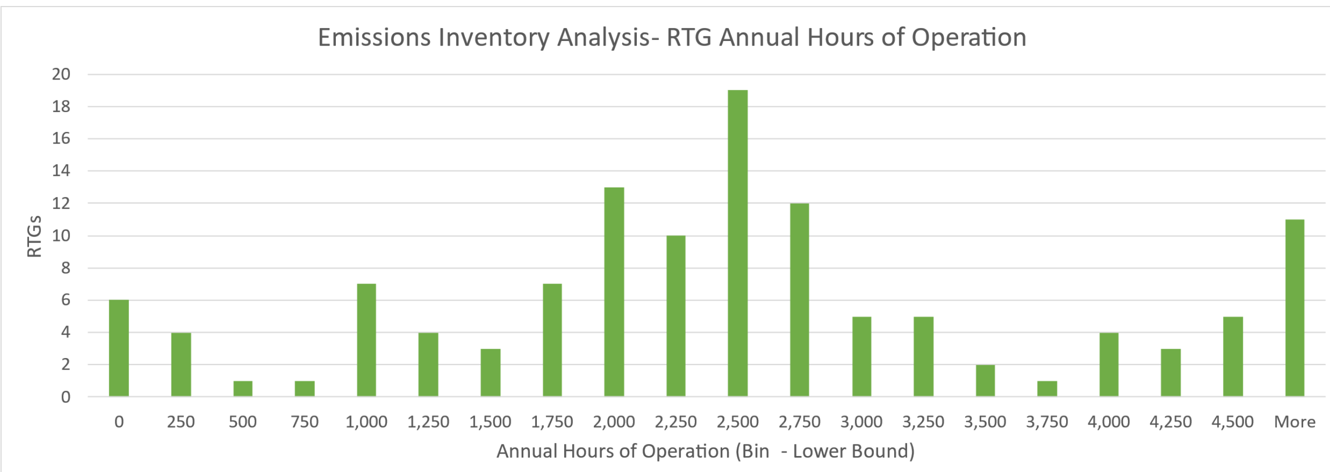


Figure 19. Distribution of annual operating hours for RTG cranes at the San Pedro Bay Ports

7.3. Application of Operational Feasibility Criteria

Marine terminals rely on a complex system of equipment working together to move cargo between ships, trucks, and rail cars. Each piece of equipment is responsible for executing a portion of a cargo move. For example, a standard container import process begins with ship-to-shore cranes moving containers from ships to yard tractors. The yard tractors then move the containers into the yard where the containers are stacked by an RTG crane or top handler. The imported container will later be transferred from a stack to a drayage truck by an RTG crane or top handler, or moved to a yard tractor and delivered to a rail car. Delays caused by any single piece of equipment have the potential to affect the utilization of many other pieces of equipment in the chain. Increasing the number of equipment deployed to offset efficiency losses can create other challenges, including requiring increased labor and parking demands. To avoid these impacts, it is assumed that any operationally feasible technology should offer a one-to-one replacement for existing diesel equipment. Consequently, the evaluated ZE and NZE platforms are compared against the equipment specifications and operational capabilities of the baseline diesel equipment described in the preceding section. Application of these criteria helps measure which key criteria are met, collectively providing a snapshot of operational feasibility.

7.3.1. Basic Performance and Endurance

Yard Tractors

The basic performance parameters for the baseline diesel yard tractor and emerging ZE and NZE models using two commercially available platforms (battery-electric and natural gas ICE) are provided in Table 23. It is important to note that calculations in this table have been based on OEM specifications, pending actual operational data generated and evaluated by MTOs during revenue-service demonstrations (expected to be concluded before 2024). Note that in the 2018 Assessment, Orange EV's battery-electric yard tractor model was included in this analysis; it has been removed from the current Assessment's analysis because that model is not intended for typical duty cycles required by MTOs at the Ports. However, Orange EV has announced intent to commercialize a yard tractor model specifically designed for use at marine terminals; production is scheduled to begin in 2022.

As shown in the table, the BYD and Kalmar ZE battery-electric yard tractors and the Capacity NZE LNG yard tractor meet the basic performance specifications of the diesel baseline unit. As described elsewhere in this Assessment, "endurance" is defined as the operational time between fueling/charging opportunities; it is estimated under two conditions. The single "tank" condition is the estimated endurance for the yard tractor on a single tank of fuel or single charge. The "inter-shift fueling" condition is the estimated endurance for a yard tractor starting with a full tank/battery charge and receiving a 45-minute window to fuel/charge between the first and second shift. Note that TICO's currently available CNG yard tractor model (refer back to 5.2.1) typically includes a 21 diesel gallon equivalent (DGE) fuel capacity using a single CNG tank. This capacity on onboard natural gas storage is not sufficient to meet a single shift endurance requirement, and it therefore is not considered further in this Assessment.[82] Autocar, which also offers NZE natural gas models as options for its diesel yard tractors, does not list specifications for DGE of onboard natural gas storage (see https://www.autocartruck.com/terminal-tractor/).

Table 23. Comparison of yard tractor specifications

Model	Kalmar T2, Capacity TJ7000	BYD 8Y	Kalmar T2E	Capacity TJ9000
Fuel/Technology Type	Diesel (Baseline)	Battery-Electric	Battery-Electric	NG ICE (LNG*)
Axle Configuration	4x2	4x2	4x2	4x2
Wheel base	116 inches	118 inches	126 inches	144 inches
Engine Power	170 HP	241 HP	215 HP	250 HP
GCWR	81,000 lbs.	102,000 lbs.	81,000 lbs.	125,000 lbs.
Top speed	25 mph	32 mph	45 mph	33 mph
Fuel / Energy Capacity[83]	50 gallons of diesel	217 kWh (30-40 DGE @ EER 5.3-7.0)	132-220 kWh (Largest pack: 30-40 DGE @ EER 5.3-7.0)	58 DGE* of natural gas
Fuel/Charge Rate	10 gal/minute	120 kW[84]	70 kW	10-15 DGE/minute
Estimated Endurance (single "tank")	20 hours	12-16 hours	12-16 hours	21 hours
Estimated Endurance (inter-shift fueling)	30 hours	17-23 hours	15-20 hours	31 hours

*Capacity's pre-commercial NZE natural gas TJ9000 units that were demonstrated at POLA (22 tractors) used **LNG** fuel systems with 58 DGE of onboard fuel storage capacity. Post-demonstration, Capacity representatives indicated that any next-generation TJ9000 natural gas tractor will likely use **CNG** fuel systems capable of carrying roughly the same volume (about 60 DGE) of natural gas fuel (if full commercialization is pursued).

[82]In early 2022, TICO is expected to announce it will commercially offer NZE CNG-fueled yard tractors specifically designed for use at SPBP marine terminals (and other major seaport terminal).To provide the endurance needed by MTOs, it is possible that TICO will offer a configuration with two CNG tanks, providing approximately 42 DGE of capacity. Should TICO, Capacity, or another OEM offer a CNG yard tractor with enough capacity for exceeding a single shift, future assessments could revisit the use of CNG yard tractors.

[83]Diesel Gallons Equivalent for electric yard tractors are calculated as DGE = kWh*(3.6 MJ/kWh)*EER/(134.47 MJ/DGE)

[84]BYD has transitioned to the use of a standard CCS-1 charging interface, reducing the charging rate to 120 kW as compared to its prior AC charging interface rated at 200 kW.

As discussed previously, yard tractors may experience shift lengths of up to 10 hours under an extended 2-shift schedule, and as much as 23 hours under a 3-shift schedule. However, for the purposes of this Assessment, maximum endurance requirements are assumed not to exceed current diesel yard tractor capabilities, which is estimated at 20 hours.

Table 24 lists results of the basic performance comparisons for endurance, based on the previously described assumptions for energy consumption/efficiency on amount of fuel/energy storage. To summarize, commercially available NZE natural gas (LNG) yard tractor technology is diesel-equivalent with regard to endurance, for all shift scenarios. Commercially available battery-electric yard tractor technology achieves diesel endurance levels when using inter-shift charging for a 2-shift schedule, but it is not (yet) diesel equivalent for a 3-shift schedule. The LNG yard tractor meets the 20 hours endurance requirement on a single tank (58 DGE) and is therefore assumed to be equivalent to diesel with respect to endurance. The BYD and Kalmar yard tractors meet the ten-hour shift endurance requirement. However, the Kalmar unit's ability to meet a 20-hour endurance with an inter-shift charging event is marginal, because the shift duration is at the upper end of the estimated endurance for the unit. Neither battery-electric unit can meet the 20-hour endurance requirement on a single charge.

Table 24. Summary of basic performance results for new yard tractors

Model	BYD 8Y Battery Electric	Kalmar T2E Battery Electric	Capacity TJ9000 NG ICE (LNG)
Basic Specifications	**Yes**	**Yes**	**Yes**
Standard 2-shift Endurance	**Marginal** (single charge) **Yes** (inter-shift charge)	**Marginal** (single charge) **Yes** (inter-shift charge)	**Yes**
Extended 2-shift Endurance	**No** (single charge) **Marginal** (inter-shift charge)	**No** (single charge) **Marginal** (inter-shift charge)	**Yes**
3-Shift Endurance	**No**	**No**	**Yes**

In Janury 2022, the University of California-Riverside (UCR) published results from testing battery-electric yard tractors at the Port of Long Beach. Under the C-PORT demonstration, UCR "data logged" an early commercial Kalmar-TransPower battery-electric yard tractor while in revenue service at a major marine terminal. The UCR team compared the battery-electric yard tractor for basic performance attributes versus a datalogged diesel yard tractor. (UCR performed a similar test on battery-electric top handlers, as was described in the Commercial Availablity section.) UCR found that "in general, the battery-electric (yard tractor) was able to provide comparable hours of operation to the diesel (yard tractor) over a typical 8-hour shift." In sum, UCR's testing under C-PORT successfully demonstrated that early commercial battery-electric yard tractors can complete one or more shifts of operation between charging events. UCR also noted that, relative to diesel units, battery-electric yard tractors could "provide considerable benefits in terms of emissions reductions and energy consumption," both of which have positive implications for operational feasibility. The UCR team also implied that "future generations" of battery-electric yard tractors will benefit from OEM design improvements that should be evaluated through additional revenue-service demonstrations.[85]

Endurance Degradation

The estimated endurance hours for the four yard tractor models (three different fuel-technology types; refer back to Table 23) are implicitly based on new equipment. As these off-road vehicles age, their effective endurance will decrease. In the case

[85] Frederickson, C., Durbin, T., Li, C., Ma, T. et al., "Performance and Activity Characteristics of Zero Emission Battery-Electric Cargo Handling Equipment at a Port Terminal," SAE Technical Paper 2022-01-0576, 2022, doi:10.4271/2022-01-0576.

of baseline diesel and natural gas yard ICE yard tractors, endurance will decrease as fuel economy declines due to engine and driveline. However, for a well-maintained ICE vehicle such fuel economy degradation should be minimal. Notably, neither CARB's EMFAC model nor EPA's MOVES model include any significant vehicle efficiency deterioration for on-road heavy-duty trucks, as the vehicles age. Consequently, the ability of the natural gas yard tractor model to meet endurance requirements is assumed to not significantly deteriorate over the vehicle's life.

As battery-electric equipment age, endurance degrades because the battery system's usable capacity gradually reduces over repeated charging cycles. This degradation rate is highly dependent on the battery chemistry, battery system design, depth of discharge, recharging rate, environmental conditions, and duty cycle of the equipment. These factors make predictions of degradation difficult, and early commercial battery-electric yard tractors have only recently begun to be demonstrated and tested in marine terminal revenue service. No units have accrued sufficient hours and/or charge cycles to make meaningful estimates of battery degradation based on demonstration data.

Batteries for EVs are typically assumed to reach their end of life when they have less than 80 percent of their original capacity remaining. BYD indicates that the cycle life of its lithium iron phosphate cells is 3,000 to 5,000 cycles, depending on the depth of discharge per cycle.[86] Based on the annual usage histogram provided in Figure 18, yard tractors with the highest utilization rates at the two Ports generally do not exceed 3,500 annual operating hours. Assuming the majority of their operations are standard 2-shift schedules, this implies 220 days per year of operation, likely requiring two charges per day, for a total of 440 charge cycles per year. Hence, these high-utilization tractors would reach 3,000 to 5,000 battery cycles in 7-11 years. The 2021 Assessment (updated from 2018) assumes a diesel yard tractor's average useful life is 10-12 years, and suggests that today's battery-electric yard tractors would experience battery degradation below 80 percent of initial capacity before the end of their useful lives.

Consequently, a battery-electric yard tractor operator should anticipate that the maximum endurance of the yard tractor could degrade to less than 80 percent of its original endurance over the course of its service life. This means that battery-electric yard tractors with marginally compliant or compliant endurance could degrade below compliant levels before the end of their useful lives. It should be noted that future versions of battery-electric yard tractors could include larger batteries to meet endurance requirements more comfortably for standard two-shift schedules, allowing for degradation. However, before OEMs can get clarity on how much additional battery capacity will be required, it may be necessary to complete current demonstrations at the two Ports. This will better characterize the range of duty cycles for yard tractors and how they impact actual degradation rates on battery packs.

RTG Cranes

Refer back to Table 20 for basic performance parameters provided by MTOs for baseline diesel RTG cranes. Because most modern baseline RTG cranes are electric-drive machines that generate their own electricity from on-board diesel generators, diesel-hybrid and grid-connected versions have the same basic performance capabilities. The key difference between the two types of RTG cranes is the source of electricity and how it reaches the electric-drive system (and that grid-electric RTG cranes are a ZE architecture, while diesel-electric units are an NZE architecture).

A notable difference from the 2018 Feasibility Assessment is that MTO-provided performance specifications for baseline RTG cranes have been reassessed for 2021 to include an 800 HP engine. This was reduced from the 2018 assumption of a 1,000 HP engine (the largest power rating reported for RTG cranes in the Ports' emission inventories). The revised MTO-provided specification of 800 HP is comparable to a Konecranes RTG crane, for which ZE grid-connected and NZE hybrid-electric models exist. Therefore, it is assumed that RTG cranes of both types are available that provide comparable performance to baseline diesel RTG cranes.

Because hybrid RTG cranes consume significantly less fuel than conventional versions (at least 40 percent based on OEM and MTO estimates), they provide greater endurance than conventional RTG cranes (assuming the same size of diesel fuel tank). Grid-connected RTG cranes are continuously powered with electricity, which makes endurance irrelevant.

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[86] Presentations by BYD, "BYD Electric Tough," 2018 https://byd-forklifts.com/wp-content/uploads/2018/BYD8Y.PDF, and "BYD Electric Vehicles," 2016 https://www.theicct.org/sites/default/files/BYD%20EV%20SEDEMA.pdf,

7.3.2. Speed and Frequency of Fueling/Charging

As previously noted, MTOs currently rely on wet hosing to fuel their baseline diesel CHE (refer back to Section 7.2.4). Vehicles and equipment are typically fueled before the start of each shift. Yard tractors are fueled every day and RTG cranes are fueled every two to three days. Wet fueling allows yard tractors to be fueled in less than five minutes; RTG cranes take less than thirty minutes to fuel. To wet fuel all their CHE, a typical SPBP MTO utilizes three to four dedicated fueling trucks, normally allowing them to fuel all of their equipment in approximately two hours.

Additional application- and fuel-specific details about fueling/charging are discussed below.

Yard Tractors

The battery-electric CHE platforms evaluated in this Assessment are likely to require inter-shift charging for any shift configuration, particularly when battery degradation is considered. The peak charging power requirement occurs when charging between the first and second shift, and requires that the yard tractor have a minimum of ten hours of endurance available at the end of the charging period. A 45-minute charge window during this one-hour period is assumed based on the fact that "fueling" personnel would be required to connect each yard tractor at the beginning of the charging period and disconnect each yard tractor at the end of the period. Even when allowing less than one minute to connect/disconnect each yard tractor, the sequential nature of this process means that each truck would have less than the full hour to charge. For a theoretical parking area with 50 yard tractors, a 30-second time requirement for connection would require at least 12.5 minutes and two "fuelers" to sequentially connect all yard tractors. Note that a 30-second allowance for connecting or disconnecting yard tractors is strictly an approximation, as no demonstrations within the ports have occurred at this scale.

Estimates of the required power (per yard tractor) are shown in Table 25. Note that both the BYD and Kalmar platforms only have sufficient charging capacity when assuming a high energy economy ratio (EER) for the yard tractor. (EER refers to relative efficiency; CARB assumes battery-electric CHE have an EER of 2.7 compared to their baseline diesel ICE counterparts.) Further, the Kalmar unit is assumed to be equipped with the largest available battery capacity (220 kWh).

Table 25. Estimated charging requirements for commercially available battery-electric yard tractors

Charging Requirement	BYD 8Y	Kalmar T2E
Endurance at End of First 9-hour Shift	3-7 hours*	3-7 hours
Additional Endurance to be Charged between Shifts	3-7 hours	3-7 hours
Charging Energy Required (per Yard Tractor)	36-118 kWh	33-114 kWh
Charging Power (45-minute window)	49-157 kW	44-153 kW

*A demonstration of yard tractors at the ITS terminal indicated that energy consumption averaged approximately 20 to 30 kWh per hour. At this consumption rate, the BYD and Kalmar yard tractors would both have an endurance of 7 to 11 hours, versus the 12 to 16 hours estimated for this Assessment under certain duty cycles.

For the assumed LNG platform, the 58 DGE fuel system allows for fueling once a day, which is the current practice used by MTOs for fueling diesel yard tractors. Therefore, a fueling rate of approximately 11 DGE per minute (which is achieved at typical commercial LNG fueling stations for on-road applications today) is assumed to be sufficient. This is equal to the baseline diesel fueling rate after considering a 10 percent fuel efficiency penalty for spark-ignited natural gas engines (relative to compression-ignition diesel engines).

RTG Cranes

ZE Grid-connected RTG cranes do not need to be fueled, per se; they continuously draw power directly from the grid while in operation. Peak power demand from a grid-electric RTG crane is roughly equivalent to the output power of the conventional diesel RTG crane it is replacing. For an RTG crane with an 800 HP engine, produced electrical power is estimated at 760 HP when accounting for a 95 percent efficient generator. Hence, a grid-connected version of the same machine would be expected to draw 760 HP, or 570 kW. Batteries can be integrated into grid-connected RTG cranes to help mitigate peak demand, in which case the average load for the RTG would determine its peak demand. In their emissions inventories, the Ports assume a typical load factor for RTG cranes of 0.2, meaning that the average load for an RTG crane is 20 percent of its peak power rating. An 800 HP RTG would have an average load of 160 HP over its typical duty cycle. Adjusting for generator efficiency, this would equate to a 150 HP demand or 110 kW. In the current Assessment, products from Conductix Wampfler and others indicate that grid-connected RTG crane systems are now being equipped with batteries designed to help mitigate peak grid demands and provide regenerative braking of the gantry. Consequently, it is assumed that grid-connected RTG cranes will limit their apparent peak load on the grid to approximately 110 kW per unit.

It should also be noted that the connection/disconnection process for grid-connected RTG cranes can add significant time to the process of moving an RTG crane between runs. The demonstration at Pier J in the Port of Long Beach will provide an opportunity to characterize the potential operational impacts from this activity.

Fueling of NZE diesel-hybrid RTG cranes is equivalent to that of conventional diesel RTG cranes, and could potentially occur less frequently owing to the higher efficiency (reduced fuel consumption) of the hybrid system. For the purposes of this Assessment, the operational feasibility of fueling NZE diesel-hybrid RTG cranes is assumed to be equivalent to conventional RTG cranes.

7.3.3. Operator Comfort, Safety, and Fueling Procedures

An operationally feasible technology must provide a similar level of operator comfort and safety as existing diesel equipment. Additionally, fueling/charging procedures must be practical and safe to perform for assigned personnel.

Operator Comfort

Operator comfort is a difficult metric to assess as it is highly qualitative and varies for each operator. Ride quality, sound levels, visibility, and various amenities all impact the operator's sense of comfort within a particular piece of equipment. To assess a minimum level of operator comfort as discussed in this Assessment, it is assumed that any equipment platform that can be configured similarly to existing diesel equipment would be sufficient.

Yard Tractors - Demonstrations of early commercial battery-electric yard tractors are ongoing at both Ports. Based on prior testing involving pre-commercial yard tractors – as well as on-road trucks and buses – battery-electric yard tractors will exhibit very low noise levels. Drivers have also routinely noted reduced vibration as being positive attributes for heavy-duty battery-electric technology.

LNG yard tractors have previously been demonstrated at the Ports.[87] Driver feedback collected during the prior demonstration was positive, with 67 percent of drivers rating the LNG yard tractor as generally superior to the baseline diesel yard tractor. In particular, the reduced noise levels found in the LNG yard tractor were emphasized by drivers. More recent demonstrations of both 8.9L and 6.7L LNG yard tractors confirmed that the units compared favorably to diesel units, with 10 out of 11 drivers rating the LNG units as "better" or "much better" than the diesel units.[88]

Both ZE battery-electric yard and NZE natural gas ICE yard tractors are being developed on platforms intended to be equivalent to existing diesel platforms. For example, Kalmar's battery-electric T2E tractor and Capacity's TJ9000 LNG yard tractor are both very similar in size, look, and general specifications to their respective diesel platforms. Demonstration of these platforms, along with BYD's 8Y battery-electric model (BYD does not make diesel yard tractors), are expected to show similar or better driver comfort compared to diesel yard tractors.

RTG Cranes - As previously discussed, diesel-hybrid and grid-connected RTG cranes are functionally equivalent to their conventional diesel RTG counterparts with respect to the operator. For a baseline diesel crane, the genset is located near the base of the RTG crane and the operator cabin sits atop the crane. Thus, operators are largely isolated from the diesel genset's heat and vibration (although not necessarily from its exhaust fumes, which should be reduced for an NZE hybrid version).

[87] Calstart, "Liquefied Natural Gas (LNG) Yard Hostler Demonstration and Commercialization Project", August 2008. http://www.cleanairactionplan.org/documents/sound-energy-solutions-ses-liquefied-natural-gas-lng-yard-hostler-demonstration-and-commercialization-project-1-final-report-august-2008.pdf/ (must be pasted into browser).

[88] Leonard, Jonathan, Patrick Couch, Kent Johnson, and Thomas Durbin. 2021. *Developing, Demonstrating, and Testing Advanced Ultra-Low-Emission Natural Gas Engines in Port Yard Trucks.* California Energy Commission. Publication Number: CEC-500-2021-037.

Effectively, operator comfort should be similar to (or possibly better than) conventional diesel RTG cranes. Notably, noise levels for ZE RTG cranes (no diesel engine) and NZE RTG cranes (downsized diesel engine) are likely to be reduced at ground level, where other workers operate.

Safety

Commercially available ZE and NZE platforms for RTG cranes and yard tractors are being built to similar specifications as existing diesel equipment. Consequently, the safety implications of operating these platforms are not expected to be significantly different than baseline diesel equipment, provided that these platforms are functionally equivalent to their diesel counterparts.

Preliminary trials of one OEM's battery-electric yard tractor identified one particular operational concern for MTOs as they evaluated initial versions of this fuel-technology platform. MTOs noted the inability of pre-commercial electric yard tractors to raise or lower the fifth wheel while in motion. This capability, which is available on all diesel yard tractors used at the Ports, is important to allow drivers to compensate for changes in terrain (dips, rail crossings, etc.) that might otherwise impact the trailer landing gear. This is an example of a specific and important development issue for a single platform that comes to light during MTO demonstrations of pre- or early commercial CHE. This process has helped OEMs continue to improve battery-electric yard tractors, using ongoing engineering improvements that have resulted in newer generations of early commercial models. In this case, the OEM is improving structural integrity to help ensure that its battery-electric tractors are able to safely pull heavy loads and perform difficult maneuvers while connected to the chassis.[89]

During the C-PORT demonstration conducted at the Port of Long Beach (Long Beach Container Terminal) under CARB funding, MTO testing of an "initial prototype" hydrogen fuel cell yard tractor revealed important safety-related problems. During a test drive of the tractor, "it was discovered that the fifth wheel boom collides with the hydrogen fuel tank when making a required jack knife maneuver to back up to the bombcart." This was deemed to be "a significant safety concern that needed addressing," although it was not related to the hydrogen fuel cell technology itself. Ultimately, safety and other related concerns (e.g., failure to meet standard yard tractor specifications) with this pre-commercial platform led the Port to cancel its demonstration, in consultation with CARB staff.[90]

This type of "learning curve" issue illustrates an important point raised by MTOs. As new equipment platforms are developed – at least during the period of technology transition – they should operate in essentially the same manner as their diesel counterparts. This is particularly important for marine terminals, which rely on a labor pool of drivers that are not dedicated to a single terminal. Hence, differences in the operation of equipment between terminals can reduce efficiency, require resource-intensive training of a large workforce on multiple platforms, and perhaps most importantly create safety issues.

Additionally, safety concerns have been raised in the past about use of natural gas or batteries in HDVs such as yard tractors. Examples center on the risk of failures and accidents associated with their on-board fuel/energy storage systems. While these concerns are reasonable to raise, it is important to note that tens of thousands of heavy-duty natural gas vehicles (both CNG and LNG) have been deployed in the U.S. The current body of literature does not support the idea that these vehicles pose a higher risk relative to diesel vehicles. Similarly, over 1.7 million light-duty plug-in EVs have been deployed in the U.S. through 2020[91] and an estimated 600 heavy-duty transit vehicles are in operation (2019 data).[92] While it is true that HDV batteries store higher energy levels compared to the battery packs of light-duty vehicles, existing demonstrations and data do not provide evidence of higher risks for battery-electric HDVs relative to their diesel counterparts. However, this does not diminish the importance of designing adequate safety features into emerging-technology CHE, and this includes the need to train first responders to be prepared for unlikely emergencies.

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[89] Port of Long Beach, personal communication from staff to GNA, November 2021.

[90] Port of Long Beach, "The Commercialization of POLB Off Road Technology (C-PORT) Demonstration Final Report, prepared for the California Air Resources Board, August 19, 2021, downloaded from https://cleanairactionplan.org/wpfd_file/c-port-polb-final-report-2021-0822-compiled/.

[91] Oakridge National Laboratories, "National Energy Data Book", Table 6.02, 2021

[92] Federal Transit Administration, "2019 Annual Database Revenue Vehicle Inventory," 2021, https://www.transit.dot.gov/ntd/data-product/2019-annual-database-revenue-vehicle-inventory

Fueling/Charging Procedures

Charging of battery-electric yard tractors using conductive, plug-in charging cables is a straightforward practice that requires minimal training for personnel who perform this task. However, additional training is necessary to assess whether the EVSE is functional, and to potentially resolve relatively simple equipment issues at the charging location. Wireless charging solutions are also being demonstrated at the Ports; while these solutions have the potential to reduce needs for additional personnel to charge battery-electric CHE, implementation may require additional driver training to ensure proper positioning of each unit over its charging pad. However, neither charging procedure is expected to pose a significant burden to professional onsite personnel who recharge/refuel CHE.

Fueling of LNG vehicles differs from baseline diesel practices, and requires additional training for onsite personnel who perform this task for LNG yard tractors. However, LNG fueling is routinely conducted by drivers and professional fuelers in many locations across the U.S., including at the SPBP. Wet-hosing with LNG fuel – which is likely to be the practice for large numbers of LNG yard tractors – can create some new logistical challenges for fuelers. The fuel lines that are required for LNG fueling are typically constructed of flexible stainless steel, which becomes significantly less flexible when cooled to cryogenic temperatures. Additionally, the fueler may need to connect a second line, a vent line, to the tank if the pressure inside the tank exceeds certain levels. This typically occurs when the yard tractor has not been operated in several days. The first use of the fuel line will also require the line to be cooled down to cryogenic temperatures before liquid fuel can be transferred. While these issues are not insurmountable, they do potentially increase the time required for fueling an LNG yard tractor. Notably, in the demonstration of 22 LNG yard tractors at Everport (Port of Los Angeles), the inability to refuel LNG yard tractors as fast and conveniently as baseline diesel yard tractors limited their suitability for performing two shifts of operation per day. This largely was due to lack of a practical system for wet fueling LNG CHE (the efficient and relatively fast practice for baseline diesel CHE).[93]

7.3.4. Availability of Replacement Parts and Support for Maintenance / Training

MTOs typically perform most maintenance and repairs of their CHE on-site. Deployment of either ZE or NZE fuel-technology CHE requires additional training of mechanics. It also likely necessitates new investments in facilities and tools to maintain and repair the equipment. For initial deployments of ZE and NZE yard tractors, repairs are likely to be conducted under warranty by OEMs and their distributors. Over the full useful lives, problems can arise with advanced-technology CHE that require additional specialized in-house or outside services. Thus, good service networks are particularly important to the success of these deployments.

Notably, nearly 90 percent of the in-use yard tractors at the two Ports were built by Kalmar and Capacity. DINA yard tractors (built specifically for SSA Terminals) are also prevalent in the joint SPBP fleet. These OEMs have long-established service networks for SPBP MTOs.

Battery-Electric Yard Tractors

As battery-electric yard tractors are currently beginning demonstration in the Ports, the OEM is most likely to any service beyond basic preventative maintenance. Kalmar is able to leverage its existing service networks and assets to provide this support, while BYD is able to rely on its manufacturing facility located in Lancaster, CA, to offer a local source of support for parts and technicians to repair their equipment. Relatively new OEM BYD is establishing the necessary elements to support a maintenance and repair supply chain for yard tractors in Southern California, although this will not be tested until additional equipment is deployed in regular service. Notably, some MTOs specifically commented that BYD's service network did not always provide adequate response time for resolving issues with battery-electric yard tractors, compared to service they typically receive on baseline diesel yard tractors (from other providers).

Natural Gas Yard Tractors

OEM Capacity has dealers and service centers in Southern California that support the existing fleet of 22 LNG yard tractors at Everport, as well as other CHE deployed throughout the Ports and at surrounding facilities. Cummins and its service arms has facilities in Southern California to service and support the natural gas engines that power these yard tractors. This network

[93] Personal communications to GNA from Everport and Starcrest staff, 2021.

of service providers is capable of performing all necessary maintenance and repair of natural gas yard tractors. Additionally, Cummins offers parts and maintenance information through its standard QuickServe system.

Grid-Electric and Hybrid-Electric RTG Cranes

As discussed in the Commercial Availability and Technical Readiness sections of this Assessment, diesel-hybrid and grid-connected RTG cranes are considered mature commercial products. Conventional RTG crane manufacturers like Kalmar and Konecranes, as well as third-party equipment suppliers like Conductix Wampfler and Cavotec, provide established support channels and service networks for their equipment.

7.4. Summary of Ratings for Operational Feasibility

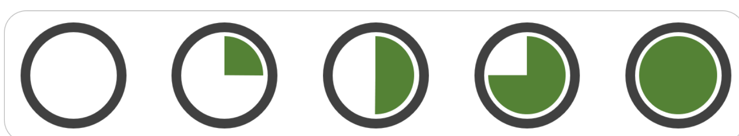
Table 26 summarizes whether yard tractors and RTG cranes with the assessed ZE and NZE platforms are deemed to be "operationally feasible" (as of late-2021). For each of the four possibilities, estimated ratings are provided about the degree to which they already meet these basic considerations as of late-2021, or at least are showing measurable progress towards achieving them by the end of 2024.

Following the table, further discussion is provided about the rationale for assigning these ratings, and the broad implications to the overall 2021 Feasibility Assessment for Cargo-Handling Equipment.

Table 26. Summary of ratings by key criteria: 2021 Operational Feasibility

"Operational Feasibility" Criteria	Base Considerations for Assessing "Operational Feasibility"	Yard Tractors		RTG Cranes	
		ZE BE	NZE NG ICE	ZE Grid-Electric	NZE Hybrid-Electric
Basic Performance	Demonstrated capability to meet MTO needs for basic performance parameters including power, torque, speed, operation of accessories, etc.	◕	●	●	●
Fuel Economy and Endurance	Demonstrated capability to achieve per-shift and daily operating time requirements found at San Pedro Bay terminals.	◑	●	●	●
Speed and Frequency of Refueling / Recharging	Demonstrated capability to meet MTO needs for speed and frequency to refuel / recharge such that revenue operation is not significantly reduced relative to diesel baseline.	◑	◕	◕	●
Operator Comfort, Safety, and Fueling Logistics	Proven ability to satisfy typical MTO needs for comfort, safety and refueling procedures.	◑	◕	●	●
Availability of Replacement Parts and Support for Maintenance / Training	Verifiable existence of and timely access (equivalent to baseline diesel) to all replacement parts needed to conduct scheduled and unscheduled maintenance procedures.	◕	●	●	●

Legend: **Operational Feasibility (2021)**



Little/No Achievement = Progress since 2018 Assessment Fully Achieved

Source: Estimated ratings are based on MTO interviews and site visits, footnoted studies, OEM product information, various government sources, and consultant's industry knowledge.

ZE Battery-Electric Yard Tractors – As shown in the above table, none of the five criteria used to collectively define Operational Feasibility are yet deemed to achieve "full" pies. However, four of the five criteria reflect ¼ pie improvements relative to the 2018 Assessment. Justification for assigning these improved ratings is largely *qualitative* and based on inputs received from multiple OEMs developing battery-electric yard tractors, and/or the marine terminals hosting demonstrations One important source of *quantitative* data is the performance testing performed by UCR under the C-PORT demonstration (as described above), which corroborated that an early commercial Kalmar-TransPower battery-electric yard tractor was able to provide comparable performance to a baseline diesel yard tractor during a typical 8-hour shift. In sum, battery-electric yard tractors are still early commercial products – but they have been shown to meet the basic performance specifications of baseline diesel units (although not consistently) while in revenue service at a SPBP marine terminal.

However, "Operational Feasibility" is a multifaceted parameter that goes well beyond technical performance as reflected in the TRL ratings discussed previously. More OEM work is needed before battery-electric yard tractors will be ready to serve as one-to-one replacements for baseline diesel yard tractors. In particular, OEMs and their technology partners need to increase endurance to enable battery-electric yard tractors to fully complete two shifts without the MTO incurring significant downtime for recharging of battery packs.

Operator comfort and safety are not expected to pose major barriers to adoption for battery-electric yard tractors, and elimination of diesel emissions can improve the health of onsite personnel . Lessons learned from demonstrations of early commercial units are helping OEMs design changes to improve robustness and protection of high-energy battery packs; this is needed for yard tractor impacts that can occur in a marine terminal operating environment. Recharging procedures for battery-electric yard tractors are relatively simple, and training appropriate personnel for these procedures is not expected to pose a barrier to adoption, once charging interfaces have been standardized.

At least three CHE OEMs are developing and commercializing battery-electric yard tractors, including one of the traditional OEMs that dominate yard tractor sales at the Ports (Kalmar). In the current 2021 Assessment, MTOs noted that Kalmar has provided good technical support for issues that arose with their battery-electric units. Both Kalmar and relatively new OEM BYD appear to have the service supply chain components needed to support significant additional deployments of yard tractors, assuming normal replacement intervals. In general, the service network for battery-electric yard tractors appears to be growing, and building confidence in the network's capacity to quickly service and repair increasing numbers of units.

NZE Natural Gas ICE Yard Tractors - Natural gas yard tractors are currently the only ZE or NZE fuel-technology platform clearly *capable* today of achieving MTO endurance requirements. Notably, during the demonstration of 22 LNG yard tractors at Everport Terminals, centralized fueling with natural gas was not conducive for those tractors to achieve two shifts between fueling events; successful fueling logistics for natural gas yard tractors may require a "wet fueling" process to emulate fueling of diesel yard tractors. Fueling rates for LNG yard tractors are comparable to baseline diesel tractors. The fueling process has procedural differences compared to diesel fueling, which may require additional training for MTO operations that rely on mobile fueling. Driver comfort and safety have proven to be equivalent to diesel yard tractors, as natural gas yard tractors are built on the same basic chassis.[94]

The 22 LNG yard tractors that continue to be operated at Everport Terminals are all built by Capacity Trucks, which has a strong existing local support network for its products. These LNG tractors are equipped with CWI's 8.9-liter natural gas engine (20 units) or its smaller 6.7-liter version (two units). Both engines are fully supported by CWI for the key provisions identified in this report (warranty, parts, maintenance, training, etc.). Several major dealerships and service networks exist in the region have proven to be fully capable of servicing these units.

ZE Grid-Connected RTG Cranes - RTG cranes powered directly by the grid are offered by several major RTG crane manufacturers and component suppliers, and they offer similar performance to conventional RTG cranes. Because of this support from manufacturers, the service supply chain is not considered a barrier to adoption. Shift endurance concerns are eliminated by the continuous grid connection but the potential for extended times needed to transition between runs may create losses in operational efficiency. Operator comfort and safety are not expected to pose major barriers to adoption, as the grid-electric versions are nearly identical to existing RTG cranes from this perspective. In addition to eliminating emissions of diesel exhaust (which may reach the operator's cabin above), grid-electric RTG cranes are expected to provide reduced noise and vibration. Section 8 on Infrastructure Availability discusses cost barriers and space constraints MTOs face with building out and using onsite charging stations.

NZE Diesel Hybrid RTG Cranes - Hybrid RTG cranes are effectively direct replacements for conventional RTG cranes that burn significantly less diesel fuel than conventional RTG cranes. They provide the same or greater performance, operational endurance, and operator comfort and safety, while emitting less diesel exhaust to which operators may be exposed. Because NZE hybrid-electric RTG cranes operate on diesel fuel, no changes are required to fueling infrastructure or procedures.

[94] Leonard, Jonathan, Patrick Couch, Kent Johnson, and Thomas Durbin. 2021. *Developing, Demonstrating, and Testing Advanced Ultra-Low-Emission Natural Gas Engines in Port Yard Trucks.* California Energy Commission. Publication Number: CEC-500-2021-037.

8. Assessment of Infrastructure Availability

8.1. Criteria and Methodology

Availability of suitable fueling infrastructure is essential for the Ports to transition to NZE and ZE fuel-technology platforms within the timeframes prescribed by the CAAP. Regardless of the energy form utilized (e.g., natural gas, propane, hydrogen, and/or electricity), marine terminals that deploy ZE and NZE CHE will require convenient, safe and affordable access to fuel.

Note that for the purposes of this Assessment, "infrastructure" includes the fuel dispenser/charger as well as the other equipment and site improvements needed to supply the dispenser. Examples of infrastructure components include storage tanks, pumps, fueling trucks, transformers, switch gear, conduit, piping, and the associated site work needed to install this equipment.

The key criteria and base considerations that were collectively used to assess Infrastructure Availability are listed in Table 27 below.

Table 27: Criteria for establishing Infrastructure Availability for emerging CHE platforms

Infrastructure Criteria / Parameter	Base Considerations for Assessing Infrastructure Availability
Time Required for Fueling/Charging	Fueling/charging can be accommodated within typical work breaks, lunches, other downtime compatible with MTO schedules and operational needs.
Infrastructure Location and Footprint	MTOs have existing onsite access to fueling infrastructure. New infrastructure can be installed without extensive redesign, reconfiguration or operational disruptions and there is sufficient utility capacity at the site.
Infrastructure Buildout	Infrastructure can be constructed at a pace consistent with fleet adoption and able to meet fleet fueling/charging requirements by the end of the assessment period.
Existence of / Compatibility with Standards	A sufficient body of codes and standards exist from appropriate organizations that enables safe and effective fueling/charging. The fueling/charging technology has already been installed at other marine terminals in the U.S., with sufficient time to assess performance and safety.
Source: Based on criteria in San Pedro Bay Ports' "Framework for Developing Feasibility Assessments", November 2017.	

8.2. Important Considerations Associated with the Baseline Diesel Infrastructure

8.2.1. Existing Fueling Infrastructure

Terminal operators primarily use two methods to supply diesel fuel to equipment: 1) on-site fuel storage with mobile fuelers, and 2) contracted mobile fueling services. When diesel fuel is stored on-site, MTOs rely on above-ground storage tanks at fueling pads that are periodically refilled by diesel suppliers. On-site mobile fueling trucks, typically holding between 2,500 and 5,000 gallons of fuel, are refilled at the fueling pads. The mobile fueling trucks then fuel CHE at various locations around the terminal. Under the second method involving a contracted third party, the contractor brings its own mobile fuelers (filled off site) to the terminal, and then provides wet hosing services.

A large terminal might store up to 100,000 gallons of diesel fuel on-site, providing significant reserve capacity to buffer against fuel supply disruptions. As a rough approximation, a fueling pad with 20,000 gallons of storage capacity and a loading area for three mobile fuelers may occupy a 75 feet x 75 feet area. Figure 20 depicts an example fueling pad layout of this sort.

When MTOs utilize mobile fueling services offered by a third party, no on-site infrastructure footprint is required.

8.2.2. Existing Equipment Parking Locations

CHE of various types may be parked in multiple locations across a marine terminal. The desire to locate equipment parking near the area of the terminal where the equipment will work is one consideration when determining parking locations. Additionally, MTOs must consider how operators will reach the equipment (shuttle bus, personal auto, on foot, etc.). Finally, terminal space constraints under existing facility layouts limit the number of units that can be parked in a given location. These combined constraints create significant differences in the quantity of CHE parked in each location. For example, one terminal in the Port of Long Beach has a "main" parking area that accommodates approximately 100 yard tractors and a second area that accommodates 24 yard tractors.[95] These differences in equipment counts do not significantly affect wet hosing strategies for diesel, but may have more significant impacts for other fueling/charging strategies.

8.3. Application of Criteria to LNG Fueling Infrastructure for Yard Tractors

As described in Section 7.3, the integrated system of equipment operating at a marine terminal dictates that operationally feasible alternatives to existing diesel equipment provide a one-to-one replacement. Purchases of additional units to accommodate reduced operational performance of the alternative equipment do not meet the operational feasibility test. Similarly, fueling/charging strategies cannot reduce equipment availability, as this would also require a greater than one-to-one replacement ratio. In the case of LNG fueling, this requirement implies that LNG mobile fueling is the applicable fueling strategy to consider for yard tractors. While there are commercially available options for on-site LNG fueling stations that could function similarly to a standard diesel fuel pump, MTOs do not drive individual yard tractors to fueling pads either on-shift or between shifts, as this would reduce equipment availability and increase labor costs. Therefore, on-site storage of LNG is only applicable to bulk tanks that would be used to refill mobile LNG fueling trucks.

8.3.1. Infrastructure Footprint

For MTOs that store fuel on site, there are two components to LNG fueling infrastructure: 1) the bulk storage tanks and dispenser at the fueling pad, and 2) the mobile LNG fueling trucks. LNG is approximately 40 percent less energy dense on a volumetric basis than diesel fuel. This means that a fleet must store 68 percent more volume of LNG than diesel to have the same amount of fuel energy available. Additionally, spark-ignited natural gas engines are typically about 10 percent less efficient than diesel engines, requiring the fleet to store an additional 10 percent volume of LNG to provide the same operating time as diesel equipment. In total, replacing one gallon of diesel fuel stored on site would require 1.85 gallons of LNG storage. For example, replacing the theoretical 20,000-gallon diesel fueling pad (refer back to Figure 20) would require 37,000 gallons of LNG storage capacity.

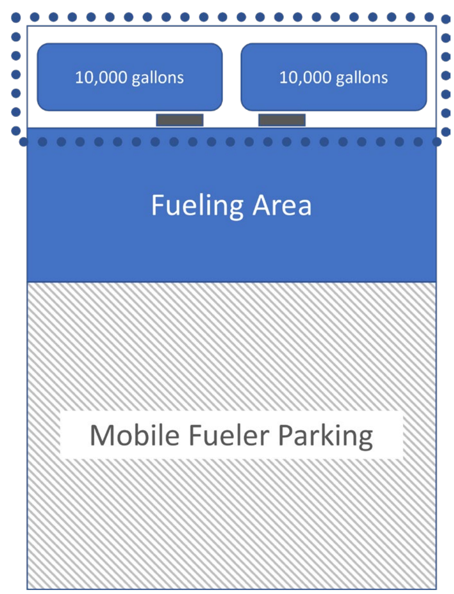


Figure 20. Example layout of an MTO's diesel fueling pad

Bulk storage tanks and dispensers

LNG is often stored in vertical tanks when space is limited. The City of Los Angeles North Central LCNG station, for example, stores 60,000 gallons of LNG in four tanks, requiring approximately 2,000 square feet of space by using a vertical tank configuration. Three tanks, equaling 45,000 gallons of LNG, could fit within the 75-feet width of the example fueling pad layout. This would provide more fuel storage than the typical horizontal diesel storage tank layout. This does not account for every possible fueling pad configuration or location, and the vertical tank configuration may not be viable in some instances.

[95] Port of Long Beach, Proposal to CEC under GFO-16-604.

But as a first approximation, the footprint of LNG fueling stations is assumed to be comparable to existing diesel fueling infrastructure.

The estimated cost of an LNG station with 45,000 gallons of storage is $1.6 million.[96] Additional storage could be added relatively easily at a cost of approximately $250,000 per 15,000 gallons, provided sufficient space exists.[97]

Mobile fueling trucks

Several "mobile" LNG fueling solutions exist and have been used to support demonstrations or small deployments of LNG equipment. For example, Chart Industries manufactures the Orca LNG mobile fueling station.[98] This system is available in three configurations, including two trailer configurations and one chassis configuration (Figure 21). The chassis configuration is similar to a conventional diesel fueling truck. The usable capacity of the truck is approximately 2,755 gallons, equivalent to about 1,640 diesel gallons. This is a lower capacity than the typical 2,500 to 5,000-gallon fuel trucks currently operated by MTOs. When accounting for the need to dispense more LNG due to the reduced efficiency of spark-ignited engines, the effective fuel capacity of the mobile fueler is approximately 1,480 diesel gallons. When the mobile fueler runs out of fuel, it must return to the fueling pad to be refilled. The additional time to refill the mobile fueler will extend the time needed to fuel the fleet of yard tractors, and may require MTOs to deploy additional mobile fuelers to complete fueling within the available fueling window prior to the first shift.

Figure 21. Examples of mobile LNG fueling stations (photos from Chart Industries)

8.3.2. Infrastructure Buildout

An estimate of the total diesel fuel stored at MTOs for yard tractor use was developed based on the estimated fuel consumption of the 1,615 yard tractors currently operating in the ports over a standard 2-shift schedule. Assuming 16 hours of operation at 2.5 gallons/hour, the daily fuel consumption for the yard tractor fleet would be 64,600 gallons. During interviews, MTOs indicated that up to 10 percent of their fleet can be out of service at any given time, reducing the estimated daily fuel consumption to 58,100 gallons. Assuming a five-day storage capacity, this would imply that MTOs currently store approximately 290,000 gallons of diesel fuel (or other diesel equivalent volumes for the 17 percent of the yard tractors that operate on gasoline or propane). This would equate to 538,000 gallons of LNG storage. Fueling pad sizes and numbers vary by terminal, and a complete survey of all fuel storage locations was not conducted as part of this Assessment. However, using

[96] Based on Clean Energy's construction costs for its Anaheim & I street LNG station. Originally constructed with 30,000 gallons of storage at a cost of $1.45 million, an additional $250,000 is added to account for a third 15,000-gallon storage tank and $150,000 is deducted to account for elimination of retail LNG dispensers and associated equipment. http://www.cleantransportationfunding.org/sites/default/files/MS08056_Clean_Energy_Final_Report.pdf

[97] Author's industry experience.

[98] Chart Industries, Orca LNG Delivery System, http://files.chartindustries.com/14901969_OrcaLNG_2013.pdf

the theoretical 45,000 LNG gallon bulk storage/fueling pad as a typical fueling pad would imply that 12 fueling pads of this size would be required. This number would also allow for one LNG storage/fueling location per container terminal in the ports. The total capital cost of this infrastructure build-out would be approximately $19.2 million. It is unlikely that 12 fueling pads could be converted to LNG within the three-year timeframe of this Assessment when design, permitting, and construction timelines are considered. However, from a construction timeline perspective, it is expected that this infrastructure could be built out prior to 2030.

The following is an example based on the specifics for one major SPBP marine terminal. The MTO uses two personnel to fuel 75 yard tractors; this occurs after the second shift of the day.[99] Assuming a standard 2-shift schedule, this implies each yard tractor would require approximately 40 gallons of fuel, or a total of 3,000 gallons for all 75 yard tractors. With two fuelers each filling approximately one yard tractor every five minutes (consistent with a dispensing rate of 10 gallons per minute), the two-person crew would fuel all 75 yard tractors in three hours, utilizing two mobile fueling trucks. Extrapolating to the entire yard hostler fleet serving the SPBP (approximately 1,615 yard tractors), it is estimated that 45 diesel mobile fuelers are required to service the existing fleet. As discussed in Section 8.3.1, the capacity of an LNG mobile fueler is approximately half that of the 3,000 diesel gallons carried by a diesel mobile fueling unit. Therefore, it is assumed that 90 LNG mobile fuelers would be required to fuel the total fleet of yard tractors. Additionally, extra skilled personnel would be required to operate the mobile fuelers, at a fully loaded cost of up to $300,000 per person per year. The additional labor costs could be as much as $13.5 million per year (across all 13 SPBP terminals under this scenario).[100]

LNG mobile fuelers often also serve as fixed LNG fueling stations, to which vehicles travel for fueling. This is particularly true of trailer-based versions of the mobile fueler. Examples of such applications include the LNG fuel supply for yard tractors previously operating at the NFI facility (formerly California Cartage) near the Ports, and the temporary LNG fuel station for the Everport demonstration of twenty NZE LNG yard tractors (8.9-liter CWI engine). To the authors' knowledge, no LNG wet hosing operations have been demonstrated yet at a marine terminal (or under similar conditions), and it is unknown what permitting timelines and requirements might be imposed on MTOs. Demonstrations of an LNG wet fueling operation from a mobile fueler would provide significant new insight for MTOs as to the viability of such an approach. Unless and until a practical system exists for wet fueling of NZE natural gas yard tractors, MTOs may be unwilling to risk two shifts of operation.

8.3.3. Codes and Standards

LNG fueling stations are regulated by well-defined codes and standards that define tank construction, connector types, and safety systems. Similarly, LNG fuel system standards and component supplies for heavy-duty trucks are well known by the major suppliers of LNG equipment. Compatibility of equipment and infrastructure, or creation of stranded assets due to changes in equipment standards, are not considered significant risks with respect to LNG fueling.

It is also important to note that, while codes and standards exist for natural gas fueling infrastructure, the permitting requirements imposed by local authorities can create significant barriers to infrastructure development. Code and standard requirements vary by jurisdiction and permitting entity. Where a local authority is unfamiliar with natural gas fueling stations, time may be required to educate the local authority regarding the appropriate codes, standards, and best practices before a permit can be secured. Additionally, local authorities may require that some equipment be listed by a particular listing entity (e.g., Underwriters Laboratories), when the equipment has been listed by an alternative agency.[101] Listing equipment with a new agency is a time-consuming, costly process that can significantly delay or even terminate a project. However, it is noteworthy that temporary, small-scale natural gas fueling stations such as those used for the Everport LNG yard tractor demonstration are different than commercially proven stations, such as those used to fuel approximately 900 LNG drayage trucks serving the two Ports.

[99] Port of Long Beach, "Zero-Emissions Terminal Equipment Transition Project," Proposal to the California Energy Commission under solicitation #GFO-16-604, January 2017.
[100] Ibid.
[101] For example, the start of the demonstration of 22 LNG yard tractors at Everport (POLA) was significantly delayed because the City of Los Angeles required UL listing of the LNG fuel skid as a whole, even though each individual component was already UL listed. Notably, LNG stations of the same design were already in use locally (outside the Ports).

These are only some of the potential barriers that may be encountered in the permitting process for infrastructure build-out projects involving emerging alternative fuels like natural gas (or hydrogen). Many municipalities now have examples of operational natural gas fueling stations in their jurisdiction (including both the City of Long Beach and City of Los Angeles, and adjacent to the Ports in Wilmington); this fact should help facilitate permitting of additional stations. However, projects that have unique attributes (wet hosing, temporary stations, proximity to certain activities/facilities, etc.) can face unexpected or new permitting challenges that extend timelines and add costs.

8.4. Application of Criteria to Battery-Electric Charging Infrastructure for Yard Tractors

Charging infrastructure can be designed to charge vehicles at a wide range of power levels, ranging from a few kilowatts to several megawatts. Specifications and design of the vehicles/equipment to be charged dictate the maximum charging rate, while operational requirements determine the minimum acceptable charging rate. Currently available yard tractors considered in this Assessment have charging rates ranging from 70 kW to 120 kW. As summarized in Table 25, current battery capacities require charging rates of up to 160 kW, to enable a yard tractor to complete an extended 2-shift schedule. However, high charging rates generally incur higher utility costs, require costlier infrastructure, and accelerate deterioration of the vehicle batteries. If future platforms provide enough battery capacity to operate for 20 hours between charging events, the charging window could be extended from 45 minutes (between first and second shift) to 1.75 hours (between second and first shift on an extended 2-shift schedule). This would reduce the charging power to approximately 65 kW per yard tractor, substantially reducing the peak power demand that must be supplied to the terminals as well as reducing electricity costs and battery degradation rates.

8.4.1. Infrastructure Location and Footprint

Due to the relatively longer charging times required for EVs as compared to diesel fueling, the only charging strategy currently being demonstrated that has the potential to maintain a one-to-one equipment replacement ratio with diesel yard tractors is the charging of electric yard tractors at their parking locations between shifts. There are at least three charging interfaces currently being demonstrated, including charging cables that are manually plugged in, systems that automate connection of the charging cable, and wireless inductive charging systems. (Additional interfaces may be under consideration.) Each of the three approaches currently under demonstration has advantages (pros) and disadvantages (cons), as summarized in Figure 22.

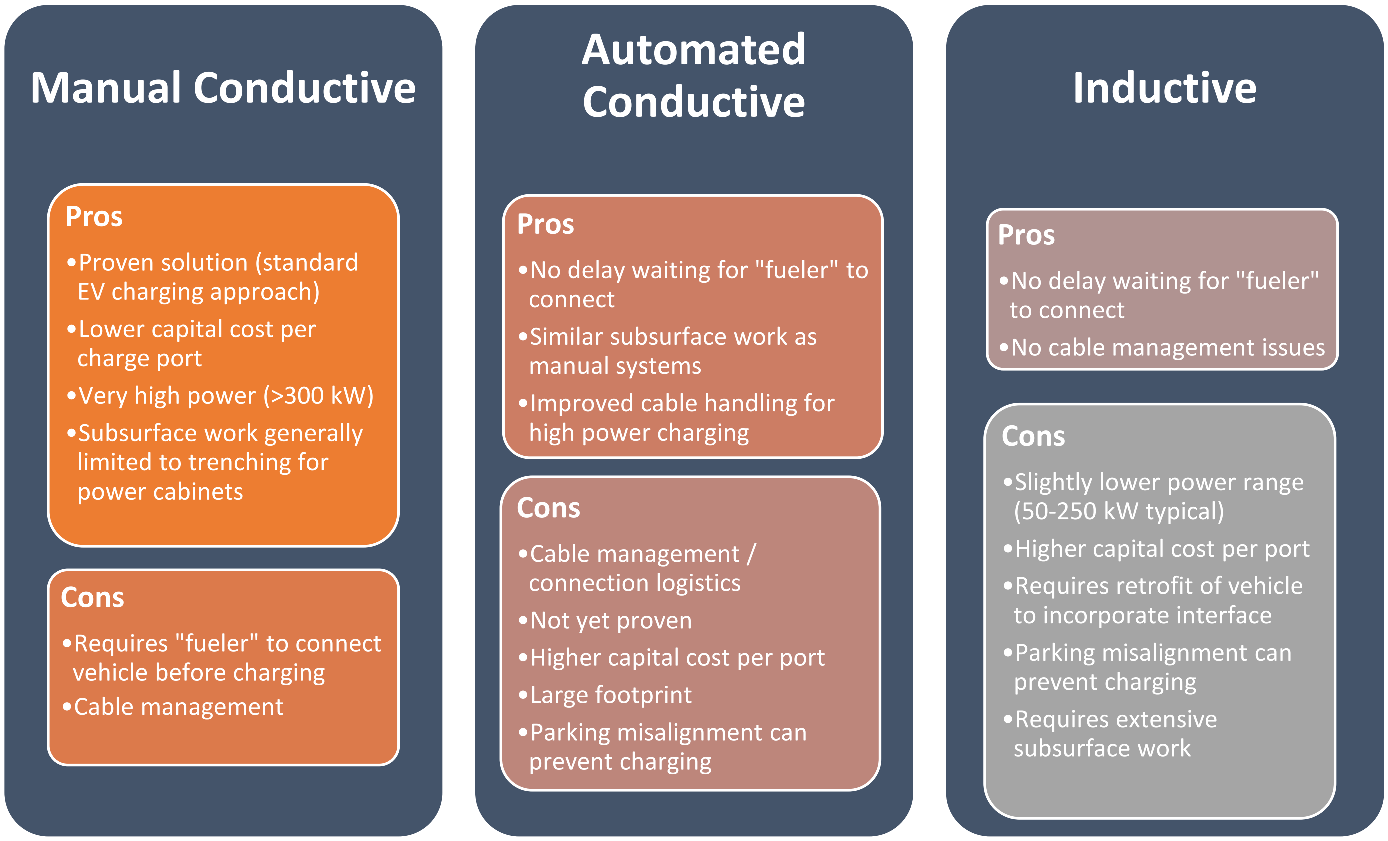


Figure 22. Comparison of EV charging interfaces

Manual conductive interfaces are standard EV charging cables that are plugged in by MTO personnel. They are simple, proven systems. However, because they must be plugged in manually, the available charging window for CHE is reduced for this method of charging interface. Cable management can also be an issue, particularly when trying to service CHE parked in lanes or stacked stalls. Particularly for larger plug-in CHEs using high-power charging systems, existing cable and connector sizes can pose ergonomic hazards, due to weight and body alignment in picking up and connecting the charger cable.

Automated conductive interfaces (see for example www.Cavotec.com) allow a battery-electric CHE to be connected immediately after parking, avoiding lost recharging time waiting for personnel to connect the vehicle. Additionally, these systems can handle large heavy cables necessary for high power transfer that might otherwise by difficult for personnel to manage manually. However, these interfaces are effectively robotic systems that have a larger on-site footprint than a typical charging pedestal and are limited in their ability to serve CHE parked in lanes or stacked stalls.

Inductive charging interfaces have the advantage of reducing space claims within the parking area, as there are no charging pedestals or cable management systems to work around. They also avoid the need for bollards that restrict existing traffic patterns and present crash hazards. However, they require substantial subsurface work in each parking location to embed the inductive coils.

The Ports are currently engaged in demonstrations using all three types of charging interface. These demonstrations should provide significantly greater understanding of the benefits and challenges of each interface type within the marine terminal environment. For the purposes of this Assessment, electric vehicle/equipment charging infrastructure is based on existing manual conductive interfaces that use either high power AC or DC charging.

Infrastructure Footprint

Charging infrastructure includes all of the equipment needed to bring charging interfaces to the parking locations for CHE to be charged (yard tractors, in this discussion). A cursory review of yard tractor parking locations at various marine terminals indicates that these ubiquitous CHE are typically parked in locations that can accommodate approximately 25 to 100 units. Referring back to the estimated power demand for charging current-technology yard tractors shown in Table 25, accommodating 25 to 100 charging interfaces would require between 4 and 16 MW. Given the large size of these loads, it is anticipated that the utilities would construct new service entrances near the parking areas. In this case, an MTO would anticipate providing space for the utility equipment (transformer, meter set, and associated equipment) and customer-side switchgear to distribute the power to either DC fast charger power cabinets or EVSE.

Estimating the footprint of the utility and customer equipment is problematic because specific site conditions significantly affect the actual footprint at each site. Furthermore, infrastructure footprint does not scale directly with power level. In other words, infrastructure for a 16 MW supply is not necessarily four times larger than the footprint for a 4 MW supply. With these limitations in mind, it is estimated that typical footprints would be on the order of 500 to 2,500 square feet.

Relative to the example fueling pad described for diesel fueling, the electrical infrastructure for charging yard tractors (excluding power cabinets or EVSE) is expected to be of similar or lesser footprint. Pro-rating the example fueling pad area (refer back to Figure 20) by 50 percent – to reflect the portion of the pad that effectively serves yard tractors – yields an estimate of roughly 2,800 square feet. This suggests that electrical infrastructure footprints are comparable to diesel fueling infrastructure footprints, with the recognition that the electrical infrastructure does not include any on-site energy storage. It must be noted, however, that existing diesel fueling pads service multiple equipment types whereas EVSE will likely need to be deployed 1:1 per piece of equipment; this will significantly add to the total footprint required to deploy enough stations for an entire fleet.

The footprint for charging infrastructure at the parking location must also be considered. When yard tractors utilize AC charging, power electronics onboard the yard tractor handle the conversion between AC and DC power. This significantly reduces the size, cost, and complexity of the external charging equipment as compared to a DC fast charger. Additionally, AC EVSE are much lighter than DC fast chargers for the same power rating. As a point of comparison, consider that a BYD 80 kW AC EVSE weighs approximately 70 lbs. and is approximately 16 inches wide by 8 inches deep.[102] A typical DC fast charging cabinet with a similar power rating will weigh more than 1,000 lbs. and is similar in size to a large refrigerator. The smaller size of the AC EVSE allows for more flexibility in locating the equipment on walls, poles, or other structures; whereas DC fast chargers are ground mounted and usually placed at the head of a parking stall. However, BYD's shift to CCS-1 standard charging interfaces suggests that yard tractors may begin to standardize around DC fast chargers rather than OEM-specific AC interfaces. Because CCS1 equipped yard tractors are demonstrating the higher charging rates needed for inter-shift charging, this Assessment considers DC fast charging to be the representative technology for battery-electric yard tractors going forward. If the endurance of battery-electric yard tractors increases and allows the required charging rate to decrease to 65 kW, as previously discussed, this would allow for 70-80 kW AC charging interfaces.

The use of DC fast charge (DCFC) equipment creates significant logistical challenges for yard tractors parked in lanes. Cable lengths of up to 33 feet (10 meters) are compliant with the current CCS DCFC standard.[103] For yard tractors parked in lanes, the cable length limits mean that the DCFC cabinets would be placed between the lanes. The spacing between lanes is typically on the order of 4 feet, allowing clearance between yard tractors and walkways for operators. However, when accounting for typical cabinet widths (approximately 3 feet) and the need for protective bollards, the DCFC equipment would likely occupy the full space between the lanes or exceed the space. In either case, the MTO would be required to reconfigure the parking area to accommodate an additional 4 feet between lanes. As the lanes are currently sized to accommodate the typical 8-foot width of a yard tractor, reconfiguring the lanes to accommodate the DCFC equipment would effectively require removing one lane of parking for every two lanes electrified. Hence, an increase of 50 percent in yard tractor parking area would be required for yard tractors parked in lanes. A review of lane parking configurations at three terminals indicated that MTOs dedicate

[102] BYD, "BYD Electric Vehicle Charging Solutions," accessed on December 7, 2021 at https://sg.byd.com/wp-content/uploads/2017/12/K9%C2%A6-%C2%A6%C3%BA%C2%BF%C3%B3-%C2%A6%C2%B5%C3%BA%C2%BC%C2%A6%C2%A6%C3%B1-%C2%A6O%C3%B3%C3%BA%C2%AC.pdf.

[103] ISO 15118-3 standard for vehicle to grid communications interface.

roughly 400 square feet per yard tractor for parking and associated walkways and lanes. For a 100-unit parking area, a DCFC charging strategy would imply an increase in required space of 20,000 square feet (0.5 acres).

When yard tractors are parked in stacked stalls, two DCFC cabinets and dispensers must be placed at the head of each stall. Allowing for typical equipment service clearances, approximately ten feet of additional space is required at the head of the stall to allow for the equipment and protective bollards. Assuming a two-foot spacing between the yard tractors, the straight-line distance from the dispenser to the second yard tractor in the stall would be around 23 feet. Allowing for three feet of cable length inside the cabinet, the minimum possible cable length would be 26 feet, leaving 7 feet of cable to accommodate cable management systems and provide slack to prevent excessive pressure on the charging connectors. This length is marginal for such purposes, but potentially feasible. Based on the assumed parking clearances of two feet around yard tractors parked in stalls, DCFC equipment would require approximately 100 square feet (10' equipment depth x 10' stall spacing) of additional space per two yard tractors. Hence, a 100-unit parking area would require an additional 10,000 square feet of space (0.25 acres).

Customer-side costs for electrical infrastructure upgrades to support DCFC equipment are estimated at approximately $50,000 per charging spot, based on POLB engineering experience with recent electric yard tractor demonstration projects. These costs do not include the charger, which may be in excess of $100,000 per unit for 150 kW charging rates. Taken together, an estimated cost of $150,000 per yard tractor is assumed for DCFC infrastructure costs.[104] These costs do not include any costs that might be borne by the utilities to provide utility-side infrastructure upgrades, nor include work that might be required to reconfigure terminal areas to allow for increased parking space or additional electrical equipment, particularly during a transitional period between diesel and electric equipment where infrastructure for both would be required.

8.4.2. Infrastructure Buildout

To provide 150 kW charging stalls for the combined 1,615 yard tractors in the ports would require 242 MW of charging infrastructure. A very large terminal can operate 180 yard tractors on a busy day, resulting in a peak charging demand of 27 MW. To put this electricity demand in context, a study by UCLA's Luskin Center found that the largest terminals, such as APMT, currently experience peak demands of 10 to 15 MW.[105] Providing charging for an electric yard tractor fleet of this size would roughly triple a terminal's baseline power demand. While the exact aggregate load that would need to be served by SCE and LADWP has not been estimated, these are clearly substantial load increases in the port region that would require investment from both utilities.

Fortunately, the total (non-diversified) power demand only represents about one percent of the combined peak load of 30 GW in the LADWP and SCE territories (see Table 28). Consequently, it is not assumed that LADWP or SCE would need to make substantial system-wide upgrades or secure additional generating resources to serve the new loads. This Assessment only considers incremental load from potential grid-charged CHE deployments evaluated in this report. Additional electrification of other loads (e.g., for alternative marine power, terminal upgrades, drayage truck charging) within the twin Ports complex (as well as other regional electrification efforts) will create incremental power and energy demands that exceed those shown in the table.

Table 28. Size of SCE and LADWP Utilities

Indicator	Southern California Edison[106]	Los Angeles Department of Water and Power[107]
Service Territory (mi^2)	50,000	464
Service Population (ppl)	15,000,000	1,500,000
2020 retail sales (MWh)	85,399,000	21,130,000

[104] The Ports have estimated higher costs (up to $344,000); there is a substantial degree of uncertainty about actual costs. It is anticipated that new and better cost estimates for infrastructure will emerge as the many demonstrations progress.
[105] UCLA Luskin Center, "Moving Toward Resiliency", 2013
[106] Edison International, "Edison International and Southern California Edison 2020 Annual Report", 2021, https://www.edison.com/content/dam/eix/documents/investors/sec-filings-financials/2020-eix-sce-annual-report.pdf
[107] Los Angeles Department of Water & Power, "Briefing Book: 2019-2020", https://www.ladwp.com/cs/idcplg?IdcService=GET_FILE&dDocName=OPLADWPCCB629209&RevisionSelectionMethod=LatestReleased

2020 peak load (MW)	23,133	6,502[108]
2020 Capital Projects Budget ($)	5,536,000,000[109]	1,600,000,000[110]

Before infrastructure can be designed and installed by either the MTOs or the utilities, a clear understanding of the performance and charging requirements of battery-electric yard tractors must be developed. Current demonstrations are expected to provide significantly more important information for these stakeholders. However, most of these demonstrations will not be completed (including their final reports) within the three-year timeframe of this Feasibility Assessment. It is therefore unlikely that sufficient charging infrastructure could be designed and installed within this timeframe.

8.4.3. Codes and Standards

EV charging infrastructure vendors have rapidly developed and improved their products over the last decade, as multiple battery-electric vehicles (especially light and medium duty) have come to market. However, there are numerous charging standards in use in the U.S., and the HDV industry has yet to unify around a particular interface. For current-technology battery-electric yard tractors identified in this Assessment, there are two types of charging standards in use:

- **Combined Charging System (CCS)** – In the U.S., the CCS Type 1 connector is commonly used on U.S. and German auto manufacturers' vehicles and on various heavy-duty trucks and buses. Rates of 50 kW are common for light duty vehicles but the standard supports charging rates of over 350 kW. These higher power rates may require the use of liquid cooled cables. Additionally, the standard contains specifications for overhead (catenary) charging interfaces, but these interfaces are currently only being applied to transit buses in the U.S. Long term, the CCS standard is being revised to support charging rates of over 1.6 MW, intended to support heavy-duty trucking and similar applications.
- **Proprietary AC/On-board Charging** – Some heavy-duty vehicle manufacturers integrate battery charging power electronics on-board the vehicle, allowing the vehicle to accept standard AC utility power – typically as 240V single phase or 208-480V three phase power. The external "charging" equipment is technically EVSE that acts primarily to safely connect, monitor, and disconnect the AC power from the vehicle. Because the power electronics are incorporated into the vehicle, the external EVSE can be significantly less expensive than comparable DC fast chargers. Such on-board power electronics systems are typically proprietary to a specific vehicle manufacturer.

Note that the GB/T 20234 standard identified in the 2018 Assessment was utilized on first-generation BYD yard tractors, but it has since been replaced with a CCS-1 standard interface.

The CCS standard may be the emerging winner for charging heavy-duty on-road battery-electric vehicles; it is currently unclear if this standard will apply for charging yard tractors. Alternatively, inductive charging may ultimately be a solution if infrastructure footprint becomes the primary barrier to adoption. The landscape for heavy-duty EV charging infrastructure is rapidly maturing and a single standard has yet to emerge as the clear winner. This is an existing barrier that stakeholders repeatedly stress will need resolution before any large-scale roll out of heavy-duty battery-electric vehicles is likely to occur.[111] The Ports are taking action to help address such barriers. For example, the Port of Long Beach published the first-ever Port Community Electric Vehicle Blueprint, which includes project elements to identify optimal procedures and locations for charging heavy-duty battery-electric vehicles and equipment.[112]

The existence of codes and standards for electric charging infrastructure do not guarantee that local authorities will not impose additional permitting requirements that can create significant barriers to infrastructure development. The diversity of charging equipment and associated power levels can further add complexity to the permitting process, as local authorities may have experience with light-duty charging infrastructure but not with heavy-duty charging infrastructure. While these issues will ultimately be addressed as local authorities and infrastructure developers gain experience, early infrastructure

[108] This peak was set in 2017. Peak demand reductions since 2017 have slightly reduced this figure in 2020 but specific values were not readily available.
[109] SCE reported this amount in capital expenditures for 2020.
[110] LADWP reported this amount of its budget dedicated to capital projects.
[111] Peer review input to authors by National Renewable Energy Laboratory, November 2018.
[112] Port of Long Beach, "Port Community Electric Vehicle Blueprint," May 2019, https://polb.com/environment/our-zero-emissions-future/

projects are likely to require more time to permit than later projects. This may slow the pace of infrastructure development in the near-term. (See Section 8.3.3 for additional discussion about permitting challenges.)

8.5. Application of Criteria to Infrastructure for Grid-connected RTG Cranes

A typical marine terminal at the SPBP uses a combination of RTG cranes and top handlers (including side handlers) to perform the majority of vertical moves of containers within the terminal. Top handlers perform approximately three-quarters of vertical moves. The remaining 25 percent are handled by RTG cranes, with these operations largely concentrated on moving inbound, loaded containers to drayage trucks.[113] RTG cranes operate along "runs" that include pavement striping for the container stack area and a lane for drayage trucks and yard tractors. The lengths of these runs exceed one mile at some terminals.

8.5.1. Infrastructure Location and Footprint

Electrification options for RTG cranes include the installation of busbars or power cable systems that run parallel to the RTG crane run. Cable systems plug in at either end of a run and use large reels to deploy and retrieve the cable as the RTG crane travels, while busbar systems utilize a set of contactors that slide along the busbar. One challenge with many of these electrification systems is that the busbar or cable trays must be installed above ground and prevent a top handler from working one side of the container stack. Additionally, when MTOs need additional storage space, they may choose to stack containers across multiple RTG crane runs and work those stacks with top handlers. In either case, the installation of permanent, above ground busbars or cable trays reduces operational flexibility for MTOs.

Fortunately, there are cable reel systems that allow for below-grade connections. One such configuration is currently being constructed for demonstration at Pier J in the Port of Long Beach. This system utilizes a trench and flexible covering system to allow the cable to be placed below grade as the RTG crane travels. Additionally, the power connecters are placed in below grade vaults, allowing unobstructed access to the stacks and terminal area. Because this approach has the least operational impact on MTOs, it is the configuration assumed for the purposes of this Assessment.

The primary infrastructure required for a grid connected RTG crane using the subsurface cable reel system described above includes modifications to existing utility substations, switchgear, substations on the terminal, subsurface vault for power connections, and the cable trench system parallel to the RTG crane run. Based on costs from SCE in its proposed Transportation Electrification Proposals for 2017, the utility estimates the costs of infrastructure improvements to be $3 million for nine RTG cranes. [114] This includes providing a total of four distribution points along two RTG crane runs. Note that these costs only include utility-side upgrades and do not include terminal-side costs, estimated at $8 million for the nine RTG cranes. Because the majority of the system is below grade, the primary footprint of the electrification infrastructure is two transformer pads that reduce the incoming 12 kV utility supply to 4,160V for the RTG crane system. Based on discussions with POLB engineering staff, the footprint for these stations is small at approximately 100 to 200 square feet.

8.5.2. Infrastructure Buildout

Hybrid-electric RTG cranes require no additional infrastructure. The buildout of infrastructure to support full RTG crane electrification is dependent on a combination of utility improvements, terminal modifications, and equipment modifications/replacements. There are approximately 125 baseline diesel RTG cranes in the Ports 2020 emissions inventories that would require either conversion to grid-connected systems or replacement with new grid-connected RTG cranes. It does not appear practicable to replace or retrofit this quantity of RTG cranes within the three-year study period of this 2021 Feasibility Assessment.[115] Additionally, infrastructure design, permitting, and construction for every RTG crane lane at every

[113] Moffatt & Nichol, "Sustainable Freight Strategy Impact Study," Technical memorandum prepared for PMSA. 2015. http://www.pmsaship.com/pdfs/PMSA%20Sustainable%20Freight%20Strategy%20Impact%20Study%20Tech%20Memo%208918%20Final.pdf

[114] Southern California Edison, Testimony of Southern California Edison Company in Support of its Application of Southern California Edison Company (U338-E) for Approval of its 2017 Transportation Electrification Proposals, Document #: A1701021-SCE-01

[115] For example, it took approximately five years to retrofit nine conventional RTG cranes to ZE grid-electric at Pier J (POLB), according to officials familiar with the project.

container terminal could not be completed within this timeframe. However, it is reasonable to assume that such an infrastructure build-out and deployment could be completed by 2030.

To fully electrify all 156 diesel-fueled RTG cranes at the Ports (including approximately 31 advanced hybrid units), it would require 110 kW per RTG crane, for a total of 17 MW in new distribution infrastructure. A very large terminal can operate 20 to 30 RTG cranes on a busy day, resulting in a peak power demand of 2.2 to 3.3 MW. These load estimates have been significantly reduced from the 2018 Assessment, based on the assumption that future grid-connected RTG cranes will employ batteries to buffer transient loads from the grid. As previously noted, the largest terminals, such as APMT, currently experience peak demands of 10 to 15 MW.[116] Providing power for grid-connected RTG cranes would represent an increase of roughly 20 to 30 percent of a terminal's current power demand. While the exact aggregate load that would need to be served by SCE and LADWP has not been estimated, these are meaningful load increases in the twin Ports complex and region, which would require significant new investments from both utilities.

As previously discussed in Section 8.4.2, these loads are significant in a localized context around the ports, but they are small relative to the combined loads of the SCE and LADWP systems. Consequently, it is not assumed that LADWP or SCE would need to make substantial system-wide upgrades or secure additional generating resources to serve the new loads. There are, however, constraints within transmission and distribution systems that must effectively move power from generation sources to areas of concentrated power demand like the Ports. As documented in a 2019 Port of Long Beach report titled "Port Community Electric Vehicle Blueprint," major challenges can arise with greater reliance at the Ports for electrical power "from an aging utility grid." For example, California Governor Gavin Newsome issued a "Proclamation of a State of Emergency" in July 2021 that effectively prohibits terminal operators from using shore power for berthing ships during power emergencies.[117] With increased grid reliance, marine terminals may become more vulnerable to planned and unexpected grid outages, which already periodically cause terminals to close (sometimes for many hours). In sum, while there may be plenty of generating capacity from the combined SCE-LADWP systems to handle large new loads from expanded electrification, *resiliency* impacts must be understood and addressed. As has been documented, terminal shutdowns due to loss of grid power can lead to "devastating economic impacts."[118]

8.5.3. Codes and Standards

The types of electrical infrastructure required for grid-connected RTG cranes are largely standard electrical equipment for industrial facilities. There are well defined codes and standards that will be used for any such installations. The most likely potential challenge related to codes and standards may be focused on non-listed equipment. Typically, when issuing construction permits the cities of Los Angeles and Long Beach both require that equipment be listed with an approved national testing lab. In fact, all equipment operating in the County or City of Los Angeles requires certification to standards promulgated by Underwriter Laboratories (UL). Newly developed products may not be listed and this can either preclude a permit or delay construction while on-site certification is performed. This requirement has resulted in significant project delays to get new charging infrastructure and fueling stations into revenue-service operation.[119] However, there does not appear to be a fundamental barrier related to codes and standards that would preclude deployment of grid-connected RTG cranes.

8.6. Summary of Ratings for Infrastructure Availability

Table 29 summarizes whether, according to the specific criteria and base considerations outlined above, the two commercially available CHE types with corresponding ZE or NZE platforms are deemed to have sufficient "infrastructure

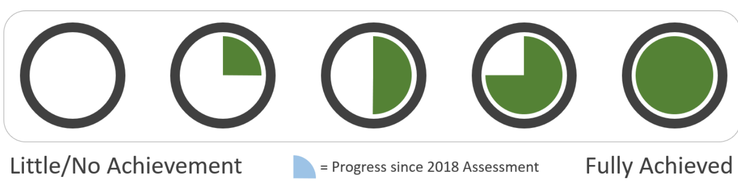
[116] UCLA Luskin Center, *Moving Toward Resiliency*, 2013
[117] State of California, Governor Gavin Newsom, "Proclamation of a State Emergency," Executive Order 7-30-21, accessed from https://www.gov.ca.gov/2021/07/30/governor-newsom-signs-emergency-proclamation-to-expedite-clean-energy-projects-and-relieve-demand-on-the-electrical-grid-during-extreme-weather-events-this-summer-as-climate-crisis-threatens-western-s/.
[118] Port of Long Beach, "Port Community Electric Vehicle Blueprint", May 2019, https://polb.com/environment/our-zero-emissions-future/.
[119] California Air Resources Board, "Appendix A: Clean Transportation Investment Project Summaries," Proposed Fiscal Year 2020-21 Funding Plan for Clean Transportation Incentives, November 2020, https://ww2.arb.ca.gov/our-work/programs/low-carbon-transportation-investments-and-air-quality-improvement-program/low-1.

availability" (as of late-2021).

Table 29. Summary of ratings by key criteria: 2021 Infrastructure Availability

"Infrastructure Availability" Criteria	Base Considerations for Assessing "Infrastructure Availability"	Yard Tractors		RTG Cranes	
		ZE Battery-Electric	NZE NG ICE	ZE Grid-Electric	NZE Hybrid-Electric
Time Required for Fueling/Charging	Fueling/charging can be accommodated within typical work breaks, lunches, other downtime compatible with MTO schedules and operational needs.				
Infrastructure Location and Footprint	MTOs have existing onsite access to fueling infrastructure. New infrastructure can be installed without extensive redesign, reconfiguration or operational disruptions and there is sufficient utility capacity at the site.				
Infrastructure Buildout	Infrastructure can be constructed at a pace consistent with fleet adoption and able to meet fleet fueling/charging requirements by the end of the assessment period.				
Existence of / Compatibility with Standards	A sufficient body of codes and standards exist from appropriate organizations that enables safe and effective fueling/charging. The fueling/charging technology has already been installed at other marine terminals in the U.S., with sufficient time to assess performance and safety.				

Legend: **Infrastructure Availability (2021)**



Source: Estimated ratings are based on MTO interviews and site visits, footnoted studies, OEM product information, various government sources, and consultant's industry knowledge

ZE Battery-Electric Yard Tractors – Heavy duty battery-electric charging standards are rapidly developing, but the industry remains in a state of change and no single standard has yet emerged as the clear winner. Charging times remain an issue for MTOs, but if battery capacities are increased, charging time may become a much less significant issue. The scope of the infrastructure build-out for a fully electrified yard tractor fleet is substantial and does not appear possible to complete within the three-year study period of this Assessment. The only change since the 2018 Assessment is a ¼ pie increase (from ¼ to ½) for "Existence of / Compatibility with Standards." This increase is warranted by the general progress the industry has made towards adopting a single charging standard, combined with increased work by the Ports in conjunction with electricity providers and MTOs to address greater standardization and commonization of charging procedures. However, there is still significant work to be done before infrastructure buildout criterion is fully achieved.

NZE Natural Gas ICE Yard Tractors – Because LNG can theoretically be wet hosed in a manner similar to diesel fuel, LNG is expected to provide similar fueling times and infrastructure footprint as diesel. However, this must be caveated as mobile

LNG fueling in the manner done for wet hosing of diesel yard tractors has not been proven and could result in extending fueling time. Permitting of mobile LNG fueling may also prove challenging given this lack of experience.

ZE Grid-Connected RTG Cranes – Fueling downtime is eliminated by the continuous grid connection but the potential for extended times needed to transition between runs may create losses in operational efficiency. While the subsurface RTG cable system considered in this Assessment reduces the infrastructure footprint for grid-connected RTG cranes, there are still small increases in the footprint required from substations.

NZE Diesel Hybrid RTG Cranes – As previously noted, hybrid RTG cranes are effectively direct replacements for conventional RTG cranes, and require no additional infrastructure buildout.

9. Assessment of Economic Workability

9.1. Criteria and Methodology

This subsection compares the capital costs (CapEx) and operational costs (OpEx) associated with purchasing and deploying NZE or ZE platforms as compared to baseline diesel costs. This includes the costs of installing specialized fueling infrastructure. It considers the availability of government incentives to buy down the capital costs of vehicles, equipment, and fueling infrastructure. The key parameters and base considerations that were collectively used to assess economic considerations and issues are listed in the table below.

Table 30: Criteria for assessing Economic Workability for emerging CHE platforms

Economic-Related Criteria / Issue	Base Considerations for Assessing General Economic Workability
Incremental Equipment Cost	The upfront capital cost for the new technology CHE is affordable to end users, compared to the diesel baseline CHE.
Fuel and Other Operational Costs	The cost of fuel / energy for the new technology is affordable, on an energy-equivalent basis (taking into account vehicle efficiency). Demand charges / TOU charges (if any) are understood and affordable. Net operational costs help provide an overall attractive cost of ownership.
Infrastructure Capital and Operational Costs	Infrastructure-related capital and operational costs (if any) are affordable for end users.
Potential Economic or Workforce Impacts to Make Transition	There are no known major negative economic and/or workforce impacts that could potentially result from transitioning to the new equipment.
Existence and Sustainability of Financing to Improve Cost of Ownership	Financing mechanisms, including incentives, are in place to help end users with incremental equipment costs and/or new infrastructure-related costs, and are likely remain available over the next several years.
Source: Based on criteria in San Pedro Bay Ports' "Framework for Developing Feasibility Assessments", November 2017.	

Cost comparisons between baseline diesel yard tractors and RTG cranes versus alternative low emission technologies are made on a total cost of ownership (TCO) basis using the average operating assumptions and costs shown in Table 31 and Table 32. The results of this analysis are presented and discussed following a presentation of the major cost elements in the TCO model.

Table 31. Cost and activity assumptions for Yard Tractors

Cost-Related Parameter	Units	Baseline Diesel	NZ LNG ICE	ZE Battery Electric
Purchase Price	$	$100,000	$150,000	$320, 000
Taxes	$	$10,250	$15,375	$32,800
Infrastructure	$	$0	$20,000	$165,000
Fuel Economy	DGE/hr	2.50	2.78	0.5
Fuel Price	$/DGE	$2.77	$2.33	$9.89 (SCE EV Rate), $11.00 (LADWP), $12.67 (SCE Non-EV Rate)
Activity	hr/yr	1,806	1,806	1,806
Maintenance	$/hr	$22.15	$22.15	$15.50
DEF	% of Diesel	4%	0%	0%
DEF Price	$/gal	$3.60		
Discount Rate	%	7%		

Table 32. Cost and activity assumptions for RTG Cranes

Cost-Related Parameter	Units	Baseline Diesel	NZE Diesel Hybrid	ZE Grid Electric
Purchase Price	$	$1,200,000	$1,350,000	$1,800,000
Taxes	$	$108,000	$121,500	$162,000
Infrastructure	$	$0	$0	$333,333
Fuel Economy	DGE/hr	9.5	5.7	2.9
Fuel Price	$/DGE	$2.77	$2.77	$5.00 (SCE EV Rate), $5.53 (LADWP), $5.09 (SCE Non-EV Rate)
Activity	hr/yr	2,646	2,646	2,646
Maintenance	$/hr	$32.12	$32.12	$24.09
DEF	% of Diesel	4%	4%	0%
DEF Price	$/gal	$3.60		
Discount Rate	%	7%		

9.2. Equipment Capital Costs

The purchase price of new equipment is a function of several factors including equipment specifications, warranties, demand, and purchase volume discounts. Equipment costs were developed from several sources, as shown in Table 33. Prices shown are assumed to be pre-tax. A generalized sales tax rate of 10.25 percent has been applied to all equipment.

Table 33. Equipment purchase price assumptions and sources

CHE and Fuel-Technology	Purchase Cost	Source
Diesel ICE Yard Tractor	$100,000	PMSA Study[120]
NZE LNG ICE Yard Tractor	$150,000	Purchase Order[121]
ZE Battery-Electric Yard Tractor	$320,000	Average of OEM prices[122]
Baseline Diesel RTG Crane	$1,200,000	PMSA Study
NZE Diesel-Hybrid RTG Crane	$1,350,000	Port of Oakland[123]
ZE Battery-electric RTG Crane	$1,800,000	PMSA Study[124]

9.3. Fuel, Operational and Maintenance Costs

Estimates for fuel costs and other operational and maintenance costs were developed and incorporated into the TCO modeling for each CHE configuration.

9.3.1. Fuel Economy and Fuel Price

The basis of the fuel economy estimates used in this analysis were detailed in Section 7.3.1.

Diesel fuel costs are based on the average on-road diesel fuel price in California for 2020, as reported by the U.S. EIA.[125] The reported fuel price is reduced by $0.61/gallon to deduct the federal and state excise taxes that are not applied to off-road

[120] Moffatt & Nichol, "Sustainable Freight Strategy Impact Study," Technical memorandum prepared for PMSA. 2015. http://www.pmsaship.com/pdfs/PMSA%20Sustainable%20Freight%20Strategy%20Impact%20Study%20Tech%20Memo%208918%20Final.pdf
[121] Based on the purchase cost of 6.7L NZE LNG yard tractors purchased under CEC grant demonstration for GFO-16-506
[122] Average of OEM prices for BYD and Kalmar EV yard tractors
[123] Port of Oakland, "Zero-Emission Cargo-Handling Equipment Feasibility Assessment," November 2019
[124] This figure is also consistent with the $600,000 incremental cost for retrofit of diesel RTG cranes as described in Port of Long Beach, Proposal to CEC under GFO-16-604
[125] U.S. Energy Information Administration, Weekly Retail Gasoline and Diesel Prices https://www.eia.gov/dnav/pet/pet_pri_gnd_dcus_sca_a.htm

applications.[126] Natural gas fuel costs are based on the 2016 through 2020 average natural gas price at Henry Hub, and adjusted to include delivery costs and California sales tax.[127] As discussed previously (section 8.3.2), LNG pricing also includes the labor costs of one additional worker per 75 yard tractors served.

New diesel equipment compliant with EPA's Tier 4 standard also consume diesel emission fluid (DEF) as needed to properly operate SCR systems that control NOx emissions. The DEF consumption rate is typically specified by the manufacturer as a fixed percentage of diesel fuel consumption. DEF costs were estimated by reviewing current DEF prices reported from Flying J's California truck stops.[128]

Electricity pricing for EV charging and RTG crane power is complex and varies based on several factors, including power demand, time of day, utility rate structure, and total energy consumption. To estimate average electricity costs for EV supply, three scenarios were evaluated for both yard tractors and RTG cranes: 1) a standard 2-shift operation; 2) an extended 2-shift operation; 3) an assumed average of a standard and extended 2-shift operation.

These scenarios and the resulting costs are described in Table 34. The first and second scenario were evaluated under two tariff rates; SCE's TOU-EV-9 (2-50 kV)[129] and LADWP's TOU A-3 rates[130]. The third scenario assumes a 50/50 mix of standard and extended 2-shift operations on a monthly basis. Because demand charges are assessed on a monthly basis, the demand charges for the extended 2-shift operation are applied to the average scenario, while the energy costs and total energy dispensed are simple averages of the two scenarios. Additionally, charging costs were assessed under SCE's TOU-8 Option E (50 kV+). Costs under this rate were evaluated because the special EV rate, TOU-EV-9, includes a demand charge waiver that phases out over five years, beginning in 2024. Because the majority of zero-emission CHE that is ultimately deployed at the ports may not be deployed until after 2024, it is reasonable to consider the costs of electricity under a more traditional rate structure like the TOU-8 Option E rate. Furthermore, in this 2021 Assessment, cost modeling under the TOU-EV-9 rate now includes an anticipated phase in of demand charges and reduction of energy charges after 2024. The costs presented here represent the 10-year or 15-year average cost of electricity under the TOU-EV-9 rate, for yard tractors and RTG cranes respectively.

The 2018 Assessment's economic analysis for yard tractors assumed a substantial difference in average electricity costs between SCE and LADWP. Because that analysis did not model the cost impacts associated with the end of the demand charge waiver under the TOU-EV-9 rate, the analysis presented an optimistic cost estimate for SCE customers using this rate. The result of the SCE EV rate analysis was to lower costs for EV charging relative to a general services rate such as the one modeled for LADWP[131] and the SCE TOU-8 general services rate. However, under the revised analysis, the difference in the "average" electricity cost between the LADWP and SCE TOU-EV-9 rates is substantially smaller, at about 10 percent as compared to the 70 percent difference in the 2018 Assessment.

MTOs at the Port of Long Beach may also be subject to an "Added Facilities" charge of $2.84/kW per month.[132] This charge is imposed under a number of conditions, but it is avoided if the new load (e.g., EV charging load) is greater than 10 MW or SCE determines that the load is best served at sub-transmission voltages of 66 kV or greater. Because the electrification scenarios considered in this Assessment explore technologies with the potential for wide-scale adoption, it is assumed that terminals would add loads greater than 10 MW and avoid "Added Facilities" charges. Notwithstanding such an assumption, it is recognized that some MTOs may be subject to this fee. In these cases, it is estimated that "Added Facilities" charges would increase charging costs by approximately 10 percent over those shown in the following tables.

[126] Combination of average state fuel tax of $0.27/gallon between July 2019 and June 2021, and federal excise tax of $0.24/gallon

[127] Fuel price structure and cost of delivery are based on a quote to Anaheim Resort Transportation for LNG delivery to a mobile fueling station. Board Item #14, April 23, 2014. This pricing structure is typical of LNG fuel supply contracts for transportation customers.

[128] Pilot Flying, https://pilotflyingj.com/fuel-prices/ Reviewed October, 2021.

[129] As proposed in SCE's Advice Letter 3853-E. These rates are not final and are pending Public Utility Commission approval.

[130] https://www.ladwp.com/ladwp/faces/ladwp/aboutus/a-financesandreports/a-fr-electricrates/a-fr-er-electricrateschedules

[131] Note that while LADWP offers a $0.025/kWh discount for EV charging, the ordinance that approved the discount requires that the vehicles served are registered with the California DMV. This implies that the rate is only applicable to on-road vehicles and would not be applicable to the majority of yard tractors nor to any RTG cranes

[132] Southern California Edison rate sheet Schedule ME. https://www1.sce.com/NR/sc3/tm2/pdf/CE358.pdf

Table 34. Yard tractor electricity cost analysis results

Scenario	Standard 2-Shift UTR	Extended 2-Shift UTR	Average UTR	Standard 2-Shift UTR	Extended 2-Shift UTR	Average UTR	Standard 2-Shift UTR	Extended 2-Shift UTR	Average UTR
Utility	SCE			LADWP			SCE		
Rate Schedule	TOU-EV-9	TOU-EV-9	TOU-EV-9	TOU A-3	TOU A-3	TOU A-3	TOU-8 Option E	TOU-8 Option E	TOU-8 Option E
Daily Energy (kWh)	287	341	N/A	287	341	N/A	287	341	N/A
Daily Operating Time (hours)	16	19	N/A	16	19	N/A	16	19	N/A
Charge Window	3a-8a, 5p-5:45p	6a-8a, 6p-6:45p	N/A	3a-8a, 5p-5:45p	6a-8a, 6p-6:45p	N/A	3a-8a, 5p-5:45p	6a-8a, 6p-6:45p	N/A
Total Energy (kWh)	104,886	124,553	114,720	104,886	124,553	114,720	104,886	124,553	114,720
Peak Power (kW)	94	166		94	166		94	166	
Energy Charges	$15,103	$20,578	$17,841	$13,072	$15,697	$14,385	$12,743	$17,038	$14,890
Demand Charges	$5,370	$9,482	$9,482	$17,337	$18,487	$18,487	$11,869	$20,958	$20,958
Fixed Charges	$3,061	$3,061	$3,061	$900	$900	$900	$3,061	$3,061	$3,061
Total Cost ($/year)	$23,534	$33,121	$30,384	$31,309	$35,084	$33,771	$27,673	$41,057	$38,910
Average Cost ($/kWh)	**$0.224**	**$0.266**	**$0.265**	**$0.299**	**$0.282**	**$0.294**	**$0.264**	**$0.330**	**$0.339**

Table 35. RTG electricity cost analysis results

Scenario	Standard 2-Shift RTG	Extended 2-Shift RTG	Average RTG	Standard 2-Shift RTG	Extended 2-Shift RTG	Average RTG	Standard 2-Shift RTG	Extended 2-Shift RTG	Average RTG
Utility	SCE			LADWP			SCE		
Rate Schedule	TOU-EV-9	TOU-EV-9	TOU-EV-9	TOU A-3	TOU A-3	TOU A-3	TOU-8 Option E	TOU-8 Option E	TOU-8 Option E
Daily Energy (kWh)	1,953	2,283	N/A	1,953	2,283	N/A	1,953	2,283	N/A
Daily Operating Time (hours)	16	19	N/A	16	19	N/A	16	19	N/A
Charge Window	8a-5p, 6p-3a	8a-6p, 7p-6a	N/A	8a-5p, 6p-3a	8a-6p, 7p-6a	N/A	8a-5p, 6p-3a	8a-6p, 7p-6a	N/A
Total Energy (kWh)	712,663	833,113	772,888	712,663	833,113	772,888	712,663	833,113	772,888
Peak Power (kW)	110	110		110	110		110	110	
Energy Charges	$88,780	$100,334	$94,557	$84,390	$99,028	$91,709	$82,903	$93,753	$88,328
Demand Charges	$8,862	$8,862	$8,862	$21,780	$21,780	$21,780	$13,917	$13,917	$13,917
Fixed Charges	$3,061	$3,061	$3,061	$900	$900	$900	$3,061	$3,061	$3,061
Total Cost ($/year)	$100,702	$112,257	$103,419	$107,070	$121,708	$114,389	$99,881	$110,731	$105,306
Average Cost ($/kWh)	**$0.141**	**$0.135**	**$0.134**	**$0.150**	**$0.146**	**$0.148**	**$0.140**	**$0.133**	**$0.136**

9.3.2. Maintenance Costs

Baseline maintenance costs are taken from the PMSA study[133] and converted to a per-hour basis using the average annual hours of operation calculated from the Ports emissions inventories. Natural gas yard tractor maintenance costs are assumed to be equal to diesel maintenance costs. The literature contains various conflicting reports of natural gas maintenance costs relative to diesel, with some analyses reporting reduced maintenance costs and others reporting increased maintenance costs. It is likely that the differences in these results are attributable to various confounding factors in the analyses and to differences in the maintenance practices between fleets.

Battery-electric yard tractor maintenance costs are assumed to be 30 percent less than the diesel baseline maintenance costs. This assumption is based on assumptions used by the Port of Oakland in its 2019 CHE technology analysis.[134] Unfortunately, there is little in-use demonstration data available in port operations to validate this assumption as of late-2021 for production intent equipment. Additionally, these maintenance costs do not incorporate the potential cost of a battery pack replacement over the 10 to 12-year life of the yard tractor. As previously noted, BYD currently offers a 12-year warranty on its battery packs in transit applications but not in yard tractors or on-road trucks. Because the cost estimates used in this Assessment exclude the cost of a battery pack replacement, it is implicitly assumed that the battery pack will last the full life of the vehicle or that the sales price assumed would include a 10-year battery warranty when vehicles are produced and sold in high volumes. As discussed in Section 7.3.1, high-utilization yard tractors could reach 3,000 to 5,000 battery charge cycles in 7-11 years. For batteries that require replacement at year 7, this would represent an additional maintenance cost beyond that shown in the total cost of ownership (TCO) results. The cost of the battery pack replacement will depend on the future cost of batteries. Using estimates of future battery prices prepared by CARB for the Advanced Clean Trucks rulemaking, battery prices in 2028 are assumed to be approximately $100 per kWh.[135] Applied to the largest battery capacity of the yard tractors considered in this analysis, 220 kWh, results in an additional maintenance cost of $22,000 beyond what is shown in Figure 23. This additional cost is small, about 3.4 percent, relative to the unsubsidized TCO for battery-electric yard tractors.

Diesel-hybrid RTG cranes are assumed to have the same maintenance costs as conventional RTG cranes. This may be a conservative estimate, because hybrid systems enable engines to run at more consistent speeds and to shut down when loads are low, thus reducing engine wear. Additionally, the engine in a hybrid RTG crane is smaller than its conventional counterpart, and service parts may be less expensive. However, it is assumed that maintenance costs are not reduced (lacking better data for the maintenance costs of hybrid RTG cranes).

Maintenance costs for grid-connected RTG cranes are assumed to be reduced by 25 percent, based on values documented in the PMSA study. An upper-end estimate on maintenance cost reductions might be 40 percent as this is consistent with the differential maintenance costs between an automated stacking crane (ASC) and a diesel RTG crane in the PMSA study. However, because ASCs are rail mounted, they are expected to have lower maintenance costs than a similarly powered electric RTG crane, given that ASCs lack tires, associated steering mechanisms, and connections/disconnections from the grid power supply.

9.3.3. Depreciation Costs

Depreciation provides a cost reduction for fleets that are able to take advantage of the tax benefits. Current federal tax rates for businesses are 21 percent and California tax rates for C-type corporations are 8.84 percent, resulting in an effective tax rate of 29.84 percent.[136] Because depreciation of business equipment such as CHE is tax deductible, this reduces taxes for years when depreciation is applied. Estimating the value of depreciation for the average MTO is difficult. The rules for depreciation are complex and MTOs may be structured as a number of business entities. For the purposes of this analysis, the value of equipment depreciation is calculated as 29.84 percent of the capital cost, and it is assumed that the equipment owner is able to fully benefit from the associated deductions over the equipment's useful life.

[133] Moffatt & Nichol, "Sustainable Freight Strategy Impact Study," Technical memorandum prepared for PMSA. 2015. http://www.pmsaship.com/pdfs/PMSA%20Sustainable%20Freight%20Strategy%20Impact%20Study%20Tech%20Memo%208918%20Final.pdf
[134] Port of Oakland, "Zero-Emission Cargo-Handling Equipment Feasibility Assessment," November 2019.
[135] California Air Resources Board, "Advanced Clean Trucks Total Cost of Ownership Discussion Document", February 2019
[136]26 U.S. Code § 11, https://www.ftb.ca.gov/file/business/tax-rates.html

9.4. Infrastructure Capital and Operational Costs

Diesel and natural gas fueling are assumed to be provided through the use of on-site storage systems and mobile fueling trucks. Because diesel fueling is the baseline case, infrastructure capital costs are assumed to be zero for diesel equipment. LNG infrastructure includes costs for the LNG storage/fueling pad and mobile fuelers, as described in Section 8.3. The combined infrastructure cost includes an estimated $1.6 million per 135 yard tractors[137] for the on-site LNG storage/fueling station and $300,000 per 75 yard tractors for the LNG mobile fuelers.

Owing to the limited charging windows available to MTOs between shifts, it is assumed that battery-electric yard tractors will be charged primarily through DCFC infrastructure. Based on the electricity charging rate analysis, the typical yard tractor would require a peak charging rate of 157 kW. This charging rate is based on a 45-minute charging window between first and second shift and delivers enough energy to allow the yard tractor to complete a 10-hour second shift length. This also implies that a one-to-one ratio of chargers to yard tractors is required. Costs for the charger are estimated at $100,000. Associated infrastructure installation costs are estimated at $50,000 per charger based on discussions with Port of Long Beach experience with recent battery-electric yard tractor infrastructure projects. These costs are similar to those observed in transit and heavy-duty electric truck analyses. The full cost of the charger and installation are attributed to a battery-electric yard tractor.

It is recognized that the installation costs for natural gas and electrical infrastructure reflect long-lived improvements such as trenching, conduit, switch gear, tanks, and power lines. For the purposes of this analysis, it is assumed the service life of these improvements will extend well beyond the 10-year useful life of the first electric yard tractors deployed.[138] Consequently, the infrastructure costs for battery-electric and natural gas yard tractors are pro-rated by 50 percent, effectively spreading out the cost of the infrastructure over two useful lives of the yard tractors.

9.5. Incentives

Historically, incentives have played a major role in spurring deployments of advanced technologies by reducing the cost of the initial capital outlay. There are uncertainties, however, surrounding the long-term availability and magnitude of incentives. Additionally, these funding programs do not necessarily align with timelines for deployment; there is funding available today for equipment purchase, but the industry may need years to develop the fueling or charging infrastructure to support this equipment, effectively limiting the incentive funds that can be accessed in the near term.

Given these uncertainties, this Assessment calculates TCO for ZE and NZE CHE platforms with and without incentives. The TCO model considers two incentive types: a purchase incentive based on applicable programs (e.g., California's CORE program), and a credit revenue stream generated through California's Low Carbon Fuel Standard (LCFS). An example of an important new incentive program is the California Energy Commission's "Energy Infrastructure Incentives for Zero-Emission Commercial Vehicles (EnergIIZE), which was introduced in mid-2021.

For this Assessment, the purchase incentive for a ZE battery-electric yard tractor is assumed to be $174,000; this is based on the current CORE voucher amount for Kalmar's T2e with a 220 kWh battery pack. Additionally, it is assumed that yard tractor purchases would qualify for a $30,000 incentive enhancement for purchase of charging infrastructure with a power rating of greater than 50 kW, as provided for in CORE. Natural gas yard tractors are not eligible for participating in CORE and are not assumed to receive incentives through a voucher program. The value of LCFS credits is based on a $186 credit price reflecting the volume-weighted average credit price for 2018 through 2020. To be conservative, it is recommended that economic workability be based on non-incentivized cost of ownership. Section 9.6.3 provides additional discussion and rationale. Additional details about key incentive funding programs are provided in Appendix B of this 2021 Assessment (including links to incentive calculations and formulas).

[137] The 2018 assessment assumed $1.6 million per 100 yard tractors. This assumption has been updated to better align with estimates elsewhere in this assessment that assume 12 fueling stations are required for the fleet of 1,615 yard tractors.
[138] Note that future modifications or reconfigurations of terminals may result in a substantially shorter useful life for these infrastructure improvements.

9.6. Total Cost of Ownership Results

9.6.1. Battery-Electric and Natural Gas Yard Tractors

The comparative cost of ownership analysis is based on the assumptions described in the preceding sections. Figure 23 summarizes the results of the cost of ownership analysis for yard tractors. The costs are reported in 2020 dollars on a net present value (NPV) basis using a 7 percent real discount rate.[139] As shown, the cost of ownership for a new diesel yard tractor is approximately $457,000 over ten years. Near-zero natural gas yard tractor costs are estimated to be $489,000, within 10 percent of the TCO for a new conventional diesel yard tractor and could be considered cost-competitive with new diesel yard tractors at the fuel price spreads assumed in this analysis. Battery-electric yard tractor cost of ownership depends on the location where the vehicle charges, as this determines the utility rate. Within SCE territory, the current battery-electric yard tractor is estimated to cost $648,000 over ten years, about $191,000 more expensive than new diesel yard tractors, when using the TOU-EV-9 rate. Within LADWP territory, the current battery-electric yard tractor is approximately $197,000 more expensive than a new diesel yard tractor. Battery-electric yard tractors charging in SCE territory on the TOU-8 Option E rate, are estimated to cost approximately $208,000 more than a new diesel yard tractor.

When incentives are included in the analysis, battery-electric yard tractors are less expensive than baseline (diesel ICE) yard tractors over the 10-year analysis period. In the 2018 Assessment, natural gas yard tractors were assumed to receive a $45,000 initial purchase incentive through HVIP. However, in this 2021 Assessment's analysis, no incentive funding is assumed to be available to natural gas yard tractors. Electric yard tractors receive a $204,000 purchase incentive through CORE and generate $75,700 in LCFS credits over 10 years ($53,700 on an NPV basis). The combined effect of these two very large incentives is to make the total cost of the battery-electric yard tractors less than baseline diesel yard tractors.

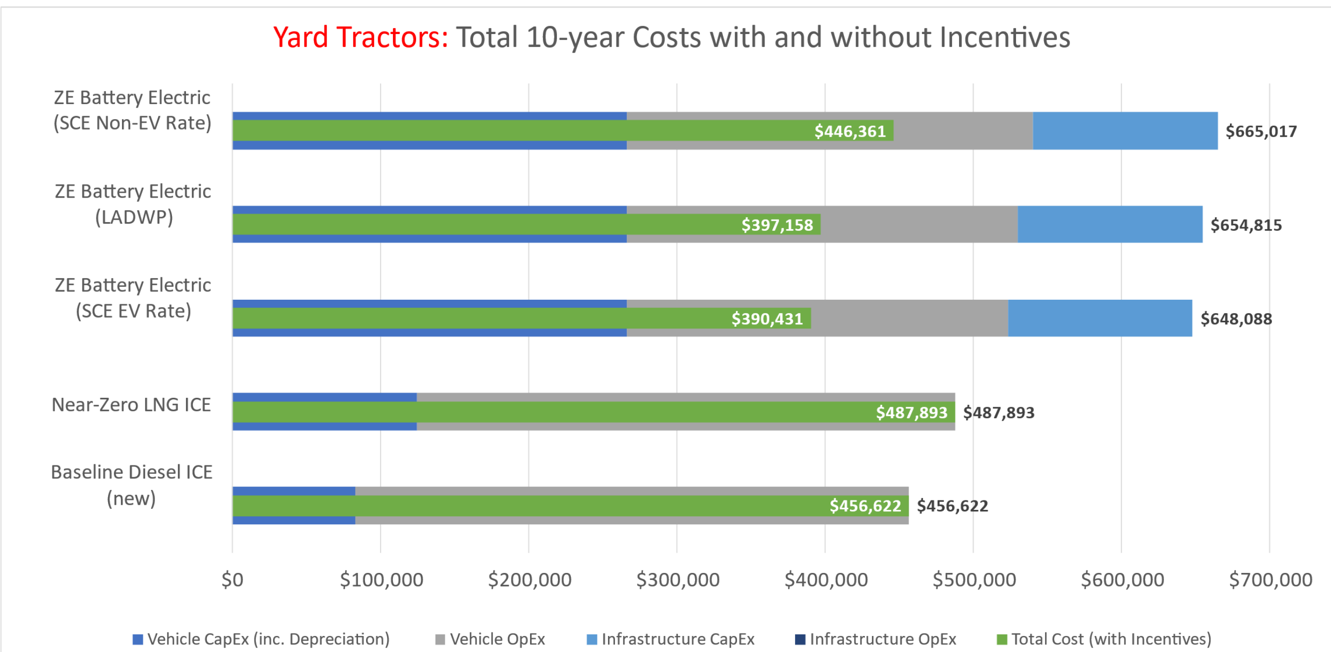


Figure 23. Total 10-year costs of ownership for "Average Yard Tractor" scenario (NPV at 7% discount rate)

The TCO results shown in Figure 23 are not directly comparable to the 2018 Assessment; based on terminal operator feedback, this most-current TCO analysis assumes a yard tractor useful life value of ten years. However, the general observations between the two assessments are the same. Near-zero natural gas yard tractors can achieve a TCO similar to diesel yard tractors with limited or no direct incentives. Battery-electric yard tractors are significantly more costly on a TCO basis compared to diesel yard tractors – unless current incentives are considered. Under a highly incentivized scenario, the TCO of a battery-electric yard tractor becomes roughly 15 percent less than its baseline diesel counterpart.

[139] The analysis uses a 7% real discount rate per the White House Office of Management and Budget Circular A-4 (2003)

9.6.2. Grid-Electric and Hybrid-Electric RTG Cranes

Figure 24 summarizes the results of the TCO analysis for RTG cranes. As shown, the TCO for a new baseline diesel RTG crane is approximately $2.43 million over 15 years. Diesel-hybrid RTG crane costs are estimated to be $2.27 million, similar but slightly less than conventional RTG cranes. As with battery-electric yard tractors, grid-connected RTG crane cost of ownership depends on the location where the RTG crane is located. Within SCE territory, the current grid-connected RTG crane is estimated to cost $2.67 million over 15 years, about $240,000 more expensive than new diesel RTG crane. Within LADWP territory, the cost is approximately $278,000 more expensive than a new diesel RTG crane. Under SCE's TOU-8 Option E rate the 15-year total cost is nearly equal to the TOU-EV-9 rate, at $2.68 million. Note that the difference in electricity costs between utilities is lower for RTG cranes than for yard tractors because of the high utilization of the infrastructure serving the RTG cranes. This reduces the benefit of SCE's demand charge waiver under its TOU-EV-9 rate as compared to the more conventional A-3 rate from LADWP and TOU-8 rate from SCE.

When incentives are included in the analysis, the costs of grid-connected RTG cranes become less expensive than diesel and diesel-hybrid platforms. Grid-connected RTG cranes are estimated to generate $436,000 in LCFS credits over 15 years ($270,000 on an NPV basis). Additionally, the incentive case assumes that grid-connected RTG cranes qualify for the maximum voucher amount of $500,000 under the CORE program. Diesel-hybrid RTG cranes are not eligible for incentives under any established program, including the LCFS, CORE, or the VW Mitigation Fund (further discussed in Section 12.4).

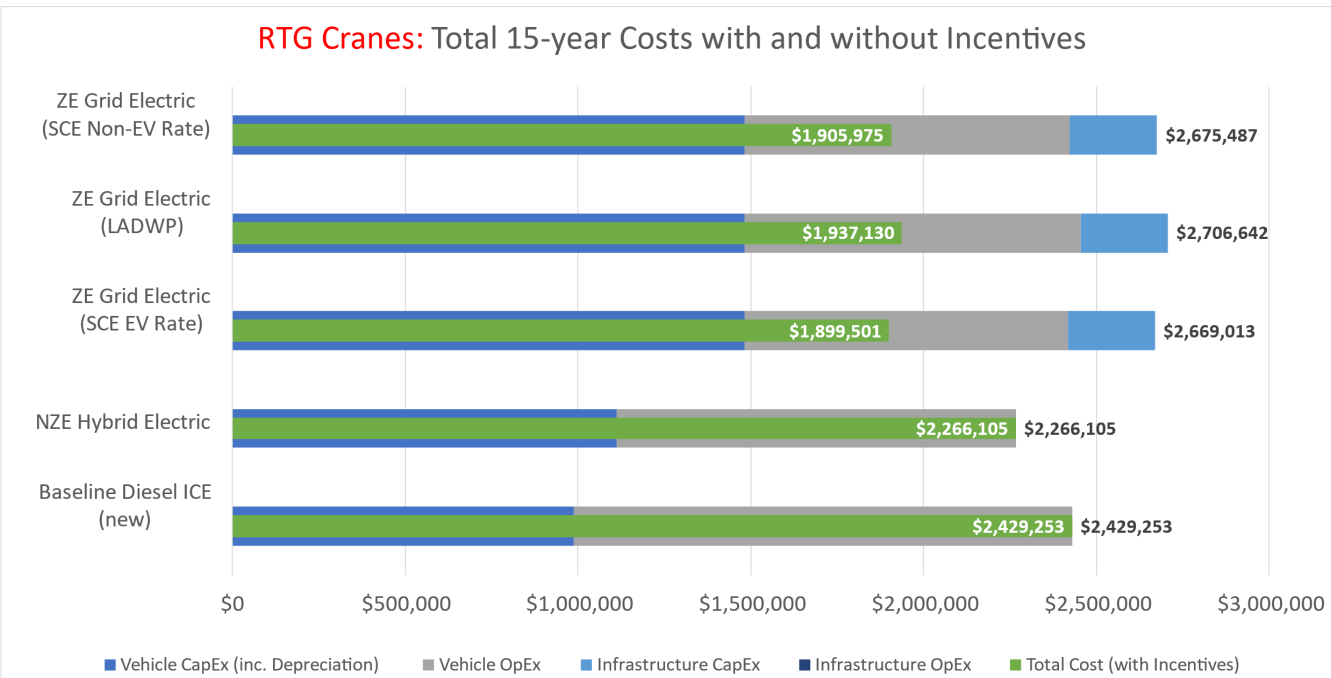


Figure 24. Total 15-year costs of ownership for the "Average RTG crane" scenario (NPV at 7% discount rate)

It is worth noting that one interviewed MTO representative cited reduced fuel consumption for diesel-hybrid RTG cranes of approximately 90 percent, resulting in an average fuel consumption rate of about 1 gallon per hour. This magnitude of reduced diesel fuel usage is significantly greater than what has been assumed for calculations in this 2021 Assessment. If NZE diesel-hybrid RTG cranes can reliably achieve a 90-percent reduction in fuel use, their TCO would decrease to $1.95 million over 15 years. This would yield a 20 percent TCO reduction compared to conventional diesel RTG cranes, resulting in an TCO that is comparably low to even highly incentivized grid-connected RTG cranes.

9.6.3. Reliance on Incentives

Reliance on incentives to determine economic workability can be problematic. Current incentive programs do not have sufficient funds to replace the entire CHE fleet, and allocations for future programs are not yet determined or guaranteed. A total of $41 million for purchasing ZE CHE was allocated in 2021 for the Clean Off-Road Equipment (CORE) voucher incentive project. Long term, a total of $140 million over the CORE program's life is anticipated. CORE has since oversubscribed the funding caps that CARB set for each equipment category, indicating a highly competitive environment for the limited incentive funding available. The VW mitigation fund will have an additional $70 million over the next three to ten years. Combined, this pot of $170 million would be sufficient to provide a $174,000 purchase incentive and a $30,000 infrastructure incentive for 830 yard tractors. This is 50 percent of the 1,615 yard tractors serving the ports. However, these funds will also serve a broad range of other CHE categories, including transportation refrigeration units, forklifts, RTG cranes, and airport ground support equipment. Given current regulatory efforts to establish additional emissions requirements for ports, warehouses, and intermodal facilities around the state, competition for these funds is likely to be significant and there is no reasonable means of estimating the funds that would be available to either yard tractors or RTG cranes. For example, replacing the 156 diesel RTG cranes in the Ports to a grid-connected ZE RTG crane would require $78 million at the $500,000 incentive amount shown in the TCO analysis. This is almost 80 percent of the remaining expected lifetime funds available under the CORE program, reducing the total funds available for yard tractors and all other CHE to $92 million. This would fund 450 yard tractors at $204,000 voucher amounts, less than 30 percent of the combined Ports' yard tractor fleet. As stated earlier, it is recommended that economic workability be based on non-incentivized cost of ownership.

9.7. Cost Effectiveness and Other Economic Considerations

The feasibility assessment framework adopted in November 2017 as part of the CAAP Update identified three additional areas of economic impact for consideration by the Ports. These areas are 1) cost effectiveness of air quality reductions, 2) workforce impacts, and 3) costs associated with potential cargo diversion.

Cost-Effectiveness

Cost effectiveness - generally represented as the cost per ton of emissions reduced - is a metric typically used to assess various air quality regulations and funding programs. The choice of costs and cost metrics are major elements of any cost-effectiveness analysis. To develop cost-effectiveness comparisons for the analysis that follows, non-incentivized costs for an average yard tractor and RTG crane were used (refer back to Figure 23 and Figure 24, respectively).

Emissions impacts were calculated using emissions factors from CARB's ORION2017 model and LCFS program, and applying those factors to annual activity and fuel economy (refer back to Table 31 and Table 32). Table 36 summarizes criteria pollutant emissions factors for a new (2021 model year) yard tractor and RTG crane, both powered by a diesel engine certified to Tier 4 standards.

Table 36. Diesel emissions factors for cost-effectiveness analysis

Emissions Profile / CHE Type	Diesel Emissions Factor (g/hr)		
	$PM_{2.5}$	NOx	ROG
Tier 4 Final Yard Tractor	0.44	13.47	1.78
Tier 4 Final RTG Crane	1.23	83.04	7.62

Criteria pollutant emissions reductions are estimated based on reduction factors, shown in Table 37. Note that the diesel-hybrid RTG crane emissions reduction factors are assumed to be equivalent to the fuel consumption reductions of the technology. This likely slightly underestimates the emissions reductions of the hybrid RTG crane as it uses a smaller engine that may be certified to a lower brake-specific emissions rate than a conventional RTG crane engine. Greenhouse gas emissions are estimated using the carbon intensity (CI) factors, also shown in Table 37 and Table 38. The CI factors for conventional fuels are based on CARB's default values for diesel and the current California-average grid.[140] The CI factor for LNG shown under the Renewable/TOU column reflect the average CI for Bio-LNG over the prior four quarters, as reported by CARB under the LCFS Quarterly Data Spreadsheet.[141] Similarly, the CI factor for conventional LNG is calculated from that same

[140] California Air Resources Board, Final Regulation Order, Table 7-1 "Lookup Table for Gasoline and Diesel and Fuels that Substitute for Gasoline and Diesel." https://www.arb.ca.gov/regact/2018/lcfs18/fro.pdf. CA grid average uses the most recent value of 75.93 gCO2e/MJ.

[141] https://www.arb.ca.gov/fuels/lcfs/dashboard/quarterlysummary/quarterlysummary_013119.xlsx

spreadsheet. The CI factor for battery-electric CHE under the Renewable/TOU column is the average carbon intensity for California grid electricity delivered during the charging windows for yard tractors and the operating windows for RTG cranes.

The carbon intensities shown in Table 37 and Table 38 are applied directly to the calculated fuel economies shown in Table 31 and Table 32. Because these fuel economies are technology specific, they already account for differences in platform efficiencies and the carbon intensities do not need to be further modified by EERs provided in CARB's LCFS regulation.

Table 37. Emissions reduction factors and carbon intensity assumptions for Yard Tractors

Fuel-Technology Type	Reduction Factor			Carbon Intensity (gCO2e/MJ)	
	NOx	$PM_{2.5}$	ROG	Conventional	Renewable/TOU
Baseline Tier 4 Diesel ICE	0%	0%	0%	100.45	
NZ LNG ICE	90%	0%	0%	96.46	57.29
ZE Battery Electric	100%	100%	100%	75.93	98.38

Table 38. Emissions reduction factors and carbon intensity assumptions for RTG Cranes

Fuel-Technology Type	Reduction Factor			Carbon Intensity (gCO2e/MJ)	
	NOx	$PM_{2.5}$	ROG	Conventional	Renewable/TOU
Baseline Tier 4 Diesel	0%	0%	0%	100.45	
NZE Diesel Hybrid	40%	40%	40%	100.45	
ZE Grid Electric	100%	100%	100%	75.93	79.82

Results of the cost-effectiveness analysis are shown in Figure 25 through Figure 28. All cost-effectiveness calculations assume a 10-year or 15-year equipment life[142] for yard tractors and RTG cranes, respectively. Criteria pollutant emissions are represented as weighted emissions, using the Carl Moyer program methodology.[143]

As shown in the figures, the cost effectiveness of criteria pollutant emissions for the NZE natural gas yard tractor compared to Tier 4 baseline diesel is $137,000 per weighted ton.[144] The cost effectiveness for battery-electric yard tractors varies between $424,000 and $461,000 per weighted ton. By comparison, note that the Carl Moyer Program limits its funding support of RTG and Yard Tractor scrappage and replacement projects to $100,000 per weighted ton of emissions reduced.

For GHG reductions, the NZE natural gas yard tractor does not have a listed cost effectiveness when using conventional (fossil) natural gas as it produces net higher GHG emissions compared to diesel. This is likely due to the fact that nearly all LNG in the California LCFS program has transitioned to renewable natural gas. This leaves only a small number of outlier volumes of fossil LNG to estimate the CI of the fuel. When using renewable LNG (RLNG), the cost effectiveness is $148/MT. The cost effectiveness for ZE battery-electric yard tractors varies between $389 and $446/MT. For reference, LCFS credit prices ranged from $105 to $217 per metric ton between 2018 and 2020.[145]

NZE and ZE RTG cranes prove to be significantly more cost effective for reducing criteria pollutant and GHG emissions than the corresponding yard tractor platforms. As shown in Figure 25, the cost effectiveness of criteria pollutant emission

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[142] Cost effectiveness uses the expected equipment life, not Carl Moyer Program project lives.
[143] Under the Carl Moyer Program, NOx, PM, and ROG emissions reductions are combined into a single weighted emissions reduction factor using the formula (NOx + ROG + 20*PM) = Weighted Emissions
[144] Cost-effectiveness limits for Carl Moyer Program are reported in Appendix C of the 2017 guidelines. https://www.arb.ca.gov/msprog/moyer/guidelines/2017gl/2017_gl_appendix_c.pdf
[145] Analysis based on data from California Air Resources Board LCFS Credit Transfer Activity Reports. https://www.arb.ca.gov/fuels/lcfs/credit/lrtcreditreports.htm

reductions for the NZE hybrid-electric RTG crane is -$87,354. The cost effectiveness for ZE RTG cranes varies between $51,350 and $59,409 per weighted ton *(Figure 26).*

For GHG reductions, the cost effectiveness of the NZE hybrid-electric RTG crane is -$86 per metric ton (MT). The GHG-reduction cost effectiveness for the ZE grid-electric RTG crane varies between $66 and $78 per MT.

Note that NZE diesel-hybrid RTG cranes result in *negative* cost-effectiveness values for reducing criteria pollutant and GHG emissions. This is because their efficiency improvements (i.e., consume less diesel fuel) provide a lower TCO relative to baseline diesel RTG cranes, while still providing significant emission reductions. NZE hybrid-electric RTG cranes are the only fuel-technology platform (of the four assessed) that simultaneously reduces TCO and emissions when replacing the baseline diesel platform.

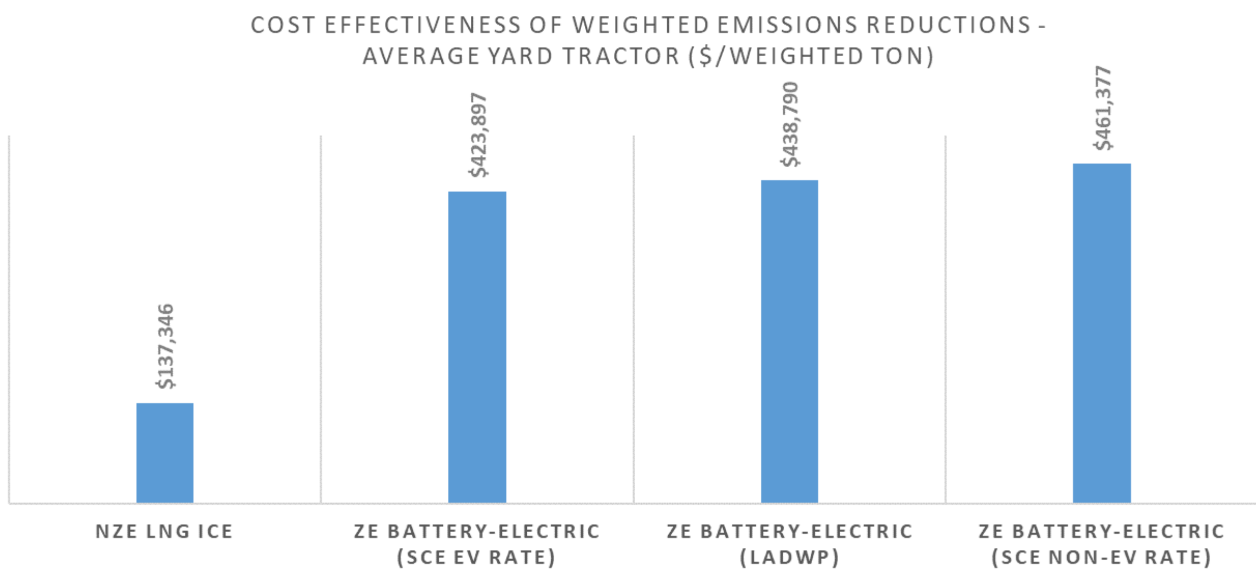


Figure 25. Cost effectiveness of criteria pollutant reductions for Yard Tractors ($/weighted ton)

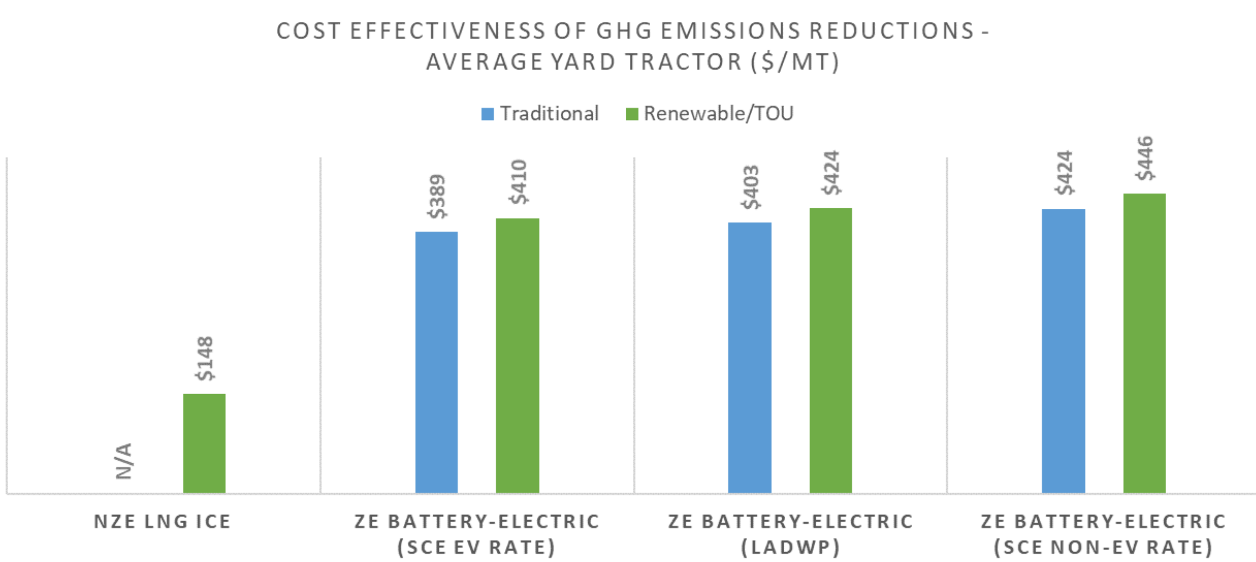


Figure 26. Cost effectiveness of GHG reductions for Yard Tractors ($/MT)

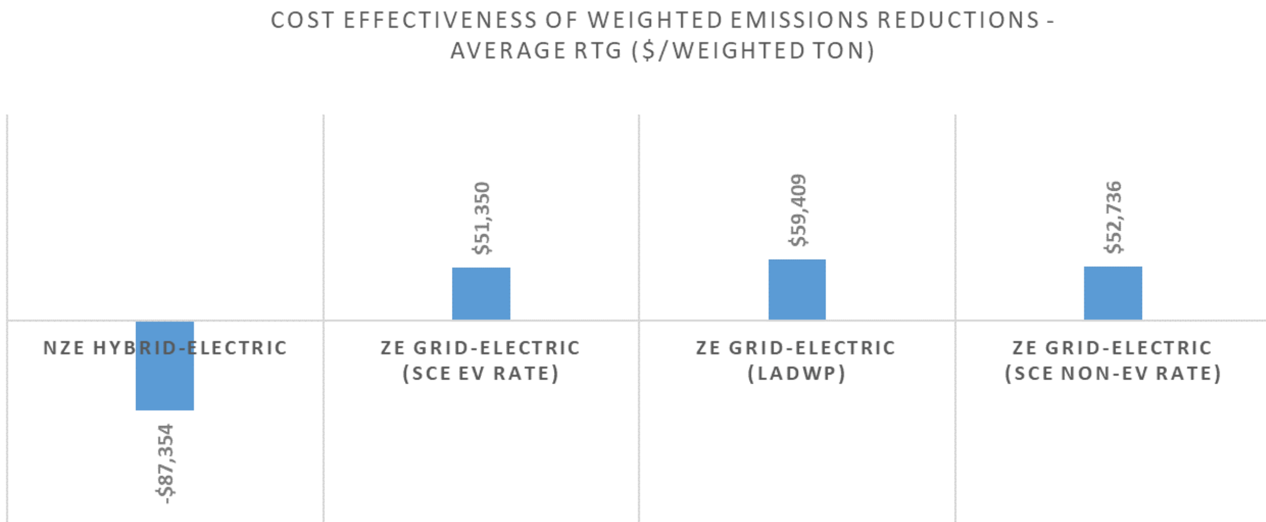


Figure 27. Cost effectiveness of criteria pollutant reductions for RTG Cranes ($/weighted ton)

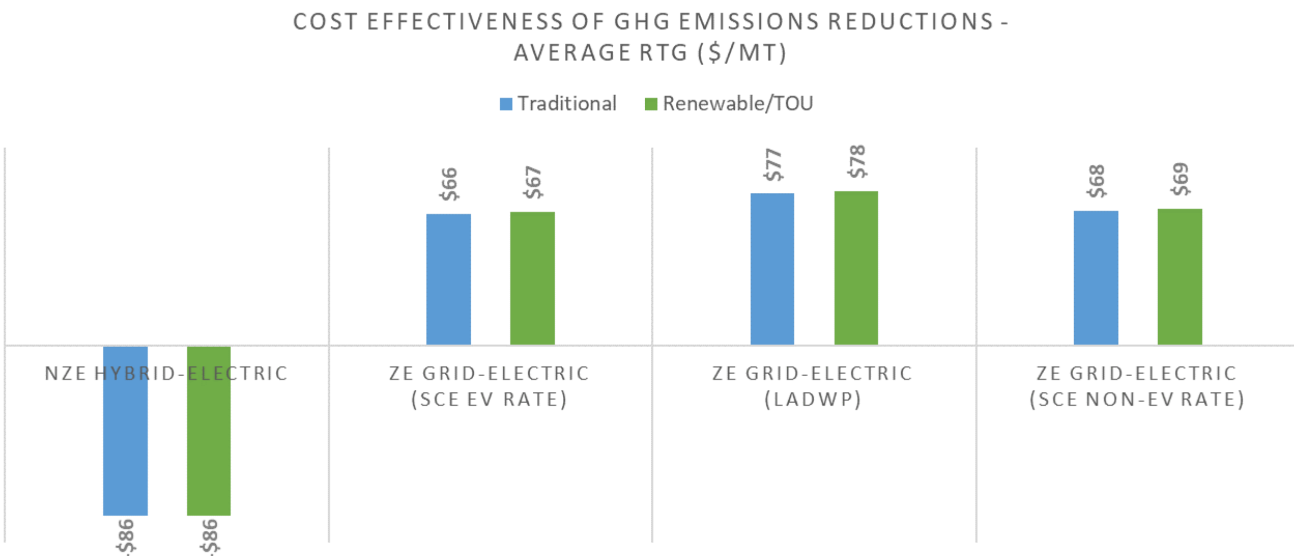


Figure 28. Cost effectiveness of GHG reductions for RTG Cranes ($/MT)

Potential for future cost-effectiveness improvements

Cost effectiveness ($ per pollutants reduced) can be improved (lowered) by reducing total costs and/or increasing reductions of CHE emissions. As described below, the potential for improving cost effectiveness varies by CHE type, fuel-technology platform and the type of emissions targeted for reduction.

ZE Battery-Electric Yard Tractors: Criteria pollutant cost-effectiveness improvements can be realized by reducing costs. This is largely dependent on reducing battery costs. This process is well underway, largely related to increased adoption of on-road battery-electric vehicles and strong competition among many types of OEMs to build and sell battery-powered vehicles for multiple applications. As noted in the Commercial Availability section, several yard tractor OEMs now sell battery-electric models as early commercial products. This increased competition, combined with the growth of EVs in both on- and off-road road markets, has been gradually reducing the incremental cost of manufacturing battery-electric yard tractors, thereby improving their cost effectiveness for reducing criteria pollutants.

GHG-reduction cost effectiveness for battery-electric yard tractors is also anticipated to improve through increased penetration of renewable electricity in the California grid, per requirements under California's Renewable Portfolio Standard. Additionally, some facilities may purchase electricity with a lower carbon intensity than the grid average, based on additional value that can be derived from the LCFS program.

NZE Natural Gas Yard Tractors: Improvements in criteria pollutant cost effectiveness are more likely to come from cost reductions. This is because NZE natural gas engines are already achieving ultra-low tailpipe emissions of NOx, PM and ROG. Improving cost effectiveness largely depends on reducing or eliminating the incremental capital cost of NZE natural gas yard tractors, compared to baseline diesel tractors. Such higher costs are mostly related to the relatively high price of current-technology on-board natural gas storage systems (LNG or CNG). These and other OEM costs can potentially be realized through economies of scale for manufacturing. Currently, natural gas yard tractors are being built and purchased in very limited volumes, and the entire U.S. market for yard tractors is relatively small. In summary, the near-term prospect for significantly reducing costs to manufacture natural gas yard tractors – and therefore improving their cost effectiveness to reduce criteria pollutant emissions – is uncertain. NZE propane engines can also power yard tractors, and this entails a lower incremental cost, due primarily to the lower cost of propane fuel tanks compared to CNG or LNG tanks. Currently, there are 160 existing propane yard tractors operating at the Ports. None are equipped with CARB-certified low-NOx engines (0.02 g/bhp-hr), but at least one OEM is reportedly pursuing this architecture specifically for sales of new yard tractors to San Pedro Bay Port MTOs.

The cost-effectiveness of achieving GHG reductions was calculated by considering a given fuel-technology "pathway" on a full-fuel-cycle basis. Notably, the GHG-reduction cost effectiveness achievable by natural gas yard tractors has been improving as the average carbon intensity of natural gas used to make CNG or LNG has decreased markedly. This is because there are a number of new RNG projects that are now producing natural gas for California NGVs while using very low (or negative) carbon intensity pathways (e.g., waste from food, biomass, and animals).

ZE Grid-Electric RTG Cranes: Criteria pollutant cost-effectiveness reductions will be realized by reducing costs, which could be realized through higher rates of adoption and larger-scale manufacturing. Like battery-electric yard tractors, GHG-reduction cost effectiveness for grid-electric RTG cranes is anticipated to improve through increased penetration of renewable electricity in the California grid, per requirements under California's Renewable Portfolio Standard. Additionally, some facilities may purchase electricity with a lower carbon intensity than the grid average, based on additional value that can be derived from the LCFS program.

NZE Hybrid-Electric RTG Cranes: As described, this fuel-technology platform already provides highly cost-effective reductions in criteria pollutants and GHG emissions. Notably, cost effectiveness of criteria pollutant reductions could be further improved if OEMs switch the diesel engines currently used to generate electricity with engines certified to CARB's lowest-tier OLNS of 0.02 g/bhp-hr. Currently, commercially available engines fueled by natural gas and propane have been certified to this ONLS level.

Workforce Impacts

Costs of workforce training for alternative technology CHE are typically associated with additional training for operators and mechanics. In the early years, MTOs would likely rely on third-party repair facilities and/or dealers to perform repairs under warranty or service contracts. Additional training will be required for mechanics and other personnel to provide these new fueling or charging services. The Ports are conducting other studies to assess the potential workforce impacts. These studies include Port of Long Beach's "Port Community Electric Vehicle Blueprint" completed in September 2021 and Long Beach City College's zero-emissions workforce assessment completed in 2019. The National Renewable Energy Laboratory is preparing an analysis on workforce impacts related to CARB's Innovative Clean Transit program, which may also provide relevant new inputs and/or methodologies.

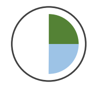
Cargo Diversion Costs

The potential for cargo diversion and the associated economic impacts have been addressed through other studies conducted by the Ports, and have therefore not been considered in this Feasibility Assessment.

9.8. Summary of Ratings for Economic Workability

Table 40 summarizes whether, according to the specific criteria and base considerations outlined above, the two commercially available CHE types and the corresponding ZE or NZE platforms have sufficient "economic workability" (as of late-2021). For each of the four possibilities, estimated ratings are provided about the degree to which they already meet these basic considerations as of late-2021, or at least show measurable progress towards achieving them by the end of 2024.

Table 39. Summary of ratings by key criteria: 2021 Economic Workability

"Economic Workability" Criteria	Base Considerations for Assessing "Economic Workability"	Yard Tractors		RTG Cranes	
		ZE BE	NZE NG ICE	ZE Grid-Electric	NZE Hybrid-Electric
Incremental Equipment Cost	The upfront capital cost for the new technology is affordable to end users, compared to the diesel baseline.				
Fuel and Other Operational Costs	The cost of fuel / energy for the new technology is affordable, on an energy-equivalent basis (taking into account vehicle efficiency). Demand charges / TOU charges (if any) are understood and affordable. Net operational costs help provide an overall attractive cost of ownership.				
Infrastructure Capital and Operational Costs	Infrastructure-related capital and operational costs (if any) are affordable for end users.				
Potential Economic or Workforce Impacts to Make Transition	There are no known major negative economic and/or workforce impacts that could potentially result from transitioning to the new equipment.				
Existence and Sustainability of Financing to Improve Cost of Ownership	Financing mechanisms, including incentives, are in place to help end users with incremental equipment costs and/or new infrastructure-related costs, and are likely remain available over the next several years.				

Legend: **Economic Workability (2021)**

Little/No Achievement = Progress since 2018 Assessment Fully Achieved

Source: Estimated ratings based on MTO interviews and site visits, footnoted studies, OEM product information, various government sources, and consultant's industry knowledge.

Further discussion about the rationale for these ratings is provided below.

ZE Battery-Electric Yard Tractors – Battery-electric yard tractors have roughly two to three times greater purchase prices relative to new diesel yard tractors and have substantial infrastructure costs associated with their deployment. While the incremental capital cost of a battery-electric yard tractor remains very high (approximately $220,000 more than a baseline diesel tractor), prices are likely to come down through economies of scale, as more battery-electric HDVs are built and sold across an array of on- and off-road applications. Conversely, the price of a baseline diesel yard tractor is likely to increase; OEMs must meet tightening emission standards that require incorporation of more-advanced emission control systems. On this broad basis, achievement of the "Incremental Capital Cost" criterion has been increased by ¼ pie (from ¼ to ½). These higher incremental costs are partially offset by lower fuel and maintenance costs, but cost of ownership is dependent on the realized electricity cost for a fleet. The effective cost of electricity is dependent on numerous factors and substantial differences in cost exist based on the utility serving a particular location. These differences lead to a broad range of battery-electric yard tractor cost-of-ownership results. However, in the scenarios considered, cost of ownership is substantially greater than diesel in the absence of incentives. Additionally, maintenance cost savings are currently highly speculative until ongoing demonstrations provide more robust data on which to refine estimates.

Incentives currently available to battery-electric yard tractors can dramatically improve their TCO relative to diesel yard tractors. In fact, the combination of purchase incentives and LCFS credits can reduce cost of ownership to 90 percent that of diesel yard tractors. Notably, the long-term availability of these incentives is not guaranteed. Notably, the "Infrastructure Capital and Operational Costs" criterion pie rating has been increased from ¼ (2018) to ½ (2021). This is based on the increased useful life assumption for yard tractors from seven to 10 years, thereby reducing the relative contribution of infrastructure to the total cost of ownership.

NZE Natural Gas ICE Yard Tractors – While natural gas yard tractors have higher incremental purchase prices and some additional infrastructure costs, their TCO over a 10-year vehicle lifetime is similar to (albeit slightly higher than) new diesel yard tractors. The cost of ownership and payback of the higher incremental purchase price is driven primarily by lower fuel costs. Current fuel price spreads between diesel and LNG provide the necessary fuel cost savings to recover most of the higher incremental purchase price. However, cost of ownership is sensitive to this price spread and actual cost savings could change significantly as price spreads change.

Incentives remain an important but uncertain part of improving cost of ownership for natural gas vehicles. Currently available purchase incentives achieve this goal, and monetary credits for the fuel (through the LCFS and federal Renewable Fuel Standard) allow fueling stations to offer RNG at a price equivalent to fossil natural gas. However, the long-term availability of these incentives is not guaranteed. Additionally, there are insufficient funds in current purchase incentive programs to provide incentives for more than a small fraction of the total yard tractor fleet. See Section 12 (Appendix B) for more about the various types of incentive programs that are relevant to CHE deployments in California.

ZE Grid-Connected RTG Cranes – The purchase cost of a new (or converted) grid-connected RTG crane is approximately 50 percent higher than a new conventional RTG crane. Infrastructure costs to enable grid connections and upgrade terminal access to sufficient power (if needed) also add significant upfront capital requirements. Fuel and maintenance cost savings partially offset these incremental costs. Currently, grid-connected RTG cranes remain 10 to 20 percent more expensive than conventional diesel RTG cranes on a TCO basis.

NZE Diesel Hybrid RTG Cranes – The purchase cost of a new (or converted) hybrid RTG crane is approximately 10 to 15 percent higher than a new conventional diesel RTG crane. This incremental cost is fully offset by the fuel cost reductions from the hybrid system over its operational life. Combined with the fact that there are no incremental infrastructure costs anticipated for this technology, diesel-hybrid RTG cranes uniquely (among the four assessed technologies)deliver a lower projected TCO than the corresponding baseline diesel equipment. While some funding programs provide incentive funding for deployment of NZE diesel-hybrid RTG cranes, their TCO advantages make incentive programs less important for the adoption of this technology.

10. Summary of Findings and Conclusions

10.1. Assessment's Scope, Methodology and Breadth of Application

This 2021 Feasibility Assessment for Cargo-Handling Equipment builds upon and updates the 2018 Assessment by applying the same five key parameters to examine which (if any) emerging zero-emission (**ZE**) and/or near-zero-emission (**NZE**) fuel-technology platforms for CHE are demonstrably capable of, and ready for, **broad deployment in revenue CHE service** at the two Ports. The applicable timeframe of this updated Assessment is mid-2021 through 2024.

The four key types of heavy-duty diesel-fueled CHE that were evaluated for overall feasibility were as follows:

- Yard tractors
- Top handlers
- Rubber tired gantry (RTG) cranes
- Large-capacity forklifts

The five parameters applied to assess overall feasibility were as follows:

- Commercial Availability
- Technical Viability
- Operational Feasibility
- Availability of infrastructure and Fuel
- Economic Workability (Key Economic Considerations and Issues)

Two of these feasibility parameters – commercial availability and technical viability – were used to initially screen five core **ZE** and **NZE** fuel-technology platforms that currently appear to hold the most promise to power large numbers of CHE. Those fuel-technology platforms that were shown to meet basic considerations for these two parameters today (or within a three-year timeframe) were then further assessed by applying the three remaining feasibility parameters (operational feasibility, infrastructure availability, and economic workability).

10.2. Summary of Findings: Screening for Commercial Availability and Technical Viability

As of late-2021, two of the four evaluated CHE types - yard tractors and RTG cranes - offer ZE and/or NZE fuel-technology platforms that sufficiently and simultaneously achieve basic parameters and criteria to be deemed "commercially available" and "technically viable." Technical viability is quantified by a Technology Readiness Level score that has reached or is approaching TRL 8. Specifics are summarized below.

Yard tractors:

- **ZE** battery-electric technology is commercially offered for yard tractors by multiple OEMs. These are effectively "early commercial" launches of products that currently achieve **TRL 7 to 8** for technical viability. ZE Battery-electric yard tractors offered by OEMs have not yet reached full commercial or technological maturity (especially for SPBP marine terminal operation). **Overall,** however, they meet the basic criteria and considerations to be deemed commercially available and technically viable in late-2021.

- **NZE** natural gas ICE technology is commercially offered for yard tractors by multiple OEMs. These are effectively "early commercial" launches of products that currently achieve **TRL 7 to 8** for technical viability. NZE Natural gas ICE yard tractors offered by OEMs have not yet reached full commercial or technological maturity (especially for SPBP marine terminal operation). **Overall,** however, they meet the basic criteria and considerations to be deemed commercially available and technically viable in late-2021.

- The other three core fuel-technology platforms that were evaluated for yard tractors – ZE fuel cell, NZE hybrid electric, and NZE diesel ICE – do not meet the basic criteria and considerations for commercially availability or technical viability. However, it is important to highlight that at least two yard tractor OEMs are making good progress to advance proof-of-concept hydrogen fuel cell yard tractors; this fuel-technology platform shows potential for low-volume, early commercial launches within the next few years.

RTG cranes:

- **ZE** grid-electric RTG cranes (new built and conversion packages) are fully commercial products with a technical viability measured at TRL 9; all four parameters that collectively define commercial availability appear to be fully achieved.
- **NZE** hybrid-electric RTG cranes (new built and conversion packages) are fully commercial products with a technical viability measured at TRL 9; all four parameters that collectively define commercial availability appear to be fully achieved. Notably, OEMs continue to reduce emissions through application of Tier 4-certified diesel gen-set engines, but emissions could be further reduced by replacing the diesel gen-set with one powered by a natural gas or propane engine certified to CARB's lowest-tier Optional Low-NOx Standard.
- **ZE** fuel cell RTG cranes are not being manufactured nor sold today by any CHE OEM. This platform does not meet the basic criteria and considerations to be deemed commercially available or technically viable in late 2021. It is difficult to assess at this time if this fuel-technology approach to RTG cranes is likely to be commercially and technically viable by 2024.

The remainder of this 2021 Assessment has been focused on further characterizing overall feasibility for yard tractors and RTG cranes using the fuel-technology platforms noted above. These combinations of CHE type and fuel-technology platforms were found to simultaneously meet basic criteria and considerations under Commercial Availability and Technical Viability, which were used as screening criteria for further assessment of overall feasibility. Further assessment consisted of three parameters: 1) Operational Feasibility, 2) Infrastructure Availability, and 3) Economic Workability.

10.3. Summary of Findings: Remaining Three Parameters

The tables that follow summarize "rolled-up" feasibility ratings for Operational Feasibility, Infrastructure Availability, and Economic Workability, as applied to the four ZE and NZE fuel-technology platforms deemed to be commercially available and technically viable.

Important notes:

The rolled-up ratings presented in each of the three tables reflect multiple feasibility criteria within that particular parameter. Each criterion is important for the success of a given fuel-technology platform in CHE operations. Thus, the rolled-up achievement rating for each CHE fuel-technology platform is based on the lowest criterion rating for the feasibility parameter identified in each table.

The tables provide pie ratings in quarter increments, which range from "little/no achievement" of a given feasibility criteria, to "fully achieved" today. The use of pie ratings is not meant to represent precise percentages of achievement for a given feasibility criteria. Rather, these ratings summarize the relative degrees of progress towards full or near-full achievement.

Table 40. Roll-up of "Operational Feasibility" ratings in 2021

Feasibility Parameter	Yard Tractors		RTG Cranes	
	ZE Battery-Electric	NZE NG ICE	ZE Grid-Electric	NZE Diesel Hybrid-Electric
Operational Feasibility				

Legend: **Achievement of Each Noted Parameter / Criteria (2021)**

Little/No Achievement = Progress since 2018 Assessment Fully Achieved

*These ratings for **Operational Feasibility** are based on the analysis of several criteria within that parameter. Because each criterion is important for the success of a given fuel-technology platform in CHE operations, the achievement ratings shown reflect the lowest criterion rating for each feasibility parameter.

Table 41. Roll-up of "Infrastructure Availability" ratings in 2021

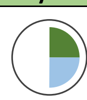
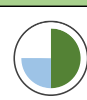
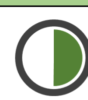
Feasibility Parameter	Yard Tractors		RTG Cranes	
	ZE Battery-Electric	NZE NG ICE	ZE Grid-Electric	NZE Diesel Hybrid-Electric
Infrastructure Availability				

Legend: **Achievement of Each Noted Parameter / Criteria (2021)**

Little/No Achievement = Progress since 2018 Assessment Fully Achieved

*These ratings for **Infrastructure Availability** are based on the analysis of several criteria within that parameter. Because each criterion is important for the success of a given fuel-technology platform in CHE operations, the achievement ratings shown reflect the lowest criterion rating for each feasibility parameter.

Table 42. Roll-up of "Economic Workability" ratings in 2021

Feasibility Parameter	Yard Tractors		RTG Cranes	
	ZE Battery-Electric	NZE NG ICE	ZE Grid-Electric	NZE Diesel Hybrid-Electric
Economic Workability				

Legend: **Achievement of Each Noted Parameter / Criteria (2021)**

Little/No Achievement = Progress since 2018 Assessment Fully Achieved

*These ratings for **Economic Workability** are based on the analysis of several criteria within that parameter. Because each criterion is important for the success of a given fuel-technology platform in CHE operations, the achievement ratings shown reflect the lowest criterion rating for each feasibility parameter.

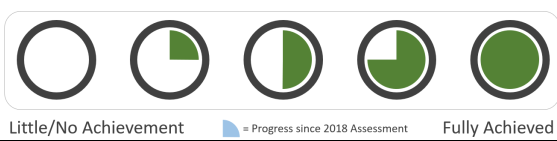
10.4. Overarching Conclusion: 2021 Feasibility Applying All Five Key Parameters

Table 43 summarizes the relative degree to which the two fully screened CHE types (yard tractors and RTG cranes, each for two fuel-technology platforms) are estimated to currently (late-2021) achieve the five key feasibility parameters, or are likely to achieve them by 2024. These estimated ratings are made in the specific context of CHE operated at marine terminals serving the SPBP. Recall that **blue** wedges in the pie ratings (which are additive to the **green** wedges) specifically highlight progress since the 2018 Assessment.

Table 43. Summary of overall "Feasibility" in 2021 according to five key parameters

Feasibility Parameter	Yard Tractors		RTG Cranes	
	ZE Battery-Electric	NZE NG ICE	ZE Grid-Electric	NZE Diesel Hybrid-Electric
Commercial Availability				
Technical Viability (TRL Rating out of 9)	TRL 7 to 8 (2024: TRL 9)	TRL 7 to 8 (2024: TRL 9)	TRL 9	TRL 9
Operational Feasibility				
Infrastructure Availability				
Economic Workability				

Legend: **Achievement of Each Noted Parameter / Criteria (2021)**



*These ratings for overall achievement of each five feasibility parameter are based on the analysis of several criteria within that parameter. Because each criterion is important for the success of a given fuel-technology platform in CHE operations, the overall achievement ratings are based on the lowest criterion rating for each feasibility parameter.

10.5. Looking Forward: Commercial and Technological Outlook

As first described in 2018 and further documented with this 2021 Assessment, most (if not all) CHE OEMs doing business with MTOs at the SPBP are now developing ZE and/or NZE fuel-technology platforms for their products. Particularly noteworthy is the accelerated progress CHE OEMs have made since 2018 to further develop, demonstrate, and commercialize **ZE battery-electric** versions of yard tractors. CHE OEMs are also making important progress to advance ZE battery-electric and fuel cell architectures for top handlers and large-capacity forklifts. OEM-backed demonstrations of first-generation technology are resulting in important lessons learned, driving towards more-advanced pre-commercial products that can better meet the needs of their end-user MTOs. ZE and NZE RTG cranes were already reaching commercial maturity and technical viability in 2018 as alternatives to conventional RTG cranes, but SPBP deployments were minimal until recently. The key progress made with ZE and NZE RTG cranes over the last three years has been their significant initial penetration into the CHE inventories at both Ports.

This growing commercial maturity and technical viability of pre- and early commercial ZE and NZE CHE has enabled planning and initiation of larger-scale, integrated deployments. Through growing public-private partnerships (involving the Ports, key government agencies, CHE OEMs and host-site MTOs), these newest collaborations are focused on complete "ecosystems" of ZE and NZE CHE, working in unison with ZE and NZE on-road drayage trucks. Such projects address all five feasibility parameters addressed in this 2021 Assessment. It is essential to continue testing the various emerging types of ZE and NZE CHE platforms *in revenue service as combined systems* at multiple SPBP marine terminals, analogous to how all MTOs currently operate baseline diesel CHE. In particular, OEMs and MTOs need experience to improve ZE battery-electric and fuel cell platforms for top handlers and large-capacity forklifts. Compared to yard tractors, these larger "vertical" CHE entail new opportunities as well as additional challenges for transitioning to ZE architectures.

Since 2018, it is clear that OEM commitments to ZE CHE markets have been growing and strengthening. As noted, for even the most-challenging CHE applications like top handlers, CHE OEMs are developing ZE architectures for their products. As of late-2021, multiple major CHE OEMs have publicly stated that they plan to transition all their CHE products to battery-electric and/or fuel cell architectures. However, before this is likely to come to fruition OEMs need additional time to address numerous critical issues associated with CHE design and functionality. For example, more work is needed to design and build products with greater endurance (the ability to work longer hours between charging events). Additionally, because marine terminals are inherently fast-paced and tough operating environments, design and/or fabrication improvements are needed to provide enhanced collision protection against battery damage and potential thermal events.

Ultimately, these products will achieve true commercialization on timelines that are commensurate with what makes good business sense for each OEM and achieves market acceptance from their customers. Even after commercially viable ZE platforms become available in a given CHE application, it will be an iterative, gradual process to widely transition the applicable SPBP fleet to ZE technologies. This must be done in close coordination with building-out of suitable fueling/charging infrastructures, in conjunction with both utilities that serve the twin Ports complex. Good progress continues to speed the pace of this transition at the Ports.

Over the next three years, it will be very important for OEMs and MTOs - through the many ongoing SPBP demonstrations - to validate these marketing statements and prove that ZE CHE platforms can meet MTO needs for performance, safety and cost metrics. In tandem, critical infrastructure build-outs will need to move forward, in proportion to vehicle rollouts. If these things come to fruition, the commercial availability and broad feasibility of ZE platforms for CHE applications will be realized at the SPBP.

11. Appendix A: Acceptable Data Sources

The following table summarizes the general types of data sources that are considered "acceptable" to use, as well as those types considered to be "unacceptable."

Acceptable Information/Data Sources	Unacceptable Information/Data Sources
• Technical reports, policy documents, and assessments prepared by government agencies with acknowledged fuel-technology expertise • Certification / verification Executive Orders by the California Air Resources Board or the U.S. EPA • Peer-reviewed journal articles • Industry trade group data, with sources • Technology demonstration reports prepared by equipment manufacturers, end users, and/or funding agencies • Official commercial product announcements and detailed product datasheets • Technical reports and whitepapers prepared by subject matter experts • Presentations from manufacturers and end users describing experience and/or analysis of relevant technologies and market dynamics • Material deemed to be credible, verifiable, technical, and relevant by Port representatives and/or TAP advisors	• Unsourced reports • Personal accounts or anecdotes (unless provided by individuals verified to be involved in an official capacity with activities listed in the "Acceptable" column of this table) • Policy advocacy documents without verifiable data/sources to support claims • Material that is deemed NOT to be credible, verifiable, technical, and/or relevant by Port CAAP representatives and/or TAP advisors

12. Appendix B: Examples of Relevant Incentive Programs

Below are additional details about key funding programs that pertain to purchasing ZE and/or NZE CHE for deployment at the SPBP.

Notably, CARB has recently launched a "Funding Finder Tool" designed to help stakeholders search and filter available heavy-duty vehicle and infrastructure incentive programs in California. This tool (https://fundingfindertool.org/?) allows filtering of eligible incentive programs by location (e.g., county, ZIP Code), vehicle or equipment type, and other parameters.

12.1. Carl Moyer Memorial Air Quality Standards Attainment Program

California's Carl Moyer Memorial Air Quality Standards Attainment (Carl Moyer) Program provides incentive grants for cleaner-than-required engines, equipment and other sources of pollution providing early or extra emission reductions. Carl Moyer Program awards are administered by local air quality management districts. Basic requirements include the following:

- Project must achieve surplus emission reductions
- Existing equipment must be in compliance with the CHE Regulation, and scrapped
- Equipment utilizing regulatory extensions are not eligible for funding
- Existing engine must be certified by CARB

SCAQMD has jurisdiction for Carl Moyer Program funds applicable to the SPBP. In 2021, SCAQMD announced availability of Carl Moyer funds to electrify certain types of CHE operating at the Ports. Specific examples of eligible CHE projects under SCAQMD's CMP implementation include the following[146]:

- Conversion or replacement of existing diesel-powered RTG cranes to zero-emission power systems - Eligible costs may include the purchase of a new crane or installation of a zero-emission engine, necessary parts for an existing RTG crane including directly related vehicle modifications, infrastructure to supply electrical power, utility construction, and costs associated with increasing the capacity of electrical power to the crane. (Ineligible costs include design, engineering, consulting, environmental review, legal fees, permits, licenses and associated fees, taxes, metered costs, insurance, operation, maintenance and repair.) Projects are evaluated on a case-by-case basis.
- Conversion or replacement of an existing CHE with a zero-emission propulsion system. Eligible costs may include the purchase of a zero-emission unit. (Ineligible costs include license, registration, taxes (other than federal excise and sales tax), insurance, operation, maintenance and repair.) Projects are evaluated on a case-by-case basis.

Maximum funding is 85% when repowering to a zero-emission system and 80% for complete equipment replacement. In addition to these maximum funding levels, all projects must not exceed the cost-effectiveness limits as specified in the 2017 Carl Moyer Program Guidelines.

12.2. California Clean Off-Road Equipment Voucher Incentive Project (CORE)

CORE is a relatively new multi-year, multi-million dollar project designed "to encourage California freight equipment users to purchase or lease currently commercialized zero-emission off-road freight equipment." Like its on-road HDV counterpart (HVIP), CORE uses a "streamlined voucher" mechanism to help offset the higher cost of zero-emission technology, by applying a point-of-sale discount. CORE has no scrappage requirement, and additional funding is available for charging and fueling infrastructure and for equipment deployed in disadvantaged communities. Eligible equipment categories for incentive funding under CORE include yard tractors, top handlers, large-capacity forklifts, and RTG cranes (notably, as of late-2021

[146] South Coast Air Quality Management District, Carl Moyer Program Funding Categories: Cargo Handling Equipment, http://www.aqmd.gov/home/programs/business/carl-moyer-memorial-air-quality-standards-attainment-(carl-moyer)-program/che-off-road-compression-ignition-equipment.

several types of CHE have "no equipment currently available" for replacement of baseline diesel CHE.[147] An example of a CORE project type that has received high-levels of funding is replacement of diesel yard tractors with battery-electric yard tractors, and eligible projects can receive roughly half of the capital cost of the ZE option. Details are available at https://californiacore.org/equipment-category/terminal-tractors/

12.3. Low Carbon Fuel Standard

California's Low Carbon Fuel Standard allows producers of alternative fuels to generate credits based on the lifecycle GHG emissions reductions of the alternative fuel relative to established diesel and gasoline benchmarks. These credits can have substantial value. CARB's most recent transaction data report a price of $190 per credit for the month of January, 2019. One credit is equal to one metric ton of GHG emissions reductions.

CARB adopted revisions to the LCFS program that went into effect January 1, 2019. These revisions extended carbon intensity requirements for diesel and gasoline fuels, requiring an 18 percent reduction from the 2010 baseline by 2030. This change is expected to significantly increase the number of deficits generated by producers and importers of conventional gasoline and diesel fuel, thereby increasing demand for credits to offset the additional deficits. However, the modifications to the LCFS program also significantly expand the potential number of generators of credits and increase the number of credits that can be generated from heavy-duty electric vehicles. These additional credits could act to reduce credit prices, particularly as current credit prices near the approximately $200/credit price cap established in the regulation.

Despite uncertainty in the future of credit prices under the LCFS program, LCFS credit values are assumed to be $149 per MT, calculated from the weighted average credit price for the first three quarters of credit transfer pricing reported by CARB.[148]

12.4. South Coast AQMD VW Mitigation Trust Freight and Marine Projects

The Volkswagen Environmental Mitigation Trust provide hundreds of millions of dollars in California to fund emission reductions projects under the State's Beneficiary Mitigation Plan. This plan currently allocates $60 million in funds for zero-emission Freight and Marine projects that can "accelerate the replacement of older, higher polluting engines, particularly in areas that are disproportionately impacted by air pollution, such as freight corridors, ports, and rail yards." For example, this program with pay a major portion of the capital cost of a battery-electric yard tractor. Details about the program relevant to the SPBP can be viewed at https://xappprod.aqmd.gov/vw/combustion.html.

12.5. Local Utility Incentive Programs for Electric CHE and/or Charging Infrastructure

Southern California Edison Charge Ready Program - SCE has received approval from the California Public Utilities Commission to install electric infrastructure at customer sites to support charging of heavy-duty vehicles, including heavy-duty drayage trucks, forklifts, and CHE. The program also allows SCE to offer rebates to customers for the purchase of charging stations. For fleets operating in SCE's business territory – which includes MTOs at the Port of Long Beach – Charge Ready helps them electrify their fleet by guiding them "through every step of the process . . . including installing the infrastructure you need to support your fleet at low or no cost" to the fleet. An overview of Charge Ready is available at https://www.sce.com/evbusiness/overview, with details at https://crt.sce.com/program-details.

Los Angeles Department of Water and Power EV Programs – LADWP also offers programs to support commercial EV deployments in its jurisdiction, which includes the Port of Los Angeles. LADWP's website (https://www.ladwp.com/) indicates the utility "is committed to a clean energy future, and putting our customers first" to facilitate adoption of EVs. This includes "Charge Up L.A." rebate programs for residents and businesses, and support to install public, workplace and fleet charging stations to create "EV communities across Los Angeles."

[147] California CORE, https://californiacore.org/

[148] California Air Resources Board, "Monthly LCFS Credit Transfer Activity Report for September 2018." Posted October 9, 2018. https://www.arb.ca.gov/fuels/lcfs/credit/20181009_sepcreditreport.pdf

SAN PEDRO BAY PORTS

CLEAN AIR ACTION PLAN

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July 2022