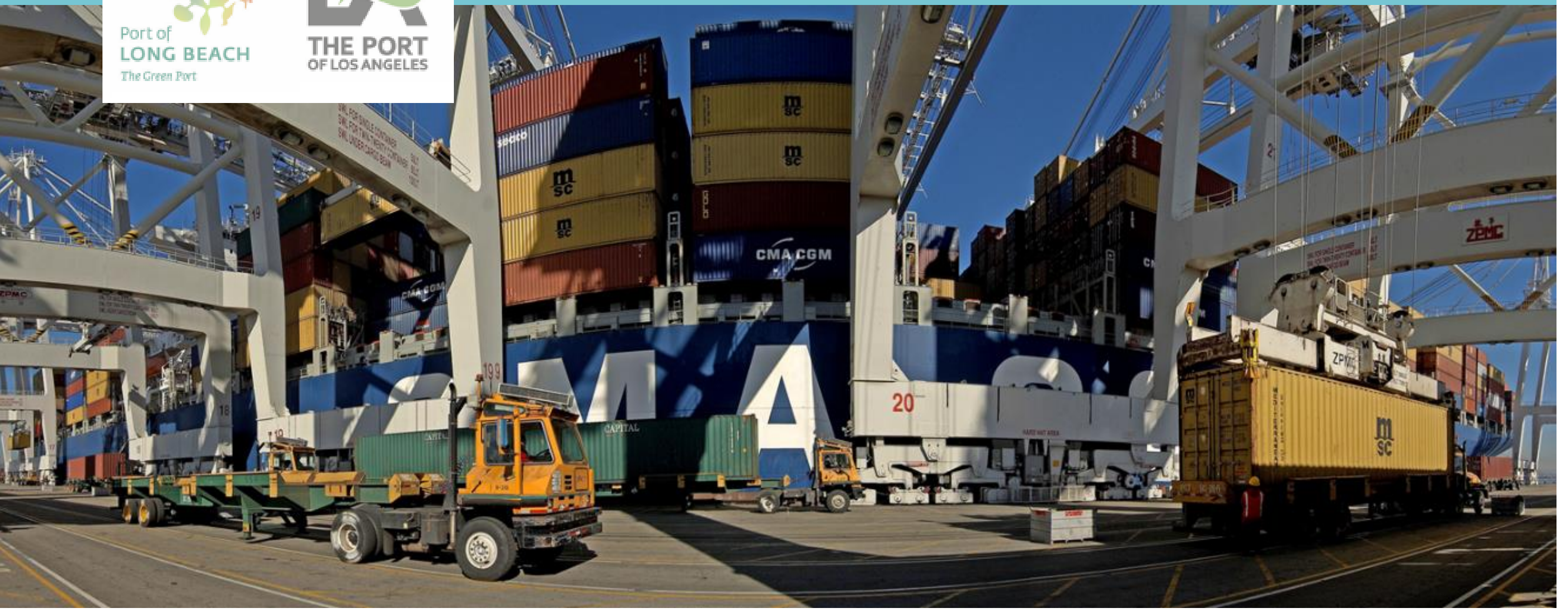

SAN PEDRO BAY PORTS

CLEAN AIR ACTION PLAN

2018 FEASIBILITY ASSESSMENT for CARGO-HANDLING EQUIPMENT

September 2019

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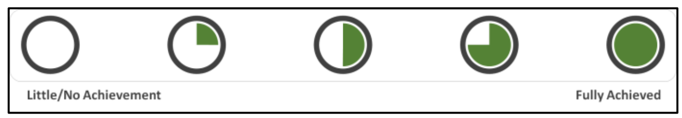
Important Notes: 2018 Feasibility Assessment for Cargo-Handling Equipment (CHE)

The San Pedro Bay Ports Clean Air Action Plan 2017 Update (CAAP) 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 2018 Feasibility Assessment for CHE is the second of the series to be released. It 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 (2018 to 2021), 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 2021). It provides a snapshot about which ZE and/or NZE CHE platforms are feasible today, or will likely be feasible by 2021 – for widespread deployment across the 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.

This Assessment uses tables to summarize ratings about the relative degree to which various CHE fuel-technology platforms are deemed to be "feasible" today. This is done for four key feasibility parameters: Commercial Availability, Operational Feasibility, Infrastructure Availability, and Economic Workability. For each main feasibility parameter and the individual criteria that define it, 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.



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, some costs calculations presented in this Assessment were calculated based on non-incentivized totals.

The Ports intend to prepare 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 (see text) for the overall process and intent, as laid forth in the CAAP.

This Assessment was developed over many months based on significant outreach, research and stakeholder feedback. The final 2018 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.

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.

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The authors gratefully acknowledge all the valued inputs from the contributing individuals and peer reviewers.

List of Terms

ACRONYM	DEFINITION
AQMP	Air quality management plan
BE	Battery Electric
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.
DGE	Diesel gallons equivalent
EER	Energy economy ration
EPA	U.S. Environmental Protection Agency
EVSE	Electric vehicle supply equipment
FC	Fuel cell
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
MT	Metric ton
MWh	Megawatt hour
NAAQS	National Ambient Air Quality Standards
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
TCO	Total cost of ownership
UTR	Utility tractor rig (aka: yard tractor)
ZE	Zero-emission

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Executive Summary

This 2018 Feasibility Assessment for Cargo-Handling Equipment applied 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, in 2018 or within approximately three years.

Collectively, about 3,500 individual CHE serve the two Ports. Seventy percent (2,447 CHE) are powered by relatively large diesel engines. Heavy-duty diesel engines in general emit high levels of key air pollutants. Four types of high-horsepower diesel-powered CHE collectively emit more than 85 percent of the total pollutants from the San Pedro Bay Ports' collective CHE fleet -- and are therefore key targets for reducing emissions under the 2017 CAAP Update.[1] These are:

1. Yard tractors
2. Top handlers
3. Rubber tired gantry (RTG) cranes
4. Large-capacity forklifts

Consequently, this 2018 Assessment focuses on the above four CHE types, to characterize their overall feasibility for transitioning large numbers to ZE and/or NZE fuel-technology platforms within approximately three years.

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

Additionally, smaller types of CHE – typically powered by non-diesel engines – are targeted for emissions reductions under the CAAP. Small-capacity forklifts powered by gasoline or propane engines are the most prominent examples. Consequently, small-capacity forklifts were also evaluated in this study for their feasibility to use ZE or NZE fuel-technology platforms. This was done separately and at a higher level; full discussion and findings are presented in Section 13 (Appendix C).

Per guidance provided by the Ports[2], the following five parameters were applied to collectively assess overall feasibility for each of the four key CHE types:

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

For each of the four CHE types, five core ZE or NZE fuel-technology platforms were initially 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 four CHE types are the subject of ongoing technology development and demonstration programs at the two Ports.

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

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

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

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 feasibility to power large numbers of CHE as if late-2018, or by 2021. Those fuel-technology platform(s) that were shown to currently achieve (or nearly achieve) the basic considerations for commercial availability and operational feasibility were then further assessed, by applying the three remaining feasibility parameters (operational feasibility, infrastructure availability and economic workability).

Summary of Findings: Screening for Commercial Availability and Technical Viability

As of late-2018, 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." Technical viability is quantified by a Technology Readiness Level score that has reached or is approaching TRL 8.

Specific findings are summarized below for the two types of CHE.

Yard tractors:

- **ZE** battery-electric technology is commercially offered for yard tractors by multiple OEMs. These are effectively "pre-commercial" or "early commercial" product launches that have achieved TRL 7, and are approaching TRL 8 through focused, multi-unit demonstrations. All four parameters that collectively define commercial feasibility are at least partially achieved.

- **NZE** natural gas ICE technology is commercially offered for yard tractor by multiple OEMs. These are effectively "pre-commercial" or "early commercial" product launches that have achieved TRL 7, and are approaching TRL 8 through focused, multi-unit demonstrations. All four parameters that collectively define commercial feasibility are at least partially achieved.

- 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.

RTG cranes:

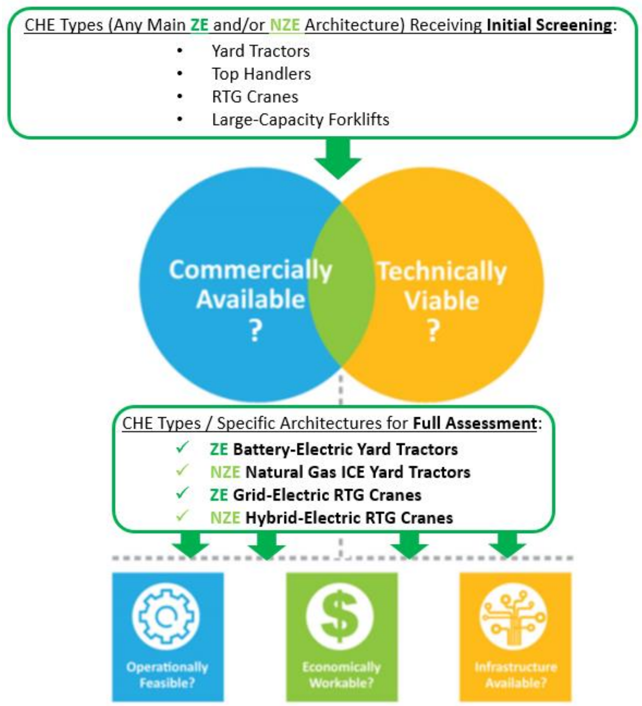
- **ZE** grid-electric RTG cranes (new built and conversion packages) are fully commercial products at TRL 9; all four parameters that collectively define commercial availability appear to be fully (or near fully) achieved. Grid-electric RTG cranes receive their electricity from a direct-grid connection (via a cable reel system or busbar), and must maintain that connection for the vast majority of their operation.

- **NZE** hybrid-electric RTG cranes (new built and conversion packages) are fully commercial products at TRL 9; all four parameters that collectively define commercial availability appear to be fully (or near fully) achieved.

- The other two core fuel-technology platforms that were evaluated for RTG cranes – **ZE** fuel cell and **NZE** diesel ICE – do not meet the basic criteria and considerations for commercially availability or technical viability.

The remainder of this 2018 Assessment was focused on further characterizing overall feasibility for yard tractors and RTG cranes powered by 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 applying individual criteria within the following three major parameters: 1) Operational Feasibility, 2) Infrastructure Availability, and 3) Economic Workability. The figure below depicts this basic screening process that was applied, resulting in the selected full assessments.



Initial screening parameters (Commercial Availability and Technical Viability), and the CHE types / architectures that emerged for further assessment (Operational Feasibility, Economic Workability, Infrastructure Availability).

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

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.

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. Equally important, the use of these "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.

Important Notes:

1) Nothing in this 2018 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 are already supporting efforts to test a variety of CHE platforms with TRL ratings in the 5-to-6 range. This is especially true in cases that include major involvement and cost sharing by CHE OEMs.

2) This Assessment is a snapshot of CHE fuel-technology platforms as of late-2018. The Ports intend to conduct the next feasibility assessment within three years, or sooner if warranted by technological and market conditions.

Roll-up of "Operational Feasibility" ratings in 2018

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 (2018)**

○ ◔ ◑ ◕ ●

Little/No Achievement … 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 <u>lowest criterion rating</u> for each feasibility parameter.

Roll-up of "Infrastructure Availability" ratings in 2018

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 (2018)**

○ ◔ ◑ ◕ ●

Little/No Achievement … 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 <u>lowest criterion rating</u> for each feasibility parameter.

Roll-up of "Economic Workability" ratings in 2018

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 (2018)**

○ ◔ ◑ ◕ ●

Little/No Achievement … 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 <u>lowest criterion rating</u> for each feasibility parameter.

Overarching Conclusion: 2018 Feasibility Applying All Five Key Parameters

The table 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 achieve the five key feasibility parameters (as of late-2108), or are likely to achieve them by 2021. These estimated ratings are made in the specific context of CHE operated at the marine terminals serving the San Pedro Bay Ports.

Summary of overall "Feasibility" in 2018 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 (2021: TRL 7 to 8)**	**TRL 7 (2021: TRL 7 to 8)**	**TRL 9**	**TRL 9**
Operational Feasibility	◔	◕	◕	●
Infrastructure Availability	◔	◕	◑	●
Economic Workability	◔	◑	◑	●

Legend: **Achievement of Each Noted Parameter / Criteria (2018)**

○ ◔ ◑ ◕ ●

Little/No Achievement … 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, Technological and Economic Outlook

As described in this report, most (if not all) CHE OEMs are now developing ZE and/or NZE fuel-technology platforms for their products. To meet CAAP objectives, it is particularly important that OEMs are making steady and measurable progress to advance various **ZE** CHE platforms towards technological maturity and market readiness. Under the CAAP – as well as state and local air quality plans – large-scale deployments of heavy-duty ZE platforms are expeditiously needed wherever overall feasibility can be established. Yard tractors are key "horizontal" CHE that are making particularly strong and important progress towards commercialization of ZE architectures. This will help advance efforts by OEMs to incorporate battery-electric and fuel cell platforms into 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.

As described in this report, the cost effectiveness of reducing key emissions ($ per mass of reductions) by deploying ZE battery-electric and/or NZE natural gas ICE yard tractors is currently about three to five times higher than the applicable limits under California's Carl Moyer Program, which serves as a useful metric for comparison. To improve (reduce) cost effectiveness for the two types of yard tractor architectures, OEMs will likely need to 1) realize significant cost reductions with the onboard energy storage systems they utilize (batteries or natural gas tanks), and/or 2) achieve greater economies of scale through higher-volume manufacturing. Both processes are underway, especially in the case of reducing battery costs for ZE battery-electric tractors. By contrast, ZE and NZE RTG cranes are significantly more cost effective as a strategy for reducing criteria pollutant and GHG emissions. This is largely because RTG cranes don't have the same challenges and higher costs associated with energy storage.[3]

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 San Pedro Bay Port fleet to ZE status. This must be done in close coordination with building-out of suitable fueling / charging infrastructures. Good progress is underway to accelerate the pace of this transition at the Ports. This can be seen in the many ZE CHE demonstrations that are now, or will soon be, underway at marine terminals serving both Ports.

Related to this expanding number of demonstrations, and equally important, OEM commitment to ZE CHE markets has been growing and strengthening. For even the most-challenging CHE applications (e.g., top handlers), CHE OEMs are developing ZE architectures for their products. One major OEM has publicly stated that by 2021, it will make and sell at least one ZE model for all four key CHE types. Ultimately, these products will achieve true commercialization on timelines that are commensurate with commercial maturity, and according to what makes good business sense for each OEM.

Over the next three years, it will be very important for OEMs and MTOs, through the many San Pedro Bay Ports 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 may fundamentally improve at the San Pedro Bay Ports.

[3] ZE RTG cranes focused upon in this report utilize a direct grid connection, and therefore do not require battery packs for on-board storage of electricity. NZE RTG cranes retain diesel power but may include relatively small battery packs for limited ZE operation.

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 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. 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.

Included in the updated CAAP is a call to accelerate the timeline for San Pedro Bay Port marine terminals to adopt and deploy zero- or near-zero-emission CHE (see below), where feasible. Extensive details about the overarching CAAP – and specifically how cleaner CHE will be phased in over time – are available on the CAAP website located at the following address: 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 **Working Definitions** 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."[4]

Working Definitions: Zero-Emission (ZE) and Near-Zero-Emission (NZE)
A **zero-emission (ZE)** fuel-technology platform for CHE has not yet been formally defined by CARB or EPA. <u>For purposes of this assessment</u>, ZE refers to any fuel-technology combination for CHE that *does not directly emit any regulated pollutants*. Effectively, this eliminates any platform that utilizes onboard fuel combustion. A **near-zero-emission (NZE)** fuel-technology platform has not yet been formally defined by CARB or EPA.* <u>For purposes of this Assessment</u>, 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, <u>or</u> the federal Tier 4 Final non-road standards (whichever is applicable)*. *CARB is expected to establish the allowable emission level for NZE <u>on-road</u> heavy-duty engines in 2020. CARB will also be responsible for certifying whether or not particular on-road engines developed by various manufacturers meet this emission level. If CARB does adopt a formal NZE standard for on-road heavy-duty engines, and/or an equivalent standards for non-road engines, the Ports will rely on these certifications as the determination of whether or not particular engines used in CHE are considered to emit at near-zero emission levels.

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

The ultimate objective is to ascertain which (if any) ZE and/or NZE goods movement platforms are now "feasible" (see **Evaluating "Feasibility"** below) to fully perform goods movement at the Ports, while also systematically and sufficiently reducing harmful emissions in line with CAAP goals. Because market conditions and technology landscapes can change rapidly, The Ports intend to prepare updated drayage 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.

Evaluating "Feasibility"

For purposes of this Assessment, *feasibility* refers to the ability of alternative fuel/technology CHE 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 2018 Feasibility Assessment for Cargo-Handling Equipment is the inaugural effort to characterize the status of ZE and NZE fuel-technology platforms that are (or may soon be) 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 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.[5] This was used to derive a near-term feasibility "snapshot" (2018 to 2021) 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 summarizes progress being made for them to become 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 2018 Feasibility Assessment for Caro-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.

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

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-2018) and expected near-term (by or before 2021) overall feasibility of emerging CHE fuel-technology platforms. This report will be updated by late 2021, or sooner if important new information becomes available.[6] Through the public process to engage stakeholders, and by continuing to consult 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 San Pedro Bay Ports 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 San Pedro Bay Ports complex. Such situations are recognized and discussed, particularly as they pertain to potential for broader application.

Assessed Types of CHE – More than 90 percent of the San Pedro Bay Ports' 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[7] (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 needs 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 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 report uses the same basic parameters and criteria (described further) to assess and compare the following five basic emerging ZE and NZE fuel-technology platforms:

6. **ZE** Battery electric (charged via manual plugs or inductively) 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 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-2018, 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* (2018 to 2021).

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 taken into account in this Assessment, and reasonable attempts have been made to incorporate emerging

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[6] 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.

[7] More than 400 top handlers (top picks) 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.

developments as they occur. It is possible, albeit 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."[8]

Following this template, the authors utilized an array of credible and relevant information sources to prepare this 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 CARB, SCAQMD and CEC staff; 2) using survey instruments to query CHE OEMs and technology providers; and 3) visiting three San Pedro Bay Ports MTOs, at the invitation of 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.

Table 1. General types of unacceptable information / data sources for 2018 Feasibility Assessment

Unacceptable Types of Information/Data Sources for 2018 Feasibility Assessment
• 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 Source) • Policy advocacy documents without verifiable data/sources to support claims • Fuel additives and/or devices that have not been fully evaluated and verified by CARB, including a multimedia evaluation • Material lacking sufficient information to be judged credible, verifiable, and/or relevant by Port CAAP representatives and/or TAP advisors

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

3. Overview of San Pedro Bay Ports CHE Fleet

3.1. Late-2018 Snapshot by Key Fuel-Technology Types

As reported in the Ports' respective most-current Emission Inventories (2017), there are approximately 3,500 individual CHE in the collective San Pedro Bay Ports fleet. Approximately 90 percent fall within the four CHE categories focused upon for this feasibility assessment. Figure 1 provides 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:

- 1,693 yard tractors (hostlers), of which 83 percent are powered by diesel ICE technology
- 412 top handlers, of which 100 percent are powered by diesel ICE technology.
- 169 RTG cranes, of which 92 percent are powered by conventional diesel ICE/hybrid-electric technology (the remaining 8 percent are equipped with advanced, lower-emission diesel ICE/hybrid-electric technology).
- 757 forklifts, of which 221 (29 percent) are "large capacity" units powered by diesel ICE technology.

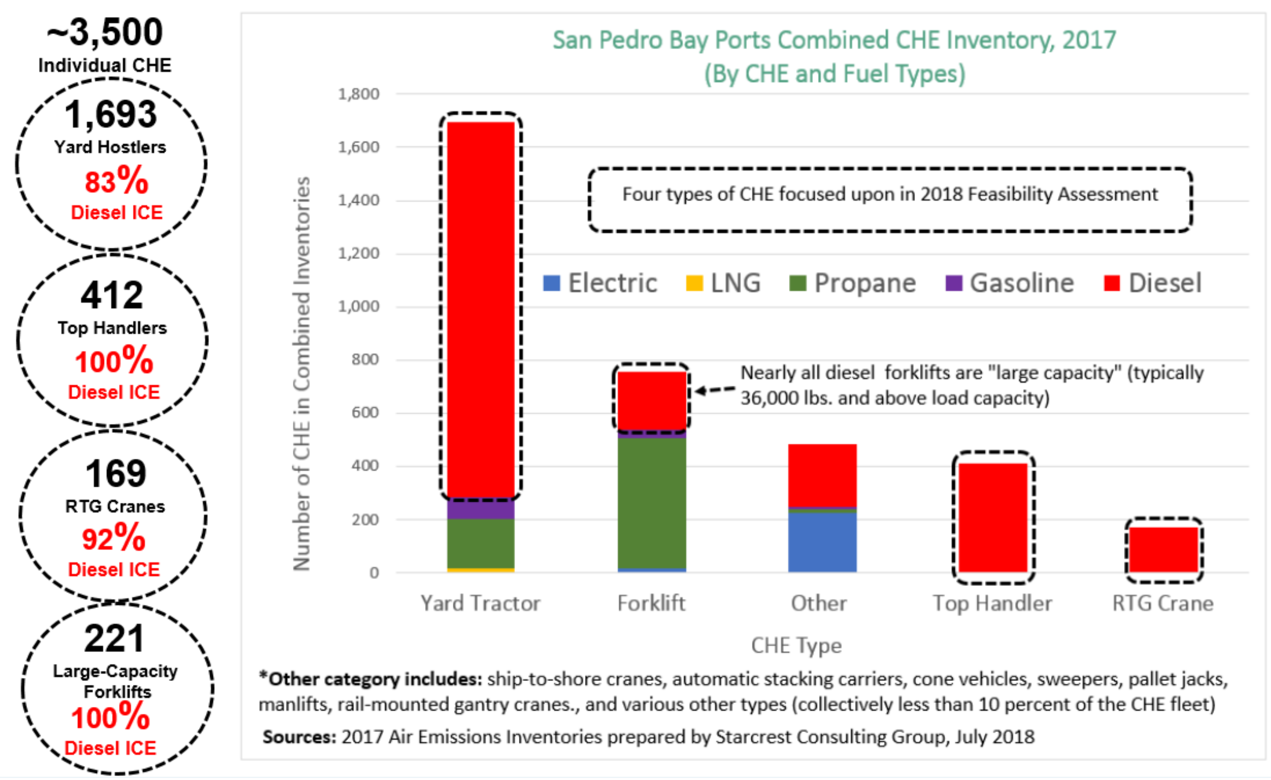

Figure 1. San Pedro Bay Ports CHE inventory by equipment type (2017)

3.2. The Importance of Integrated CHE Operations at Marine Terminals

San Pedro Bay Port 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 optimally, economically and safely move cargo 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 speed during cargo moves at San Pedro Bay Port marine terminals.

3.3. 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.[9] Hence, this Assessment focuses on the near-term feasibility to replace (or convert) conventional diesel-engine CHE to versions that incorporate ZE and NZE fuel-technology platforms.

However, the Ports' collective emissions inventory includes hundreds of CHE fueled by propane and gasoline using spark-ignition engines. As can be seen in Figure 1 above (the bars with green or purple shading), these non-diesel fueled CHE 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 are listed in the CHE inventory, they are significantly different than the high-horsepower CHE described above that are focused upon in the feasibility assessments. Nonetheless, 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. Such a separate analysis is provided in Section 13 (Appendix C).

[9] 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.

4. Applied Parameters and Initial Screening

This 2018 Feasibility Assessment for CHE applied five key parameters to 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 outlined by the Ports[10] 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. Simply put, 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 basic screening procedure.

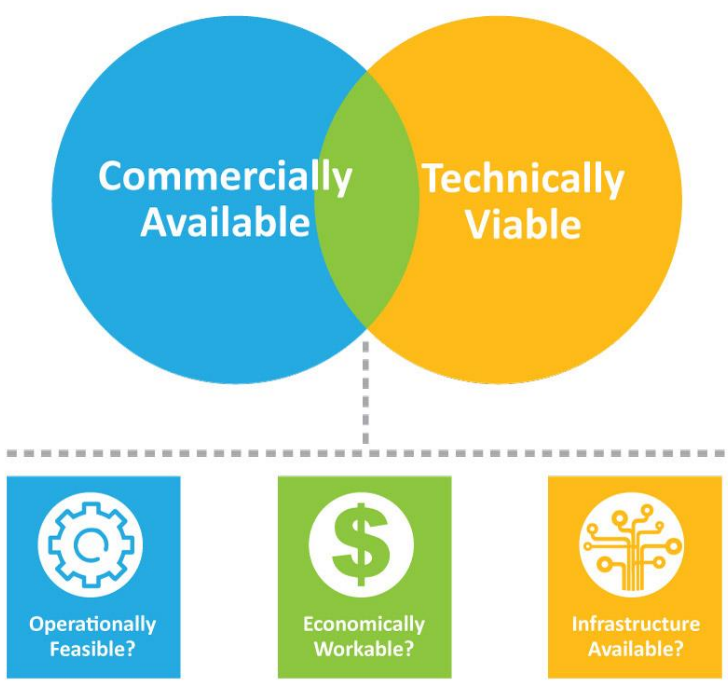

Figure 2. General screening procedure for applying feasibility parameters to assess fuel-technology platforms

[10] 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 2018 Feasibility Assessment for CHE represents a snapshot in time (late-2018, with potential for feasibility by 2021). 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-2018) could still exhibit rapid advancement and development. Recognizing this potential, the Ports intend to prepare the next feasibility assessment for CHE at least every three years, or sooner if warranted by accelerated technological progress, significant expansion in commercial platforms, improving economics, etc.

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 large quantities and within similar timeframes as the baseline equipment (usually powered by diesel ICE technology), and (2) it has (or approaches) 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.[11] 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.	

5.2. Production with Major OEM Involvement

A common denominator among the criteria above is emphasis on the essential role that major CHE OEMs must play to develop, fully certify, sell and support large numbers of ZE and/or NZE CHE of the various types. To gather and summarize the current status of major OEM involvement in these markets, two key sources of information were utilized: 1) surveys completed by senior OEM representatives (allowing anonymous responses); and 2) public statements and information released by the OEMs. Further details and findings are described below.

In mid-2018, surveys were prepared and sent to senior-level representatives from existing major CHE OEMs, as well as startup OEMs. The objective was to obtain anonymous[12] feedback from the OEMs describing 1) their existing or near-term-planned product offerings that incorporate ZE or NZE fuel-technology platforms (as previously defined); and 2) how they perceive opportunities, challenges, and timelines associated with new or expanded markets for ZE and/or NZE CHE at the San Pedro Bay Ports. Such OEM input was recognized for its value in preparing this assessment, while not necessarily assuming it was fully up-to-date and/or accurate.

Ten CHE OEMs and one manufacturer of conversion systems were sent this survey. As summarized in Table 3, these 11 different companies produce and sell a wide range of CHE products -- including all four key types assessed in this report. Nine of the 11 different CHE-related OEMs that received the survey provided some type of written response**.** To augment and corroborate survey inputs, the authors also reviewed and tallied relevant public statements and literature disseminated by

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

[12] 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.

these OEMs. Also, where relevant (primarily yard tractors), the authors further gauged commercial availability by information provided by CARB under its California's Hybrid Truck and Bus Voucher Incentive Program (HVIP).

Table 3: CHE OEMs receiving survey on ZE/NZE products, opportunities and challenges

Category of OEM	Name of OEM	Most-Relevant CHE Product(s)
Major Existing CHE OEM	**Capacity Trucks**	• Yard Tractors
	Kalmar - Cargotec	• Yard Tractors, Top Handlers, RTGs
	TICO	• Yard Tractors
	Autocar	• Yard Tractors
	Taylor Machine Works	• Top Picks / Reachstackers, Large Capacity Forklifts
	Hyster-Yale	• Top Picks / Reachstackers, Large Capacity Forklifts
	Hoist Lift Trucks	• Yard Tractors, Top Pick / Reachstackers, Large Capacity Forklifts
	Konecranes	• Top Picks / Reachstackers, RTGs, Large Capacity Forklifts
Start-Up / Emerging CHE OEM	**BYD**	• Yard Tractors
	Orange EV	• Yard Tractors
OEM for Conversion Systems	**Conductix Wampfler**	• RTGs

As is further described below, various CHE types are in different stages of commercialization for ZE and/or NZE fuel-technology platforms, as follows: 1) ZE grid-electric and NZE hybrid-electric RTG cranes are fully commercial products; 2) ZE battery-electric and NZE natural gas yard tractors are in "early commercialization" stages (just beginning demonstrations, with very little or no experience in revenue service, to date); and 3) ZE architectures (battery-electric and fuel cell) are primarily in technology development stages for top handlers and large-capacity forklifts.

Note: Many CHE OEMs are working with, and relying upon, smaller-volume start-up* OEMs, technology providers[13] 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 developed with OEMs to develop and help commercialize ZE and NZE CHE technologies.

*The term "start-up OEM" is used in this report in the context of North American sales for heavy-duty vehicles and equipment.

5.2.1. ZE / NZE Yard Tractors: OEM Involvement

With the exception of RTG cranes (see Section 5.2.3), yard tractors have demonstrated the greatest progress for commercialization of ZE and/or NZE technologies. As Table 4 below summarizes, as of late-2018 six CHE OEMs indicated they commercially offer at least one yard tractor model powered by a ZE and/or NZE technology. Figure 3 provides photos of the six basic product offerings.

Key findings in Table 4 include the following:

- Three CHE OEMs are selling ZE battery-electric yard tractors. These are: Kalmar Ottawa (a major existing OEM), plus BYD and Orange EV (two relatively new CHE OEMs). All three companies are selling ZE yard tractors that are certified and listed by CARB as eligible for incentive funds under the California HVIP. However, there have been almost no revenue-service deployments for any ZE yard tractors at an SPBP MTO, as of late-2018. An especially important issue for battery-electric yard tractors in port operation is whether or not they can achieve diesel-equivalent shift operating time between battery charging events. These groundbreaking CHE products are further discussed and analyzed in Section 7 (Operational Feasibility), specifically for their ability to achieve two shifts of operation between charging events when

[13] At least three "technology providers" of ZE and/or NZE drive systems -- TransPower, US Hybrid and Meritor -- are working with these various CHE OEMs to advance and incorporate their platforms into OEM CHE. Activities of these companies are reflected in OEM products.

moving cargo at SPBP marine terminals.

- Three CHE OEMs (all major existing) are selling NZE natural gas yard tractors: Capacity Trucks, TICO and Autocar. Capacity offers two LNG-fueled models (8.9 and 6.7-liter engines), and TICO offers one model with either a CNG- or an LNG-fueled engine. (TICO also expects to offer a propane-fueled version of its NZE yard tractor product lineup.) Autocar is believed to sell at least one CNG-fueled yard tractor that incorporates one of the newer, lower-emission engines (i.e., certified to CARB's Optional Low-NOx Standard, or OLNS). As with the battery-electric tractors, the emerging NZE natural gas yard tractors have not yet accrued any significant time in revenue service at SPBP MTOs. NZE natural gas yard tractors are further discussed and analyzed in Section 7 (Operational Feasibility), specifically for their ability to achieve two shifts of operation between fueling events when moving cargo at SPBP marine terminals. **NOTE:** for nearly a decade, non-NZE versions of LNG tractors have been successfully used to move containers at a yard near the Port of Los Angeles. These are older-generation yard tractor models / engines that have been discontinued by their respective manufacturers.[14]

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

Make	Model	ZE Battery-Electric	ZE Fuel Cell	NZE Hybrid Electric	NZE CNG ICE	NZE LNG ICE	HVIP Status / First Year	Status: SPBP Deployment*
BYD	8Y	✓	✗	✗	✗	✗	Certified, 2017	Pre-Tests, 2018
Kalmar Ottawa	T2 4X2	✓	✗	✗	✗	✗	Certified, 2019	Planned, 2019
Orange EV	T-Series	✓	✗	✗	✗	✗	Certified, 2015	Underway (warehouse, not MTO)
Capacity Trucks	TJ9000	✗	✗	✗	✗	✓	Pending?	Planned, 2019
TICO	Pro-Spotter	✗	✗	✗	✓	✓	Pending?	Unknown
Autocar	ACTT XSPOTTER	✗	✗	✗	✓[1]	✗	Unknown	Unknown

Sources: OEM survey responses, websites and publicly available literature (e.g., HVIP); *SPBP deployment status based on various grant awards for POLA and/or POLB demonstration / deployment projects.
[1]Autocar clearly offers a CNG engine/fuel option for its terminal tractors. While Autocar offers a CARB OLNS-certified CNG engine for refuse trucks, it is not clear that Autocar offers this option for yard tractors. See https://www.autocartruck.com/actt.

Notwithstanding the distinction by OEMs that they may commercially sell these various ZE and/or NZE yard tractors, it is very important to distinguish between CHE products that clearly constitute fully commercial products today (i.e., they meet all the basic considerations described in this section), versus those that are available for sale but in "early commercial" or "pre-commercial" stages of development. These two terms are defined further below. The various models of ZE and NZE yard tractors described above are essentially being offered in an early commercialization capacity. To date, none have accumulated significant operational time and data in revenue service at any San Pedro Bay Ports marine terminal. Other types of CHE are less advanced and constitute pre-commercial OEM offerings. Additional discussion on this general topic is provided in Section 5.6, within the context of the many CHE demonstration programs that are just getting underway at the San Pedro Bay Ports.

[14] According to the combined 2017 inventories of the two Ports, a total of 12 Ottawa LNG-fueled yard tractors are still operational within the Port of Los Angeles inventory. These LNG-yard tractors, which are operated at an off-Port warehousing and logistics yard, are equipped with natural gas engines certified to CARB's 2010 heavy-duty engine emissions standard. As such, they do not achieve NOx emission levels that meet this Assessment's NZE definition. The two different natural gas engine models in these 12 tractors have been discontinued by the OEM (Cummins).

BYD Battery-Electric Yard Tractor

Kalmar Ottawa Battery-Electric Yard Tractor

Orange EV Battery-Electric Yard Tractor

TICO CNG Yard Tractor

Capacity LNG Yard Tractor

Autocar CNG Yard Tractors

Figure 3. Snapshot of commercially offered yard tractors with ZE (top three) or NZE (bottom three) platforms

"Pre-Commercial" vs. "Early Commercial"

Per CARB's use* of these terms, "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 <u>in CHE service at the Ports</u>. Thus, a CHE platform in an "early commercial" phase by this terminology may not yet have reached that stage <u>in the specific context of operation at a San Pedro Bay Port marine terminal</u>. Emerging CHE platforms at this stage are better described as "pre-commercial" with regard to use at the two Ports. Again using CARB's terms, a pre-commercial CHE does not yet meet all of the above tests, and is generally "focused on first-time demonstrations of advanced technologies in new applications." Most of the CHE types and platforms identified in this Assessment as "early commercial" fall somewhere between these two definitions.

A common element is that, as of late-2018, virtually no "pre-commercial" or "early commercial" CHE units have yet received significant revenue service operation at the Ports. **The next 12 to 24 months will be critical for OEMs and end users to corroborate overall feasibility in real-world CHE service at the Ports**.

5.2.2. ZE / NZE Top Handlers: OEM Involvement

This CHE category significantly lags behind yard tractors with regard to progress for commercialization of ZE and/or NZE fuel-technology platforms. In fact, as of late-2018, there are no commercialized top handler makes/models equipped with ZE or NZE fuel-technology platforms; largely, this is because there have been no drivers for OEMs to make the added investments. However, at least two top handler OEMs are actively developing ZE architectures for their products, in cooperation with technology providers and/or other OEMs. As many as nine battery-electric top handlers and at least one fuel cell top handler will be demonstrated at the San Pedro Bay Ports over the next several years (see Section 5.6).

5.2.3. ZE / NZE RTG Cranes: OEM Involvement

Conventional RTG cranes already use a hybrid-electric architecture as their baseline technology. Specifically, diesel-fueled engines generate electricity for powering electric motors, which provide the smooth, high-torque motive force that RTG cranes require. To reduce energy consumption and emissions, conventional RTG cranes can be replaced with, or converted to, fully electric (ZE) RTG cranes that are commonly known as "E-RTGs." They can also be replaced with, or converted to, advanced hybrid-electric (NZE) RTG cranes that utilize a smaller diesel engine and more-efficient electric drive system. Both types of RTG technologies are commercially available today, as recognized by the marine terminal industry for several years[15] and recently corroborated by the State in CARB's latest CHE technology assessment.[16] MTOs can obtain E-RTG cranes and/or hybrid-electric RTG cranes as new-build purchases, or, as an alternative, they can convert existing conventional RTG cranes using commercially available retrofit packages.

A number of CHE OEMs doing business in North America are well engaged in this market for E-RTG cranes and/or hybrid-electric RTG cranes. Kalmar, Konecranes, ZPMC, Mitsui, Mi-Jack/Kůnz[17] and Paceco are some of the companies that commercially offer RTG cranes equipped with ZE or NZE drivetrains. Fully electric (ZE) E-RTG cranes are available with two types of ZE architectures: battery electric or grid electric. However, grid-connected models are generally favored for U.S. marine terminal applications that have robust existing electricity infrastructure.[18] Grid-electric RTG cranes, which receive their electricity from direct-grid connections, offer both advantages and disadvantages compared to battery-electric RTG cranes. As of late-2018, grid-electric RTG cranes are more mature products (commercially and technologically) than battery-electric RTG cranes.

While commercially available advanced hybrid-electric RTG cranes are not ZE platforms, they offer NZE systems that can significantly reduce direct emissions of criteria pollutants. In essence, this is because relative to conventional RTG cranes, hybrid-electric RTGs burn much less diesel fuel (for example, Kalmar cites a 56 percent reduction).

E-RTG cranes and hybrid-electric RTG cranes are both beginning to gain significant market share at major world seaports. Europe and Asia are showing the strongest adoption rates, but North American sales are accelerating.[19] 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.

Specific examples of commercially available ZE and NZE platforms for RTG cranes sold in North America are described below.

- Kalmar, Konecranes and Shanghai Zhenhua Port Machinery (ZPMC) sell new-build ZE RTG cranes. Grid power can be supplied either by a motorized cable reel or a conductor bar/rail system. These units are equipped with battery systems to store and manage regenerative electricity from the down-stroke of each RTG lift.
- Kalmar, Konecranes and ZPMC also offer new-build NZE hybrid-electric RTG cranes. These products reduce emissions and fuel use by utilizing smaller, more-efficient diesel engines and adding regenerative energy storage systems. Some (or all) of these companies also sell NZE hybrid-electric conversion kits for RTG cranes.
- Conductix Wampfler and Cavotec sell aftermarket systems that convert conventional RTG cranes into either ZE grid-electric or NZE hybrid-electric versions. These use similar technology approaches as the new-build units offered by the OEMs described above.

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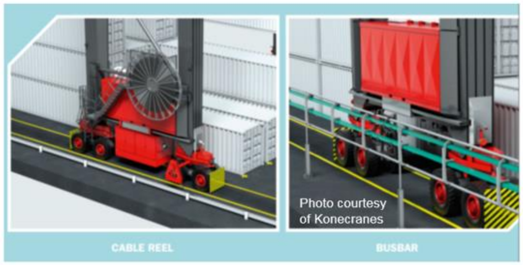
[15] Pacific Merchant Shipping Association, "Technical Memorandum: Sustainable Freight Strategy Impact Study," December 4, 2015, http://www.pmsaship.com/pdfs/PMSA%20Sustainable%20Freight%20Strategy%20Impact%20Study%20Tech%20Memo%208918%20Final.pdf.
[16] California Air Resources Board, "Proposed Fiscal 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.
[17] 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.
[18] GreenPort.com, "The Benefits of Battery Hybrid Powered Port Equipment," https://www.greenport.com/news101/energy-and-technology/the-benefits-of-battery-hybrid-powered-port-equipment.
[19] 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.

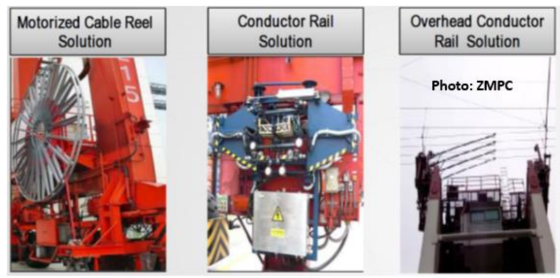
Figure 4 shows photographs of example ZE and NZE RTG crane products that are available as fully commercial products.



Konecranes ZE Grid Electric Options: Cable Reel vs. Bus (Conductor) Bar

Conductix Wampfler Conversion to ZE Grid-Electric RTG

Kalmar NZE Hybrid-Electric RTG Crane



ZPMC's Available "Solutions" for Hooking New-Built ZE RTG Crane to Grid

Figure 4. Various commercial products for ZE grid-electric and NZE hybrid-electric RTG cranes

Worldwide, more than one hundred ZE (fully electric) and NZE (hybrid-electric) RTG cranes have been put in revenue service at major seaports. To date, most deployments have been in Europe and Asia; for example, the Port of Shanghai operates more than 30 all-electric E-RTG cranes.[20] A slower rate of adoption has occurred at North American seaports, but deployments of E-RTG cranes and hybrid RTG cranes (new-build and conversions) have been steadily increasing over the last decade, including a deployment underway at the Port of Long Beach. Examples of key North American deployments include the following:

- Since 2012, the Port of Savannah (Georgia Ports Authority) has been testing and demonstrating at least four ZE grid-electric RTG cranes. The project entailed converting conventional Konecrane RTG cranes to grid-connected E-RTG cranes using Conductix-Wampfler conductor rail systems.[21]
- At the Port of Los Angeles' Fenix Terminal (formerly known as Eagle Marine Services Terminal), 10 grid-electric rail mounted gantry (RMG) cranes operated from 1996 to 2014. These RMG cranes were eventually removed due to various technical and operational limitations including obsolete parts availability and space constraints in the terminal yard. The RMG cranes were replaced with top handlers.[22]
- In 2013, APMT Pier 400 (Port of Los Angeles) became the first San Pedro Bay marine terminal to deploy a ZE grid-electric RTG crane that received power from a bus-bar. This equipment was removed after less than a year because of inconsistent performance due to technical limitations.[23]
- In 2012, West Basin Container Terminal (WBCT) at the Port of Los Angeles tested ZE grid-electric RTG cranes that received power from a cable reel connected to the terminal floor. This equipment was removed after one year due to operational limitations resulting from space constraints in the terminal yard.[24]

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[20] ZPMC, "Energy Saving Technologies: Lithium Battery RTG," product brochure, provided by the Port of Long Beach, January 2019.
[21] World Cargo News, "All-electric RTGs hit the USA," January 2013, https://eslpwr.com/wp-content/PDF/WCN-considerations-of-electrified-RTGs-0213.pdf.
[22] Personal communication from Port of Los Angeles representative to Gladstein, Neandross & Associates, April 2019.
[23] Ibid.
[24] Ibid.

- At the Port of Oakland, SSA Terminals is upgrading its entire fleet of 13 RTG cranes (at Oakland International Container Terminal) to be hybrid electric systems made by Mi-Jack. The retrofit project is partially funded through the Carl Moyer Program. These hybrid RTGs at are capable of operating in zero-emissions mode, using their battery packs.[25]
- At multiple terminals in Mexico, SSA Mexico has converted more than 30 RTG cranes to E-RTG cranes using Conductix-Wampfler technology. It has also purchased multiple new-build E-RTG cranes from ZPMC.[26]

As noted above, E-RTGs have been deployed at several port terminals in North America. However, E-RTGs can have significant operational impacts depending on the configuration of a specific terminal or area within a terminal. For example, areas with short container stacking areas that require frequent transitions between stacking areas may be operationally problematic for E-RTGs. These issues are discussed further in the section "Assessment of Operational Feasibility."

According to the most-current (2017) official CHE inventories for the two Ports, there are no operational ZE RTG cranes (E-RTG cranes) at the San Pedro Bay Ports, although nine RTG cranes with grid-electric architectures will be demonstrated at the Port of Long Beach by the end of 2019. A total of 13 NZE RTG cranes (advanced hybrid-electric) are listed in the 2017 inventory. As further described below, both Ports are participating in projects to demonstrate RTG cranes with ZE and/or NZE architectures at marine terminals within their respective port boundaries.

5.2.4. ZE / NZE Large-Capacity Forklifts: OEM Involvement

Similar challenges that exist for OEMs to incorporate ZE and/or NZE fuel-technology platforms in top handlers also apply to large-capacity forklifts. Given this and the commonality of OEMs in both markets, it is likely that these two types of CHE will follow parallel paths for development, demonstraton and eventual commercial deployment. As of late-2018, there are no commercialized large-capacity forklift makes/models equipped with ZE or NZE fuel-technology platforms. As with top handlers, OEMs of large-capacity forklifts are currently developing proof-of-concept demonstration units with ZE battery-electric and/or ZE fuel cell architectures. Under two different demonstrations (one at each Port), the Ports plan to deploy 12 OEM-built battery-electric large-capacity forklifts over the next three years. This includes funds that CARB has awarded under California's Zero and Near Zero Emission Freight Facilities (ZANZEFF) program. As part of a partnership led by the Port of Long Beach under its ZANZEFF award, 12 OEM battery-electric large-capacity forklifts will also be demonstrated at the Port of Stockton.[27]

Note: Sections 5.6 and 5.7 contain extensive 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 further discussed and assessed in Appendix C (Section 13), multiple OEMs commercially offer <u>small</u> forklifts that utilize some type of ZE fuel-technology platform. Some of these products are applicable to forklift use by MTOs at the Ports.

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

This Assessment assumes that commercially available ZE and/or NZE CHE must be sold by OEMs that have the demonstrated capability to provide essential (diesel-equivalent) support 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.

Based on the survey responses and publicly available literature, OEMS that now commercially offer ZE and/or NZE platforms (i.e., yard tractors and RTG cranes) already meet this basic requirement. In general, major CHE OEMs will not sell any products (including those with ZE or NZE architectures) before they can provide full support, service, and warranty packages. As ZE

[25] Port of Oakland, comments on "Draft 2018 Feasibility Assessment for Cargo-Handling Equipment," May 2019.
[26] 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/.
[27] 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.

and/or NZE platforms are fully developed and become ready for 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.[28]

It 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 San Pedro Bay Ports MTOs. Past performance indicates that the major OEMs should be able to meet the basic requirements outlined for this criterion. 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 commercialized ZE and/or NZE CHE to enable systematic replacement of the entire San Pedro Bay Ports 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, taking into account normal replacement cycles for the particular CHE type.

As previously described, yard tractors and RTG cranes are the two types of CHE for which OEMs are selling ZE and/or NZE platforms (as of late-2018). These two specific cases are further discussed below:

- Yard tractors: To fully replace the existing San Pedro Bay Ports fleet, almost 1,700 in-use yard tractors would need to be systematically (but gradually) replaced with (or converted to) a ZE or NZE architecture. 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). In general, these OEMs appear to have such capability; this seems especially the case for existing major OEMs that have been selling yard tractors at the two Ports for decades (e.g., Kalmar and Capacity). However, before large-scale manufacturing proceeds, it will be important for the OEMs and their customers (the MTOs) to complete the numerous demonstration programs that are just beginning to deploy ZE and NZE CHE of various types and architectures in revenue service (see Section 5.6).
- RTG Cranes: To fully replace the existing San Pedro Bay Ports fleet, nearly 160 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, 13 units have been put in service at the two Ports within the last few years, and larger numbers have been in commercial service across the world for at least a decade. In general, the OEMs (and conversion companies) engaged in this market appear capable of providing sufficient quantities to gradually convert the San Pedro Bay Ports total fleet. This does not discount the importance for RTG crane OEMs and their customers completing the numerous demonstration programs that are just beginning to deploy emerging RTG crane architectures in revenue service. 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 7).

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 2021, assuming orders were placed. However, future availability is unknown at this time, and will remain unknown until the equipment is successfully demonstrated. Thus, it remains to be seen if sufficient numbers could be built by 2021 to replace a large portion of the entire San Pedro Bay Ports fleets.

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

The San Pedro Bay Ports and various MTOs are now working with key government agencies (CARB, CEC and SCAQMD) to purchase and demonstrate nearly 180 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

[28] Gladstein, Neandross & Associates, Questionnaire for CHE OEMs, August 2018.

others they involve early commercial or pre-commercial products (yard tractors). This parameter for commercial availability is essentially met for yard tractors and RTG cranes, but not for top handlers and large-capacity forklifts.

5.6. Advancing Commercial Availability: Essential Role of Near-Term CHE Demonstrations

Over the next few years, early commercial and pre-commercial demonstrations will play an essential role in expediting full commercialization and wide deployment of ZE and NZE CHE. Demonstrations are the key to enable OEMs and their customers to gain revenue-service operational experience, i.e., in the rigorous duty cycles that typify San Pedro Bay CHE applications. OEMs of heavy-duty vehicles (on-road as well as off-road) are well aware that customers need to fully understand emerging ZE and NZE products before making major investments in new equipment and fueling infrastructure. For example, before a CHE (or truck) OEM commercializes a battery-electric product, the company and its customers need 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.[29] Gathering this information requires sufficient demonstration and testing time for multiple pre-production units in revenue CHE operation.

To address the current paucity of revenue service operational data on CHE with ZE and NZE architectures, the Ports (and government agencies like CARB, CEC and SCAQMD) have joined with various MTOs to initiate important new demonstrations. In fact, over the next two to three years, at least 24 major projects hosted by San Pedro Bay marine terminals will test emerging-technology CHE of all-four key types. These demonstration projects involve major existing CHE OEMs, partnered in some cases with start-up OEMs and CHE technology providers. Over the next three years, at least 167 individual CHE (mostly early commercial or pre-commercial units) are scheduled to be demonstrated. Table 5 provides a breakout of the CHE to be demonstrated at California ports (mostly the San Pedro Bay Ports), by type (yard tractor, top handler, RTG crane, large-capacity forklift) and the ZE or NZE architecture they will utilize.

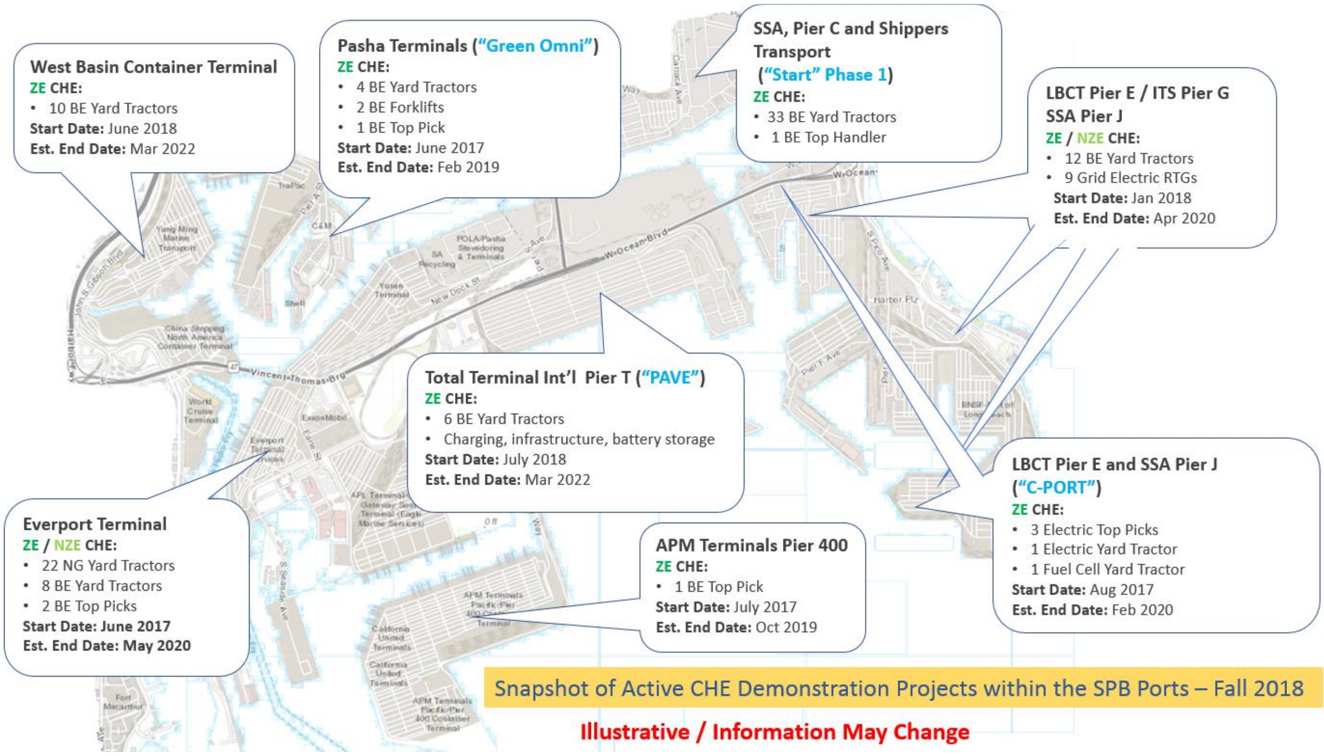
Table 5. Break out of CHE demonstrations at San Pedro Bay Port marine terminals

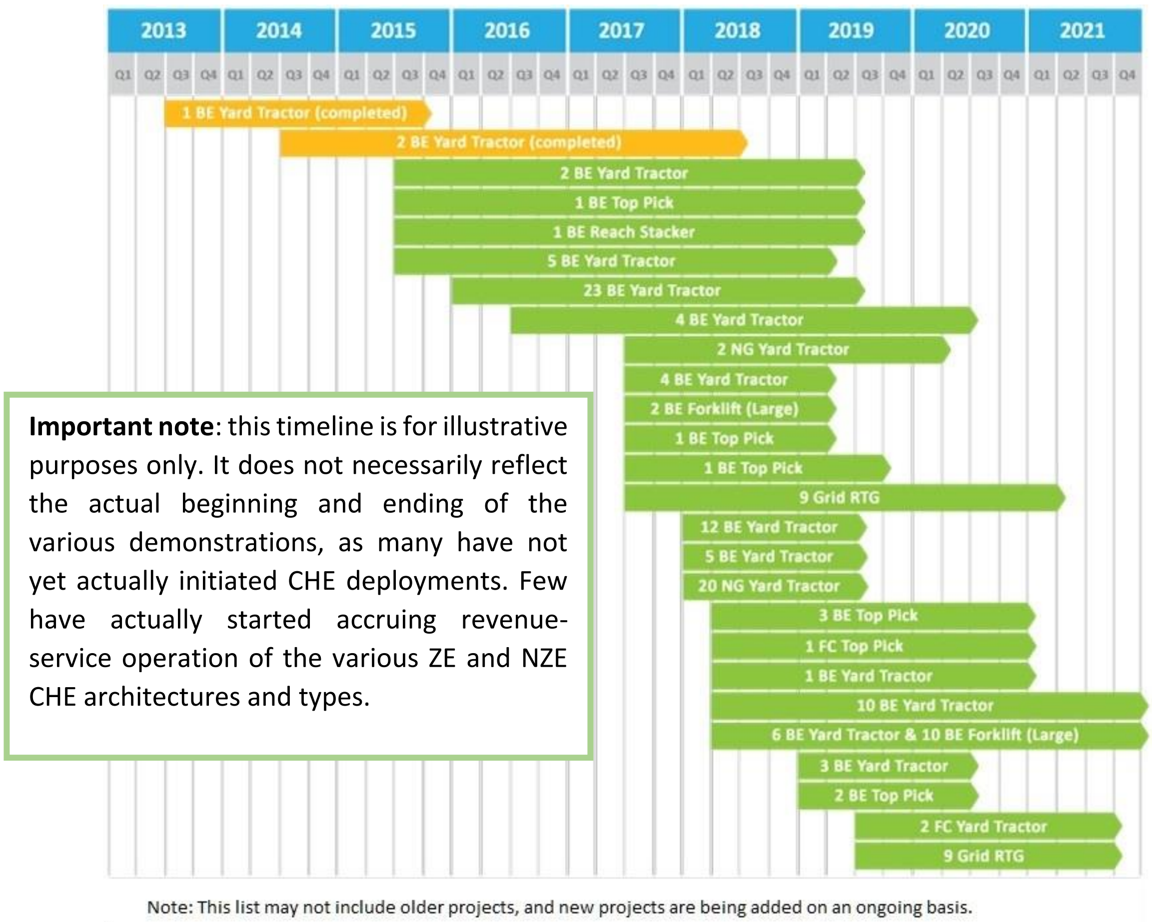
Yard Tractors	Top Handlers*	RTG Cranes	Large-Capacity Forklifts
• **111 ZE battery-electric**	• 10 ZE battery electric	• 9 ZE grid electric	• 12 ZE battery electric
• **2 ZE fuel cell**	• 1 ZE fuel cell		
• **22 NZE natural gas ICE**			

*The top handler category includes one battery-electric reach stacker.
Source: Grant announcements from the San Pedro Bay Ports and various government agencies
Note: this information is evolving and is not meant to be definitive.

As currently planned, these government-funded demonstrations will be conducted at ten different MTO host sites located across the twin Ports complex. Figure 5 illustrates the anticipated host site locations, specific CHE types and fuel-technology architectures to be demonstrated. Many of these CHE demonstration projects have not yet started deployment and testing of demonstration units at the selected host sites. Figure 6 summarizes the timelines for the many different port-related projects involving various types of ZE and NZE CHE. The start / end dates refer to each project's full schedule (award, set-up, demonstration, and close out). Even older projects with start dates in the 2016-2017 time frame may not have initiated the actual demonstrations, or completed the full demonstration time slated for each type of CHE. Some key demonstrations have been delayed in getting started; reasons include longer-than-expected lead times for CHE manufacture and delivery, and unanticipated permitting requirements for fueling or charging infrastructure. Thus, most ZE and NZE CHE demonstrations will not yield significant operational data until well into 2019, or possibly 2020. 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 Section 7 (Operational Feasibility).

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





Important note: this timeline is for illustrative purposes only. It does not necessarily reflect the actual beginning and ending of the various demonstrations, as many have not yet actually initiated CHE deployments. Few have actually started accruing revenue-service operation of the various ZE and NZE CHE architectures and types.

Figure 6. Type and timeline of ZE and NZE CHE demonstrations at San Pedro Bay Port marine terminals.

5.7. 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 recent progress being made to commercialize ZE and NZE CHE that have potential for wide-scale use at the San Pedro Bay Ports. However, as the timeline suggests, existing and potential end users (MTOs) are just beginning to deploy early commercial and pre-commercial CHE. As the various MTOs receive and deploy their demonstration ZE and NZE CHE units in 2019, they will obtain operational experience and data in revenue experience that will be instrumental in more fully assessing overall feasibility.

Increasingly, San Pedro Bay Ports CHE demonstrations are emphasizing *integrated* operation of various CHE types using ZE and/or NZE platforms. For example, under CARB's Zero and Near Zero Emission Freight Facility (ZANZEFF) program, the Port of Long Beach has joined with the Ports of Oakland and Stockton to initiate the Sustainable Terminals Accelerating Regional Transformation (START) Project. The START project will deploy 38 battery-electric yard tractors, nine grid-electric gantry cranes, and 18 battery-electric heavy lift forklifts. Also under ZANZEFF awards, the Port of Los Angeles will deploy battery-electric and fuel cell yard tractors, as well as battery-electric heavy lift forklifts. These ZE CHE will be used to help load 10 ZE hydrogen fuel cell drayage trucks.[30]

Notwithstanding the critical importance of these already-awarded demonstration programs, the Ports recognize the need to rapidly move into larger-scale pre-commercial and early commercial deployments involving ZE and NZE CHE platforms. In tandem, there is a strong need to help MTOs understand and test corresponding types of fueling infrastructure. Consequently, the Ports may choose to initiate new, larger-scale demonstration programs, which are most likely to be focused on ZE fuel-technology platforms. Such new efforts would likely seek to build upon the numerous smaller-scale demonstrations that are now underway or will soon be initiated.

5.8. Summary of Ratings on Commercial Availability

For each of the four major CHE types, a table is provided below that 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 currently meet these basic considerations, or at least show measurable progress towards meeting them by approximately 2021.

Important Note: The commercialization landscape for these products is dynamic, and subject to unforeseen rapid change. For this reason, the Ports will update this 2018 Feasibility Assessment for Cargo-Handling Equipment every three years, or sooner if warranted by major new developments regarding technological maturity and/or expanded commercial offerings.

[30]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.

5.8.1. Yard Tractors

Table 6. Summary of findings: 2018 Commercial Availability of key ZE / NZE Yard Tractor platforms

"Commercial Availability" Criteria	Base Considerations for Assessing "Commercial Availability"	Yard Tractors: Achievement of Criteria in 2018 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 (2018) ○ ◔ ◑ ◕ ● Little/No Achievement … 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 <u>yard tractors</u>:

- **ZE** battery-electric technology is commercially offered for yard tractors by multiple OEMs. These are effectively "early commercial" product launches. All four parameters that collectively define commercial feasibility are at least partially achieved.

- NZE natural gas ICE technology is commercially offered for yard tractor by multiple OEMs. These are effectively "early commercial" product launches. All four parameters that collectively define commercial feasibility are at least partially achieved.

- 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 2018, nor do they appear (at this time) to be on that path by 2021. (See the next section about "Technology Readiness Levels" and the potential for NZE diesel ICE technology to rapidly advance towards full commercial feasibility.)

5.8.2. Top Handlers

Table 7. Summary of findings: 2018 Commercial Availability of key ZE / NZE Top Handler platforms

"Commercial Availability" Criteria	Base Considerations for Assessing "Commercial Availability"	Top Handlers: Achievement of Criteria in 2018 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 (2018) ○ ◔ ◑ ◕ ● Little/No Achievement … 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 top handlers:

- 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, even in early commercial or pre-commercial capacities. None meet the basic criteria and considerations to be deemed commercially available in late 2018, nor do they appear (at this time) to be on that path by 2021. (See the next section about the potential for NZE diesel ICE technology to rapidly advance and achieve immediate commercial feasibility.)

5.8.3. RTG Cranes

Table 8. Summary of findings: 2018 Commercial Availability of key ZE / NZE RTG Crane platforms

"Commercial Availability" Criteria	Base Considerations for Assessing "Commercial Availability"	RTG Cranes: Achievement of Criteria in 2018 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 (2018)

○ ◔ ◑ ◕ ●

Little/No Achievement — 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 appear to be fully achieved. However, no E-RTG cranes appear to be actively deployed at the San Pedro Bay Ports. Successful installation and operation of E-RTG cranes depends in part on region- and site-specific factors (e.g., which utility is providing a grid connection and electricity). The upcoming demonstration of nine (or more) E-RTG crane units at the Port of Long Beach will provide important information and lessons learned specifically in the context of a San Pedro Bay marine terminal and the utility that serves it.

- **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 13 NZE hybrid-electric RTG cranes are operational as of late-2018, at marine terminals serving both Ports. 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 natural gas or propane ICE that has been certified to CARB's lowest-tier OLNS of 0.02 g/bhp-hr.

- **ZE** fuel cell RTG cranes are currently not being manufactured nor sold by any CHE OEM. This platform does not meet the basic criteria and considerations to be deemed commercially available in late-2018, nor does it appear (at this time) to be on that path by 2021.

5.8.4. Large-Capacity Forklifts

Table 9. Summary of findings: 2018 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 2018 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 (2018)

○ ◔ ◑ ◕ ●

Little/No Achievement … 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:

- None 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, even in early commercial or pre-commercial capacities. None meet the basic criteria and considerations to be deemed commercially available in late-2018, nor do they appear (at this time) to be on that path by 2021. (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 as a means 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 commercial). For this 2018 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 San Pedro Bay Ports over the next several years.

The U.S. Department of Energy (DOE) has published a guidebook[31] 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 10 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 many 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 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.

[31] 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 10. 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 mission 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 2018 Technology Readiness Level (TRL) Ratings (with Prognoses for 2021)

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, TRL ratings have been assigned for the core emerging ZE and NZE platforms discussed in this report, and educated prognoses have been made for how those TRL ratings are expected to change by 2021. 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 text summarize the estimated TRL rating (late-2018) for each of the four assessed CHE types (by leading fuel-technology platform). This includes "educated prognoses" about how or if each TRL rating is expected to change by 2021.

6.2.1. Yard Tractors

Table 11. Yard Tractors: Technical Viability (late-2018) using TRL values (with 2021 prognoses)

TRL	Relative Stage of Development	Late-2018 TRLs for Leading Fuel-Technology Platforms **(Yard Tractors)**	~2021: Educated Prognoses (by or before)	Comments / Basis for 2021 Educated Prognosis
TRL 9	**Systems Operations**			
TRL 8	**Systems Conditioning**		ZE Battery NZE NG ICE **(TRL 7 to 8)**	**ZE Battery Electric / NZE NG ICE:** strong OEM involvement and roll-outs of pre-commercial products; both platforms need significantly more operational time in real-world CHE service at Ports.
TRL 7		ZE Battery NZE NG ICE **(TRL 7)**	ZE FC or NZE PHEV **(TRL 6 to 7?)**	**ZE Fuel Cell:** technology demos are needed to ID and 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**	ZE Fuel Cell or NZE PHEV **(TRL 5 to 6)**	NZE Diesel ICE **(TRL 5 to 6, or higher?)**	
TRL 5	**Technology Development**	NZE Diesel ICE **(TRL 5)**		**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 **NZE** natural gas ICE yard tractors are both currently at **TRL 7** (early commercial demonstration and system conditioning). Both platforms may move into **TRL 7 to 8 by (or before) 2021**, benefitting from major OEM / government support and successful adaptation from on-road applications.
- **ZE** fuel cell and **NZE** hybrid-electric yard tractors are currently at **TRL 5 to 6** (technology development and demonstration). Both fuel-technology platform show good long-term promise, but technology demos are needed to ID and address remaining technical hurdles. Fuel cell and/or hybrid-electric yard tractors may move up to **TRL 7 by (or before) 2021**.
- **NZE** diesel ICE yard tractors are currently at **TRL 5** (technology development). If a suitable diesel engine gets certified to CARB's OLNS, NZE diesel ICE yard tractors could leapfrog to **TRL 8 or 9 by (or before) 2021**.

6.2.2. Top Handlers

Table 12. Top Handlers: Technical Viability (late-2018) using TRL values (with 2021 prognoses)

TRL	Relative Stage of Development	Late-2018 TRLs for Leading Fuel-Technology Platforms **(Top Handlers)**	~2021: Educated Prognoses (by or before)	Comments / Basis for 2021 Educated Prognosis
TRL 9	**Systems Operations**			
TRL 8	**Systems Conditioning**			
TRL 7			ZE Battery (TRL 6 to 7)	ZE Battery Electric good OEM involvement in proof-of-concept demonstrations.
TRL 6	**Technology Demonstration**		ZE FC or NZE PHEV (TRL 6?) NZE Diesel ICE (TRL 5 to 6, 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 Battery (TRL 5) ZE FC or NZE PHEV (TRL 5) NZE Diesel ICE (TRL 5)		**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 5** (technology development). The first demonstration top handlers using this fuel-technology platform have been constructed, and several units are expected to begin demonstration at marine terminals serving both Ports, starting in mid-2019. Notably, battery-electric top handlers are benefitting significantly from OEM / government support and transferable technology development from on-road and yard tractor applications. In sum, they appear likely to attain **TRL 6 by (or before) 2021;** possibly, they will reach **TRL 7** by that timeframe.
- ZE fuel cell and NZE hybrid-electric top handlers are currently in the early stage of **TRL 5** (technology development). Both platforms show good long-term promise for top handler applications, but significant technical challenges remain that require demonstration time to address. It is estimated that fuel cell and/or hybrid-electric top handlers may move up to **TRL 6 by (or before) 2021**.

- NZE diesel ICE top handlers are currently at **TRL 5** (technology development). NZE diesel ICE top handlers may stay at **TRL 5 to 6 by 2021**, but they could also leapfrog to **TRL 8 or 9** (see other NZE diesel ICE examples).

6.2.3. RTG Cranes

Table 13. RTG Cranes: Technical Viability (late-2018) using TRL values (with 2021 prognoses)

TRL	Relative Stage of Development	Late-2018 TRLs for Leading Fuel-Technology Platforms **(RTG Cranes)**	~2021: Educated Prognoses (by or before)	Comments / Basis for 2021 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 in final stages of development and sold commercially; demonstrations of 9 "E-RTG" (grid-electric) units will provide important MTO experience.
TRL 8	**Systems Conditioning**			***Hybrid:** Emissions could be reduced significantly more 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. TRL 6 and above requires working out challenges in an actual demonstration.
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 mission conditions). No ZE grid-electric RTG cranes are currently in operation at the Ports. POLB's 9-unit demonstration will provide important MTO experience (e.g., best grid connection).

- NZE hybrid-electric RTG cranes are also at **TRL 9** (actual system in its final form and operated under full range of operating mission conditions). At least 13 units (new or conversions) are operating at the Ports. Emissions could be further reduced by replacing the down-sized diesel gen-set engine with an OLNS-certified natural gas or propane engine.

- ZE fuel cell RTG cranes are currently at **TRL 5** (technology development). An aftermarket conversion is available, but there are no known deployments. Moving **to TRL 6 by 2021** will require revenue-service demonstration(s).

6.2.4. Large-Capacity Forklifts

Table 14. Large-Capacity Forklifts: Technical Viability (late-2018) using TRL values (with 2021 prognoses)

TRL	Relative Stage of Development	Late-2018 TRLs for Leading Fuel-Technology Platforms (Large-Capacity Forklifts)	~2021: Educated Prognoses (by or before)	Comments / Basis for 2021 Educated Prognosis
TRL 9	**Systems Operations**			
TRL 8	**Systems Conditioning**			
TRL 7				**ZE Battery Electric** good OEM involvement in proof-of-concept demonstrations.
TRL 6	**Technology Demonstration**		**ZE Battery (TRL 6)** **ZE FC or NZE PHEV (TRL 6?)** **NZE Diesel ICE (TRL 5 to 6, or higher?)**	**ZE Fuel Cell:** likely to benefit from yard hostler and top pick demonstrations; **NZE Plug-in Hybrid:** OEM interest is hard to gauge
TRL 5	**Technology Development**	**ZE Battery (TRL 5)** **ZE FC or NZE PHEV (TRL 5)** **NZE Diesel ICE (TRL 5)**		**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 5** (technology development). Similar to the case with top handlers, this fuel-technology platform is moving towards **TRL 6 by (or before) 2021.** They generally benefit from good OEM support and transferable technology development, and will possibly reach **TRL 7** in that time frame.
- **ZE** fuel cell and **NZE** hybrid-electric large-capacity forklifts are currently at **TRL 5** (technology development). Both fuel-technology platforms show good long-term promise for this application, but significant technical challenges remain that require demonstration time to address. It is estimated that fuel cell and/or hybrid-electric large-capacity forklifts may move up to **TRL 6 by (or before) 2021**.

- NZE diesel ICE large-capacity forklifts are currently at **TRL 5** (technology development). As with top handlers, this platform may stay at **TRL 5 to 6 by 2021**, but it could also leapfrog to **TRL 8 or 9**.

6.3. Comparison to CARB's TRL Ratings and CHE Technology Snapshot

In a report titled Proposed Fiscal Year 2018-19 Funding Plan for Clean Transportation Incentives,[32] CARB staff provided its most recent updates about the technological readiness and commercial viability of various CHE types using ZE and NZE CHE architectures. CARB staff noted that CHE OEMs (like truck and bus OEMs) have been steadily advancing emerging ZE and NZE technologies, for virtually all CHE types. CARB staff assigned "snapshot" TRL ratings to the leading CHE platforms, using NASA's TRL scale (which is similar to the U.S. DOE TRL scale previously described). CARB emphasized it intended to "provide directional information" about where various ZE and NZE platforms rank (as of mid-2018), while recognizing that the technology landscape can change rapidly in some cases.

Figure 7 summarizes TRL ratings provided by CARB staff that basically correspond with the four CHE types assessed in this report: yard tractors (hostlers), RTG cranes, top handlers, and large-capacity forklifts. (Note: CARB lumped together top handlers and large-capacity forklifts as heavy-duty "Lift/Container Pick/CHE".) In the graph, the "X" axis reflects TRL ratings made by CARB staff, and the "Y" axis reflects the relative market penetration expected by staff for a specific CHE / architecture. Items with **green** text involve ZE CHE platforms like battery-electric (BE) and fuel cell (FC). Items with **blue** text involve NZE CHE platforms, which in this case is limited to low-NOx natural gas (NG) engines. (CARB did not specifically call-out hybrid-electric configurations for CHE.)[33]

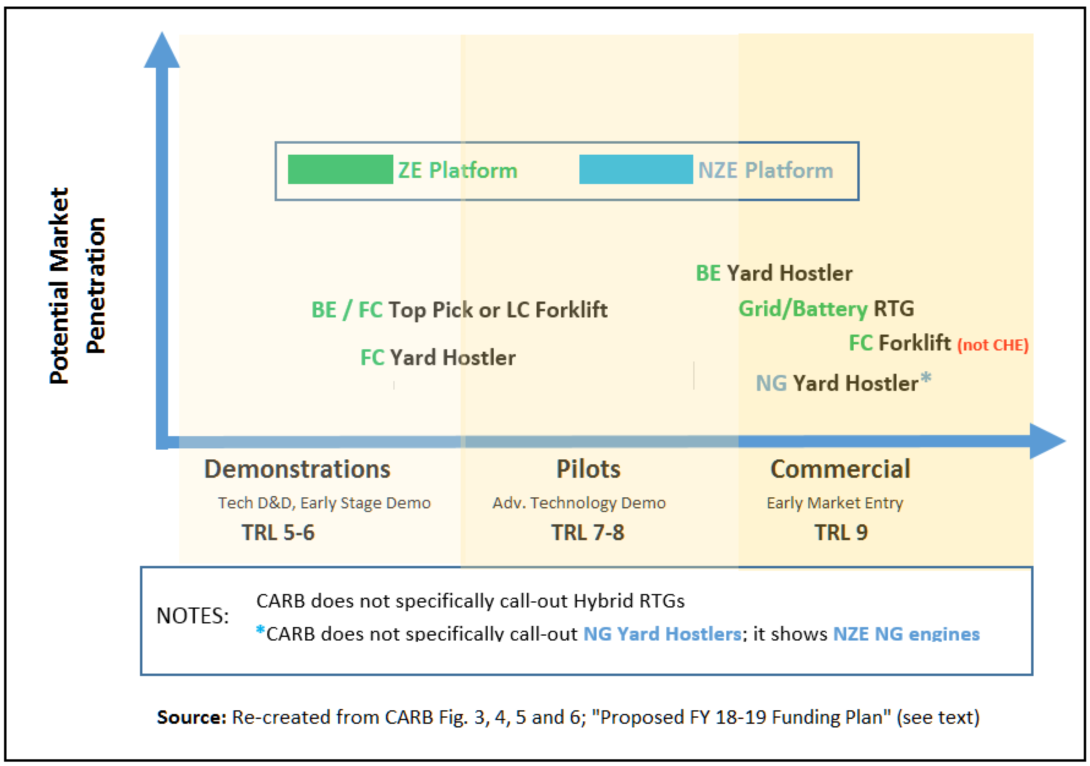


Figure 7. Summary of CARB's draft TRL ratings (NASA scale) for ZE and NZE HDV platforms

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[32]California Air Resources Board, "Proposed Fiscal Year 2018-19 Funding Plan for Clean Transportation Incentives for Low Carbon Transportation Investments and the Air Quality Improvement Program," September 21, 2018, https://www.arb.ca.gov/msprog/aqip/fundplan/proposed_1819_funding_plan.pdf.

[33]Ibid. See the section titled "Technology Status Updates" beginning on page D-5.

Table 15 compares CARB staff's assigned (estimated) TRL ratings to those assigned for this Feasibility Assessment, 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 report's rating. The last column provides observed reasons for the two cases where the degree of difference is "moderate."

Table 15. Comparison of CARB Staff's snapshot 2018 TRL ratings, by key CHE and ZE or NZE platform

CHE Type	Fuel-Technology Platform	CARB TRL	Feasibility Assessment TRL	Degree of Difference	Observed Reason(s) for Difference (if applicable)
Yard Tractors	Battery Electric	8+ / 9-	7	Moderate	1) CARB's TRL rating is described as "early market entry;" this is essentially the same as "TRL 7 moving to 8" as assigned in this Assessment, using the DOE TRL scale. 2) CARB's TRL rating appears applicable to all yard tractor uses (i.e., not specific to port use)
	Natural Gas ICE	9*	7	Moderate	
	Hydrogen Fuel Cell	5 to 6	5 to 6	None	**N/A**
Top Picks / Large-Capacity Forklifts	Battery Electric	5 to 6	5	Insignificant	
	Hydrogen Fuel Cell	5 to 6	5	Insignificant	
RTG Cranes	Battery- or Grid-Electric	9	9	None	
	Hybrid-Electric	Not Rated	9	(N/A)	
	Hydrogen Fuel Cell	Not Rated	5	(N/A)	

*For this case, CARB's TRL rating does not specifically call-out yard tractors or any other specific type of on-/off-road application. Staff assigns a TRL 9 rating to "0.02 g NOx" natural gas engines, which are commercially offered by multiple OEMs in yard tractors.

To summarize, CARB staff's 2018 TRL ratings and assessments for commercial maturity are generally similar to, and consistent, with those presented in this 2018 Feasibility Assessment for Cargo-Handling Equipment. In the two cases (involving yard tractors) where CARB staff assigned higher TRL ratings, the differences appear related to the following:

- CARB utilized a different TRL scale (NASA), while this Assessment applied a U.S. DOE TRL scale.
- CARB's TRL ratings appear to apply to generic CHE use, i.e., they are not specific to the challenging duty cycles that typify CHE operation at San Pedro Bay Port marine terminals. This is a very important distinction. None of the early commercial ZE or NZE yard tractors have been demonstrated in revenue service at any San Pedro Bay Port MTO (as of late-2018). CARB's assessment of ZE and/or NZE yard tractor models at the TRL 9 level appear to be based on use in warehouse and distribution applications, rather than use by MTOs to move loaded containers.

6.4. Summary of Ratings for Technical Viability

The Technical Viability parameter evaluated under this 2018 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 needs of the MTOs for acceleration, gradeability, 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 San Pedro Bay Ports 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. [34]

As summarized below and in Table 16, four different ZE and NZE fuel-technology platforms for two CHE types (yard tractors and RTG cranes) are currently found to be "technically viable" (as of late-2018), 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

Table 16. CHE fuel-technology platforms found to have "Technical Viability" (late-2018) based on TRL values

TRL	Relative Stage of Development	"Technically Viable" CHE Fuel-Technology Platforms (TRL Value Near 8 or Above as of Late-2018*)	
9	Systems Operations		**RTG Cranes*** **1) ZE Grid Electric** **2) NZE Hybrid Electric** **(TRL 9)**
8	Systems Conditioning	**By or before 2021** **(TR 7 to 8)**	
7		**Yard Tractors*** **1) ZE Battery Electric** **2) NZE Natural Gas ICE** **(TRL 7)**	
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).			

6.5. Implications to Remainder of 2018 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 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).

[34] 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.

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) become (or can soon become) a fully certified product offered by a major CHE OEM, it is premature and overly speculative to evaluate its potential for broad-scale deployment in the San Pedro Bay Ports' CHE fleet by 2021 (the timeframe of this study).

Consequently, the remainder of this 2018 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:

1) 1) Nothing in this 2018 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 are already supporting efforts to test a variety of CHE platforms with TRL ratings in the 5-to-6 range. This is especially true in cases that include major involvement and cost sharing by CHE OEMs. (see Section 5.6).

2) This Assessment is a snapshot of CHE fuel-technology platforms as of late-2018. The Ports intend to conduct the next feasibility assessment within three years, or sooner if technological and market conditions warrant an accelerated schedule.

3) As noted in Section 3, gasoline- and propane-powered small forklifts (typically below 26,000 lbs. capacity) contribute significantly to the Ports' collective air emissions inventory. Unlike larger diesel-fueled CHE (yard tractors, top handlers, RTG cranes and large-capacity forklifts), small forklifts with ZE platforms (primarily battery electric) have been commercially available and technically viable for many years. **Appendix C** provides a separate analysis of this CHE category for overall feasibility. This is done at a higher level, because small forklifts have a longstanding history of ZE commercialization. Moreover, they impose significantly reduced adverse societal impacts (environmental and public health) compared to high-horsepower diesel-fueled CHE.

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 San Pedro Bay Ports' MTOs to efficiently, affordably and safely move cargo. 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 several types of 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.[35] 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. MTOs do not yet have much 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, over the next 18 months that is expected to change significantly, as there are many important demonstration programs just getting underway (as were described in Section 5.6).

Table 17 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 be deemed operationally feasible as of late-2018.

Table 17: 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 San Pedro Bay 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

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

comfort, availability of replacement parts); 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 18 and Table 19 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.

Table 18. Representative specifications for Yard Tractors

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

Table 19. Representative specifications for RTG Cranes

Representative RTG Crane Specification	
Example Baseline Equipment	Konecranes, Kalmar, ZPMC RTG cranes
Lift Capacity	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
Engine Power	600-1,000 HP
Fuel Capacity	700 gallons
Estimated Endurance	70+ hours

7.2.2. Typical Fuel Consumption and Equipment Life

Surveyed MTOs combined to provide estimates of hourly fuel consumption for each CHE type, and typical useful lives for their equipment. These values are shown in Table 20. MTO-provided fuel consumption estimates were compared to other data sources, and found to be generally in agreement.

Table 20. Fuel consumption and useful life estimates

Equipment Type	Fuel Consumption	Useful Life
Yard Tractors	2.5 gallons/hour	7-10 years
Conventional RTG Cranes	9.5 gallons/hour	15-25 years
Hybrid RTG Cranes	5.5 gallons/hour	15-25 years

Prior demonstrations of proof-of-concept yard tractors reported fuel consumption rates of 1.7 to 2.6 gal/hour[36], 1.9 gal/hour[37], and 1.1 to 2.9 gal/hour.[38] 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.[39] 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.[40] 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. Additionally, the only hybrid RTG cranes currently in use at the Ports are of the battery-electric type.

An analysis of the 2017 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 an RTG is 14 years, with some RTG cranes being as old as 20 years. The median age for a yard tractor was 6 years, with 95 percent of units being 10 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

[36] 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/
[37] 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/
[38] 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/
[39] Starcrest LLC, "Rubber Tire Gantry (RTG) Crane Load Factor Study", November 2009. http://www.polb.com/civica/filebank/blobdload.asp?BlobID=6915
[40] Starcrest LLC, "Rubber-Tired Gantry Crane Hybridization Demonstration Project", January 2012, http://www.cleanairactionplan.org/documents/lbct-ecocrane-final-report-january-2012.pdf/

staffing of the equipment. To estimate endurance requirements, MTOs were asked to describe their regular operating conditions, which are largely governed by shift lengths.

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 8. **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.

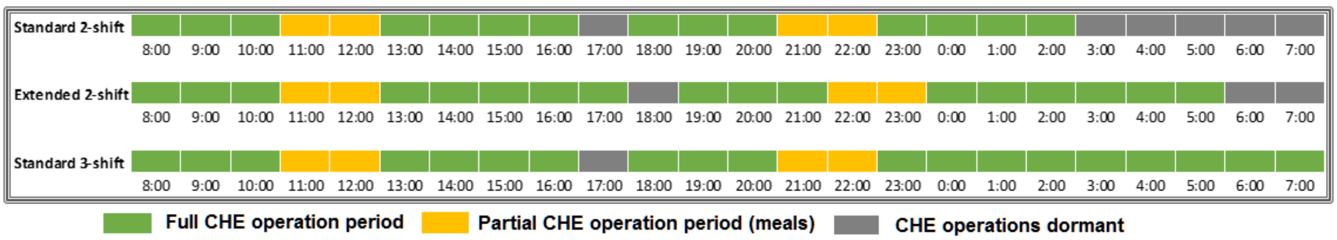

Figure 8. Examples of typical CHE operator shift schedules

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 in a standard two-shift schedule with a hoot shift added.

Under the standard two-shift schedule, CHE must have an endurance of 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 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 appearances, marine terminals are highly constrained on space. Annual land lease costs can exceed $200,000 per acre.[41] 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 9) but some yard tractors can also be found parked in this configuration depending on the specifics of the terminal layout and parking area.

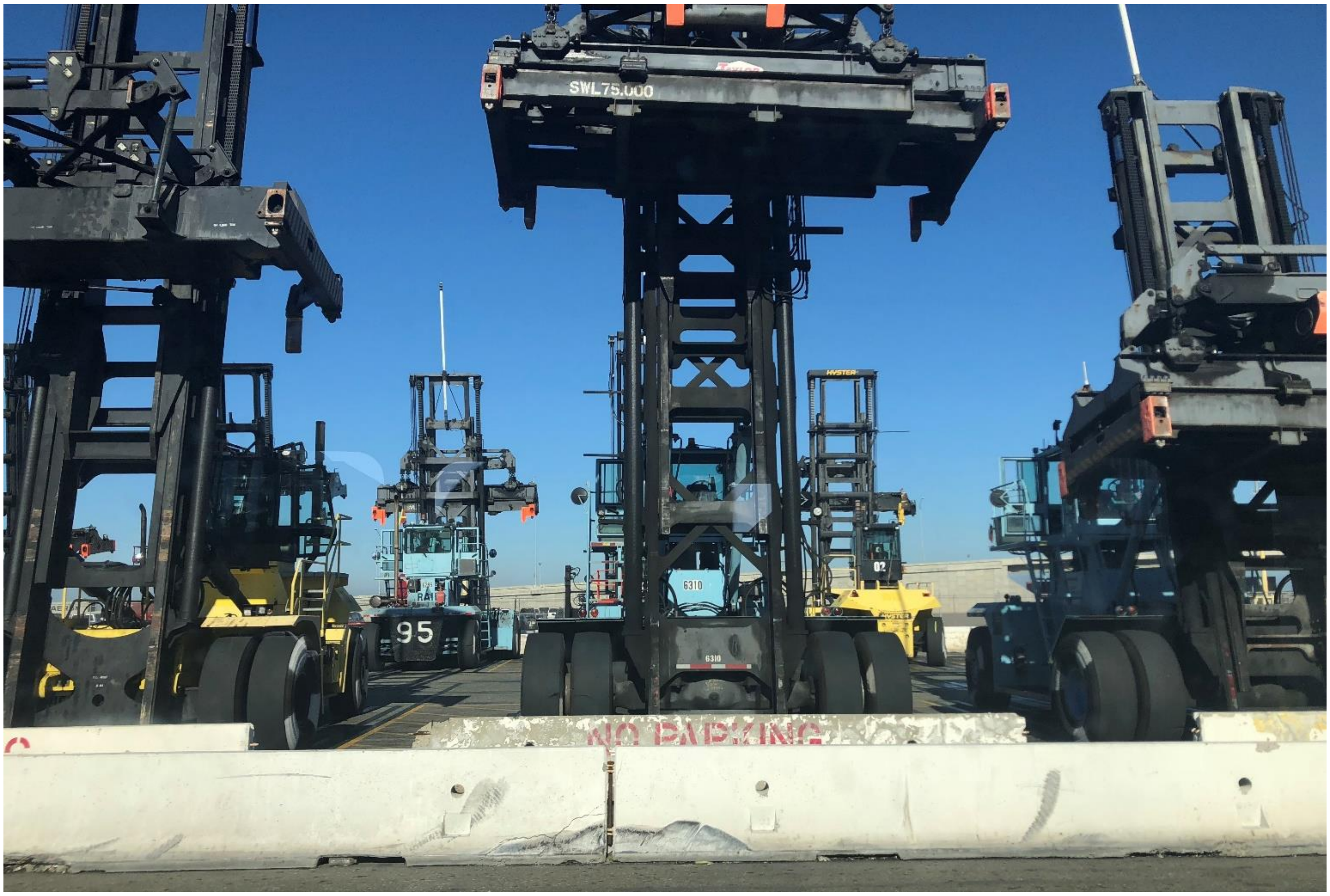

Figure 9. Top Handlers parked in individual stalls

Yard tractors were also found to be parked in two other common configurations, lanes and stacked stalls. Figure 10 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 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.

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[41] 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.

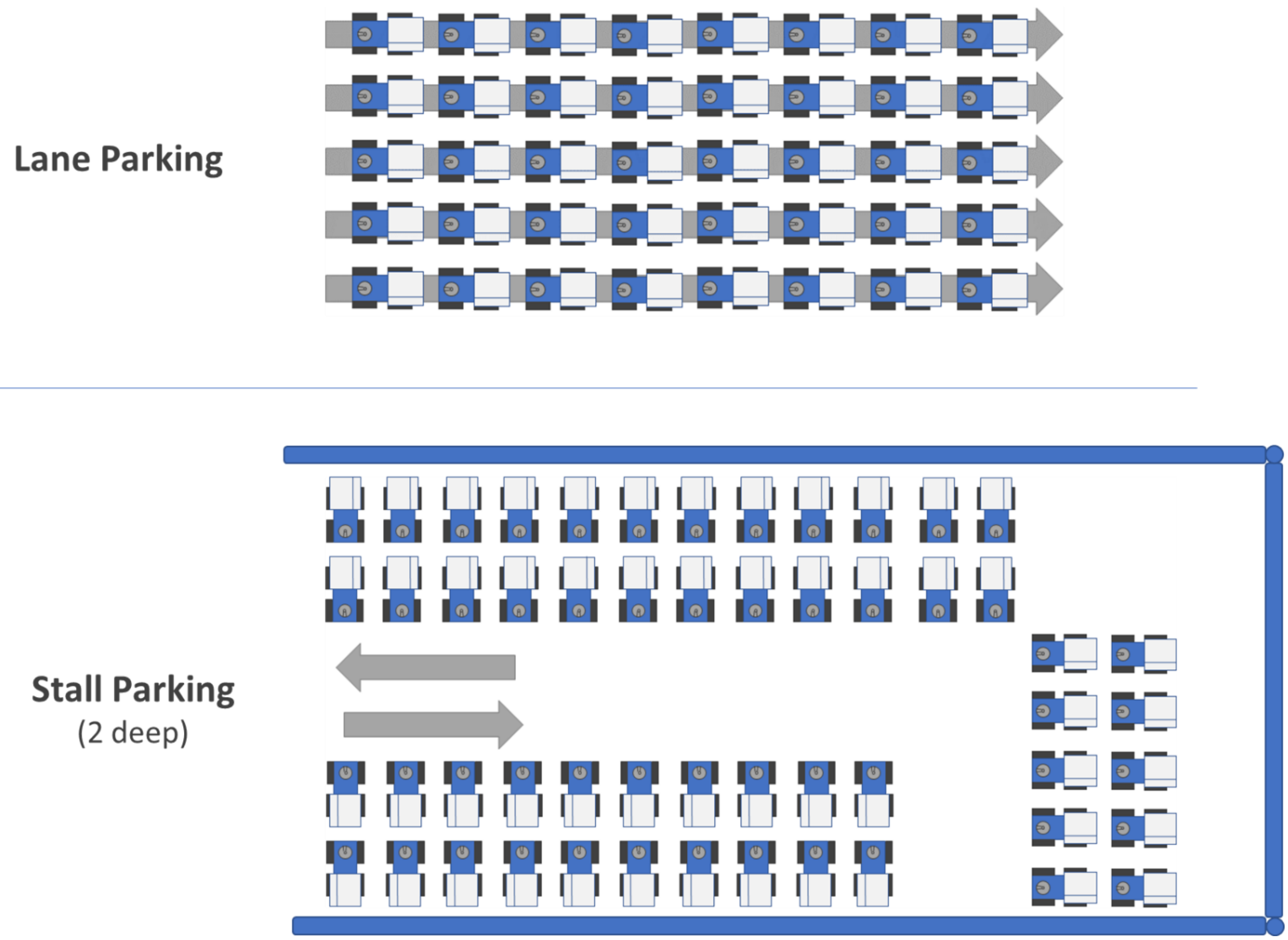

Figure 10. Example parking configurations for yard tractors

7.2.5. Annual usage

An analysis of the 2017 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 11 and Figure 12. Summary statistics are provided in Table 21.

Table 21. Summary statistics for annual operating hours of Yard Tractors and RTG Cranes

Equipment Type	Average Hours Per Year	Median Hours Per Year
Yard Tractors	1,662	1,644
RTG cranes	2,102	2,047

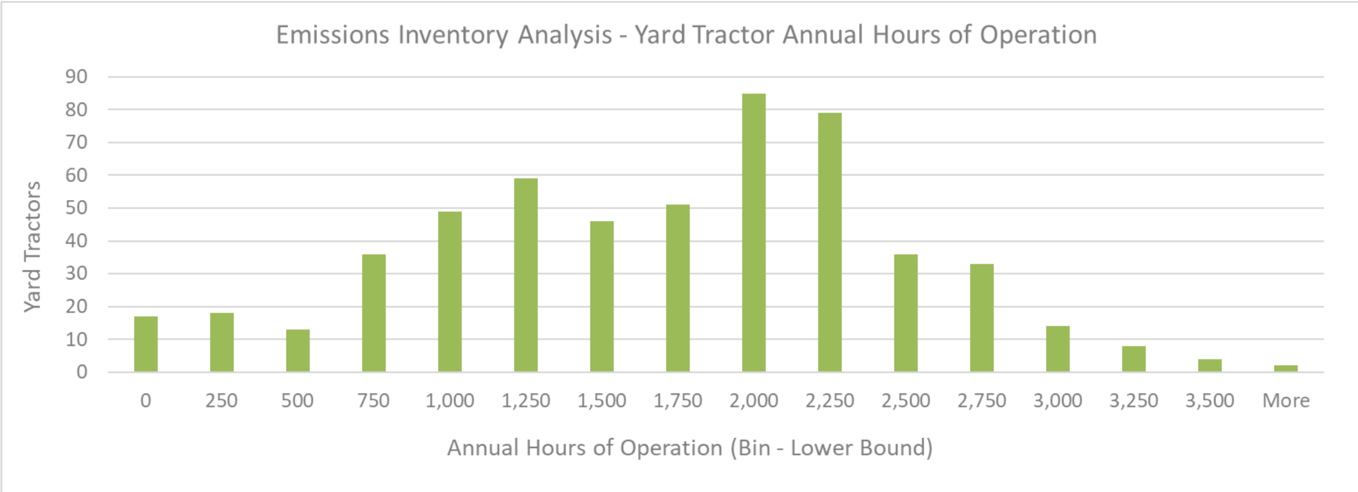

Figure 11. Distribution of annual operating hours for yard tractors at the San Pedro Bay Ports

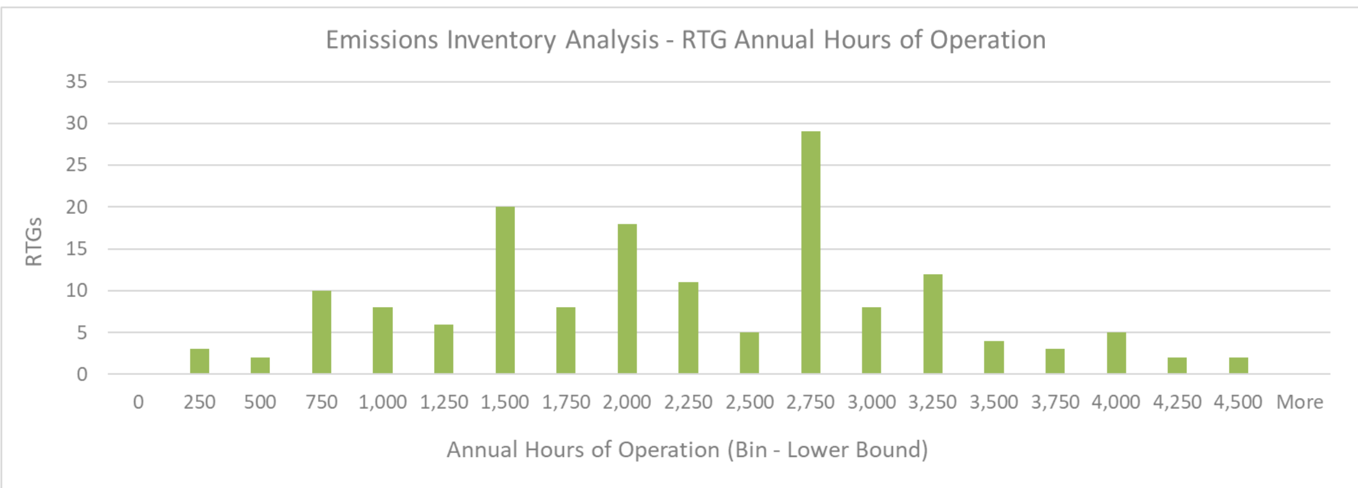

Figure 12. Distribution of annual operating hours for RTG cranes at the San Pedro Bay Ports

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 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 22. It is important to note that calculations in this table have been based on OEM specifications pending real-world data, which are expected to be generated in 2019 and 2020 during revenue service demonstrations by MTOs.

As shown in the table, the BYD and Kalmar battery-electric yard tractors and the Capacity LNG yard tractor meet the basic performance specifications of the diesel baseline unit. The Orange EV battery-electric tractor marginally complies with the top speed requirement, as it is limited to 25 mph. While some terminals choose to limit their existing terminal tractors to 25 mph, other terminals allow and specify higher speeds. Note that the Orange EV model does not appear to publish specifications for wheel base or engine power, so these parameters cannot be compared to the diesel baseline specification. Note that TICO's CNG yard tractor offering typically includes a 21 DGE fuel capacity using a single CNG tank. This capacity is insufficient to meet a single shift endurance requirement and is not considered further in this assessment. It is possible that TICO may offer a configuration with two CNG tanks, providing 42 DGE of capacity, sufficient to meet a single shift endurance requirement. Should TICO (or another OEM) offer a CNG yard tractor with enough capacity for a single shift, future assessments could revisit the use of CNG yard tractors.

Endurance 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.

Table 22. Comparison of Yard Tractor specifications

Model	Kalmar T2, Capacity TJ7000	BYD 8Y	Kalmar T2E	Orange EV	Capacity TJ9000
Fuel/Technology Type	Diesel (Baseline)	Battery-Electric	Battery-Electric	Battery-Electric	NG ICE (LNG)
Axle Configuration	4x2	4x2	4x2	4x2	4x2
Wheel base	116 inches	118 inches	126 inches	n/a	144 inches
Engine Power	200-240 HP	241 HP	215 HP	n/a	250 HP
GCWR	81,000 lbs.	102,000 lbs.	81,000 lbs.	81,000 lbs.	125,000 lbs.
Top speed	25-33 mph	32 mph	45 mph	25 mph	33 mph
Fuel / Energy Capacity[42]	50 gallons	217 kWh (30-40 DGE @ EER 5.3-7.0)	132-220 kWh (Largest pack: 30-40 DGE @ EER 5.3-7.0)	80-160 kWh (Largest pack: 22-30 DGE @ EER 5.3-7.0)	58 DGE
Fuel/Charge Rate	10 gal/minute	200 kW	70 kW	80 kW	10-15 DGE/minute
Estimated Endurance (single "tank")	20 hours	12-16 hours	12-16 hours	9-12 hours	21 hours
Estimated Endurance (inter-shift fueling)	30 hours	21-28 hours	15-20 hours	12-16 hours	31 hours

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

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, estimated at 20 hours.

Table 23 lists results of the basic performance comparisons for endurance. 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 is diesel-equivalent for endurance 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 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. Neither battery-electric unit can meet the 20-hour endurance requirement on a single charge.

Table 23. Summary of basic performance results for new Yard Tractors

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

Endurance Degradation

The estimated endurance hours for battery-electric yard tractors (refer back to Table 22) are implicitly based on new equipment. As battery-electric equipment ages, endurance degrades as the usable capacity of the battery system degrades 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 terminal 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 4,000 cycles, depending on the depth of discharge per cycle.[43] Based on the annual usage histogram provided in Figure 11, 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 4,000 battery cycles in 7-9 years; a close match to the expected useful life of the equipment.

[43] Presentation by BYD, 2016, https://www.theicct.org/sites/default/files/BYD%20EV%20SEDEMA.pdf

Consequently, a battery-electric yard tractor operator should anticipate that the maximum endurance of the yard tractor could degrade to 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 complaint 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 more comfortably meet endurance requirements for standard 2-shift schedules, and to allow 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 help them better understand the range of duty cycles for yard tractors, and actual degradation rates of the batteries under those duty cycles.

RTG cranes

Basic performance parameters for the baseline diesel RTG were provided in Table 19. Because most modern RTG cranes are electric-drive machines that generate their electricity from on-board diesel generators, diesel-hybrid and grid-connected versions of the machine have the same basic performance capabilities. The key difference between the machines is their source of electricity. Additionally, it is noted that the MTO-provided performance specifications for the baseline RTG include a 1,000 HP engine, which is the largest power rating reported for RTG cranes in the Ports emissions inventories. This MTO-provided specification is comparable to a Konecranes RTG crane, for which ZE grid-connected and NZE hybrid-electric models exist. Therefore, it is assumed that RTG products of both types are available that provide comparable performance to baseline diesel RTG cranes.

Regarding endurance, hybrid RTG cranes use approximately 40 percent less fuel than conventional RTG cranes. Assuming comparable fuel tank size, they should provide greater endurance than conventional RTG cranes. Grid-connected RTG cranes do not need to be fueled or charged, making endurance irrelevant.

7.3.2. Speed and Frequency of Fueling/Charging

As previously noted, MTOs currently rely on wet hosing to fuel their CHE (refer back to Section 7.2.4). Equipment is typically fueled before the start of the first 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, and RTG cranes to be fueled in less than thirty minutes. To wet fuel all their CHE, MTOs will utilize three to four fueling trucks, allowing them to fuel all of their equipment in approximately two hours on a typical day. During busy days with more equipment in use, fueling may occur prior to the first shift and between the first and second shift.

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

Yard Tractors

For the assumed LNG platform, the 58 DGE fuel system allows for fueling once a day, as is done with diesel yard tractors today. Therefore, a fueling rate of approximately 11 DGE per minute is assumed to be sufficient; this is equal to a diesel fueling rate after taking into account a 10 percent fuel efficiency penalty for spark-ignited natural gas engines (relative to compression-ignition diesel engines).

The battery-electric CE 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 connect all of the 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 24. Note that the charging power required for the Orange EV yard tractor exceeds the charging capacity of the truck and the Kalmar platform only has sufficient charging capacity when assuming a high EER for the yard tractor.

Table 24. Estimated charging requirements for commercially available battery-electric yard tractors

Charging Requirement	BYD 8Y	Kalmar T2E	Orange EV
Endurance at End of First 9-hour Shift	3-7 hours	3-7 hours	0-2 hours
Additional Endurance to be Charged between Shifts	3-7 hours	3-7 hours	8-10 hours
Charging Energy Required (per Yard Tractor)	48-118 kWh	44-114 kWh	123-175 kWh
Charging Power (45-minute window)	64-166 kW	59-153 kW	165-233 kW

RTG cranes

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 diesel-hybrid RTG cranes is assumed to be equivalent to conventional RTG cranes.

Grid-connected RTG cranes do not need to be fueled, per se, as they continuously draw power directly from the grid while in operation. Peak power demand from an E-RTG is roughly equivalent to the output power of the conventional diesel RTG it is replacing. For an RTG with a 1,000 HP engine, produced electrical power is estimated at 950 HP when accounting for a 95 percent efficient generator. Hence, a grid-connected version of the same machine would be expected to draw 950 HP, or 710 kW. Batteries can be integrated into E-RTG cranes that 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 is 20 percent of its peak power rating. A 1,000 HP RTG would have an average load of 200 HP over its typical duty cycle. Adjusting for generator efficiency, this would equate to a 190 HP demand or 140 kW. However, emerging demonstrations of E-RTG cranes at the Port of Long Beach (Pier J) do not incorporate a battery for demand buffering.

It should also be noted that the connection/disconnection process for E-RTG cranes can add significant time to the process of moving an RTG 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.

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.

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 for the purposes of this feasibility assessment, it is assumed that any equipment platform that can be configured similarly to existing diesel equipment would be sufficient.

Yard Tractors - LNG yard tractors have previously been demonstrated at the Ports.[44] Driver feedback collected during the prior demonstration was generally 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.

Demonstrations of early commercial battery-electric yard tractors are just commencing 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.

Both LNG and battery-electric 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. Additionally, because the genset is located near the base of the RTG and the operator cabin sits atop the RTG, operators are largely isolated from the diesel genset's heat and vibration (although not necessarily from its exhaust fumes). Consequently, operator comfort should be similar to existing diesel RTG cranes. However, 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 this emerging platform. MTOs noted the inability of the pre-commercial electric yard tractor to raise or lower its fifth wheel while the yard tractor was 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 implementation issue on a single platform. The battery-electric yard tractor OEM is in the process of addressing the problem through engineering changes.

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, there are often safety concerns raised with respect to the use of natural gas or batteries in heavy-duty vehicles such as yard tractors. While these concerns are reasonable to raise, it must be recognized 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, almost 750,000 light-duty EVs had been

[44] 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).

deployed in the U.S. through 2017[45] and an estimated 285 heavy-duty transit vehicles are in operation (2017 data).[46] 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.

Fueling/Charging Procedures

Charging of battery-electric yard tractors using conductive, plug-in charging cables is a straightforward practice that requires minimal "fueler" training. Wireless charging solutions are also being demonstrated at the Ports; while these solutions have the potential to reduce needs for additional fuelers, it will likely require additional training of drivers to ensure the vehicles are properly positioned over the charging pad. However, neither charging procedure is expected to pose a significant burden to professional fuelers.

Fueling of LNG vehicles differs from baseline diesel practices. Thus, it does require additional training for personnel who fuel LNG yard tractors. However, LNG fueling is routinely conducted by drivers and professional fuelers in many locations across the U.S., including at the San Pedro Bay Ports. 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.

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

MTOs typically perform most maintenance and repairs of their CHE on-site. This requires special training of mechanics, tools, and suitable facilities to maintain. Deployment of ZE or NZE technology will require additional training of mechanics, and likely also require new investments in facilities and tools as needed 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, making the service networks important to the success of these deployments.

Natural Gas Yard Tractors

The two most prevalent brands of yard tractors in use at the Ports are Kalmar and Capacity, holding 42 and 47 percent of the market-share, respectively. Dina is the third largest brand and is built specifically for SSA Terminals. Both Capacity and Kalmar have dealers and service centers in Southern California that support the existing fleet of yard tractors at the Ports and the surrounding warehouses and intermodal facilities. Additionally, Cummins Pacific has two facilities in Southern California providing engine OEM support for the only natural gas engines currently available for yard tractors. This network 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.

Battery-Electric Yard Tractors

As battery-electric yard tractors are currently beginning demonstration in the Ports, most service and maintenance beyond basic preventative maintenance is likely to be provided by the yard tractor manufacturer. 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. It appears that BYD has the necessary elements to support a maintenance and repair supply chain for yard tractors in Southern California, but this supply chain will not be tested until additional equipment is deployed into regular service. Orange EV offers on-site warranty

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[45] Lutsey, N., "California's continued electric vehicle market development" International Council on Clean Transportation, The International Council on Clean Transportation, May 2018, https://www.theicct.org/sites/default/files/publications/CA-cityEV-Briefing-20180507.pdf

[46] Federal Transit Administration, "2017 Annual Database Revenue Vehicle Inventory," 2018, https://www.transit.dot.gov/ntd/data-product/2017-annual-database-revenue-vehicle-inventory

service for its battery-electric terminal tractors. The company notes that Orange EV "has already established service areas supporting commercial deployments across the United States" (including California); moreover, the "strength of Orange EV's service model" has been acknowledged by "a broad range of fleet customers."[47] For example, the Port of Oakland indicates that Orange EV is successfully supporting "a few" electric terminal tractors trucks operating in "off-dock service" in or near the port. Notwithstanding these important accomplishments with establishing a support and parts network, it appears that Orange EV would need to significantly expand its service capabilities in Southern California before it could fully support near-term, large-scale deployments (hundreds of units) at the San Pedro Bay Ports.

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 and Cavotec, provide established support channels and service networks for their equipment.

7.4. Summary of Ratings for Operational Feasibility

Table 25 summarizes whether yard tractors and RTG cranes with the assessed ZE and NZE platforms are deemed to be "operationally feasible" (as of late-2018). For each of the four possibilities, estimated ratings are provided about the degree to which they already meet these basic considerations as if late-2018, or at least are showing measurable progress towards achieving them by the end of 2021.

Following the table, further discussion is provided about the rationale for assigning these ratings, and the broad implications to the overall 2018 Feasibility Assessment for Cargo-Handling Equipment.

[47] Orange EV, comments submitted to the San Pedro Bay Ports about the "2018 Feasibility Assessment for Cargo-Handling Equipment," May 2019.

Table 25. Summary of ratings by key criteria: 2018 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 (2018)**

○ ◔ ◑ ◕ ●

Little/No Achievement → **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 -While several truck manufacturers are currently developing and demonstrating battery-electric yard tractors, currently available OEM models do not have sufficient endurance to complete two shifts between charging events. Only one platform supports sufficient charging speeds to allow the yard tractor to complete two shifts if the MTO incorporates charging between the two shifts.

Operator comfort and safety are not expected to pose major barriers to adoption. Recharging procedures are simple and training appropriate personnel for these procedures is not expected to pose a barrier to adoption.

Current battery-electric yard tractors are supported by three manufacturers, including a conventional manufacturer of yard tractors. However, only one manufacturer (BYD) supports the charging rates needed to complete two shifts. BYD appears to have the service supply chain components needed to support significant additional deployments of yard tractors. In general, the service network for battery-electric yard tractors will need to grow, to create 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 likely to achieve MTO endurance requirements. However, this needs to be proven in the revenue service demonstrations that are now expected to commence in early 2019. 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 are expected to be equivalent to diesel yard tractors, as natural gas tractors are built on the same basic chassis. This has been corroborated during demonstrations of pre-commercial LNG tractors conducted at/near the Ports.[48]

The 22 LNG yard tractors that are currently being delivered for demonstration at the Ports are all built by Capacity Trucks, which has a strong existing support network for yard tractors deployed at the Ports. The LNG tractors are equipped with CWI's 8.9-liter natural gas engine (20 LNG tractors), or CWI's smaller 6.7-liter version (two LNG tractors). 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 that are capable of fully 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.

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 putting out lest 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.

[48] For example, see CALSTART's report "Liquefied Natural Gas (LNG) Yard Hostler Demonstration and Commercialization Project Final Report," prepared for the Port of Long Beach, August 2008, http://www.polb.com/civica/filebank/blobdload.asp?BlobID=5547.

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 cargo handling equipment will require convenient, safe and affordable access to fuel.

Note that for the purposes of this feasibility 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.

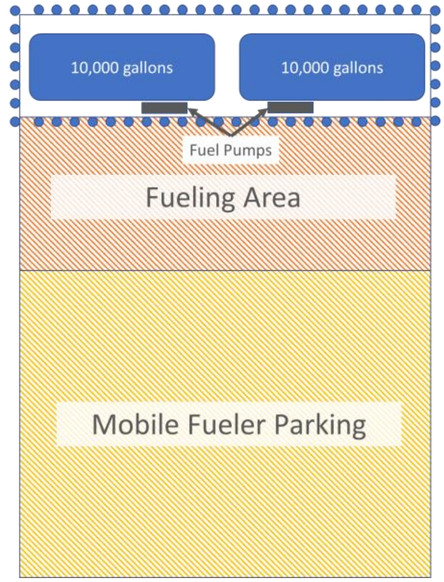

Figure 13. Example layout of an MTO's diesel fueling pad

The key criteria and base considerations that were collectively used to assess Infrastructure Availability are listed in Table 26 below.

Table 26: 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 13 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.[49] 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 onsite, 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 onsite would require 1.85 gallons of LNG storage. For example, replacing the theoretical 20,000-gallon diesel fueling pad (refer back to Figure 13) would require 37,000 gallons of LNG storage capacity.

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

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

The estimated cost of an LNG station with 45,000 gallons of storage is $1.6 million.[50] Additional storage could be added relatively easily at a cost of approximately $250,000 per 15,000 gallons, provided sufficient space exists.[51]

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 manufacturers the Orca LNG mobile fueling station.[52] The system is available in three configurations, including two trailer configurations and one chassis configuration (Figure 14). 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 14. 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 1,693 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 67,700 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 61,000 gallons. Assuming a five-day storage capacity, this would imply that MTOs currently store approximately 305,000 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 565,000 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 the theoretical 45,000 LNG gallon bulk storage/fueling pad as a typical fueling pad would imply that 13 fueling pads of this size would be required. This number would also allow for one LNG storage/fueling location per container terminal in the

[50] 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

[51] Author's industry experience.

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

ports. The total capital cost of this infrastructure build-out would be approximately $20.8 million. It is unlikely that 13 fueling pads could be converted to LNG within the three-year timeframe of this assessment when design, permitting, and construction timelines are considered. However, there is little reason to doubt that these fueling stations could not be constructed prior to 2030.

The following is an example based on the specifics for one major San Pedro Bay Ports marine terminal. The MTO uses two personnel to fuel 75 yard tractors; this occurs after the second shift of the day.[53] 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 host fleet serving the San Pedro Bay Ports (1,693 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 San Pedro Bay Ports terminals under this scenario.[54]

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 operating at the NFI facility (formerly California Cartage) near the Ports, and the planned 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.

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, when the equipment has been listed by an alternative agency. Listing equipment with a new agency is a time-consuming, costly process that can significantly delay or even terminate a project.

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 LNG (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 (temporary stations, proximity to certain activities/facilities, etc.) can face unexpected or new permitting challenges that extend timelines and add costs.

[53] Port of Long Beach, "Zero-Emissions Terminal Equipment Transition Project," Proposal to the California Energy Commission under solicitation #GFO-16-604, January 2017.
[54] Ibid.

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 200 kW. As summarized in Table 24, current battery capacities require charging rates of up to 150-160 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 truck, 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 and disadvantages, as summarized below.

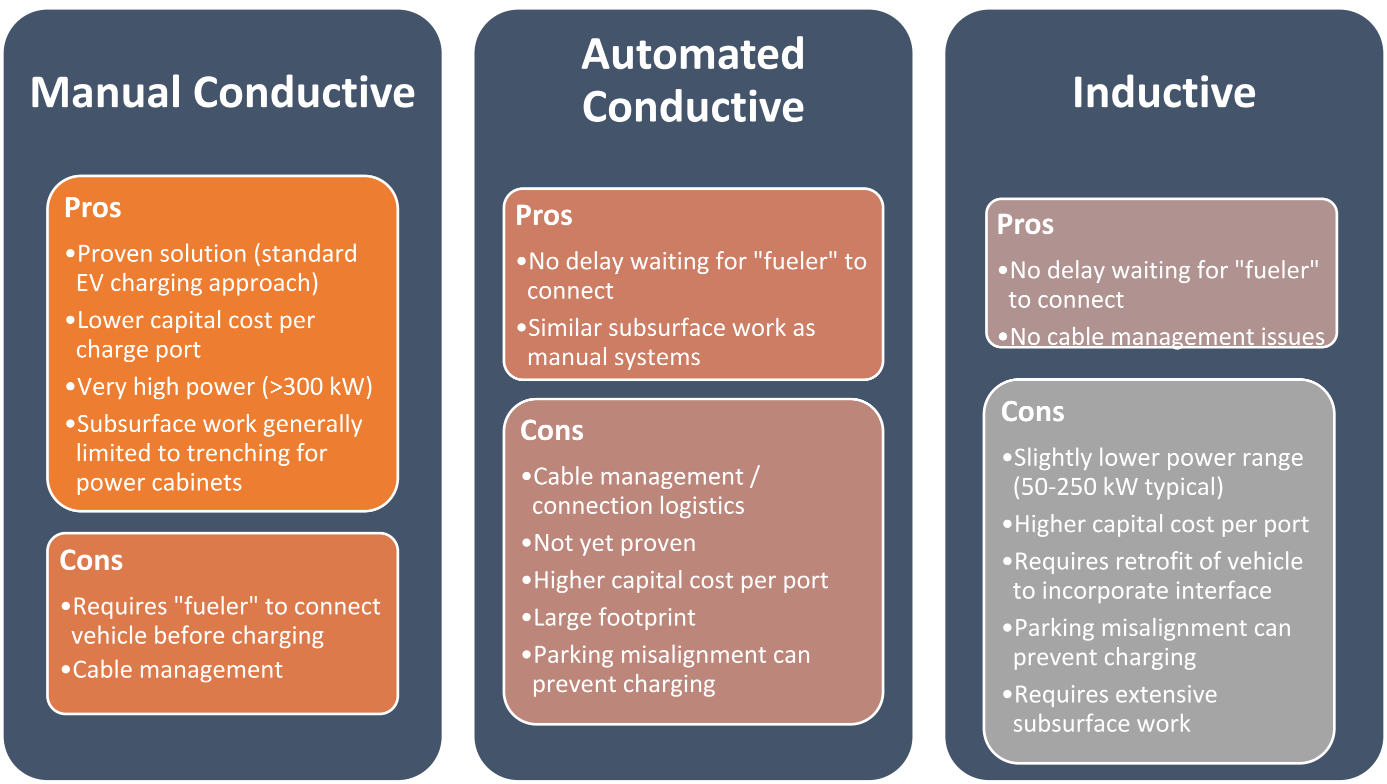

Figure 15. Comparison of EV charging interfaces

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.

Automated conductive interfaces (see for example Cavotec.com) allow a battery-electric CHE to be connected immediately after parking, avoiding lost recharging time waiting for personnel to connect the vehicle. 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.

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. Additionally, cable management can be an issue, particularly when trying to service CHE parked in lanes or stacked stalls.

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 MTOs 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 24, 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 electric vehicle supply equipment (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 shown in Figure 13 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.[55] 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. Because the BYD yard tractor is currently the only battery-electric platform that supports charging rates high enough to meet inter-shift charging requirements, and

[55] http://bydeurope.com/innovations/technology/index.php

because the BYD platform achieves those rates through DC fast charging, this assessment considers DC fast charging to be the representative technology for battery-electric yard tractors. 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 the 70-80 kW AC charging interfaces currently used by BYD, Kalmar, and Orange EV.

The use of DC fast charging 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 DC fast charging standard.[56] 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 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 truck 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.[57] 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 1,693 yard tractors in the ports would require 254 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 demand in context, a study by UCLA's Luskin Center that the largest terminals, such as APMT, currently see peak demands of 10 to 15 MW.[58] Providing charging for electric yard tractors would represent roughly tripling 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 clearly substantial load increases in the port region that would require investment from both utilities.

[56] ISO 15118-3 standard for vehicle to grid communications interface.
[57] 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.
[58] UCLA Luskin Center, "Moving Toward Resiliency", 2013

Interviews with staff from both SCE and LADWP reveal that there is a high level of confidence that the five-year load forecast at the Ports can be met by the systems currently in the ground. This assessment does not, however, include a widespread transition to electric yard tractors within the five-year period.

Fortunately, the total (non-diversified) power demand only represents about 1 percent of the combined peak load of 30 GW in the LADWP and SCE territories (see Table 27). 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.

Table 27. Size of SCE and LADWP Utilities

Indicator	Southern California Edison[59]	Los Angeles Department of Water and Power[60]
Service Territory (mi^2)	50,000	464
Service Population (ppl)	15,000,000	1,500,000
2017 retail sales (MWh)	85,879,000	26,000,000
2017 peak load (MW)	23,508	6,502
2017 Capital Projects Budget ($)	3,835,000,000[61]	1,400,000,000[62]

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 in this regard. 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, unreasonable to believe that sufficient charging infrastructure could be designed and installed within this timeframe.

8.4.3. Codes and Standards

EV charging infrastructure has developed rapidly over the last decade as multiple light-, medium, and heavy-duty vehicles 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 the current battery-electric yard tractors identified in this assessment, there are three types of charging standards in use:

- **GB/T 20234** – This standard is widely used for AC and DC fast charging in China. It supports a maximum power rating of 237 kW but is frequently revised and will likely support higher power levels soon. BYD's AC charging equipment is based around GB/T, although the model 8Y's DC fast charging interface is based on CCS.
- **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

[59] Edison International, "Edison International and Southern California Edison 2017 Annual Report", 2017, https://www.edison.com/content/dam/eix/documents/investors/corporate-governance/2017-eix-sce-annual-report.pdf

[60] Los Angeles Department of Water & Power, "Briefing Book: 2017-2018", https://www.ladwp.com/ladwp/faces/ladwp/aboutus/a-financesandreports/a-fr-reports?_adf.ctrl-state=1bp7g1adzb_4&_afrLoop=1570165486631095

[61] SCE reported this amount in capital expenditures for 2017.

[62] LADWP reported this amount of its budget dedicated to capital projects.

the vehicle, the external EVSE can be significantly less expensive than comparable DC fast chargers but is typically proprietary to a specific vehicle manufacturer.

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 the preferred 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.[63] The Ports are taking action to help address such barriers. For example, the Port of Long Beach is developing 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.[64]

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 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

The typical marine terminal in the San Pedro Bay uses a combination of s and top handlers to perform the majority of vertical moves of containers within the terminal. Approximately three-quarters of vertical moves are performed by top handlers. The remaining 25 percent of moves are handled by RTG cranes, with RTG crane operations largely being concentrated in the movement of import containers to drayage trucks.[65] RTG cranes operate along "runs" that include pavement striping for the container stack area and a lane for drayage trucks and yard tractors. The length 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 Feasibility 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

[63] Peer review input to authors by National Renewable Energy Laboratory, November 2018.
[64] Port of Long Beach, Fact Sheet: Port Community Electric Vehicle Blueprint, August 2018, http://www.polb.com/civica/filebank/blobdload.asp?BlobID=14661.
[65] 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

Transportation Electrification Proposals for 2017, SCE estimates the costs of the infrastructure improvements to be $3 million for 9 RTG cranes.[66] This includes providing a total of four distribution points along two RTG crane runs. 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 100-200 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 156 RTG cranes in the Ports 2017 emissions inventories that would require either conversion to grid-connected systems or replacement with new grid-connected RTG cranes. It does not appear feasible to replace or retrofit this quantity of RTG cranes within the three-year study period of this Feasibility Assessment. Additionally, infrastructure design, permitting, and construction for every RTG crane lane at every container terminal could not be completed within this timeframe. However, it is not unreasonable to anticipate that infrastructure deployment and construction could be completed between 2021 and 2030.

To provide up to 710 kW of power for the combined 156 RTG cranes in the ports would require 111 MW of distribution infrastructure. A very large terminal can operate 20-30 RTG cranes on a busy day, resulting in a peak power demand of 14-21 MW. As previously noted, the largest terminals, such as APMT, currently see peak demands of 10 to 15 MW.[67] Providing power for grid-connected RTG cranes would represent roughly doubling 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 clearly substantial load increases in the port region that would require investment from both utilities.

As previously discussed in Section 8.4.2, while these loads are significant in a localized context around the ports, they are small loads relative to the combined 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.

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 come in the form of non-listed equipment. Typically, when issuing construction permits, both Los Angeles and Long Beach require that equipment be listed with an approved national testing lab such as Underwriter's Laboratories. Newly developed products may not be listed and this can either preclude a permit or delay construction while on-site certification is performed. 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 28 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 that have sufficient "infrastructure availability" (as of late-2018).

[66] 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
[67] UCLA Luskin Center, *Moving Toward Resiliency*, 2013

Table 28. Summary of ratings by key criteria: 2018 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 (2018)**

○	◔	◑	◕	●
Little/No Achievement				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 – 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.

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 space claim 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 29: 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 30 and Table 31. The results of this analysis are presented and discussed following a presentation of the major cost elements in the TCO model.

Table 30. 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	$310,000
Taxes	$	$9,000	$13,500	$27,900
Infrastructure	$	$0	$20,000	$165,000
Fuel Economy	DGE/hr	2.50	2.78	0.5
Fuel Price	$/DGE	$3.27	$2.52	$6.69 (SCE EV Rate), $11.60 (LADWP), $18.20 (SCE Non-EV Rate)
Activity	hr/yr	1,662	1,662	1,662
Maintenance	$/hr	$24.07	$24.07	$16.85
DEF	% of Diesel	4%	0%	0%
DEF Price	$/gal	$2.90		
Discount Rate	%	7%		

Table 31. 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	3.5
Fuel Price	$/DGE	$3.27	$3.27	$4.44 (SCE EV Rate), $5.56 (LADWP), $3.94 (SCE Non-EV Rate)
Activity	hr/yr	2,102	2,102	2,102
Maintenance	$/hr	$40.44	$40.44	$30.33
DEF	% of Diesel	4%	4%	0%
DEF Price	$/gal	$2.90		
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 32. Prices shown are assumed to be pre-tax. A generalized sales tax rate of 9 percent is applied to all equipment.

Table 32. Equipment purchase price assumptions and sources

CHE and Fuel-Technology	Purchase Cost	Source
Diesel ICE Yard Tractor	$100,000	PMSA Study[68]
NZE LNG ICE Yard Tractor	$150,000	Purchase Order[69]
ZE Battery-Electric Yard Tractor	$320,000	Average of OEM prices[70]
Baseline Diesel RTG Crane	$1,200,000	PMSA Study
NZE Diesel-Hybrid RTG Crane	$1,350,000	Port of Oakland[71]
ZE Battery-electric RTG Crane	$1,800,000	PMSA Study[72]

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

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

[68] 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
[69] Based on the purchase cost of 6.7L NZE LNG yard tractors purchased under CEC grant demonstration for GFO-16-506
[70] Average of OEM prices for BYD and Kalmar EV yard tractors
[71] Port of Oakland, "Revised Draft, Seaport Air Quality, 2020 and Beyond Plan," December 2018.
[72] 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

9.3.2. Fuel Price

Diesel fuel costs are based on the average on-road diesel fuel price in California for 2018, as reported by the US EIA. The reported fuel price is reduced by $0.60/gallon to deduct the federal and state excise taxes that are not applicable to off-road applications. Natural gas fuel costs are based on the current NYMEX natural gas price index and adjusted to include delivery costs and California sales tax.[73] LNG pricing also includes the labor costs of one additional worker per 75 yard tractors served.

New diesel equipment compliant with the Tier 4 standard also consume diesel emission fluid (DEF) as part of the operation of the SCR system used to control NOx emissions. The consumption rate of DEF is typically specified by the manufacturer as a fixed percentage of diesel fuel consumption. DEF costs were estimated by reviewing current DEF prices reported by Flying J at their California truck stops.[74]

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 33. The first and second scenario were evaluated under two tariff rates; SCE's TOU-EV-9 (2-50 kV)[75] and LADWP's TOU A-3 rates[76]. 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 D (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 D rate.

The substantial difference in average electricity costs between the two utilities under the yard tractor analysis is based on different demand charge structures. Under SCE's 2018 General Rate Case, the utility proposes to establish a series of EV-related rates. These rates eliminate demand charges for a period of five years, while increasing energy charges to recover a portion of the cost recovery that is lost from adjusting the demand charges. These changes are designed to address the utility's obligations under SB-350 to support transportation electrification. (Also, terminals on the Port of Long Beach side have access to SCE's favorable Maritime Entity rate, which is expected to be competitive with new EV-specific rates.) By contrast, LADWP's rate is a conventional general services structure with time-variable demand charges that increase the cost of power during peak periods. The result of the SCE EV rate structure is to lower costs for EV charging relative to a general services rate such as the one modeled for LADWP[77]and the SCE TOU-8 general services rate. It is also assumed that the SCE EV-9 rate is applicable to both yard tractors and RTG cranes because SCE sought to expand the definition of "vehicle" in their tariff to include all mobile sources of pollution as part of their Advice Letter.

MTOs at the Port of Long Beach may also be subjected to an "Added Facilities" charge of $2.84/kW per month.[78] This charge is imposed under a number of conditions, but 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 subtransmission 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

[73] 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.

[74] Pilot Flying, https://pilotflyingj.com/fuel-prices/ Reviewed October, 2018.

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

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

[77] 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

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

would add loads greater than 10 MW and avoid Added Facilities charges. That said, it is recognized that some MTOs may be subject to this fee. In these cases, it is estimated that the Added Facilities charge would increase charging costs by approximately 10% over those shown in the following tables.

Table 33. 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 D	TOU-8 Option D	TOU-8 Option D
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)	74,953	89,007	80,476	74,953	89,007	81,980	74,953	89,007	81,980
Peak Power (kW)	94	166		94	166		94	166	
Energy Charges	$11,903	$16,927	$14,415	$8,868	$11,112	$9,990	$5,462	$6,926	$6,194
Demand Charges	$0	$0	$0	$8,758	$15,465	$15,465	$19,115	$33,754	$33,754
Total Cost ($/year)	$11,903	$16,927	$14,415	$17,627	$26,577	$25,455	$24,577	$40,680	$39,948
Average Cost ($/kWh)	**$0.159**	**$0.190**	**$0.179**	**$0.235**	**$0.299**	**$0.311**	**$0.328**	**$0.457**	**$0.487**

Table 34. 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 D	TOU-8 Option D	TOU-8 Option D
Daily Energy (kWh)	2,091	2,483	N/A	2,091	2,483	N/A	2,091	2,483	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)	545,455	647,649	596,552	545,455	647,649	596,552	545,455	647,649	596,552
Peak Power (kW)	116	131		116	131		116	131	
Energy Charges	$66,233	$75,565	$70,899	$61,479	$72,640	$67,060	$33,284	$39,386	$36,335
Demand Charges	$0	$0	$0	$19,351	$21,769	$21,769	$23,672	$26,631	$26,631
Total Cost ($/year)	$66,233	$75,565	$70,899	$80,829	$94,409	$88,829	$56,956	$66,018	$62,966
Average Cost ($/kWh)	**$0.121**	**$0.117**	**$0.119**	**$0.148**	**$0.146**	**$0.149**	**$0.104**	**$0.102**	**$0.106**

9.3.3. Maintenance Costs

Baseline maintenance costs are taken from the PMSA study[79] 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 recent draft CHE technology analysis.[80] Unfortunately, there is little in-use demonstration data available to validate this assumption as of late-2018. Additionally, these maintenance costs do not incorporate the potential cost of a battery pack replacement over the 7-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 feasibility 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 7-year battery warranty when vehicles are produced and sold in high volumes.

Diesel-hybrid RTG cranes are assumed to have the same maintenance costs as conventional RTG cranes. This may be a conservative estimate as the hybrid system enables the engine to run at more consistent speeds and to shut down when loads are low, thus reducing wear on the engine. Additionally, the engine is smaller than in a conventional RTG crane and service parts should be less expensive. However, barring better data on the maintenance costs of hybrid RTG cranes, it is assumed that maintenance costs are not reduced.

Grid-connected RTG crane maintenance costs are assumed to be reduced by 25 percent based on values in the PMSA study. An upper end estimate on maintenance costs 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 owing to the ASCs lack of tires, associated steering mechanisms, and connections/disconnections from the grid power supply.

9.3.4. 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 8.86 percent, resulting in an effective tax rate of 29.86 percent.[81] 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 29.86 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.

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 100 yard tractors for the on-site LNG storage/fueling station and $300,000 per 75 yard tractors for the LNG mobile fuelers.

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[79] 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

[80] Port of Oakland, "Revised Draft, Seaport Air Quality, 2020 and Beyond Plan," December 2018. Appendix F

[81] 26 U.S. Code § 11, https://www.ftb.ca.gov/businesses/faq/717.shtml

Owing to the limited charging windows available to MTOs between shifts, it is assumed that they will be charged primarily through DC fast charging infrastructure. Based on the electricity charging rate analysis, the typical yard tractor would require a peak charging rate of 166 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 7-year useful life of the first electric yard tractors deployed.[82] 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 amount of incentives 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 HVIP program and the Clean Off Road Equipment Voucher Incentive Project, or (CORE), and an LCFS credit revenue stream. The purchase incentive is assumed to be $45,000 for NZE natural gas yard tractors and $165,000 for ZE battery-electric yard tractors. The value of LCFS credits is based on a $149 credit price and uses the recently adopted modifications to the LCFS program that went into effect January 1, 2019. <u>To be conservative, it is recommended that economic workability be based on non-incentivized cost of ownership</u>. Section 9.6.3 provides additional discussion and rationale. A more detailed explanation of the incentive funding calculations, including a description of the funding programs, can be found in Appendix D.

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 and in Appendix B. Figure 16 summarizes the results of the cost of ownership analysis for yard tractors. The costs are reported in current 2018 dollars on a net present value (NPV) basis using a 7 percent real discount rate.[83] As shown, the cost of ownership for a new diesel yard tractor is approximately $374,000. Near-zero natural gas yard tractor costs are estimated to be $402,000, 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 $500,000 over 7 years, about $126,000 more expensive than new diesel yard tractors. Within LADWP territory, the current battery-electric yard tractor is approximately $148,000 more expensive than a new diesel yard tractor. However, battery-electric yard tractors charging in SCE territory on the TOU-8 Option D general services rate, the current battery-electric yard tractor is approximately $176,000 more expensive than a new diesel yard tractor.

When incentives are included in the analysis, both alternative platforms are less expensive than diesel yard tractors over the 7-year analysis period. Natural gas yard tractors receive a $45,000 initial purchase incentive through HVIP and associated

[82] Note that future modifications or reconfigurations of terminals may result in a substantially shorter useful life for these infrastructure improvements.

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

finance cost reductions for the balance of the purchase price. These yard tractors would also generate additional LCFS credit revenue. However, because they are assumed to use LNG and the LNG producer is the credit generator under the LCFS program, the value of the LCFS credit is assumed to be accounted for in the delivered price and consumed by the fuel provider to source RNG. Electric yard tractors receive a $165,000 purchase incentive through HVIP and generate $41,500 in LCFS credits over 7 years ($32,000 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.

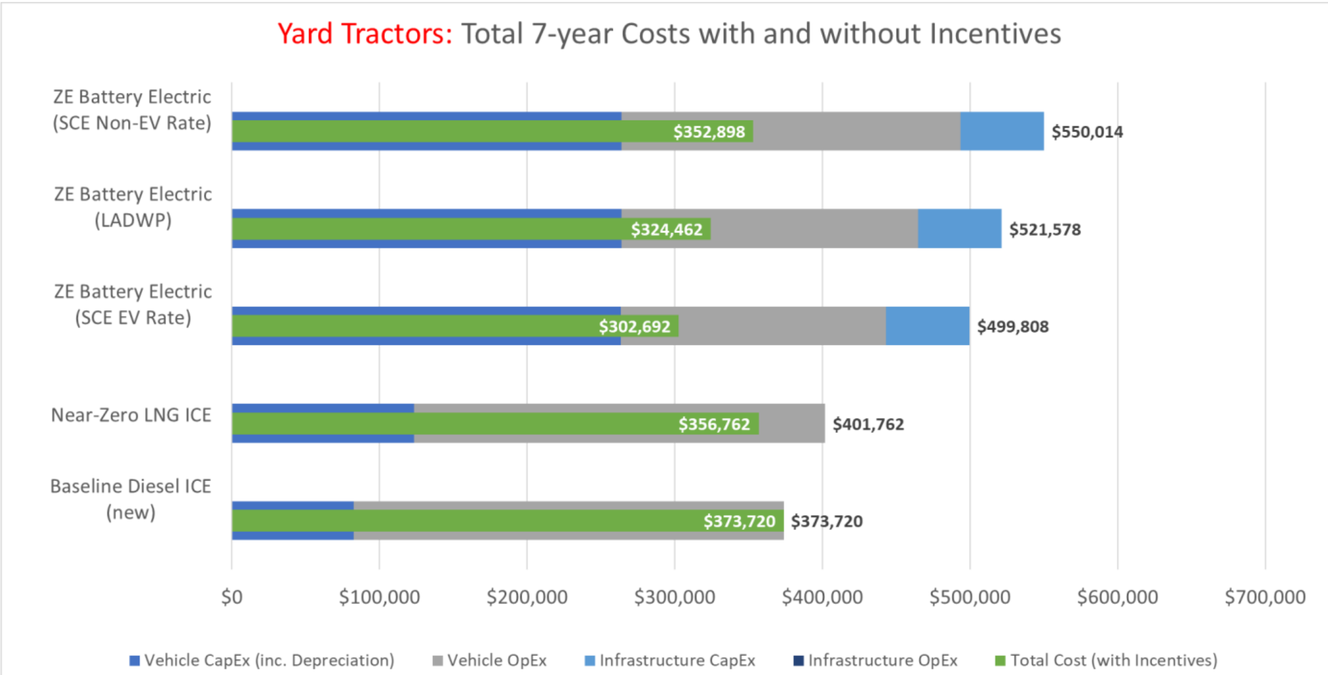

Figure 16. Total 7-year costs of ownership for "Average Yard Tractor" scenario (NPV at 7% discount rate)

9.6.2. Grid-Electric and Hybrid-Electric RTG Cranes

Figure 17 summarizes the results of the TCO analysis for RTG cranes. As shown, the TCO for a new baseline diesel RTG crane is approximately $2.38 million over 15 years. Diesel-hybrid RTG crane costs are estimated to be $2.24 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 $2.61 million over 15 years, about $245,000 more expensive than new diesel RTG crane. Within LADWP territory, the cost is approximately $309,000 more expensive than a new diesel RTG crane. Interestingly, the standard SCE TOU-8 Option D rate provides the lowest cost at $2.58 million, or about $200,000 more than a new diesel RTG. 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 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 $333,000 in LCFS credits over 15 years ($207,000 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 either the LCFS program, CORE, or VW Mitigation Fund.

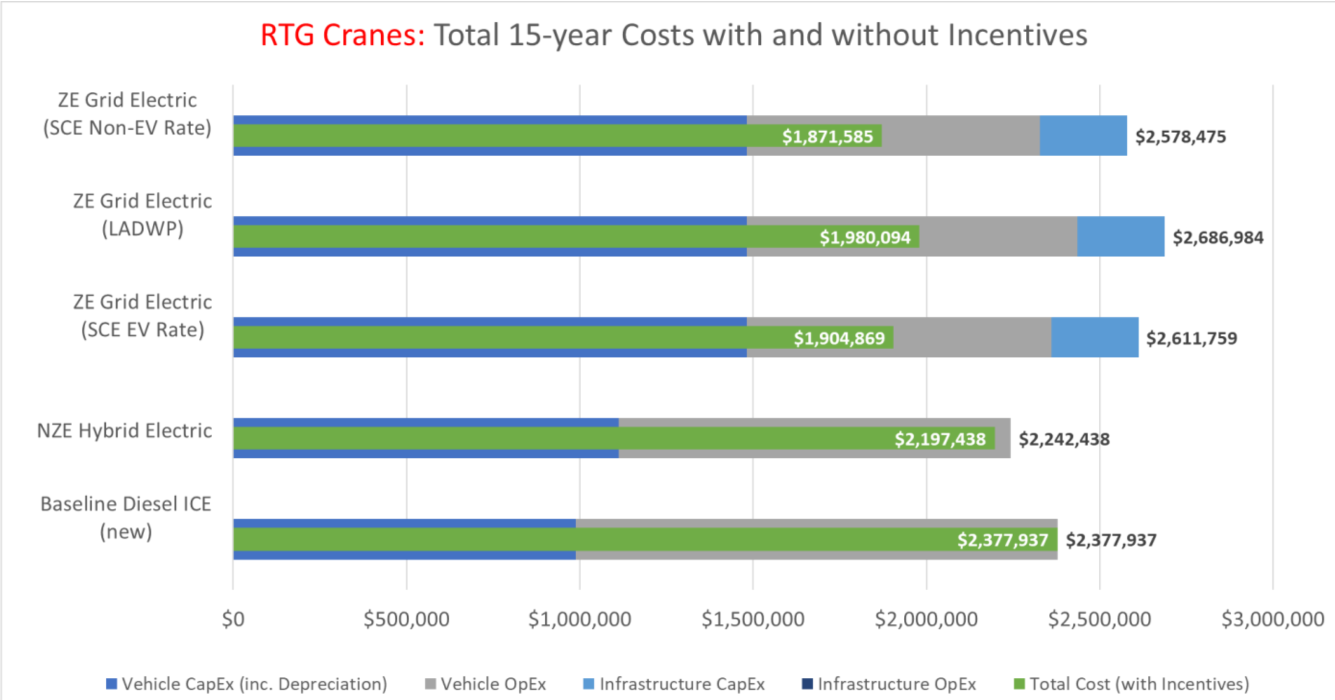

Figure 17. Total 15-year costs of ownership for the "Average RTG crane" scenario (NPV at 7% discount rate)

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. With the proposed funding for the Clean Off-Road Equipment (CORE) voucher incentive project in 2018/2019, the program will have an estimated $40 million in total funds available for purchase incentives of zero emission CHE and up to a total of $140 million over the project's life. The VW mitigation fund will have an additional $70 million over the next three to ten years. Combined, this pot of $210 million would be sufficient to provide a $165,000 purchase incentive for 1,270 yard tractors. This is 75 percent of the 1,693 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 would require $78 million at the $500,000 incentive amount shown in the TCO analysis. This is fully half of the funds available under the CORE program, reducing the total funds available for yard tractors and all other CHE to $132 million. This would fund 800 yard tractors at $165,000 voucher amounts, less than half the yard tractor fleet at the Ports. As stated earlier, it is recommended that economic workability be based on non-incentivized cost of ownership.

9.7. Cost Effectiveness, Workforce, and Cargo Diversion 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 cost effectiveness of air quality reductions, workforce impacts, and 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 regulations and funding programs. A major element of any cost effectiveness analysis is the choice of the costs that will be included in the analysis. To develop cost effectiveness comparisons for this Feasibility Analysis, the non-incentivized costs shown in Figure 16 and Figure 17 for an average yard tractor and average RTG crane, respectively, are used.

Emissions impacts are calculated using emissions factors from CARB's ORION2017 model and LCFS program, and applying those factors to the annual activity and fuel economy indicated in Table 30 and Table 31. Criteria pollutant factors for a new 2018 model year yard tractor and RTG crane using a Tier 4 final engine are summarized in Table 35.

Table 35. 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	13.29	1.75
Tier 4 Final RTG Crane	1.24	83.01	7.63

Criteria pollutant emissions reductions are estimated based on reduction factors, shown in Table 36. 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 36 and Table 37. The CI factors for conventional fuels are based on CARB's default values for diesel and the current California-average grid.[84] 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 Low Carbon Fuel Standard (LCFS) Quarterly Data Spreadsheet.[85] Similarly, the CI factor for conventional LNG is calculated from that same spreadsheet. The CI factor for BEVs 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 36 and Table 37 are applied directly to the calculated fuel economies shown in Table 30 and Table 31. 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 Energy Economy Ratios (EER) provided in CARB's LCFS regulation.

Table 36. 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 Diesel ICE	0%	0%	0%	100.45	
NZ LNG ICE	90%	0%	0%	86.44	51.51
ZE Battery Electric	100%	100%	100%	81.49	95.37

Table 37. 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 Diesel	0%	0%	0%	100.45	
NZE Diesel Hybrid	40%	40%	40%	100.45	
ZE Grid Electric	100%	100%	100%	81.49	78.89

[84] 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 draft value of 81.49 gCO2e/MJ.

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

Results of the cost effectiveness analysis are shown in Figure 18 through Figure 21. All cost-effectiveness calculations assume a 7-year or 15-year project life for yard tractors and RTG cranes, respectively. Criteria pollutant emissions are represented as weighted emissions, using the Carl Moyer program methodology.[86]

There is no established value broadly considered to be a reasonable limit for cost effectiveness when derived through this type of analysis. However, the Carl Moyer program's cost-effectiveness limit criteria can be used as one point of comparison for the cost effectiveness values calculated in this Feasibility Analysis. As shown in the figures, the cost effectiveness of criteria pollutant emissions for the NZE natural gas yard tractor is $239,000 and is far higher than the Carl Moyer Program base limit of $30,000 and the $100,000 limit for ZE and NZE on-road technologies.[87] The cost effectiveness for battery-electric yard tractors varies between $430,000 and $601,000 per weighted ton, and is also significantly above the Carl Moyer Program limit of $100,000.

For GHG reductions, the cost effectiveness of the NZE natural gas yard tractor is $1,627 per metric ton (MT) when assuming use of conventional (fossil) natural gas, and $166/MT when assuming use of renewable LNG (RLNG). The cost effectiveness for ZE battery-electric yard tractors varies between $380 and $549/MT. For reference, LCFS credit prices ranged from $105 to $194 per metric ton between January and November 2018.[88]

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 18, the cost effectiveness of criteria pollutant emission reductions for the NZE hybrid-electric RTG crane is -$91,184, which is far lower than the Carl Moyer Program base limits. The cost effectiveness for ZE RTG cranes varies between $53,980 and $83,189 per weighted ton (*Figure* 19), which is better than the ZE yard tractor case and within the Carl Moyer Program limit of $100,000.

For GHG reductions, the cost effectiveness of the NZE hybrid-electric RTG crane is -$84 per metric ton (MT). The GHG-reduction cost effectiveness for the ZE grid-electric RTG crane varies between $70 and $109 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 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 reduce TCO and emissions when replacing the baseline diesel platform.

[86] 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

[87] 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

[88] Analysis based on data from California Air Resources Board LCFS Credit Transfer Activity Reports. https://www.arb.ca.gov/fuels/lcfs/credit/lrtcreditreports.htm

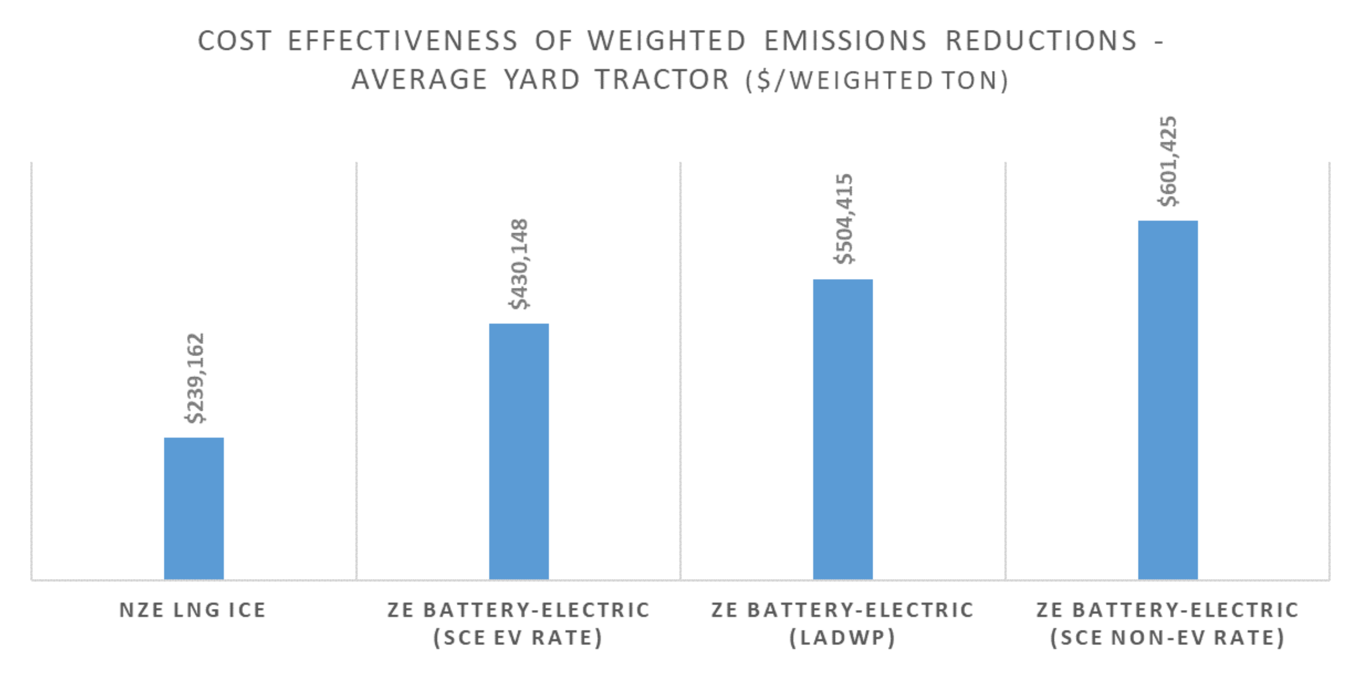

Figure 18. Cost effectiveness of criteria pollutant reductions for Yard Tractors ($/weighted ton)

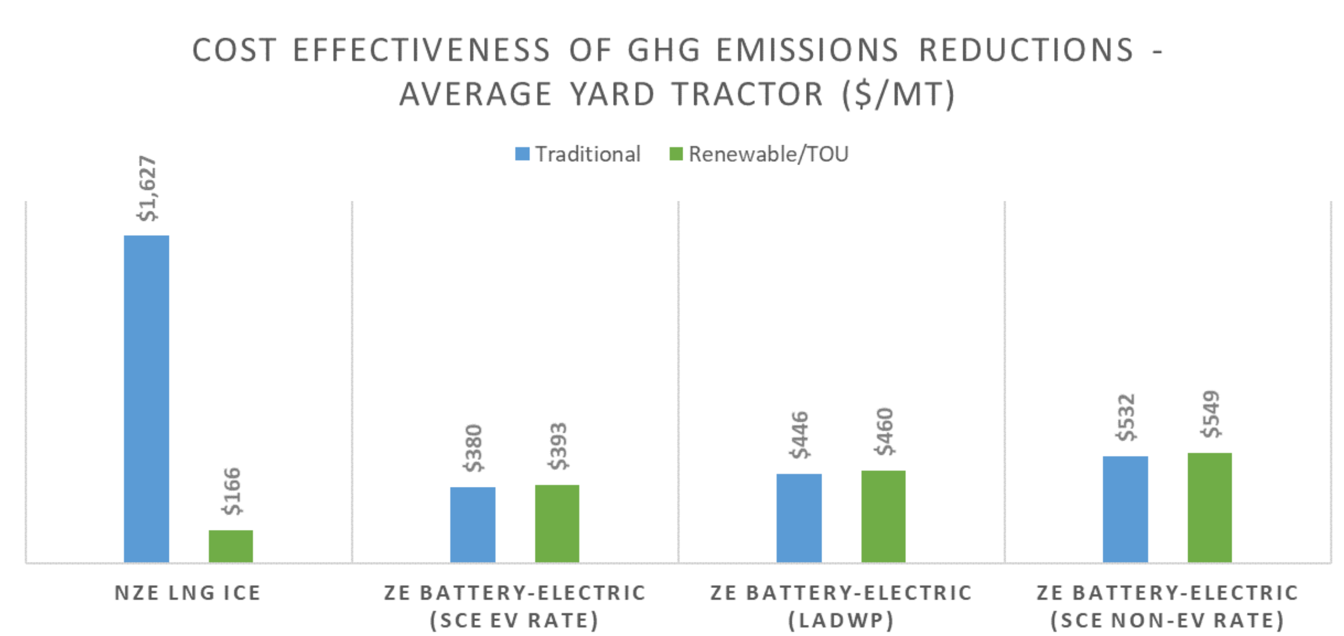

Figure 19. Cost effectiveness of GHG reductions for Yard Tractors ($/MT)

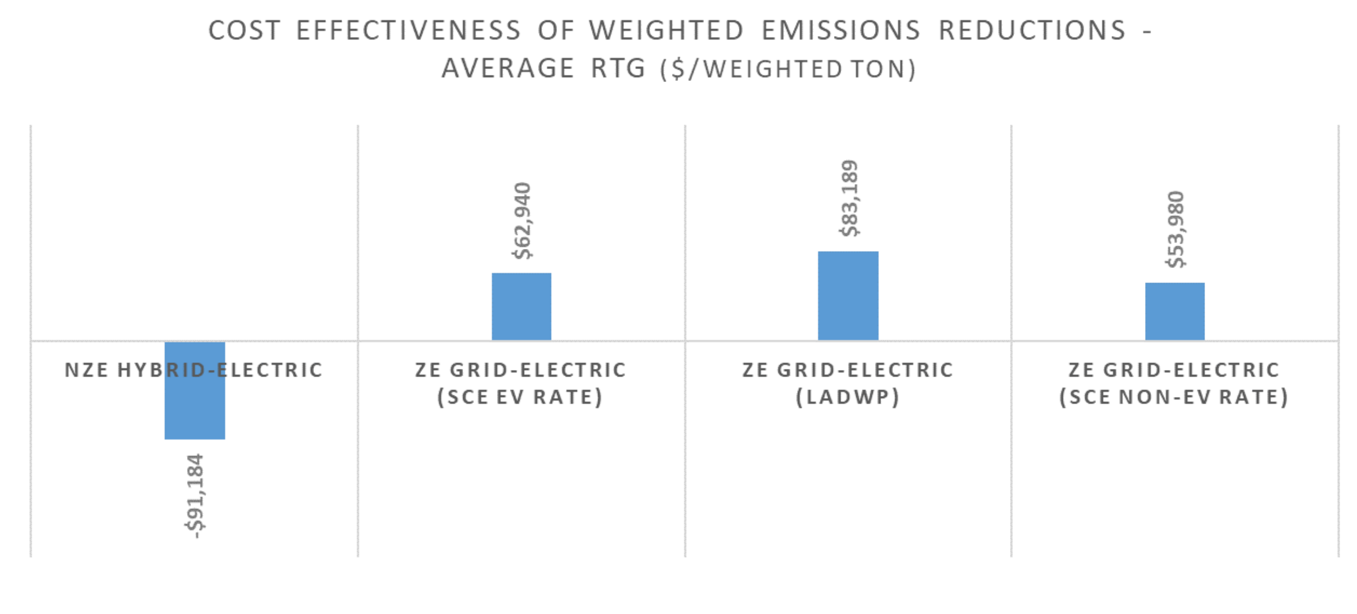

Figure 20. Cost effectiveness of criteria pollutant reductions for RTG Cranes ($/weighted ton)

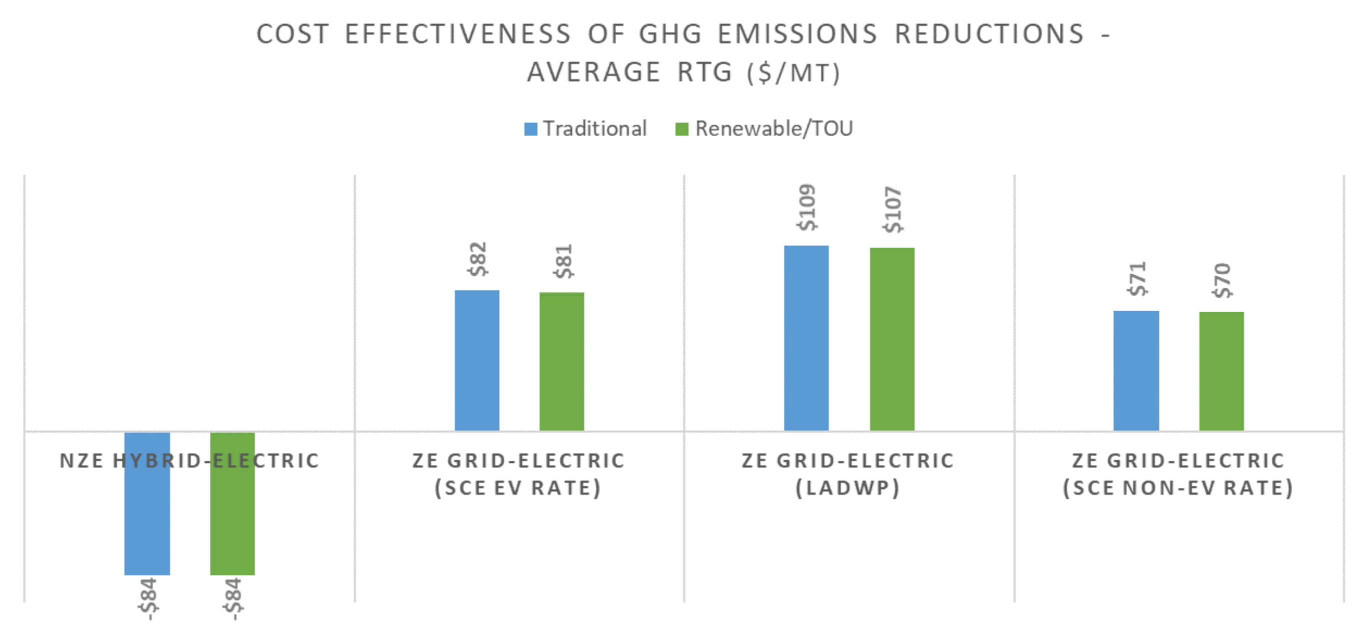

Figure 21. Cost effectiveness of GHG reductions for RTG Cranes ($/MT)

Potential for future cost-effectiveness improvements

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

NZE **Natural Gas Yard Tractors**: Improvements (reductions) 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 LNG storage systems. These and other OEM costs can potentially be realized through economies of scale for manufacturing. Currently, LNG 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 LNG yard tractors – and therefore improving their cost effectiveness to reduce criteria pollutant emissions – is uncertain.

The cost-effectiveness of achieving GHG reductions is calculated by considering a given fuel-technology "pathway" on a full-fuel-cycle basis. Improving the GHG-reduction cost effectiveness achievable by LNG yard tractors will mostly depend on achieving further reductions for the average carbon intensity of natural gas used to make LNG, as new sources of RNG enter the California market. There are a number of RNG projects under development in California that utilize very low (or negative) carbon intensity pathways involving waste from food, biomass, and animals. Many of these projects will likely have lower carbon intensities than the current average carbon intensity for RNG in California.

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 offer battery-electric models, or plan to do so by 2021. This increased competition, combined with the growth of EVs in both on- and off-road road markets, could significantly reduce the incremental cost to manufacture battery-electric yard tractors and improve their cost effectiveness for reducing criteria pollutants.

GHG-reduction cost effectiveness for battery-electric yard hostlers 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.

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 hostlers, 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.

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 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" to be completed in June 2019 and Long Beach City College's zero-emissions workforce assessment to be completed in early 2019.

Cargo Diversion Costs

The potential for cargo diversion and the associated economic impacts are considered in other studies being conducted by the Ports.

9.8. Summary of Ratings for Economic Workability

Table 38 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-2018). For each of the four possibilities, estimated ratings are provided about the degree to which they already meet these basic considerations as of late-2018, or at least are showing measurable progress towards achieving them by the end of 2021.

Table 38. Summary of ratings by key criteria: 2018 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 (2018)**

○ ◔ ◑ ◕ ●

Little/No Achievement … **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.

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. 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 alter the cost of ownership relative to diesel yard tractors. Purchase incentives combined with credits through the LCFS program can reduce cost of ownership to 80-90 percent that of diesel yard tractors. Unfortunately, the long-term availability of these incentives is not guaranteed.

NZE **Natural Gas ICE Yard Tractors** – While natural gas yard tractors have higher incremental purchase prices and some additional infrastructure costs, their cost of ownership over a 7-year vehicle lifetime is similar to - though slightly higher than - that of 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 the cost of ownership for natural gas vehicles such that they become significantly less expensive to operate than diesel equipment, even as fuel price spreads change. Currently available purchase incentives achieve this goal and fuel credits through the LCFS and federal RFS allow natural gas stations to offer fossil natural gas or renewable natural gas at equivalent prices. 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.

ZE **Grid-Connected RTG Cranes** – Grid-connected RTG cranes have significant incremental purchase costs of approximately 50 percent relative to conventional RTG cranes. Infrastructure costs also add significant upfront capital requirements. Fuel and maintenance cost savings partially offset these incremental costs but grid-connected RTG cranes remain 10-20 percent more expensive than diesel RTG cranes on a TCO basis.

NZE **Diesel Hybrid RTG Cranes** – Purchase costs for hybrid RTG cranes are approximately 10 to 15 percent higher than conventional diesel RTG cranes. This incremental cost is fully offset by the fuel cost reductions from the hybrid system over its operational life. Combined with the fact that no incremental infrastructure costs are anticipated for this technology, diesel-hybrid RTG cranes are the only technology assessed that has a lower projected TCO than baseline diesel equipment. And while there are few funding programs that would provide incentives for diesel-hybrid RTG crane deployments, these programs are less important for the adoption of the technology based on the TCO advantages of hybrid RTG cranes.

10. Summary of Findings and Conclusions

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

This 2018 Feasibility Assessment for Cargo-Handling Equipment applied 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, in 2018 or within approximately three years.

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

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

Additionally, small forklifts -- most of which are powered by gasoline or propane engines -- were evaluated (separately, and at a higher level) for their feasibility to use ZE or NZE fuel-technology platforms. Full discussion and findings are presented in Section 13 (Appendix C).

The five parameters applied to qualitatively and collectively asses 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 appear to hold the most promise to power large numbers of CHE as if late-2018, or by 2021. 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-2018, 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 "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 provided below.

Yard tractors:

- **ZE** battery-electric technology is commercially offered for yard tractors by multiple OEMs. These are effectively "early commercial" product launches that have achieved TRL 7 and are approaching TRL 8 through focused, multi-unit demonstrations. All four parameters that collectively define commercial feasibility are at least partially achieved.

- **NZE** natural gas ICE technology is commercially offered for yard tractor by multiple OEMs. These are effectively "early commercial" product launches that have achieved TRL 7 and are approaching TRL 8 through focused, multi-unit demonstrations. All four parameters that collectively define commercial feasibility are at least partially achieved.

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.

RTG cranes:

- **ZE** grid-electric RTG cranes (new built and conversion packages) are fully commercial products 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 at TRL 9; all four parameters that collectively define commercial availability appear to be fully achieved.
- **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 2018, nor does it appear (at this time) to be on that path by 2021.

The remainder of this 2018 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.

10.1. 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.

10.2. Overarching Conclusion: 2018 Feasibility Applying All Five Key Parameters

Table 39. Roll-up of "Operational Feasibility" ratings in 2018

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 (2018)**

○ ◔ ◑ ◕ ●

Little/No Achievement … 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 <u>lowest criterion rating</u> for each feasibility parameter.

Table 40. Roll-up of "Infrastructure Availability" ratings in 2018

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 (2018)**

○ ◔ ◑ ◕ ●

Little/No Achievement … 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 <u>lowest criterion rating</u> for each feasibility parameter.

Table 41. Roll-up of "Economic Workability" ratings in 2018

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 (2018)**

○ ◔ ◑ ◕ ●

Little/No Achievement … 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 <u>lowest criterion rating</u> for each feasibility parameter.

Table 42 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-2108) achieve the five key feasibility parameters, or are likely to achieve them by 2021. These estimated ratings are made in the specific context of CHE operated at marine terminals serving the San Pedro Bay Ports.

Table 42. Summary of overall "Feasibility" in 2018 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 (2021: TRL 7 to 8)**	**TRL 7 (2021: TRL 7 to 8)**	**TRL 9**	**TRL 9**
Operational Feasibility				
Infrastructure Availability				
Economic Workability				

Legend: **Achievement of Each Noted Parameter / Criteria (2018)**

Little/No Achievement **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.

10.3. Looking Forward: Commercial and Technological Outlook

As described in this report, most (if not all) CHE OEMs are now developing ZE and/or NZE fuel-technology platforms for their products. To meet CAAP objectives, it is particularly important that OEMs are making steady and measurable progress to advance various **ZE** CHE platforms towards technological maturity and market readiness. Under the CAAP – as well as state and local air quality plans – large-scale deployments of heavy-duty ZE platforms are expeditiously needed wherever overall feasibility can be established. Yard tractors are key "horizontal" CHE that are making particularly strong and important progress towards commercialization of ZE architectures. This will help advance OEM efforts to incorporate battery-electric and fuel cell platforms into 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.

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 San Pedro Bay Port fleet to ZE status. This must be done in close coordination with building-out of suitable fueling / charging infrastructures. Good progress is underway to accelerate the pace of this transition at the Ports. This can be seen in the many ZE CHE demonstrations that are now, or will soon be, underway at marine terminals serving both Ports.

Related to this expanding number of demonstrations, and equally important, OEM commitment to ZE CHE markets has been growing and strengthening. For even the most-challenging CHE applications (e.g., top handlers), CHE OEMs are developing ZE architectures for their products. One major OEM has publicly stated that by 2021, it will make and sell at least one ZE model for all four key CHE types. Ultimately Of course, these products will achieve true commercialization on timelines that are commensurate with commercial maturity, and according to what makes good business sense for each OEM.

Over the next three years, it will be very important for OEMs and MTOs, through the many San Pedro Bay Ports 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 may fundamentally improve at the San Pedro Bay Ports.

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 • Fuel additives and/or devices that have not been fully evaluated and Verified by CARB, including a multimedia evaluation • Material that is deemed NOT to be credible, verifiable, technical, and/or relevant by Port CAAP representatives and/or TAP advisors

12. Appendix B: Additional Information on Demonstrations

Below, additional application-specific details are provided about key types of demonstrations that are underway at the San Pedro Bay Ports, or will soon get started. (Refer back to Figure 5 on page 25.)

12.1. ZE Yard Tractor Demonstrations

Based on publicly announced grant awards from various sources, approximately 16 yard tractor demonstrations featuring ZE architectures are underway or planned at San Pedro Bay Port marine terminals. Over the next few years, these projects will demonstrate approximately 111 battery-electric yard tractors and 2 hydrogen fuel cell yard tractors. The two leading ZE architectures, battery-electric and hydrogen fuel cell, are both expected to play key roles in meeting the CAAP's long-term plans for ultra-clean CHE. CHE and other heavy-duty vehicles / equipment using these two ZE architectures are pillars of CARB's and SCAQMD's mobile source control plans to attain National Ambient Air Quality Standards for ozone in the South Coast Air Basin.

Battery-electric yard tractors (including plug-in hybrids with ICE technology) have already been tested in limited capacity by MTOs at the San Pedro Bay Ports. Such testing has almost exclusively involved pre-commercial prototypes built by existing / startup OEMs, and/or technology providers (such as TransPower/Meritor[89] and U.S. Hybrid[90]). Technology providers have played key roles to design, build and demonstrate proof-of-concept yard tractors (and other HDVs) with ZE and/or NZE architectures.

Existing and start-up OEMs are just beginning to build and deploy more more-advanced, early commercial versions of battery-electric yard tractors; some continue to work with the above-noted technology providers. Virtually all of the 111 battery-electric yard tractors noted in the timeline above will be produced as early commercial products by BYD or Kalmar Ottawa. Orange EV is also expected to manufacture some of the ZE battery-electric yard tractors that will be deployed in these early commercialization demonstrations. The company emphasizes that its terminal tractors have already been deployed elsewhere in the United States specifically to support "seaport container traffic."[91]

The upshot is that ZE battery-electric yard tractors have not yet transitioned into full commercial status for revenue service at marine terminals of the San Pedro Bay Ports. Over the next two years, the large number of battery-electric yard tractor demonstrations (and two fuel cell demonstrations) are expected to yield important operational data and "lessons learned" about the necessary logistics associated with charging/fueling infrastructure. Peer-reviewed results and reports are expected in 2020, with possible interim results available in late 2019. Sections 7 (Operational Feasibility) and 8 (Infrastructure Availability) provide detailed discussions about the important need to conduct, complete and document these demonstrations.

12.2. NZE Yard Tractor Demonstrations

Based on publicly announced grant awards from various sources, 22 NZE LNG-fueled[92] yard tractors will be demonstrated at the San Pedro Bay Ports over the next two years. Capacity Trucks is building all 22 LNG yard tractors, of which 20 are being equipped with the Cummins Westport, Inc. (CWI) 8.9 liter natural gas engine. The other two LNG tractors are being equipped

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[89] Meritor is a "leading global supplier of drivetrain, mobility, braking and aftermarket solutions for commercial vehicle and industrial markets." In 2017, Meritor announced a strategic investment in TransPower, which is "a leader in electrification technologies for large commercial vehicles." See http://www.meritor.com.

[90] US Hybrid "specializes in the design and manufacturing of zero emission powertrain components for electric, hybrid, and fuel cell medium and heavy-duty municipality vehicles, commercial trucks, buses, and specialty vehicles. See https://ushybrid.com.

[91] Orange EV, comments submitted to the San Pedro Bay Ports about the "2018 Feasibility Assessment for Cargo-Handling Equipment," May 2019.

[92] At least one OEM offers an NZE yard tractor model equipped with a compressed natural gas (CNG) fuel system instead of LNG. See Section 7 (Operational Feasibility) for discussion about how fuel system choice (LNG vs. CNG) impacts operational feasibility of NZE natural gas yard tractors for use at the San Pedro Bay Ports.

with CWI's 6.7-liter LNG engine. Actual deployments are expected to begin in mid-2019. To enable these demonstrations, the host MTO(s) have been working with natural gas infrastructure providers to obtain access to on-site LNG fueling. As further discussed in Section 8 (Infrastructure Availability), establishment of on-site LNG fueling infrastructure can involve challenging permitting and logistics requirements. This is not uncommon for heavy-duty vehicle demonstration projects that require build-out of alternative fuel infrastructure. Authorities such as local fire marshals may not have the same level of comfort and familiarity they have with diesel stations. The result can be significant delays in starting heavy-duty vehicle / equipment demonstrations, but this is part of the overall learning process.

Natural gas ICE technology is not new to this application. Over the last decade, at least 17 LNG yard tractors have been deployed to move cargo within (or near) the San Pedro Bay Ports. The Port of Los Angeles lists twelve active LNG yard tractors in its most-recent (2017) CHE inventory. These constitute only a small fraction (less than one percent) of the total San Pedro Bay Ports yard tractor fleet. Still, yard tractors using natural gas ICE technology are proven alternatives to diesel yard tractors.

However, it is important to recognize that the current fleet of 12 LNG yard tractors in the Ports' collective inventory has been operated only in warehouse / logistics yard applications. This entails different duty cycles and use characteristics compared to moving containers at San Pedro Bay Port marine terminals. As of mid-2019, no current-technology LNG yard tractors have been operated at any port container terminal. Such demonstrations are expected to commence in Q3 of 2019, at a single marine terminal serving the Port of Los Angeles.

Similar to the case with ZE battery-electric yard tractors, the upshot is that NZE LNG-fueled yard tractors have not yet transitioned into full commercial status for revenue service at marine terminals of the San Pedro Bay Ports. Demonstrations of the 22 NZE LNG yard tractors over the next two years are needed to provide important operational data on the tractors, and lessons learned about how to optimally provide LNG fueling infrastructure. Peer-reviewed results and reports are expected in 2020, with possible interim results available in late 2019. Sections 7 (Operational Feasibility) and 8 (Infrastructure Availability) provide additional discussion about the important need to conduct, complete and document these demonstrations.

12.3. ZE Top Handler Demonstrations

Top handlers are very large "vertical" CHE that present greater challenges than yard tractors ("horizontal" CHE) for application of ZE or NZE architectures. Examples of application-specific challenges are discussed in detail in Section 7 (Operational Feasibility). Top handler OEMs such as Taylor, Kalmar and Hyster are developing ZE platforms that include battery-electric and fuel cell architectures. Based on published reports, nine battery-electric top handlers and one fuel cell top handler are scheduled to be demonstrated at San Pedro Bay Port marine terminals over the 12 to 24 months. Demonstration of some battery-electric top handlers were originally scheduled to be completed by late 2019 or mid-2020. However, initial product builds and deployments have been delayed. It's possible (although perhaps not likely) that some important information (operational data, MTO comparative evaluations) will be available by late 2020.

12.4. ZE RTG Crane Demonstrations

RTG cranes using advanced hybrid-electric technology are examples of commercially and technologically mature NZE CHE technology. Today, the San Pedro Bay Ports collectively operate 13 NZE hybrid-electric RTG cranes, and there does not appear to be major need to initiate demonstrations for this particular CHE fuel-technology platform.

By contrast, there are no ZE grid-electric E-RTG cranes operating at either Port today (based on 2017 inventories). This is not due to insufficient commercial maturity. E-RTG cranes are proven alternatives to conventional RTG cranes, as evidenced by growing deployments at seaports around the world. Still, each installation and deployment of a grid-electric RTG crane entails region- and site-specific challenges. Demonstration programs can provide an important way for MTOs to understand and address such challenges on a pilot scale, prior to fully converting their RTG crane fleet. One such demonstration program is now getting started at the Port of Long Beach. Under grant funding provided by the California Energy Commission and augmented by the U.S. EPA (via the Diesel Emission Reduction Act), the Port is working with SSA Marine, Southern California Edison and other industry partners to convert nine (9) conventional RTG cranes over to grid-electric E-RTG cranes. This demonstration will provide important operational experience for the MTO on E-RTG cranes, and help overcome electricity infrastructure challenges (e.g., optimal ways to make grid connections) while minimizing disruption of terminal operations.

Section 8 (Infrastructure Availability) and other parts of this report provide further discussion about the challenges, benefits and overall feasibility of E-RTG cranes.

12.5. ZE Large-Capacity Forklift Demonstrations

Like top handlers, large-capacity forklifts present significant challenges for application of ZE or NZE architectures. OEMs such as Hyster-Yale and Hoist are developing ZE platforms that include battery-electric and fuel cell architectures. Based on published reports, at least 12 battery-electric forklifts of larger capacities are scheduled to be demonstrated at San Pedro Bay Port marine terminals over the 12 to 24 months. Most if not all of these will occur in Southern California Edison's territory (i.e., on the Port of Long Beach side). One demonstration involving two battery-electric forklifts was originally scheduled to be completed by late 2019, while a larger demonstration (10 additional units) won't be completed before 2022. It's possible that some important information (operational data, MTO comparative evaluations) will be available in 2020.

13. Appendix C: Assessment of Small-Capacity Forklifts

13.1. Introduction

Gasoline- and propane-powered small forklifts (typically below 16,500 lbs. capacity) contribute to the Ports' collective air emissions inventory. Unlike larger diesel-fueled CHE (yard tractors, top handlers, RTG cranes and large-capacity forklifts), small-capacity forklifts with ZE platforms (primarily battery electric) have been commercially available and technically viable for many years. This section provides a separate analysis of the overall feasibility for small-capacity forklifts serving San Pedro Bay Ports MTOs to utilize ZE and/or NZE fuel-technology platforms. This analysis was performed at a higher level than the CHE types assessed in the main body of this report, for two key reasons: 1) small-capacity forklifts have a longstanding history of being powered by commercially available ZE platforms, and 2) these non-diesel CHE types impose significantly reduced adverse societal impacts (environmental and public health) compared to high-horsepower diesel-fueled CHE.

13.2. Inventory

An analysis of the equipment inventories used to develop the Ports' most-recent (2017) emissions inventories indicates that there are 536 non-diesel forklifts. These non-diesel forklifts have weight capacities ranging from 2,750 to 16,500 lbs., as shown in Figure 22. These small-capacity forklifts are primarily used to move ancillary equipment at the marine terminals.[93] Examples of work performed by these forklifts include moving container locking cone bins, transporting diesel generator sets for refrigerated containers, and stacking container chassis.

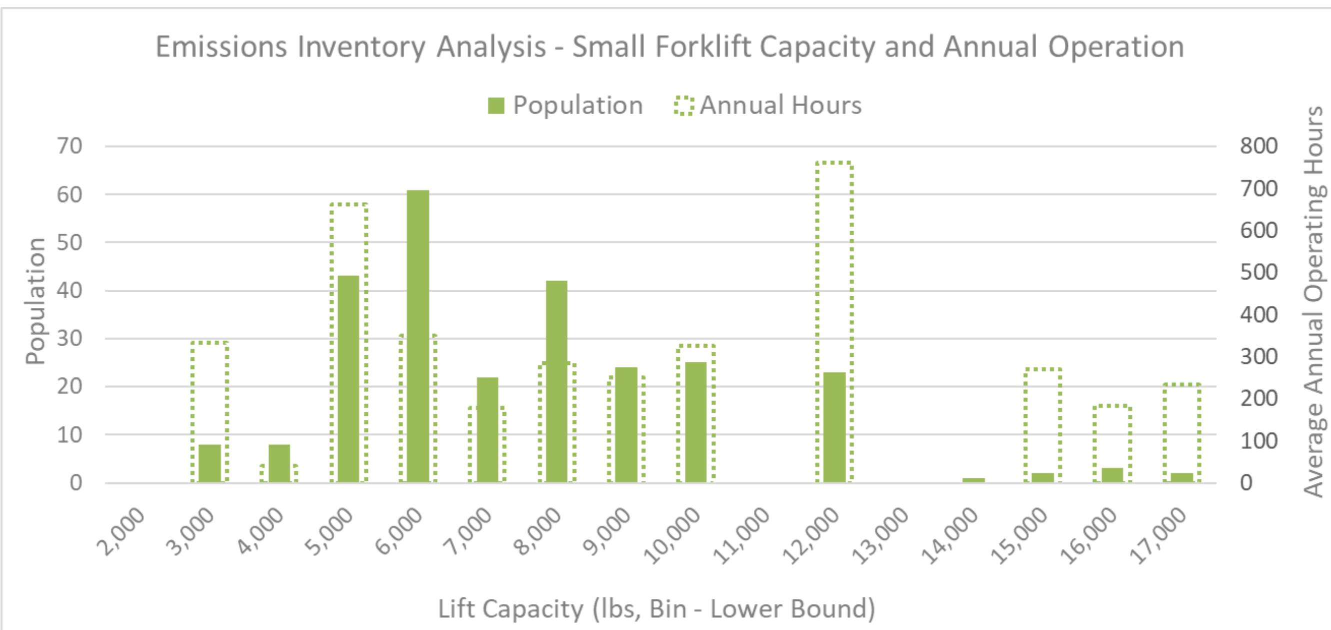

Figure 22. Distribution of small-capacity forklift populations and operating hours by capacity

13.3. Commercial Availability

The term "forklift" encompasses a wide range of equipment, from electric pallet jacks to aircraft tow tractors. In the port environment, forklifts must be rated for outdoor use, in contrast to indoor-only forklifts typically used in

[93] Note that, of the total non-diesel forklift population in the inventory (536 units), only 288 offered sufficient model information to determine lift capacity.

warehouse applications. Forklifts are divided into the following seven different classes, based on their design and propulsion type:

Class I: Electric Motor Rider Forklifts

Class II: Electric Motor Narrow Aisle Forklifts (Reach Trucks, Order Pickers)

Class III: Electric Pallet Jacks, Stackers, and Tow Tractors

Class IV: Internal Combustion Cushion Tire Forklifts

Class V: Internal Combustion Pneumatic Tire Forklifts

Class VI: Electric/IC Engine Tow Tractors

Class VII: Rough Terrain Forklifts

13.3.1. ZE Battery-Electric Forklifts

The majority of small-capacity forklifts used at the ports fall within Class V (ICE pneumatic tire). The pneumatic tire design is suitable for outdoor applications, whereas the cushion tire design (Class IV) is more suitable for indoor applications. Battery-electric versions of both pneumatic and cushion tire forklifts have long been commercially available for indoor applications, where emissions from diesel or gasoline engines are problematic. In fact, according to Toyota, electric forklifts now account for nearly 60 percent of the North American forklift market, "due to advances in technology that are allowing them to operate more comparably to internal combustion engine forklifts" for performance and run time.[94]

A review of major forklift OEMs in the U.S. market shows that several offer battery-electric Class V pneumatic tire forklifts. The majority of the battery-electric Class V models are limited to lift capacities of 12,000 lbs. or less. For example, Toyota's largest battery-electric Class V model is rated up to 12,000 lbs.[95]; Hyster has its own battery electric Class V forklift rated up to 12,000 lbs.[96]

These various commercial offerings of battery-electric platforms sufficiently cover the range of small-capacity forklifts currently listed in the collective San Pedro Bay Ports inventory. In sum, as of late-2018, small-capacity forklifts are commercially available in ZE battery-electric configurations that are suitable for wide deployment by San Pedro Bay Port MTOs.

13.3.2. ZE Fuel Cell Forklifts

Similar to battery-electric forklifts -- but at a lower stage of commercial maturity, and primarily for niche uses – small-capacity forklifts using hydrogen fuel cell platforms are now being deployed for industrial applications. Manufacturers such as Nuvera and Plug Power offer fuel cell retrofit packages for existing forklifts. For example, Plug Power offers a "full suite" of its GenDrive fuel cell systems that "fit seamlessly into existing electric forklifts," although this appears to be limited to Class I, II and III forklift types.[97] In other words, this ZE fuel-technology platform replaces an existing, commercially available ZE battery-electric platform. Hyster has teamed with Nuvera to offer hydrogen fuel cell versions of its small-capacity forklifts, although this product line appears to be in its infancy compared to Hyster's battery-electric small-capacity forklifts.

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[94] Toyota, "Electric vs. Internal Combustion Engine Forklifts," https://www.toyotaforklift.com/resource-library/material-handling-solutions/products/forklift-fuel-options-and-buying-consideration.

[95] Toyota, "Electric Forklifts," https://www.toyotaforklift.com/

[96] Hyster, "4 Wheel Electric Trucks," https://www.hyster.com/north-america/en-us/products/4-wheel-electric-trucks/.

[97] Plug Power, "GenDrive Fuel Cell Power," https://www.plugpower.com/products/gendrive/.

In summary, hydrogen fuel cell retrofit systems for small-capacity forklifts are emerging now as pre-commercial or early commercial products. These systems are designed to fit in the same space as existing lead-acid batteries for electric forklifts, providing a largely drop-in replacement option to batteries. Examples of deployments to date include primarily smaller Class I forklifts (up to approximately 6,000 lbs.) and Class II and Class III reach trucks, pallet jacks, etc. Fuel cell options for Class IV and V small-capacity forklifts most commonly used at San Pedro Bay Ports marine terminals are not commercially available, as of late-2018.

13.3.3. NZE Propane Forklifts

As noted in the main body of this report, propane is already a commonly used fuel for small-capacity forklifts at multiple San Pedro Bay Port marine terminals. This has potentially important ramifications. Heavy-duty propane engines have now been certified to CARB's lowest-tier OLNS (0.02 g/bhp-hr), joining natural gas engine technology. As yet (late-2018), no CHE OEM has announced commercialization plans for an NZE propane-fueled forklift. However, should this happen, an NZE propane forklift option would represent a direct replacement for existing forklifts, and it would leverage existing fueling infrastructure for MTOs that already operate propane forklifts. Moreover, renewable propane – which is a low-carbon-intensity, drop-in replacement for conventional propane – has now been incorporated under the California LCFS, and may gradually become available to these MTOs.

In this way, longer-term potential exists for MTOs to simultaneously achieve major reductions of ozone-forming NOx as well as climate-changing GHG emissions, by gradually phasing in NZE propane-powered equipment, and also using renewable propane (if it can be produced and purchased in suitable quantities). This could be done with relatively small new investments in propane fueling infrastructure.

However, NZE propane ICE forklifts are not commercially available for MTOs today. If and when this changes, future CHE feasibility assessments can re-evaluate the potential for this type of fuel-technology platform, including availability, cost and benefits of phasing in renewable propane.

13.4. Technical Readiness

ZE battery-electric small-capacity forklifts (up to approximately 19,800 lbs.) are mature commercial product offerings that achieve a TRL 9 rating (using the previously referenced U.S. DOE scale). These commercially available, technically viable product offerings are suitable for wide use in many, but not necessarily all, uses of small-capacity forklifts by MTOs serving the San Pedro Bay Ports.

Fuel cell forklifts in smaller capacities (up to approximately 6,000 lbs.) have been demonstrated and deployed by several large U.S. fleets; examples include WalMart, Amazon, Wegmans, and Sysco. These types of forklifts are generally used for indoor applications (where zero emissions are most important). However, there is nothing that inherently restricts fuel cell forklifts from also being used for outdoor applications. For these **non-port**, lighter capacity applications, fuel cell forklifts achieve TRL 9.

13.5. Operational Considerations

Small-capacity forklifts are versatile pieces of equipment and are used to perform many functions at marine terminals. This versatility results in significant day-to-day usage variation at a given terminal, as well as use that varies on a terminal-specific basis. A review of reported annual operating hours of small-capacity (non-diesel) forklifts at the ports shows relatively low average annual usage, ranging from 40 to 760 hours per year (see Figure 22). However, some forklifts performed up to 5,436 annual hours of operation, and a significant number reported 2,000 to 3,000 hours of annual operation.

As Figure 23 shows, the distribution of annual operating hours for small-capacity forklifts exhibits two peaks: the first is at approximately 200 hours of operation, and the second is at approximately 2,000 hours of operation. This indicates that many of these small-capacity forklifts are used infrequently, while others are used for 8 to 10 hours per day.

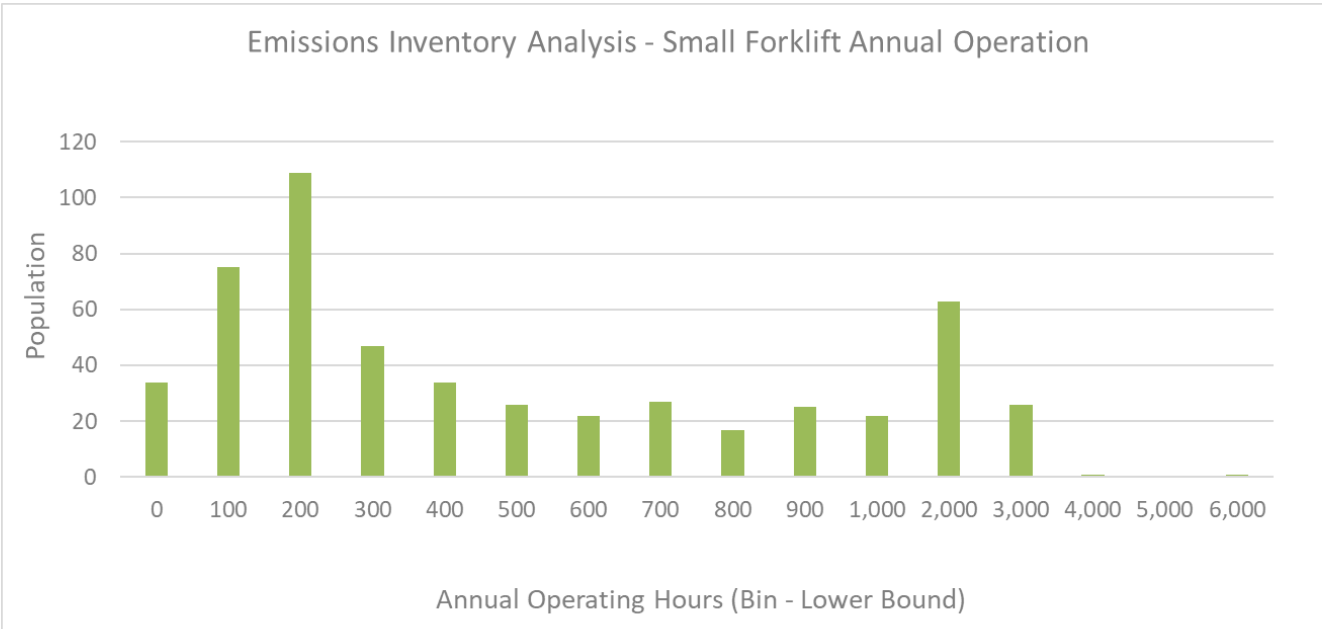

Figure 23. Distribution of annual operating hours for non-diesel forklifts

As previously described, the battery-electric forklifts (as well as fuel cell forklifts, at the lower capacity sizes) are essentially electric-drive, no-combustion versions of propane, gasoline, or diesel ICE forklifts. It is reasonable to assume that the long-standing commercially available battery-electric forklift platforms can perform similar basic work with respect to lift capacity, lift height, and other relevant specifications. However, operating endurance remains a potential issue, especially when considering battery-electric forklifts for routine use at marine terminals.

Battery-electric forklifts are typically expected to complete a single shift of operation before being recharged or swapping batteries. To be operationally feasible as replacements for infrequently used ICE (baseline) forklifts, it is unlikely that ZE battery-electric forklifts would be limited by battery capacity and endurance. However, for higher-utilization forklifts (2,000+ hours per year of operation) it is unclear whether current battery systems would provide sufficient range between charges to be operationally feasible.

One key advantage ZE hydrogen fuel cell platforms offer over ZE battery-electric platforms is that they are fueled in similar fashion to ICE platforms. Consequently, fuel cell-powered forklifts in smaller lifting capacities are less likely to encounter endurance issues than battery-electric forklifts, and offer rapid fueling options available that can minimize shift disruptions. However, hydrogen fuel cell platforms suitable for use in for small-capacity forklift applications at marine terminals are not yet commercially mature and technically viable.

Small-capacity forklifts have not yet been a focus for ZE CHE demonstrations by MTOs at the Ports, and no detailed studies have been conducted about operational requirements for this equipment category. Hence, while it is very likely that ZE battery-electric forklifts would be able to meet the operational requirements of many small-capacity forklift applications at the Ports, the extent of their applicability to higher-utilization operations remains unclear.

13.6. Economic and Infrastructure Considerations

Absent additional study of the operational requirements and conditions of small capacity forklifts, an informed assessment of economic costs and infrastructure requirements cannot be performed. However, some observations can be made for the two leading ZE platforms, as described below.

13.6.1. Battery-Electric Forklifts

The capital costs of electric forklifts are generally 20 percent more expensive than propane forklifts, excluding the cost of the battery pack and charger.[98] When including the cost of the charger and battery, the capital cost of an electric forklift can be 40 to 50 percent higher than a comparable propane forklift. However, fuel and maintenance cost reductions can provide a net reduction in the total cost of ownership. These cost savings are dependent on utilization, with higher utilization providing greater savings for electric forklifts relative to propane forklifts. In low-utilization applications, the maintenance and fuel cost savings of battery-electric forklifts do not pay back the higher capital cost.

The Electric Power Research Institute offers a cost of ownership calculator for lift trucks that can be used to explore these cost tradeoffs.[99] The calculator suggests that at low annual hours of operation (100 to 400 hours per year), battery-electric forklifts have a total cost of ownership approximately $2,000 to $8,000 higher than propane over six years. However, as annual operating hours increase, electric forklifts become less expensive than propane forklifts. At 1,000 operating hours per year, savings range from $5,000 to $9,000 over six years. At 2,500 hours per year, savings increase to $25,000 to $38,000 over six years. Based on the distribution of operating hours shown in Figure 23, approximately 57% of the fleet operates less than 400 hours a year, while only about 17% of the fleet operates more than 1,000 hours per year.

It must be noted that the cost comparison described above does not account for infrastructure improvements to supply battery chargers. Small-capacity forklifts may only require 5 to 10 kW chargers that can be supplied relatively easily using 208/240V circuits, while simultaneously charging several forklifts. Large-capacity forklifts may require 20-25 kW chargers that will typically require 480V circuits, particularly when more than one forklift is charging in a given area. The costs of electrical infrastructure improvements to supply charging infrastructure are highly dependent on site-specific conditions, but could offset the cost of ownership savings even for high-utilization equipment.

13.6.2. Fuel Cell Forklifts

The economic case for fuel cell forklifts is typically predicated on high-utilization environments where the relatively fast fueling time of fuel cell forklifts (3 minutes) provides significant labor savings in multi-shift applications compared to battery swapping for electric forklifts (15 minutes). Additionally, larger fleets (30+ units) are better able to distribute the cost of hydrogen fueling infrastructure over greater fuel throughput, improving costs relative to electric forklifts. The National Renewable Energy Laboratory (NREL) developed a total cost of ownership comparison for battery-electric and fuel cell forklifts. NREL found that, for an average fleet of 58 forklifts operating each unit 2,400 hours per year, fuel cell forklifts provided a cost savings of approximately $1,900 per year, per forklift. The results of NREL's cost model are very sensitive to assumptions about the number of battery changes and the cost of charging/fueling infrastructure. For low-utilization applications and small fleets,

[98] CAT Lift Trucks, "Choosing Electric (AC) Lift Trucks over Internal Combustion (IC)", 2011

[99] https://et.epri.com/Calculators_LiftTruckComparison_with_cap2.html

the cost of fuel cell forklifts is likely to be greater than battery-electric forklifts, as well as baseline propane forklifts.[100]

Adding fueling infrastructure for fuel cell forklifts can be relatively simple, for a relatively small fleet consuming low volumes of hydrogen. This includes options to rent or lease small-scale hydrogen fueling stations. Hydrogen fuel infrastructure becomes an increasingly complex proposition as fuel demand dictates increasing volumes for on-site fuel storage and dispensing. When fuel throughput exceeds about 200 kg/day -- the capacity of commonly used gaseous hydrogen tube trailers -- a marine terminal user would likely seek cryogenic (liquefied) hydrogen storage. These systems are similar to "LCNG" (liquefied compressed natural gas) stations for heavy-duty NGVs, and can be costly to install. Given that the primary value proposition for fuel cell forklifts is using them in high-utilization fleets, it is unlikely that fuel cell forklifts will be cost competitive with propane or electric forklifts in the majority of cases at marine terminals.

13.7. Findings and Conclusions

This high-level analysis concludes the following about the overall feasibility of small-capacity forklifts operating at the San Pedro Bay Ports to utilize ZE and/or NZE platforms, as replacements for conventional ICE forklifts.

Commercial Availability – Battery-electric forklifts up to about 19,800 lbs. lift capacity are commercially available. Fuel cell forklifts are commercially available up to approximately 6,000 lbs. lift capacity.

Technical Readiness – Battery-electric forklifts are considered mature and achieve TRL 9. Commercially available fuel cell forklifts are also considered mature and achieve TRL 9.

Operational Feasibility – Small-capacity forklifts have not yet been a focus for ZE CHE demonstrations by MTOs at the Ports. While it is very likely that ZE battery-electric forklifts would be able to meet the operational requirements of many small capacity forklift applications at the ports, the extent of their applicability to higher utilization operations is unproven and remains unclear.

Economic and Infrastructure Considerations – Both battery-electric and fuel cell forklifts are anticipated to be more expensive to operate than baseline propane forklifts for low-utilization equipment. As utilization increases, above about 500 hours per year, battery-electric forklifts are expected to become economically competitive with propane. The costs of electrical infrastructure improvements to supply charging infrastructure are highly dependent on site-specific conditions, but could offset the cost of ownership savings even for high-utilization equipment. Fuel cell forklifts are not anticipated to be economically competitive except in very high utilization applications with 20 to 30 forklifts, or more, utilizing the same fueling equipment.

[100] Todd Ramsden, National Renewable Energy Laboratory, "An Evaluation of the Total Cost of Ownership of Fuel Cell-Powered Material Handling Equipment," Technical Report NREL/TP-5600-56408, https://www.nrel.gov/docs/fy13osti/56408.pdf.

14. Appendix D: Summary of Relevant Incentive Programs

14.1. Carl Moyer Memoria 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. For the jurisdiction in which the San Pedro Bay Ports are located, SCAQMD has announced availability of Carl Moyer funds that can be specifically focused on CHE. Under SCAQMD's 21st year of CMP implementation, eligible off-road equipment types include the following[101]:

- 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, and 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 other existing CHE (yard tractors, top handlers, etc.) 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 for both types of project is 85 percent when repowering to a zero-emission system, and 80 percent 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.

14.2. California Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP)

The HVIP program offers incentives for the purchase of new heavy-duty vehicles using hybrid, electric, or natural gas technologies. Funding is provided through the State's Greenhouse Gas Reduction Fund (GGRF). Current funds available in the program total $85 million for all approved technologies. The 2018 funding plan will add an additional $125 million to the program's available funding.[102] Annual award totals are not capped, but CARB staff anticipate that the current funding allocations will meet demand for several years.

The maximum voucher amount available to ZE battery-electric Class 8 yard tractors is $150,000, or $165,000 for yard tractors deployed in disadvantaged communities. HVIP also offers incentives for charging infrastructure but has noted, "…infrastructure installation is a complex issue with long lead times, which is incongruous with HVIP's simplified approach, and statutory expenditure deadlines."[103] Staff have proposed to continue infrastructure funding through 2018/2019 and reevaluate the funding for the 2019/2020 funding year. Given this uncertainty, it is not assumed that MTOs would have access to infrastructure incentives through HVIP. HVIP also provides up to $45,000 for the purchase of NZE natural gas engines, when paired with renewable natural gas. Fleets of 10 or fewer vehicles are exempt from RNG usage requirements.

14.3. 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.

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[101] 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.

[102] https://www.arb.ca.gov/regact/nonreg/2018/fundingplancleantransportation2018.pdf

[103] https://www.arb.ca.gov/msprog/aqip/fundplan/proposed_1819_funding_plan.pdf

CARB recently 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.[104]

14.4. VW Mitigation Trust Funds

The Volkswagen Environmental Mitigation Trust will provide $423 million to the State to fund emission reductions projects under the State's Beneficiary Mitigation Plan. This plan allocations $70 million in funds for zero-emission Freight and Marine projects and will fund up to $175,000 for battery-electric cargo handling equipment. It is not clear whether or not a grid-connected RTG would qualify for funding under this program. Note that while it is possible to combine incentives between certain programs (such as HVIP and the VW mitigation trust), these programs have limitations on the percentage of the vehicle cost that can be funded. For example, HVIP limits funding from all public sources to 90 percent of the total vehicle cost, while the VW Beneficiary Plan limits VW funding to 75 percent of the total vehicle cost.

14.5. Clean Off Road Equipment Voucher Incentive Project (CORE)

The CORE program funds the deployment of commercialized zero-emission off-road freight technologies to facilitate GHG emissions reductions. Currently, CORE has $40 million in funds available through an appropriation of $140 million from the State's Greenhouse Gas Reduction Fund. Anticipated voucher amounts include up to $180,000 for yard tractors and $500,000 for RTG cranes. Funding under this program is not additive with HVIP and will replace HVIP funding for yard tractors when the CORE program is operational.[105]

14.6. Southern California Edison's Charge Ready Transport 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 buses, medium and heavy-duty trucks, forklifts, and cargo handling equipment. The program also allows SCE to offer rebates to customers for the purchase of charging stations. This program has been authorized for up to $343 million to support 870 sites and at least 8,490 vehicles. A minimum of 25 percent of funds, and up to 75 percent of funds could be available for heavy-duty equipment serving the ports and warehouses.[106] This implies that between $86 million and $257 million would be available for infrastructure development. The program is currently under development and details on funding allocations and per-site or per-charger funding limits have not been released. This program differs from the other funding programs described above as it provides funding only for charging infrastructure and does not fund vehicle purchases.

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[104] 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

[105] California Air Resources Board, "Implementation Guide for the Clean Off-Road Equipment Voucher Incentive Project," November 2018, https://ww2.arb.ca.gov/sites/default/files/2018-11/CORE%20IMPLEMENTATION%20GUIDE%20%28DRAFT%29.pdf.

[106] California Public Utilities Commission, Decision on the Transportation Electrification Standard Projects, May 31, 2018, http://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M215/K380/215380424.PDF.

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CLEAN AIR ACTION PLAN

2018 FEASIBILITY ASSESSMENT for CARGO-HANDLING EQUIPMENT

September 2019