University of California, Irvine

A Comprehensive and Replicable Infrastructure Blueprint for Zero-Emission Medium- and Heavy-Duty Vehicles Operating at a Port Terminal

Prepared for: **California Energy Commission**

Prepared by: **Advanced Power and Energy Program**
University of California, Irvine

Primary Authors **Ghazal Razeghi, Ph.D.**
Michael Mac Kinnon, Ph.D.
Scott Samuelsen, Ph.D.

ABSTRACT

This report presents comprehensive and replicable infrastructure blueprint for zero-emission medium- and heavy-duty vehicles operating at a port terminal" with the goal to facilitate deployment of zero-emission medium-duty and heavy-duty (MD/HD) vehicles by delineating the required charging/fueling infrastructure.

To achieve the goal, the at University of California, Irvine (UCI) Advanced Power and Energy Program (APEP) partnered with the International Transportation Service (ITS) terminal at the Port of Long Beach (POLB). The blueprint includes:

- Previous California Energy Commission efforts and existing plans.
- A detailed description of the required infrastructure to support zero-emission cargo handling equipment at a marine terminal.
- Recommended technologies to support zero-emission MD/HD.
- A suggested timeline and milestones to achieve state energy and environmental goals.
- Impacts on disadvantaged communities.

TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

EXECUTIVE SUMMARY

Facilities that are associated with goods movement face challenges in managing energy requirements, including growing demand, maintaining economic competitiveness, increasing efficiencies of operation, and improving the resiliency, reliability, and security of energy supplies. Currently, seaports and marine terminals are working to balance global and local economic viability and sustainability. Ports face the challenging task of minimizing or eliminating environmental impacts of their operations, including reducing the emissions of toxic air contaminants and criteria pollutants, as well as reducing or eliminating greenhouse gas (GHG) emissions, all while retaining their economic competitiveness. The sources of emissions from ports include ocean-going vessels, heavy-duty yard tractors, drayage trucks, harbor craft, railroad locomotives, and cargo handling equipment (CHE).

A key strategy to reduce criteria pollutant and GHG emissions from port terminals, is to replace medium- and heavy-duty (MD/HD) vehicles and CHE with zero-emission options such battery-electric and hydrogen fuel cell-electric options. With the electrification of CHE, alternative marine power (AMP), port vehicles, port electricity, and hydrogen demand will increase significantly. The reliance of ports on electricity and hydrogen will increase the vulnerability of ports to power outages, hydrogen supply and infrastructure. Thus, it is necessary to consider and provide solutions to enhance reliability and resiliency. New infrastructure is required to support the charging and hydrogen fueling needs of new MD/HD battery-electric and fuel cell-electric fleets. To accomplish this, the University of California, Irvine (UCI) Advanced Power and Energy Program (APEP) developed a comprehensive and replicable infrastructure blueprint to support zero-emission MD/HD vehicles and CHE at a marine terminal.

To this end, the existing energy and environmental goals at the state and local level were first summarized. While the state of California has stringent energy and GHG reduction goals (Assembly Bill 32, Senate Bill 350, and Executive Orders S-3-05 and B-30-15) and regulations to accelerate transition to zero-emission MD/HD (Executive Order N-79-20, Advanced Clean Truck Regulation), the San Pedro Bay Ports – the combined Ports of Los Angeles and Long Beach – have set GHG reduction targets in the San Pedro Clean Air Action Plan (CAAP). The CAAP requires that all terminal equipment and on-road trucks be transitioned to zero-emission options by 2030 and 2035, respectively. To meet the CAAP goals, the blueprint developed under this project required all CHE at the port terminal be zero-emission by 2030 and all required charging and fueling infrastructure be installed by 2030.

Second, a list of existing and previous demonstration projects at the San Pedro Bay Ports funded by the California Energy Commission and California Air Resources Board with the goal to accelerate the deployment of zero-emission CHE was compiled along with decarbonizing demonstrations at other ports across the U.S.

Third, barriers and constraints in deploying zero-emission CHE were identified from both literature reviews and interviews with employees from the International Transportation Service (ITS) terminal at the Port of Long Beach, which partnered with APEP in this project. The barriers and constraints include: economic barriers (such as capital cost of installing new infrastructure), lack of standardization of charging and hydrogen fueling of MD/HD vehicles and specifically CHE at ports, workforce development and training, vehicle range, limited space and time for charging and fueling, and the need for mobile hydrogen fueling.

Fourth, using emissions inventories from the San Pedro Bay Ports, the types of CHE contributing the most emissions were identified including yard tractors, top handlers, rubber-tire gantry cranes, and forklifts. Data and analyses showed that by replacing these four types of CHE with zero-emission options, the emissions from CHE will be reduced by around 90 percent. Thus, the blueprint focused on the transition of these four types of CHE to zero-emission by examining the operational need of these CHE using two years of operating hours data (monthly) sourced from the ITS terminal. Using these data, the average need of a fleet of each type of CHE is determined, as well as a maximum case (worst case) during busy days where the demand is significantly higher than the average to ensure that the zero-emission fleet can not only handle the average day-to-day operations but also very busy days. These analyses were followed up by establishing the technology readiness of existing zero-emission CHE options currently offered by original equipment manufacturers.

Next, the charging needs of battery-electric CHE and the hydrogen demand of fuel cell-electric CHE were determined. To accomplish this, several scenarios were analyzed, each with a different mix of battery-electric and hydrogen fuel cell-electric CHE. The initial two scenarios encompassed a 100 percent battery-electric CHE fleet and the second assumes a 100 percent hydrogen fuel cell-electric CHE fleet. These two bracketing scenarios were followed by a detailed analysis of scenarios spanning 0 percent to 100 percent battery-electric CHE and 0 percent to 100 percent hydrogen fuel cell-electric CHE. For some of the battery-electric CHE, the operation and energy demand, as well as battery size, were derived from existing vehicles and demonstrations. For other CHE, including hydrogen fuel cell-electric CHE, the demand was estimated by using the diesel demand and taking into account higher efficiencies of battery-electric and hydrogen fuel cell-electric counterparts.

Using the charging needs of the battery-electric CHE, and focusing on use of direct current fast charging (DCFC) electric vehicle supply equipment (EVSE), the infrastructure required to support the battery-electric CHE charging was established including the required grid upgrades, the layout changes to existing parking lots, and the additional space that will be required to install EVSE. A detailed analysis was conducted (for average and busy days at the terminal) to determine what percentage of charging occurs at each charging opportunity and the associated electricity costs. Given that the charging windows at most terminals are limited to 3:00 a.m. to 8:00 a.m., 12:00 p.m. to 1:00 p.m., 5:00 p.m. to 6:00 p.m., and 10:00 p.m. to 11:00 p.m. (with the 5:00 p.m. to 6:00 p.m. being the peak demand hours and undesirable due to the cost of electricity during that time period), the impacts of delayed charging and smart charging to reduce peak demand usage, the use of alternatives to DCFC, and the use of distributed energy resources to reduce electricity demand and costs were assessed.

The infrastructure for hydrogen was assumed to be similar to the existing (diesel) fueling strategy on the port terminals, namely hydrogen storage on the terminal and a mobile hydrogen fueler that drives around the terminal and refuels fuel cell-electric CHE once a day. While the size of hydrogen storage was determined based on the hydrogen needs of each scenario, hydrogen demand can range from 500 kilograms per day (kg/day) to 1,500 kg/day in the implementation options recommended in the blueprint and can reach up to 3,500-5,000 kg/day in scenario with 100% hydrogen fuel cell-electric CHE.

Based on the analysis and discussions provided in this report, it is concluded that a mix of electric (battery-electric or grid-tied) and hydrogen fuel cell-electric options is required. Charging infrastructure can be costly and will most likely require significant grid upgrades. Moreover, battery-electric CHE require a change to current duty cycle operations since many vehicles may need to be charged multiple times per shift and, in the absence of automatic or wireless charging, a gearman (a longshoremen job classification for a person who fuels vehicles) to plug in the CHE will be required which might delay the start of a charging session. Hydrogen infrastructure, on the other hand, while more expensive than EVSE, is similar to existing diesel fueling strategy and, while possibly requiring additional space, does not require a change in operations or behavior. Fuel cell-electric CHE, like their diesel counterparts today, will be fueled by mobile refueling trucks that transport hydrogen from locally sited storage tanks, preferably on the terminal, in a process known as "wet hose refueling." However, since battery-electric options have a higher technology readiness level, they can be readily deployed in the short-term (2023-2025). In order to avoid reliance on one source of energy, though, hydrogen fuel cell-electric options are recommended to be deployed in the medium-term (2025 to 2030) to long-term (2030 and beyond) as they become commercially available. This should increase the resiliency of port operations, as well as take advantage of possible future hydrogen ecosystem at the ports.

Based on the data and analyses conducted, this blueprint provides a series of recommendations and feasible options to fully transition a CHE fleet zero-emission operation by 2030 and thereby substantially reduce emissions, improve air quality, and reduce public health impacts regionally and particularly in disadvantaged communities surrounding the ports.

1 Framing the Blueprint

1.1 Introduction

Facilities that are associated with goods movement face challenges in managing energy requirements, including growing demand, maintaining economic competitiveness, increasing efficiencies of operation, and improving the resiliency, reliability, and security of energy supplies. Currently, seaports and marine terminals are working to balance economic viability and sustainability. They face the challenging task of minimizing or eliminating environmental impacts of their operations, including reducing the emissions of toxic air contaminants and criteria pollutants, as well as reducing or eliminating greenhouse gas (GHG) emissions, all while retaining their economic competitiveness.

The State of California has stringent energy and environmental goals. The state, through Assembly Bill 32 (AB 32) [1] and several Executive Orders (S-3-05, and B-30-15) [2] has set the following targets:

- Reduce GHG emissions to 1990 level by 2020,
- Reduce GHG emissions to 40 percent below 1990 levels by 2030,
- Reduce GHG emission to 80 percent below 1990 levels by 2050.

In response to AB 32, California Air Resources Board (CARB) developed the Low Carbon Fuel Standard (LCFS) program in order to reduce the carbon intensity of transportation fuel by at least 20 percent by 2030 [3], [4].

Additionally, through Clean Energy and Pollution Reduction Act (Senate Bill 350 (SB 350)) [5], the state's renewable electricity procurement goal was increased from 33 percent by 2020 to 50 percent by 2030. SB 350 also requires doubling the energy efficiency in electricity and natural gas by 2030. Moreover, SB 350 authorizes utilities to undertake transportation electrification, which has resulted in many projects involving medium-, and heavy-duty (MD/HD) zero-emission vehicles (ZEV) and their respective fueling infrastructure (more information is provided in Section 1.3).

Furthermore, the Advanced Clean Truck Regulation [6] mandates the increased sale of zero-emission MD/HD vehicles through 2035. The Advanced Clean Truck Regulation accelerates transition of zero-emission MD/HD vehicles with a gross vehicle weight rating of more than 8,500 pounds (vehicle weight Class 2b to Class 8). Executive Order N-79-20 [7] directs that 100 percent of the MD/HD fleet in the state be zero-emission by 2045 everywhere feasible and for all drayage trucks to be zero-emission by 2035. The Hybrid and Zero-Emission Truck and Bus Voucher Incentive Program (HVIP) and Low-NO_x Engine Incentive Program incentives benefit the citizens of California by providing immediate air pollution emission reductions while stimulating development and deployment of the next generation of zero-emission, hybrid, and low-NO_x commercial vehicles (Classes 2-8) [8], [9].

In addition to state level programs and targets, the cities of Long Beach and Los Angeles have their own sustainability and GHG goals. The mayors of both cities have joined the Compact of Mayors which is a global coalition of mayors and city officials committing to reduce local GHG emissions. In 2015, the City of Los Angeles adopted the Sustainable City pLAn [10], which called for reducing GHGs to 45 percent below 1990 levels by 2025 and to 60 percent below 1990 levels by 2035, in addition to statewide targets. Prior to that, however, the cities' respective ports were making changes on their own.

The Port of Long Beach (POLB) and the Port of Los Angeles (POLA) are the largest fixed sources of emissions and air pollutants in southern California, emitting more 100 tons per day of particulate-forming NO_x, which is more than all of the cars in the area, combined. To reduce emissions from the ports and their operations, POLB and POLA collaborated and drafted the San Pedro Bay Ports Clean Air Action Plan (CAAP). The CAAP has set targets to reduce emissions and transition to zero-emission cargo handling equipment (CHE) and drayage trucks, paving the way for zero-emission ports. The CAAP aims to reduce emissions from port operation from every source. Since 2005, CAAP strategies achieved 58 percent reduction in NO_x and 87 percent reduction in particulate matter [11], [12]. Additionally, South Coast Air Quality Management District (South Coast AQMD) introduced its Clean Port Initiative, which includes four guiding principles and seven action items outlining steps that the South Coast AQMD, along with federal and state agencies and local and international ports, can take to help reduce port pollution in the region.

In 2017, the CAAP was updated and put the ports on the pathway to become zero-emission goods movement hubs. The 2017 CAAP update requires that all terminal equipment and on-road trucks be transitioned to zero-emission options by 2030 and 2035, respectively. Thus, for the purpose of the current project, the blueprint adopts the timeframe of 2023-2030 to achieve zero-emission CHE at the port terminal selected and determine the required infrastructure to support charging and hydrogen fueling of the zero-emission CHE. Furthermore, the blueprint timeline includes short-term (2023-2025), medium-term (2025-2030), and long-term (2030 and beyond).

The United States Environmental Protection Agency (U.S. EPA) has utilized the CAAP as a case study and provided best practices and lesson learned from the efforts [13], emphasizing the importance of building alliances with local policymakers, environmental non-governmental organizations, and labor organizations, and creating partnerships and coordination between stakeholders, including the shipping industry, technology developers and manufacturers, near-port residents, and local, state, and federal governments. Furthermore, POLA and POLB conducted a study in 2018, as well as 2021 to determine the feasibility of meeting CAAP zero-emission CHE goals by analyzing technology viability and readiness, and commercial availability [14]. This study was leveraged to develop this blueprint, taking into account the technological progress and demonstrations since the study was conducted.

1.2 Project Goals

The goals of this blueprint project were to (1) develop a comprehensive and replicable infrastructure blueprint to support zero-emission MD/HD vehicles and equipment at a marine terminal, and (2) ensure that the blueprint is available to, and benefits from, community and stakeholder input. To achieve the goals of the project, four objectives were met:

1. Assessed the benefits of zero-emission MD/HD vehicles operating at a port terminal to disadvantaged and low-income communities.

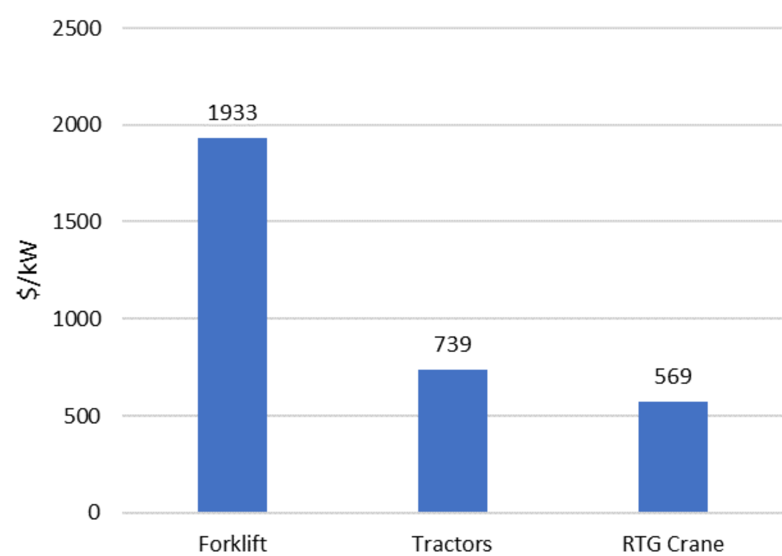
2. Conducted community outreach for input.
3. Developed a replicable and comprehensive blueprint for the infrastructure necessary to support a zero-emission MD/HD fleet operating at a marine terminal by defining the blueprint parameters and boundaries, including technical, economic and environmental goals.
4. Conducted a technology assessment in order to optimize MD/HD EVSE and hydrogen fueling infrastructure.

1.3 Background: Previous and Existing Efforts

Transportation electrification has been identified as a significant measure to help meet California GHG and environmental goals. SB 350 authorizes investor-owned utilities to accelerate transportation electrification. The California Energy Commission (CEC), CARB, and the California Public Utilities Commission (CPUC) support this effort by directing utilities to programs and investments. The CPUC authorized Southern California Edison (SCE), San Diego Gas and Electric (SDG&E) and Pacific Gas and Electric (PG&E) to invest $41 million for 15 transportation electrification pilots and demonstrations. These priority review projects (PRP) are limited to 12 months and cost about $4 million each.

Through SB 350 PRPs, SCE, SDG&E, and PG&E installed 94 Level-2 chargers and 40 direct current fast charger (DCFC) for MD/HD ZEVs, including 10 DCFC for drayage trucks and yard tractors, 9 Level-2 chargers for forklifts, and 9 DCFC for rubber tire gantry (RTG) cranes [15]. The infrastructure costs for electric CHE associated with SB 350 PRPs are shown in Figure 1. It is expected that the tractor, RTG, and forklift pilots will result in GHG reductions totaling 383 metric tons (MT), 3,100 MT, and 8 MT, respectively.

Figure 1. Infrastructure Costs for Electric CHE



Credit: Southern California Edison, San Diego Gas and Electric, and Pacific Gas and Electric [15]

1.3.1 San Pedro Bay Ports

To meet the goals of the CAAP and achieve zero-emissions operations, multiple projects demonstrating zero-emission and near-zero emission technologies were conducted at POLB and POLA. A summary of these projects can be found in *San Pedro Bay Ports Technology Assessment Report* [12]. These projects include demonstration of zero-emission CHE including electric yard tractors, hydrogen fuel cell-electric yard tractors, electric forklifts, electric top handlers, electric RTG cranes, and ocean-going vessels and harbor craft utilizing alternative marine power (AMP).

Examples of these zero-emission projects include:

- An $8 million CEC grant for a hydrogen fueling station that will dispense hydrogen sourced exclusively from biogas at POLB using a technology known as tri-generation that produces electricity, heat, and hydrogen fuel to support the use of hydrogen fuel cell Class 8 drayage trucks [16].
- A $41 million CARB award to POLA for its Zero- and Near Zero-Emission Freight Facilities project, creating funding for ten hydrogen fuel cell drayage trucks, two hydrogen fueling stations along drayage routes within the region, and zero-emission off-road equipment: two yard tractors and the increased use of zero-emission forklifts [17].

1.3.1.1 Port of Long Beach

POLB received $80 million in total funding from the CEC and CARB for six project that are demonstrating zero-emission equipment and CHE, as well as advanced energy systems, such as microgrids and battery energy storage systems [18]. A summary of some of these projects is provided below. In addition to these projects, POLB is developing the Dynamic Energy Forecasting Tool (DEFT) which enables terminal operators to forecast energy demand as well as infrastructure costs associated with the deployment of zero-emission CHE.

Zero-Emission Terminal Equipment Transition Project

This project received $9.7 million from the CEC with the goal of deploying zero-emission CHE and hybrid and electric drayage trucks. The project includes 12 electric yard tractor, 9 electric RTG cranes and 4 plug-in hybrid and battery-electric drayage trucks. The zero-emission CHE will be deployed and demonstrated at piers F, G, and J.

C-Port Zero Emission Demonstration Project

This project received $5.3 million in funding from CARB for a collaboration between POLB, SSA Marine at Pier J, and Long Beach Container Terminal (LBCT) at Pier E to demonstrate novel battery-electric top handlers and hydrogen fuel cell-electric and battery-electric yard tractors, and enable a comparison of the two zero-emission technologies for specific port operations.

Port Advanced Vehicle Electrification Project

This project received $8 million in funding from the CEC to design and deploy charging infrastructure to support battery-electric yard tractors and forklifts. The project site is Total Terminals International’s facility at Pier T.

Sustainable Terminals Accelerating Regional Transformation Project

This $50 million CARB project, which includes POLB, the Port of Oakland, and the Port of Stockton deployed more than 100 zero-emission CHE including (at POLB pier C), 34 zero-emission battery-electric yard tractors, two of the cleanest container ships to call on the West

Coast[1], an electric-drive tugboat, five electric trucks at an off-dock container yard, and two heavy-duty truck charging outlets.

POLB Microgrid Project

This project received $5 million from the CEC to demonstrate a microgrid at a critical facility to increase resiliency of future zero-emission terminals. The microgrid includes photovoltaic solar and energy storage and will be capable of operating in islanded mode[2].

Port Community Electric Vehicle Blueprint

POLB received $200,000 from the CEC to develop a port-wide blueprint to identify the path toward electric vehicle (EV) planning and charging at the port [19].

Middle Harbor Project

In addition to projects previously mentioned, POLB invested nearly $1.5 billion in zero-emission fueling infrastructure for the Middle Harbor Terminal Project, with another $700 million invested in CHE (mostly battery-electric zero-emission[3]), highly sophisticated computer and software systems, and workforce training by Long Beach container terminal (LBCT) [20]. The project, completed in 2021, has transformed two aging terminals into one of the most technologically-advanced container terminals in the U.S.

Almost all of the 200 CHE at the Long Beach container terminal at Middle Harbor run entirely on electricity and include 102 battery-electric automated vehicles and 72 automated grid-tied electric stacking cranes. A unique aspect of this terminal is a battery exchange process in which each automated vehicle swaps an expended battery for a fully charged battery. The swap takes five minutes, and the equipment can immediately return to work.

1.3.1.2 Port of Los Angeles

In addition to projects mentioned previously, POLA has had several CHE demonstrations and pilots. Some of these projects are provided below:

Advanced Yard Tractor Deployment & Eco-FRATIS Drayage Truck Efficiency Project

This project received nearly $4.9 million from the CEC to demonstrate five battery-electric yard tractors and 20 near-zero-emission LNG yard tractors.

Everport Advanced Cargo Handling Demonstration Project

This project received $4.52 million from the CEC to demonstrate of two battery-electric top handlers, three battery-electric yard tractors, and corresponding charging infrastructure.

Green Omni Terminal Project

This project received $14.5 million from CARB and includes demonstration of 2 battery-electric Class 8 trucks, 4 battery-electric yard tractors, 3 battery-electric 21-ton forklifts (repower), one at-berth emissions control system, and a solar powered microgrid.

---

[1] Two NASSCO and Matson Tier 3 low-NOx Jones Act Container Ships

[2] Microgrids can disconnect from the traditional grid and operate autonomously which is referred to as islanded mode or islanded operation.

[3] https://polb.com/port-info/news-and-press/the-making-of-a-state-of-the-art-terminal-08-26-2021/

Zero- and Near Zero-Emission Freight Facilities (ZANZEFF) Shore to Store Project

This project received $42 million from CARB and South Coast AQMD to demonstrate 10 Class 8 hydrogen fuel cell-electric trucks, 2 hydrogen fueling stations, 2 battery-electric yard tractors, and 2 battery-electric forklifts and the installation of its infrastructure.

Zero Emission Freight Vehicle Advanced Infrastructure Demonstration Project

This project received $7.8 million from the CEC and $2.9 million from South Coast AQMD to demonstrate 10 battery-electric yard tractors, 10 wireless inductive charging stations, and a battery storage system.

1.3.2 Other Ports

In addition to POLB and POLA, ports across the U.S. have adopted programs and strategies to reduce emissions from their operations. In this section, a summary of some these efforts is provided.

The San Diego Port Climate Action Plan aims to reduce GHG emissions by 10 percent by 2020 and 25 percent by 2035 [21]. The CEC, through the Clean Transportation Program, funded a $6 million project called San Diego Port Sustainable Freight Demonstration Project [22] to reduce GHG emissions, improve air quality, and ultimately improve the health of surrounding communities, which includes disadvantaged communities. The project reduced GHG emissions by 52.5 metric tons and helped the Port of San Diego (POSD) meet its environmental goals. Ten battery-electric vehicles and CHE were demonstrated in the project including battery-electric forklifts, battery-electric yard tractors, and battery-electric drayage trucks. Additionally, POSD was awarded a $4.9M project by the CEC to install a renewable microgrids at the Tenth Avenue Marine Terminal [23]. The microgrid will help reduce GHG emissions and reduce utility bills by 60 percent. Moreover, the microgrid will increase resiliency by providing back-up power to critical facilities at the port.

In West Oakland, the Bay Area Air Quality Management District (BAAQMD) and West Oakland Environmental Indicators Project (WOEIP) are developing the *West Oakland Community Air Action Plan* (WOCAAP) [24], [25]. The WOCAAP intends to integrate, as appropriate, specific strategies from relevant concurrent planning efforts, including the *2020 and Beyond Plan*, the *West Oakland Truck Management Plan*, and the *West Oakland Specific Plan*. These strategies include promoting the pathway to zero-emission equipment and developing infrastructure to support this transition. A cornerstone of the *2020 and Beyond Plan* is the use of renewable electricity to fuel battery-electric mobile equipment and to provide power to berthed vessels. As a public utility, the Port of Oakland has the authority to directly build out its electrical infrastructure in support of microgrids, EVSE, and vehicles. This effort is an integral part of the transition to a decarbonized seaport. The port committed capital resources for the reconstruction of two major electrical substations in its Capital Improvement Program, as well as electrical charging infrastructure.

The Green Operator program at the Virginia Port Authority encourages the testing, demonstration, and lease or purchase of battery-electric, hybrid, or other alternative fuel-powered CHE and operations support vehicles [26].

The Port of Houston Authority (PHA), the sixth largest port in the world, has explored several options for clean air emission technologies for port operations and developed a three-level, long-term sustainability plan which includes: improving energy efficiency, sourcing electricity from renewables, and electrification of CHE [27]. The PHA expects an 80 percent reduction in CO_2 emission intensity by 2045 (using emissions from 2018 as the baseline).

The Georgia Ports Authority (GPA) has converted all 27 of its ship-to-shore cranes from diesel to electric, which has reduced the amount of diesel fuel used by the ports by nearly 1.9 million gallons annually. Electrification of equipment and fuel-efficiency saves more than 6.8 million gallons of fuel annually. By using electrified refrigerated container racks, GPA terminals have reduced diesel fuel utilization by 4.5 million gallons per year [28]. The GPA has also been aggressive in replacing RTG cranes used to handle containers at terminals. As of 2016, about one-third of the GPA's RTG cranes were electric. Hybrid electric RTG cranes use up to 95 percent less diesel fuel than conventional RTG cranes, and the electric engines on these cranes are easier to maintain, resulting in significant cost savings.

Improving air quality and reducing impacts on climate change are key priorities for the Port of Tacoma (POT). To accomplish this, POT partnered in 2008 as an inaugural member with the Northwest Ports Clean Air Strategy (NWPCAS) [29], a voluntary collaboration between POT, the Port of Seattle, the Northwest Seaport Alliance, and the Port of Vancouver to reduce, and ultimately eliminate, air pollutants and GHG emissions from seaport activities in the Puget Sound-Georgia Basin Airshed. The NWPCAS addresses emissions from ocean-going vessels, commercial harbor craft, heavy duty trucks, locomotives, CHE, and port administration and tenant facilities.

1.4 Constraints, and Barriers

Ports are essential to the economy; therefore, transitioning to zero-emission options needs to occur with minimal impact on the economics and cost of port operations and not adversely impact terminal operations. Major constraints to deploying zero-emission CHE at ports were identified as vehicle range, limited time for charging and fueling, as well as the capital cost of installing new infrastructure [30].

For charging battery-electric CHE, the ITS terminal at POLB requires that the yard tractors be charged once a day and that the battery charge lasts for two eight-hour shifts. While opportunity charging might be feasible, a single charge is preferable. The costs and lifetimes of batteries (in vehicles as well as stationary batteries to support charging) are additonal economic barriers.

For hydrogen fueling, though, the terminal requires mobile fueling tankers similar to those currently fueling diesel and gasoline CHE. Currently, two gearmen[4] are onsite per shift for fueling. For this blueprint, it was assumed that two gearmen per shift will be responsible for plugging in and unplugging the vehicles to their EVSE, as well as hydrogen fueling. In 2017,POLB provided the following requirements for a battery-electric equipment demonstration: 250 amperes (A), 480 volts (V), 3-phase, with maximum 13,000 ampere interrupting capacity (AIC) withstand rating [31].

---

[4] A longshoremen job classification for a person who fuels vehicles.

Another constraint to consider is space required to accommodate the footprint of charging and fueling infrastructure. Inductive charging is one strategy to reduce the space that would be otherwise required for battery-electric charging.

Another barrier is the lack of standardization of charging and hydrogen fueling of MD/HD vehicles and specifically CHE at ports. A detailed description of the status of charging standards for port applications is provided in the POLB report *Charging Ahead: The Port Community Electric Vehicle Blueprint* [32]. For fueling hydrogen fuel cell-electric vehicles, the following standards are currently applicable:

- SAE J2601/2 provides performance requirements for hydrogen dispensing systems used for fueling 35 megapascal (MPa) heavy-duty hydrogen transit buses and vehicles (other pressures are optional) [33].
- SAE J2601/3 establishes safety limits and performance requirements for gaseous hydrogen fuel dispensers used to fuel hydrogen-powered industrial trucks, including forklifts, tractors, pallet jacks, on- and off-road utility vehicles, and specialty vehicles of all types, including CHE operating at ports [34].
- SAE J2799 specifies the communications hardware and software requirements for fueling light-duty hydrogen fuel cell-electric vehicles (FCEV), but may also be used, where appropriate, for heavy-duty vehicles with compressed hydrogen storage [35].

Another barrier is the required workforce and training for the zero-emission CHE and the associated charging and hydrogen fueling infrastructure. A detailed assessment of the workforce requirement is provided POLB's *Zero-Emission Port Equipment Workforce Assessment* [36]. In preparation for this blueprint, APEP collaborated with Saddleback College to prepare coursework and curricula to support training the workforce.

Several surveys were conducted by the San Pedro Bay Ports to identify the port terminals and surrounding communities understanding of zero-emission options, uncertainties, and risks [32], as well as to determine the feasibility of achieving zero-emission goals of the CAAP [37]. One of these surveys was conducted as a part of the Port Community Electric Vehicle Blueprint Project funded by the CEC and conducted by the POLB [19], [32]. Below are some of the major takeaways from this survey:

- The lack of charging infrastructure is a primary concern for stakeholders.
- Terminal operators reported little awareness of the various providers for electric charging infrastructure and hydrogen fueling infrastructure. All other stakeholders reported high familiarity with these items.
- Terminal operators confirmed that they will likely need one charger for each piece of equipment.
- Terminal operators reported limited knowledge of their own duty cycles which is critical to understand the performance and operational requirements of new zero-emission equipment.
- 60 percent of terminal operators said they needed equipment capable of charging in less than four hours; 42 percent of other stakeholders – including many infrastructure providers – said at least six to eight hours of charging would be tolerable for terminal

operators, and 11 percent of stakeholders said more than eight hours. The results show a disparity between terminal operators and infrastructure providers.

- One of the most noticeable barriers is unfamiliarity with the level and types of funding available.
- Most terminal operators did not know, or flatly rejected the idea, that zero emissions could lead to a competitive business advantage.
- 91 percent of respondents were aware of the port's zero-emission terminal equipment by 2030 goal.
- The vast majority of the respondents indicated participation in (84 percent), or monitoring of (93 percent), existing pilot programs.
- When asked what types of ZEVs are most appealing for port operations, 46 percent responded battery-electric and 31 percent favored hydrogen fuel cell-electric.
- Equipment prices (45 percent), financing and leasing options (21 percent), and reducing charge times (18 percent) were among the leading limiting factors for adopting ZEV/equipment at ports.
- On-site support and refueling infrastructure are the two greatest concerns related to manufacturer warranties.
- 84 percent of fleet operators responded that they do not know how much spare electricity capacity currently exists at the site of their terminal.
- 75 percent of terminal operators responded that they do not generally have space for the required charging stations.
- 100 percent of terminal operators responded that they are not interested in third-party ownership and operation of charging infrastructure. 78 percent of other stakeholders including EVSE manufacturers, technology developers, and OEMs, were interested in third-party ownership, though.
- 58 percent of technology developers and OEMs, regulatory agencies, and financial entities responded that detailed assessments of operational costs of zero-emission options are available; only 22 percent of other stakeholders were aware of the existing assessments.
- 53 percent of technology developers and OEMs, regulatory agencies, and financial entities responded that detailed assessment of maintenance costs of zero-emission options are available; 44 percent of other stakeholders agreed.
- Regarding the availability of financing for ZEVs, 68 percent responded that while external financing is available, they are limited.
- Regarding the availability of financing for chargers, 54 percent responded that while external financing is available, they are limited.
- Providing funding associated with installation of infrastructure and equipment purchase were preferred programs.
- The majority of stakeholders are aware of the CEC's principal funding programs for ZEVs, equipment, and infrastructure.
- While the majority of stakeholders are aware of CARB and AQMD programs, they are more familiar with the CEC programs.

- 85 percent of participants indicated that they believe that warranties will adequately protect the purchaser or lessor of zero-emission equipment, and that this would be highly impactful.
- The majority of the respondents (63 percent) believe there is less than a 20 percent chance of increased insurance costs, with 50 percent of respondents identifying these costs as insignificant or minor impacts.
- The majority of stakeholders (81 percent) identified a more than 80 percent likelihood that upfront costs will be greater than traditional equipment.
- Overall, stakeholders were not concerned about long-term uncertainty of operating costs.
- Nearly 40 percent of respondents indicated a significant likelihood that revenues would increase after adopting zero-emission technologies; however, 74 percent did not believe the impacts would be significant.
- The majority of respondents (68 percent) believe that the likelihood of cost increases is low and the cost increase is expected to be less than 20 percent.
- The respondents identified that if significant operational changes were required, the impacts would be moderate to highly significant (77 percent).
- The majority (75 percent) of respondents believe that the port can meet its 2030 goals for 100 percent zero-emission terminal equipment deployment by 2030, and that the impacts will be significant.
- The majority of respondents (65 percent) believe that it is unlikely that the deployment of zero-emission CHE will result in a reduction in operational flexibility.
- Majority of responses identified insufficient existing infrastructure as high likelihood (57 percent) and high impact (55 percent).
- Respondents almost universally agreed that the adoption of zero-emission technologies are likely to result in significant air quality and health improvements.
- 60 percent believe that there will be a high likelihood of increased job opportunities associated with the transition to zero-emission technologies and that the impact will be significant (60 percent).
- 70 percent were optimistic that there will be enough qualified personnel to operate and maintain the zero-emission equipment.
- 60 percent responded that there is a high likelihood of requiring education and training of current employees.
- While 55 percent responded that there is high likelihood of operational disruption with zero-emission equipment, the majority agreed that the impacts will be minimal.

2 Establishing a Baseline

2.1 Identifying Priorities

Port operations are a source of significant criteria pollutant emissions, resulting in degraded air quality in the region and especially in disadvantaged and low-income communities in the near vicinity of the ports. The criteria pollutants of concern are particulate matter that is less than 10 microns in diameter (PM_{10}), particulate matter that is less than 2.5 microns in diameter ($PM_{2.5}$), diesel particulate matter (DPM), oxides of nitrogen (NO_X), oxides of sulfur (SO_X), carbon monoxide (CO), and hydrocarbons (HC), as well as greenhouse gases (equivalents of carbon dioxide, CO_2e). The sources of emissions include ocean-going vessels, heavy-duty and drayage trucks, harbor crafts, railroad locomotives, and CHE. The emissions from different CHE at the ports are used to identify the order and priority of CHE to transition to zero-emission options. A detailed inventory of CHE operating on POLB and POLA can be found in *Port of Long Beach 2020 Air Emissions Inventory* (2020 AEI) and *Inventory of Air Emissions for Calendar Year 2020*, respectively [38], [39]. These inventories include the type of CHE, fuel, engine type, power, energy use, model year and annual operating hours.

POLB and POLA emissions from these sources in 2020 are provided in Table 1 and Table 2, respectively.

Table 1. Port of Long Beach 2020 Emissions

Source	PM_{10} (tons)	$PM_{2.5}$ (tons)	DPM (tons)	NO_X (tons)	SO_X (tons)	CO (tons)	HC (tons)	CO_2e (MT)
Ocean-going vessels	73	67	40	3,490	189	294	132	286,037
Harborcraft	20	18	20	597	1	444	66	50,171
Cargo handling equipment	4	4	3	245	1	742	31	121,060
Locomotives	20	19	20	536	0	127	31	44,453
Heavy-duty vehicles	6	6	6	1,052	4	269	42	386,990
Total:	**123**	**113**	**89**	**5,920**	**195**	**1,876**	**301**	**888,712**

Data Source: Port of Long Beach 2020 Air Emissions Inventory [38]

Table 2. Port of Los Angeles 2020 Emissions

Source	PM_{10} (tons)	$PM_{2.5}$ (tons)	DPM (tons)	NO_X (tons)	SO_X (tons)	CO (tons)	HC (tons)	CO_2e (MT)
Ocean-going vessels	52	48	34	2,867	96	273	127	212,248
Harborcraft	24	22	24	721	1	539	82	60,374
Cargo handling equipment	6	5	4	366	2	643	66	165,961
Locomotives	29	27	29	786	1	189	45	65,987
Heavy-duty vehicles	6	6	6	1,075	4	284	43	398,679
Total:	**117**	**108**	**97**	**5,814**	**104**	**1,928**	**363**	**903,250**

Data Source: Port of Los Angeles Inventory of Air Emissions for Calendar Year 2020 [39]

A key strategy in reducing the environmental impacts from marine terminal operations is addressing emissions from all CHE, which includes yard trucks, top handlers, side handlers, reach stackers, forklifts, and gantry cranes. At POLB alone, diesel-powered RTGs comprise only 5.0 percent of the port's equipment fleet, but generate 20 percent of all port equipment emissions. Other CHE, such as yard tractors and top handlers, account for nearly 60 percent of the port's equipment inventory and contribute a significant percentage of overall port emissions. In addition, more than 3,200 pieces of CHE operate at the San Pedro Bay Ports, comprising 6.0 percent of the port's overall diesel particulate matter (DPM) emissions, 7.0 percent of NO_X emissions and 17 percent of GHG emissions [40].

A summary of CHE at POLB and POLA is provided in Table 3 and Table 4.

Table 3. Port of Long Beach CHE Summary

Equipment	Electric	Propane	Gasoline	Diesel	Total
Forklift	8	97	24	110	239
RTG crane	0	0	0	56	56
Side handler	0	0	0	7	7
Top handler	2	0	0	192	194
Yard tractor	6	2	135	505	648
Sweeper	1	8	0	12	21
Other	218	7	2	62	289
Total:	**235**	**114**	**161**	**944**	**1,454**

Data Source: Port of Long Beach 2020 Air Emissions Inventory [38]

Table 4. Port of Los Angeles CHE Summary

Equipment	Electric	LNG	Propane	Gasoline	Diesel	Total
Forklift	29	0	181	6	105	321
Wharf crane	86	0	0	0	0	86
RTG crane	0	0	0	0	103	103
Straddle carrier	0	0	0	0	67	67
Top handler	2	0	0	0	194	196
Yard tractor	5	22	158	0	781	966
Other	40	0	1	4	131	176
Total:	**162**	**22**	**340**	**10**	**1,381**	**1,915**

Data Source: Port of Los Angeles Inventory of Air Emissions for Calendar Year 2020 [39]

POLB and POLA 2020 emissions from different types of CHE are provided in Table 5 and Table 6. Assessing the data presented in Table 6 and Table 7, the highest emissions are from: yard tractors, top handlers, RTG cranes and forklifts. Thus, replacing them with zero-emission options can offer a 90 percent reduction throughout all CHE emissions, on average, and meeting the San Pedro Bay Ports CAAP. As a result, this blueprint focuses on replacing these four CHE types (yard tractors, top handlers, RTG cranes and forklifts) with zero-emission options and determining the required infrastructure to support their charging/fueling. Battery-electric and hydrogen fuel cell-electric options for yard tractors, top handlers, forklifts, and RTG cranes are being demonstrated at the ports.

By the end of 2020, POLB and POLA included the following zero-emission and near zero-emission vehicles and infrastructure [12]:

- 37 zero-emission drayage trucks (battery-electric and hydrogen fuel cell).
- 80 zero-emission terminal equipment, including yard tractors, top handlers, RTG cranes, and forklifts.
- 5 near-zero emission drayage trucks.
- 20 near-zero emission yard tractors.
- 114 new electric charging stations.
- 2 new hydrogen fueling stations.
- 1 near-zero emissions tugboat with Tier 4 engines and an electric-drive system.

Table 5. Emissions from CHE at POLB in 2020

Port Equipment	Engine Type	PM_{10} (tons)	$PM_{2.5}$ (tons)	DPM (tons)	NO_X (tons)	SO_X (tons)	CO (tons)	HC (tons)	CO_2e (MT)
Bulldozer	Diesel	0	0	0	0.9	0	0.2	0.1	95
Cone vehicle	Diesel	0	0	0	0.8	0	1.4	0.1	127
Crane	Diesel	0	0	0	0.1	0	0.1	0	15
Excavator	Diesel	0	0	0	0	0	0	0	0
Forklift	Diesel	0.1	0.1	0.1	7.2	0	10.7	0.7	2,008
Forklift	Gasoline	0	0	0	0.3	0	5.9	0.1	180
Forklift	Propane	0	0	0	4.9	0	16.1	1.6	482
Loader	Diesel	0.1	0.1	0.1	1.8	0	3.9	0.5	1,637
Man lift	Diesel	0	0	0	0.2	0	0.4	0	63
Man lift	Gasoline	0	0	0	0	0	0.2	0	52
Material handler	Diesel	0	0	0	1.4	0	0.5	0.1	244
Miscellaneous	Diesel	0	0	0	0.1	0	0.1	0	7
Rail pusher	Diesel	0	0	0	0.2	0	0.2	0	64
Hybrid RTG	Diesel	0	0	0	0.7	0	3	0.3	1,222
RTG crane	Diesel	0.5	0.5	0.5	63.6	0.1	16.6	3.9	7,647
Side handler	Diesel	0	0	0	0.4	0	0.3	0	135
Skid steer loader	Diesel	0	0	0	0.1	0	0.1	0	22
Sweeper	Diesel	0	0	0	1.4	0	1.6	0.1	541
Sweeper	Propane	0	0	0	0.1	0	0.3	0	21
Top handler	Diesel	1.1	1	1.1	101.7	0.5	94.7	14.3	44,262
Tractor	Diesel	0	0	0	0	0	0	0	1
Tractor	Propane	0	0	0	0.1	0	1.7	0	39
Truck	Diesel	0.1	0.1	0.1	3	0	2.2	0.3	1,052
Yard tractor	Diesel	0.9	0.8	0.9	48.2	0.6	143.7	7.6	46,292
Yard tractor	Gasoline	1.3	1.2	0	7.6	0.2	438.3	0.7	14,897
Yard tractor	Propane	0	0	0	0	0	0	0	3
Total:		**4.3**	**3.9**	**2.9**	**244.8**	**1.4**	**742.2**	**30.5**	**121,060**

Data Source: Port of Long Beach 2020 Air Emissions Inventory [38]

Table 6. Emissions from CHE at POLA in 2020

Port Equipment	Engine	PM_{10} (tons)	$PM_{2.5}$ (tons)	DPM (tons)	NO_X (tons)	SO_X (tons)	CO (tons)	HC (tons)	CO_2e (MT)
Bulldozer	Diesel	0	0	0	0.2	0	0.1	0	42
Cone vehicle	Diesel	0	0	0	1	0	1.2	0.1	123
Crane	Diesel	0.1	0.1	0.1	2.2	0	0.9	0.2	244
Forklift	Diesel	0.1	0.1	0.1	5.2	0	7	0.5	1,529
Forklift	Gasoline	0	0	0	0	0	0.7	0.1	18
Forklift	Propane	0.1	0.1	0	4.1	0	40.6	1.3	1,274
Loader	Diesel	0	0	0	3.5	0	1.8	0.3	718
Man lift	Diesel	0	0	0	0.6	0	0.5	0	72
Man lift	Gasoline	0	0	0	0	0	0	0	2
Material handler	Diesel	0.1	0.1	0.1	12	0	4.6	1.1	2,123
Miscellaneous	Diesel	0	0	0	0.7	0	0.3	0.1	127
Rail pusher	Diesel	0	0	0	0.1	0	0.1	0	42
Reach stacker	Diesel	0	0	0	0.4	0	0.6	0.1	283
Hybrid RTG	Diesel	0	0	0	1.2	0	4.1	0.5	1,792
RTG crane	Diesel	1	0.9	1	83.9	0.2	34	7.2	15,595
Side pick	Diesel	0	0	0	0.5	0	1.2	0.1	554
Skid steer loader	Diesel	0	0	0	0.4	0	0.3	0	39
Hybrid Straddle Carrier	Diesel	0	0	0	0.4	0	4.3	0.1	681
Straddle carrier	Diesel	0.2	0.1	0.2	12.9	0.1	14.6	2.3	6,691
Sweeper	Diesel	0	0	0	0.6	0	0.6	0.1	241
Sweeper	Gasoline	0	0	0	0.3	0	2.6	0	127
Telehandler	Diesel	0	0	0	0.1	0	0.1	0	10
Top handler	Diesel	1.4	1.2	1.4	108	0.6	109	16.9	50,009
Truck	Diesel	0.3	0.3	0.3	7.5	0	4	0.7	1,862
Truck	Propane	0	0	0	0.3	0	0.7	0	18
Yard tractor	Diesel	1.3	1.1	1.3	79.3	0.9	167.8	10.7	69,407
Yard tractor	LNG	0	0	0	0	0	0.4	0	529
Yard tractor	Propane	1.2	1.2	0	40.3	0	241.4	24.1	11,809
Total:		**5.8**	**5.4**	**4.5**	**365.6**	**1.8**	**643.3**	**66.5**	**165,961**

Data Source: Port of Los Angeles Inventory of Air Emissions for Calendar Year 2020 [39]

The electric equipment operating on POLB in 2020 is shown in Table 7. Zero-emission CHE operating on POLB and at ITS terminal in 2020 will be used as the baseline for the blueprint.

Table 7. Electric Equipment at POLB (2020)

Vehicle	Amount
Automated guided vehicle	72
Automated stacking crane	55
Crane	6
Electric pallet jack	2
Forklift	8
Man Lift	2
Material handler	1
Ship to shore crane	74
Sweeper	1
Top handler	2
Truck	6
Yard tractor	6
Total:	**235**

Data Source: Port of Long Beach 2020 Air Emissions Inventory [38]

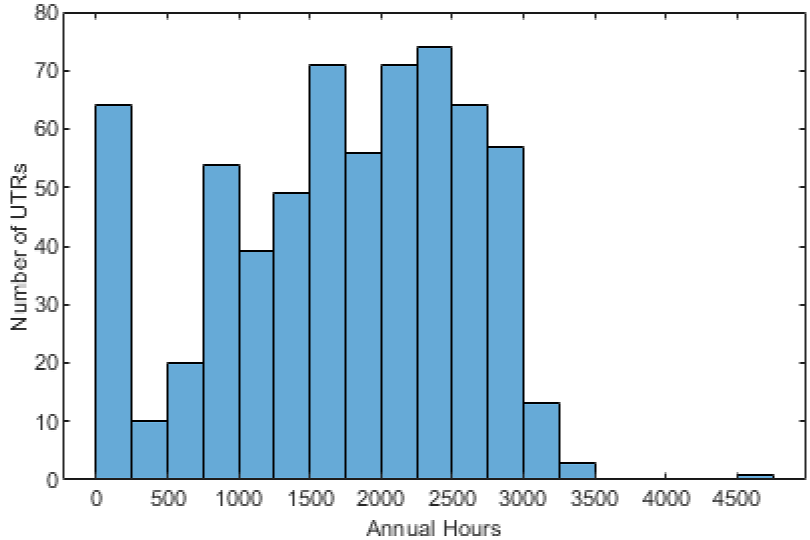
2.2 Analysis of Existing CHE Fleet

To identify appropriate zero-emission options for different CHE, it is first necessary to analyze and assess how different types of CHE are used and operated across the terminal and which technologies can meet the needs and constraints of terminal operations. In this section, an analysis of operation of existing CHE fleet is provided for several types of different CHE in order to establish a baseline for the operation of CHE in the terminals.

2.2.1 Yard Tractors

Yard tractors are trucks used in moving trailers and containers short distances around freight terminals and port facilities. Based on the CHE data provided in POLB's 2020 AEI, 648 yard tractors were operating in 2020. Of these, roughly 78 percent were diesel and 21 percent were gasoline. The hours of operation of yard tractors across POLB in 2020 is shown in Figure 2. Removing the yard tractors from the inventory with no reported operating hours, the average yard tractor operates 1,832 hours per year, equivalent to six to seven hours per day. While the average is six to seven hours per day, there are many yard tractors that operate much longer, often up to 18 hours per day, which should be considered when transitioning to zero-emission options.

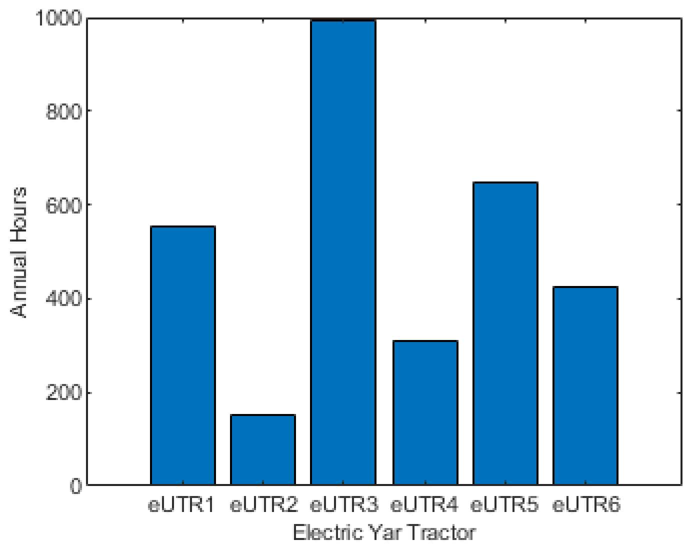
Figure 2. Histogram of UTRs Annual Hours at POLB 2020



Credit: Advanced Power and Energy Program, University of California, Irvine (APEP)
Data Source: Port of Long Beach 2020 Air Emissions Inventory [38]

Six battery-electric yard tractors were reported in POLB's 2020 AEI. The annual hours of operations for these are shown in Figure 3. Note that the average annual hours for electric yard tractors is 513 hours (about two hours per day), with a maximum of 992 hours (around four hours per day).

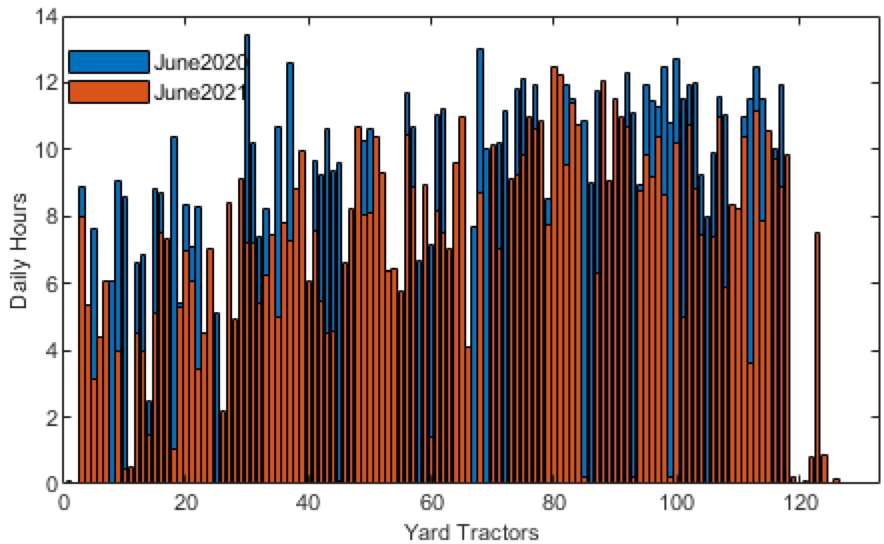
Figure 3. Electric UTR Annual Hours at POLB 2020



Credit: APEP
Data Source: Port of Long Beach 2020 Air Emissions Inventory [38]

As previously mentioned, the ITS terminal, a project partner, was used as the case study for this blueprint. APEP obtained data associated with operation of the ITS terminal, including: number, type, and specs of CHE operating on the terminal, and CHE monthly operating hours for years 2020 and 2021. ITS has about 120 yard tractors on its terminal, two of them are LNG and the rest are diesel. Daily hours of operation for each yard tractor on this terminal are shown for June 2020 and June 2021 in Figure 4.

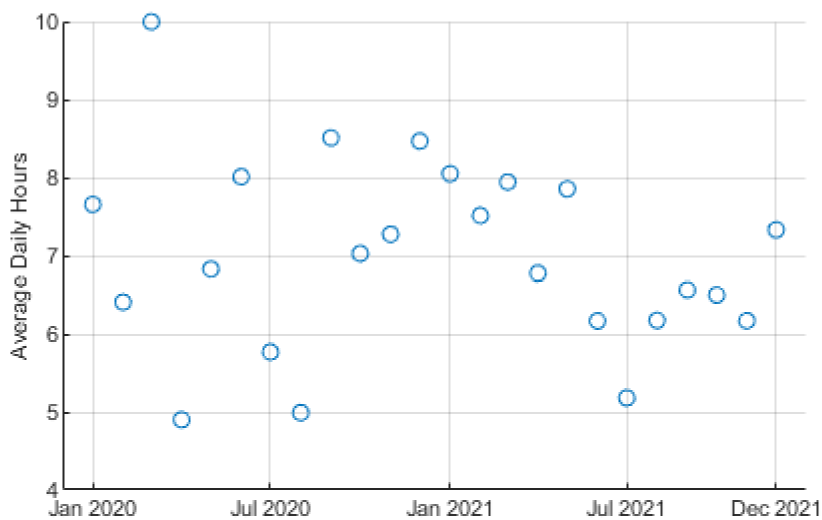
Figure 4. Yard Tractor Daily Hours for Case Study



Credit: APEP

Average daily hours that each yard tractor in the fleet is driven for each month (January 2020 to December 2021) is shown in Figure 5. This figure shows that the average daily hours range from 5 to 10 hours, with an average of seven hours for this terminal, which is consistent with the overall yard tractor fleet at POLB.

Figure 5. Average Daily Hours for the Yard Tractor Fleet

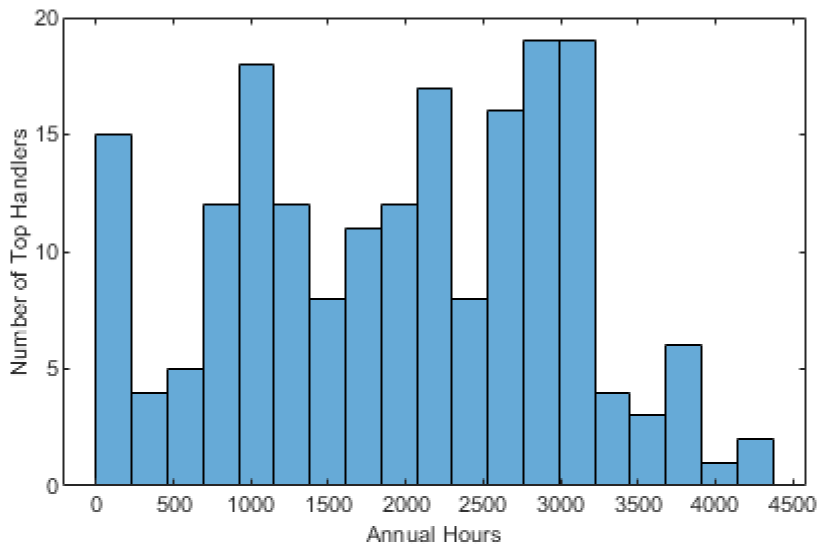


Credit: APEP

2.2.2 Top Handlers

Top handlers are a type of CHE with an overhead boom for loading containers onto trucks and trains, unloading them, and stacking them on terminals between pickups and deliveries. In addition to top handlers, reach stackers are also included in this section. Data from POLB's 2020 AEI show that 194 top handlers (two battery-electric and the remainder diesel) and seven reach stackers were operating at POLB in 2020. The hours of operation of top handlers across POLB in 2020 is shown in Figure 6. The average top handler at POLB operates 1,941 hours per year (about seven to eight hours per day); however, as shown in the figure, many of these top handlers operate more than 11 hours per day, with several operating around 15 to 17 hours per day.

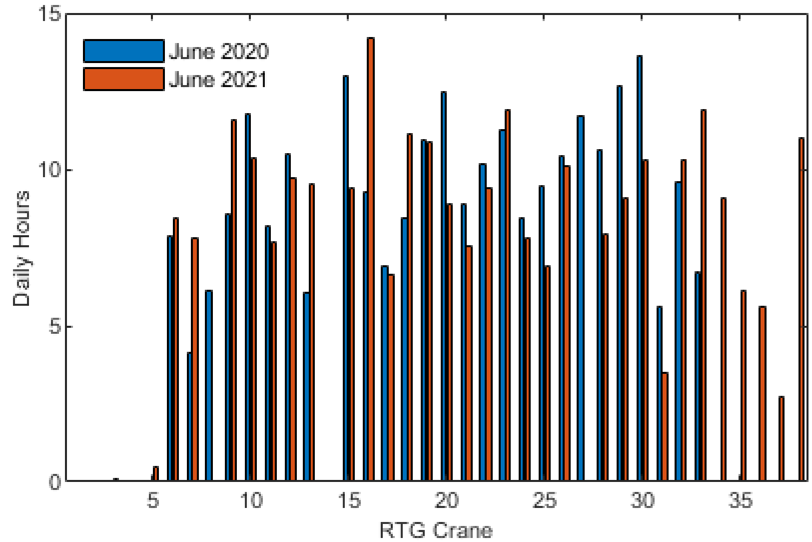
Figure 6. Histogram of Top Handlers Annual Hours at POLB 2020



Credit: APEP
Data Source: Port of Long Beach 2020 Air Emissions Inventory [38]

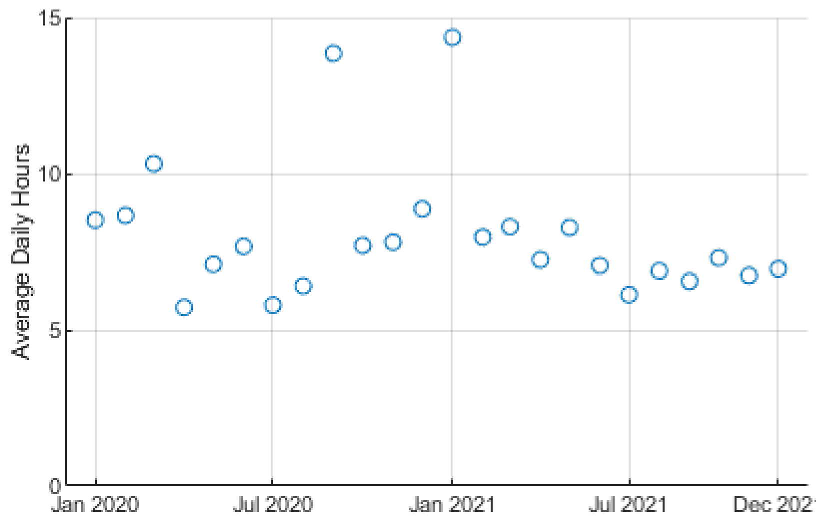
The ITS terminal used for the case study in this project includes 38 top handlers and reach stackers. Average daily hours for these CHE are shown in Figure 7 for June 2020 and June 2021. Average daily hours for the top handler fleet for each month (January 2020 to December 2021) is shown in Figure 8. Figure 8 shows that the average daily hours range of 5.5 hours to 14 hours with an average of eight hours for this terminal which is consistent with the overall top handler fleet at POLB.

Figure 7. Top Handler Daily Hours for Case Study



Credit: APEP

Figure 8. Average Daily Hours for the Top Handler Fleet

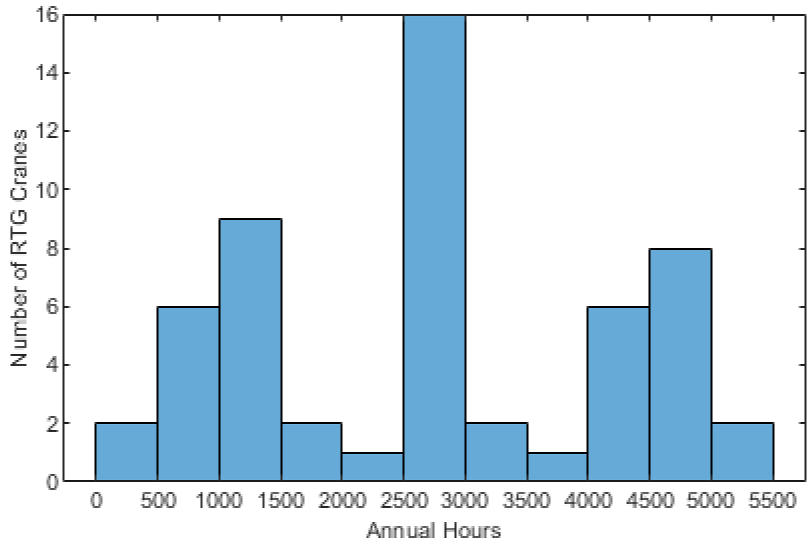


Credit: APEP

2.2.3 Rubber Tire Gantry Cranes

A RTG crane is a wheeled mobile gantry crane that is used to move, stack, or ground containers in a port terminal. Data from the 2020 AEI indicate that 56 RTG cranes were operational at POLB in 2020, with 20 of them being hybrids. The hours of operation of RTG cranes across POLB in 2020 is shown in Figure 9. The average RTG crane in POLB operates 2,731 hours per year (10 to 11 hours per day); however, many of these RTG cranes operate more than 11 hours per day and several around 15 to 20 hours per day.

Figure 9. Histogram of RTG Cranes Annual Hours at POLB 2020

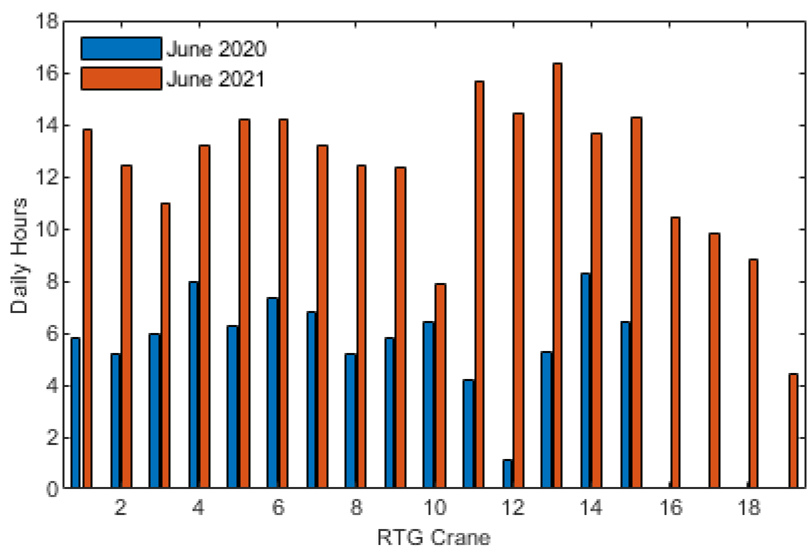


Credit: APEP

Data Source: Port of Long Beach 2020 Air Emissions Inventory [38]

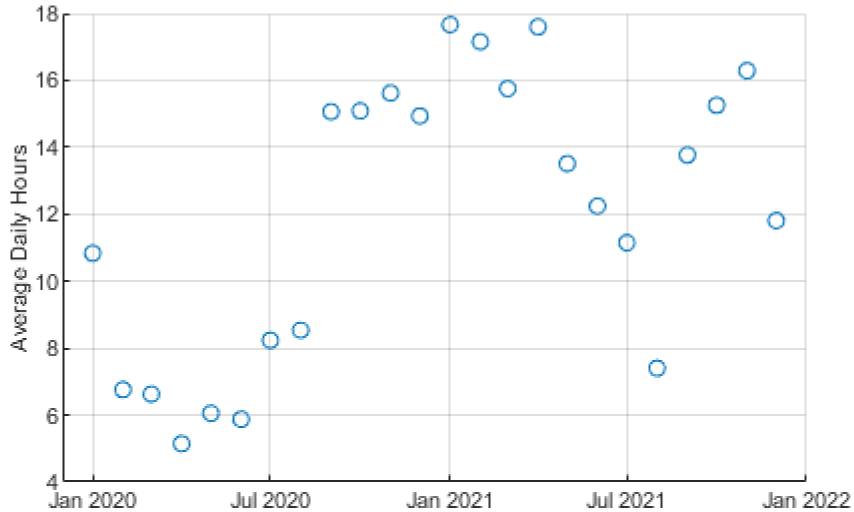
The ITS terminal under study operated 15 RTG cranes (hybrid) in 2020. The number of RTG cranes increased to 24 in 2022 on this terminal. The average daily hours for each of the RTG cranes are shown in Figure 10 for June 2020 and June 2021. Average daily hours for the entire RTG crane fleet are shown in Figure 11. The average daily hours for the fleet range from 5 to 18 hours, with an average of close to 12 hours per day, which is slightly higher than that of POLB average.

Figure 10. RTG Crane Daily Hours for Case Study



Credit: APEP

Figure 11. Average Daily Hours for the RTG Crane Fleet

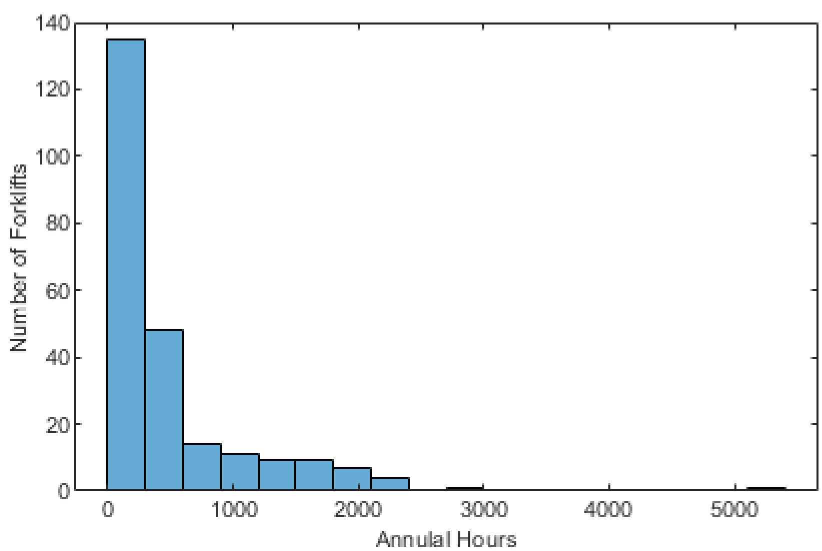


Credit: APEP

2.2.4 Forklifts

Data from the 2020 AEI indicate that there were 239 forklifts (110 diesel, 24 gasoline, 97 propane and 8 electric) at POLB in 2020. The hours of operation of forklifts across POLB in 2020 is shown in Figure 12. The average operating hours for forklifts is 521 hours per year (about two hours per day) with a maximum of 5,145 annual hours (about 19 hours per day). The forklifts are further divided in two groups: small forklifts (100 horsepower (hp) and lower), and large forklifts (above 100 hp).

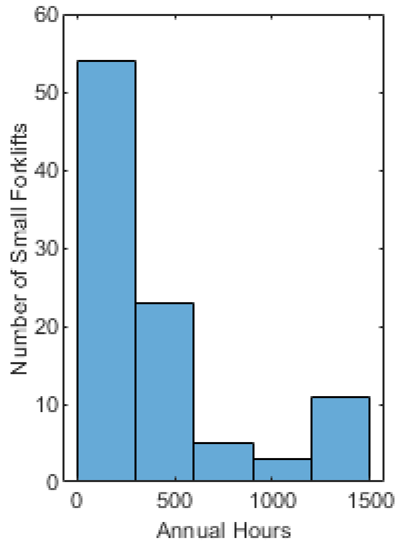
Figure 12. Histogram of Forklifts Annual Hours at POLB 2020



Credit: APEP
Data Source: Port of Long Beach 2020 Air Emissions Inventory [38]

Annual hours of operations for small and large forklifts are shown in Figure 13. The annual average for small forklifts is 422 hours (about 1.5 hours per day) and 577 hours (about 2.5 hours per day) for large forklifts.

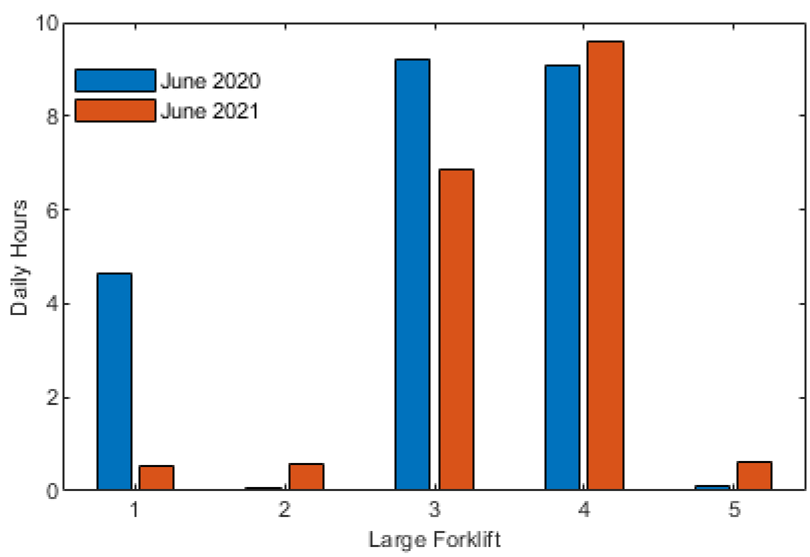
Figure 13. Histogram of Small and Large Forklifts Annual Hours at POLB 2020



Credit: APEP
Data Source: Port of Long Beach 2020 Air Emissions Inventory [38]

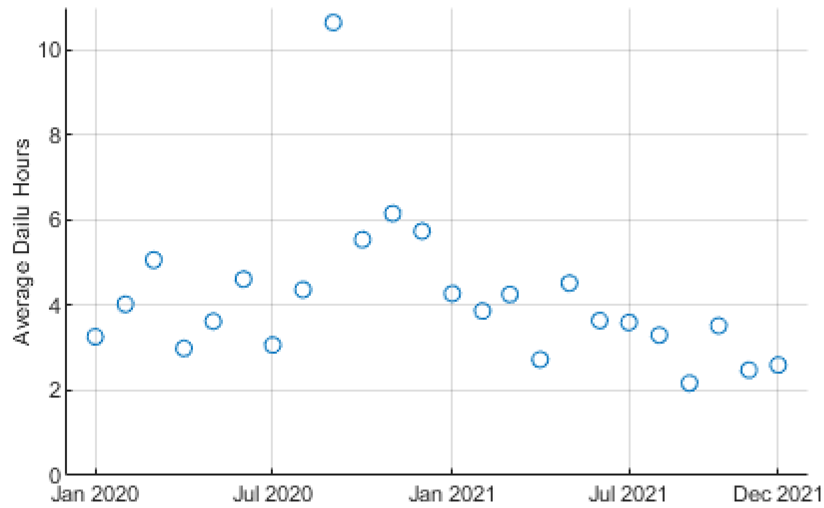
The ITS terminal under study includes five large forklifts (all diesel) and 12 small ones (six diesel and six propane). The average daily hours for each of the five large forklifts are shown in Figure 14 for June 2020 and June 2021. The average daily hours for the five large forklifts are shown in Figure 15. The average daily hours for this fleet range from 2.0 hours to 10.5 hours with an average of four hours per day which is higher than the POLB average.

Figure 14. Large Forklift Daily Hours for Case Study



Credit: APEP

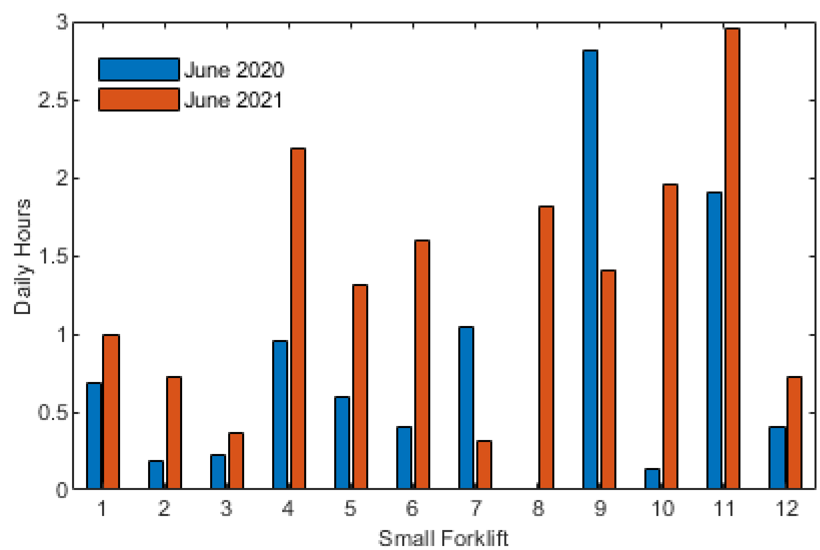
Figure 15. Average Daily Hours for the Large Forklift Fleet



Credit: APEP

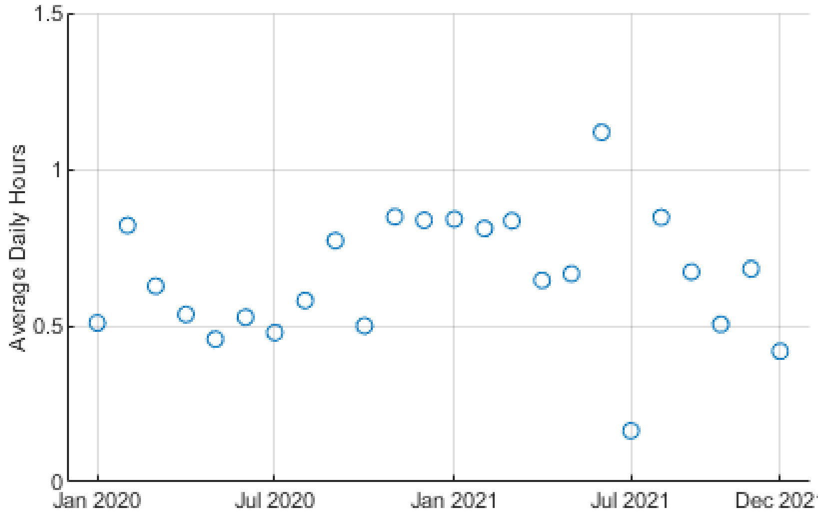
For June 2020 and June 2021, average daily hours for the twelve small forklifts are shown in Figure 16. The average daily hours for each month from January 2020 to December 2021 is shown in Figure 17. The average daily hours range from 0.2 to 1.2 hours with an average of 0.7 hours, which is lower than the average across POLB.

Figure 16. Small Forklift Daily Hours for Case Study



Credit: APEP

Figure 17. Average Daily Hours for the Small Forklift Fleet



Credit: APEP

2.3 Zero-Emission Options for Cargo Handling Equipment

There are two main options available for zero-emission MD/HD vehicles: battery-electric and hydrogen fuel cell-electric. The San Pedro Bay Ports have conducted several feasibility assessments on the status and TRL of battery-electric and hydrogen fuel cell-electric CHE and whether or not the ports consider them commercially available and ready for deployment [14], [37].

For yard tractors, battery-electric options are considered commercially available and technically viable, with a TRL score of 8[5] (Figure 18), while hydrogen fuel cell-electric options are not; however, there has been significant progress in hydrogen fuel cell-electric yard tractors, and it is expected that they will be commercial in a few years, and two are being demonstrated at POLA [41]. While terminal operators prefer that the battery-electric CHE last for two shifts, the available battery-electric yard tractors might be required to be charged twice or more per day. This can be accommodated (and discussed in the next chapter) by charging between the shifts, opportunity charging during meal breaks, or having larger batteries in future iterations of this technology. The latter option, however, might result in higher capital costs and possibly increasing the amount of power required for charging. Capacity Trucks introduced a "hydrogen electric hybrid" yard tractor at the 2022 ACT Expo that uses a hydrogen fuel cell as range extender on battery-electric yard tractor [42]. A similar product was introduced by the Gaussin Group as well.

For RTG cranes, electric options are considered fully commercial and viable (TRL-9) including both new and repower options. The San Pedro Bay Ports 2021 feasibility assessment [37] does not consider hydrogen fuel cell options viable; however, Japan New Energy Development Office (NEDO) recently awarded a project to a team led by Mitsui to develop and demonstrate

---

[5] Technology Readiness Assessment Guide
https://www.directives.doe.gov/directives-documents/400-series/0413.3-EGuide-04-admchg1/@@images/file

a hydrogen fuel cell powered RTG crane at POLA and it is expected to be deployed in 2023 [43].

Figure 18. Battery-Electric Yard Tractor at POLB

Credit: Port of Long Beach (https://polb.com/port-info/news-and-press/more-zero-emissions-equipment-moving-cargo-in-long-beach-10-08-2020/)

Small capacity battery-electric forklifts have been available for several years and small capacity hydrogen fuel cells have been demonstrated in warehouses. For large forklifts, as well as top handlers and reach stackers, the battery-electric and hydrogen fuel cell-electric options are not yet considered commercial and not a viable solution. There has been, however, significant progress, and an electric top handler with a hydrogen fuel cell range extender is being demonstrated at POLA with wireless charging and it is expected that the hydrogen fuel cell-electric options will be demonstrated soon, as well [43]. While zero-emission large capacity forklifts are not considered commercial, there has been significant progress and three battery-electric large forklifts (prototypes) were deployed on POLA [44].

Near zero-emission and hybrid options are considered in the San Pedro Bay Ports assessment and available for some types of CHE and have been demonstrated at the ports, such as demonstration of 20 LNG yard tractors equipped with certified near-zero 0.02 gram/bhp-hr NO_X engine at POLA [45]. In this blueprint, near-zero emission options are considered only as an option in the sort-term until zero-emission options become available.

Based on the information provided in Section 2.3 and the San Pedro Bay Ports feasibility assessment, it is concluded that battery-electric options are ahead of hydrogen fuel cell-electric options in terms of commercialization and maturity. Thus, in the short-term (2023-2025) transition to zero-emission, battery-electric options will be more probable to be used and when the hydrogen fuel cell-electric options become commercial in the medium-term (2025-2030) to long-term (2030 and beyond) in the blueprint, they can be deployed at the ports. A variety of scenarios with different market penetration of battery-electric and hydrogen fuel cell-electric CHE will be discussed in the next chapter.

3 Forecasting Future Electricity and Hydrogen Needs

In this chapter, based on the operational needs of each type of CHE presented and discussed in the previous chapter, as well as any available data of existing zero-emission CHEs, the battery-electric charging and hydrogen fuel cell-electric fueling requirements were determined. First, two scenarios were assessed: (1) Assuming only battery-electric options will be deployed, and (2) only hydrogen fuel cell-electric options will be deployed. While the second scenario is unlikely since, as discussed in the previous chapter, battery-electric options are further along in terms of maturity and commercialization, this scenario serves as an extreme case to determine hydrogen demand of a hydrogen fuel cell electric-only CHE fleet. Next, scenarios with a mixed fleet of battery-electric and hydrogen fuel cell-electric zero-emission CHE were assessed and compared.

3.1 Scenario I: Battery-Electric Fleet

In this scenario, it was assumed that all the CHE at the ITS terminal consist of battery-electric or grid-tied options. This extreme scenario provides an upper bound for the electric charging requirement and the required infrastructure to support this upper bound charging demand. Data from previous and existing demonstrations, when available, were used to determine the energy requirements for this scenario.

3.1.1 Yard Tractors

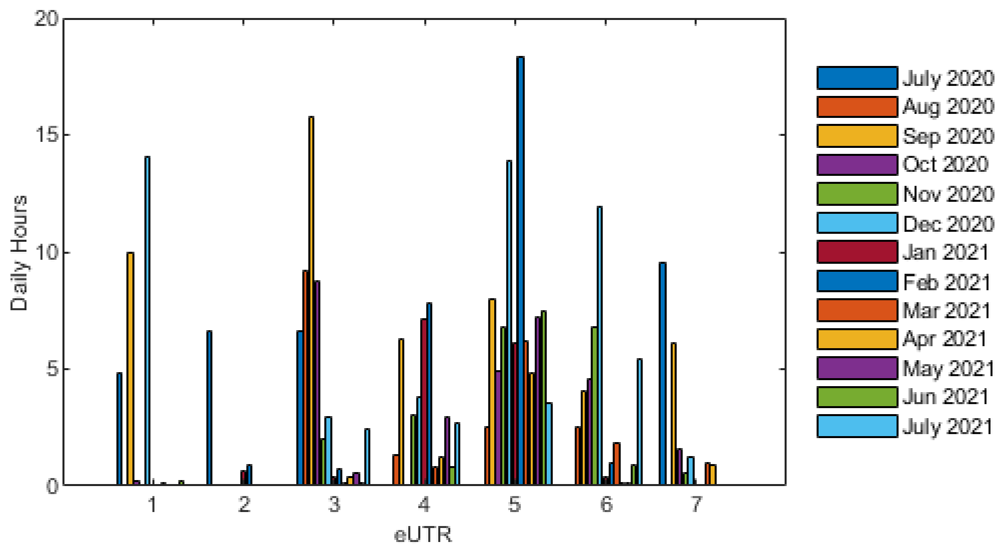
Several CHE OEMs, including Kalmar Ottawa and BYD, offer battery-electric yard tractors that are listed by CARB as eligible to receive incentives under the California Clean Off-Road Equipment (CORE) project [46]. Three BYD battery-electric yard tractors were demonstrated at POLA as a part of the Everport Advanced Cargo Handling Equipment Demonstration Project [47]. Five battery-electric yard tractors (2 BYD, 1 Kalmar, and 2 TransPower) were demonstrated at the Pasha terminal as part of the POLA Multi-Source Green Omni Terminal Project [44]. One Kalmar-TransPower T2E battery-electric was demonstrated as a part of the C-PORT project funded by CARB with a 70 kilowatt (kW) charging station [48].

As a part of a $9.7 million grant by the CEC, the Port Advanced Vehicle Electrification Project demonstrated seven BYD model 8T battery-electric yard tractors on ITS terminal. As a part of the project, SCE modernized the existing grid infrastructure to help support the charging needs of the battery-electric yard tractors [12]. The project included six 200 kW charging stations (BYD charger) and one smart charger from Cavotec [49], the latter of which enables charging of the vehicles without the need of human intervention by using a robotic arm that connects automatically to the vehicle. This is especially useful for ports because the driver is not allowed to plug-in the vehicle.

The battery-electric yard tractors that were demonstrated have a 150 kilowatt-hour (kWh) to 240 kWh battery pack and a 70 kW to 200 kW charger, depending on the OEM. The published reports from the C-PORT demonstration show that the battery-electric yard tractor used 15±5 kWh per hour (kWh/hr) with an average of 15.2 kWh/hr. These battery-electric yard tractors were used 5.4±3.1 hours per day, and used 85±50 kWh of energy per day during the demonstration [50]. While on average this battery-electric yard tractor used 50 percent (±30 percent) of state of charge (SOC) per day, there were instances during the demonstration that energy required per day exceeded the size of the battery, requiring as a result for the battery-electric yard tractor to be charged twice per day.

For the ITS terminal under study, the results of the demonstration were published in the National Renewable Energy Laboratory's (NREL) *California Transportation Electrification Priority Review Project, Final Evaluation Report* as a part of the Transportation Electrification Priority Review Projects [15], [51]. The average daily hours for this fleet of battery-electric yard tractors are shown in Figure 19 for each month from July 2020 to July 2021. Ignoring the months that a specific yard tractor was not used, the yard tractors were in operation between 1.3 and 8.4 hours per day, with an average of 4.2 hours per day.

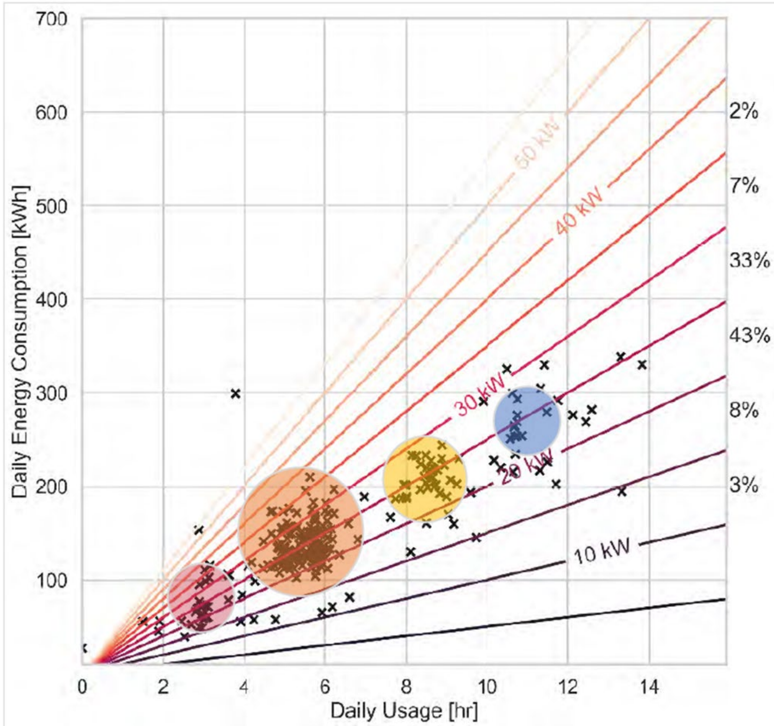
Figure 19. Electric Yard Tractor Daily Hours for Case Study



Credit: APEP

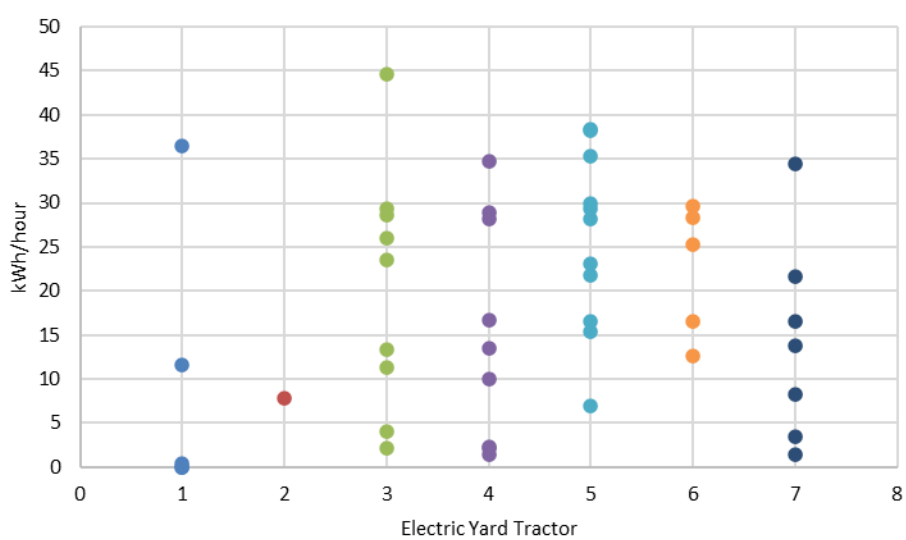
The results of the battery-electric yard tractor demonstration at the ITS terminal indicate that the fleet of battery-electric yard tractors consumed 20 kWh/hr to 30 kWh/hr, the details of which are shown in Figure 20 for battery-electric yard tractors used in rail operations (loading and unloading containers to and from cargo trains). Energy utilization for the individual battery-electric yard tractors is shown in Figure 21.

Figure 20. Daily Hours and Energy Utilization



Credit: BYD Telematics, California Investor-Owned Utility Transportation Electrification Priority Review Projects [15]

Figure 21. Energy Utilization of Battery-Electric Yard tractors at ITS terminal

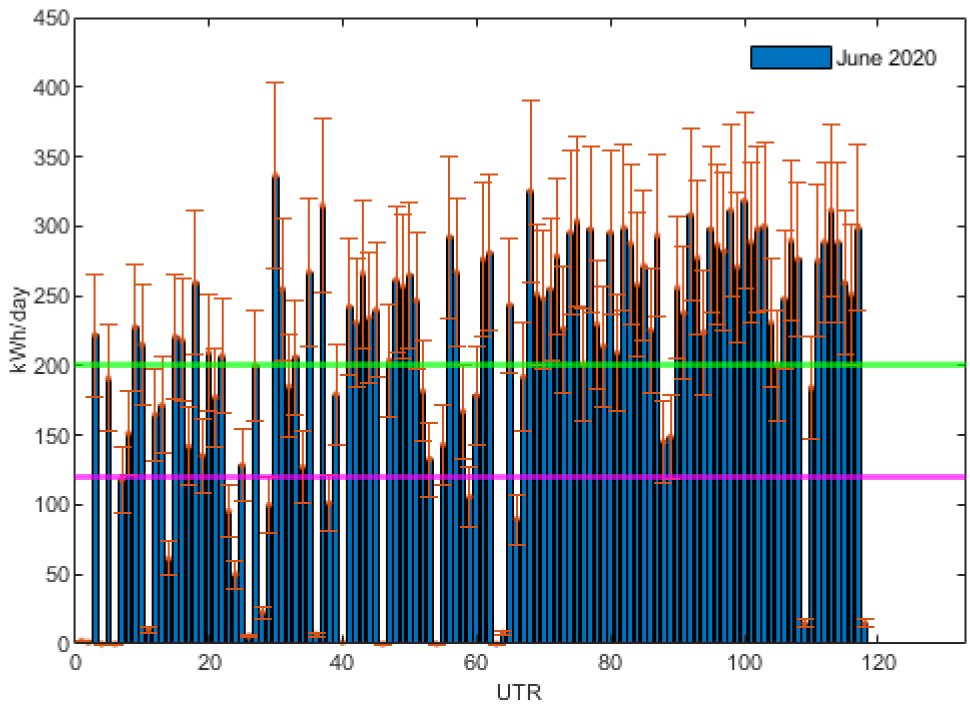


Credit: APEP

Energy utilization of battery-electric yard tractors, as measured by kWh/hr, varies across the fleet and depends on the duty cycle, weight of cargo, stop/go, and driver abilities. Assuming an energy utilization of 25 kWh/hr, and using the daily hours of operation associated with the yard tractors on the terminal detailed previously in Figure 4, the daily energy utilization of each yard tractor is determined, the results of which, for June 2020 to June 2021, are shown in Figure 22 and Figure 23, respectively. The error bars in the figures are associated with 20 kWh/hr and 30 kWh/hr energy utilization. The two horizontal lines are associated with the two sizes of batteries, 240 kWh and 150 kWh. Assuming that the minimum SOC allowable for the battery-electric fleet is 20 percent, the maximum allowable energy used per charge is 200 kWh and 120 kWh. For any energy utilization above the maximum allowable, the yard tractor needs to be charged at least twice per day, which is not ideal, but it can be accommodated by opportunity charging at break times and between shifts.

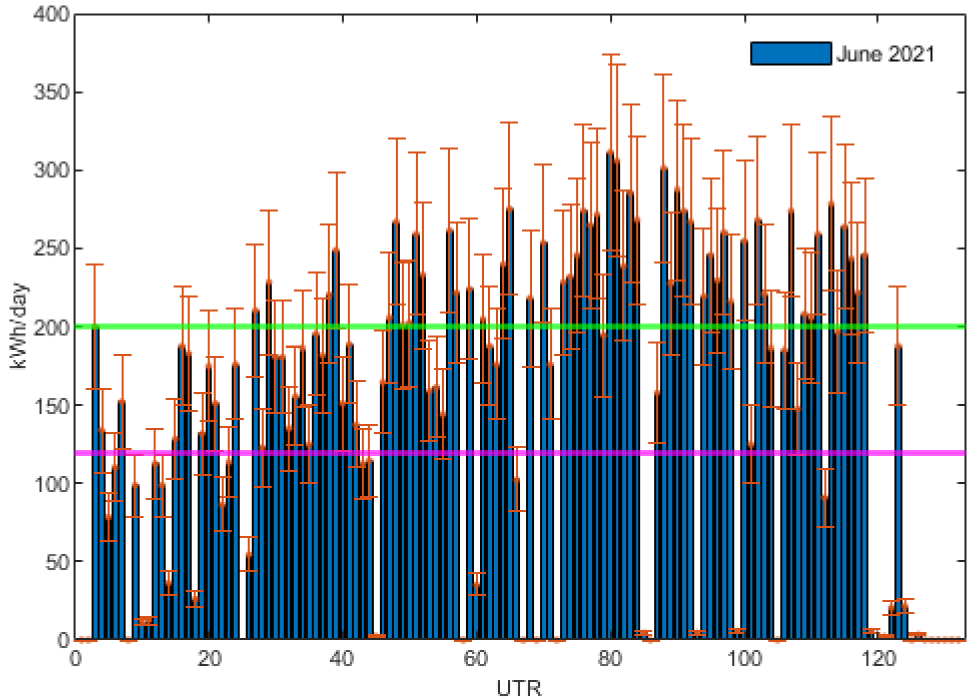
Based on this analysis, for a battery size of 150 kWh, 44 percent to 81 percent (average 68 percent) of the electric yard tractor fleet will need to be charged at least twice per day, depending on the day, hours of operation, and duty cycle. For a 240 kWh battery size, 13 percent to 67 percent (with an average of 43 percent) of the fleet needs to be charged at least twice in a day. Increasing the size of the battery to 300 kWh, reduces the average percent of the fleet that needs to be charged at least twice to 24 percent.

Figure 22. Energy Utilization of Battery-Electric Yard Tractor Fleet (June 2020)



Credit: APEP

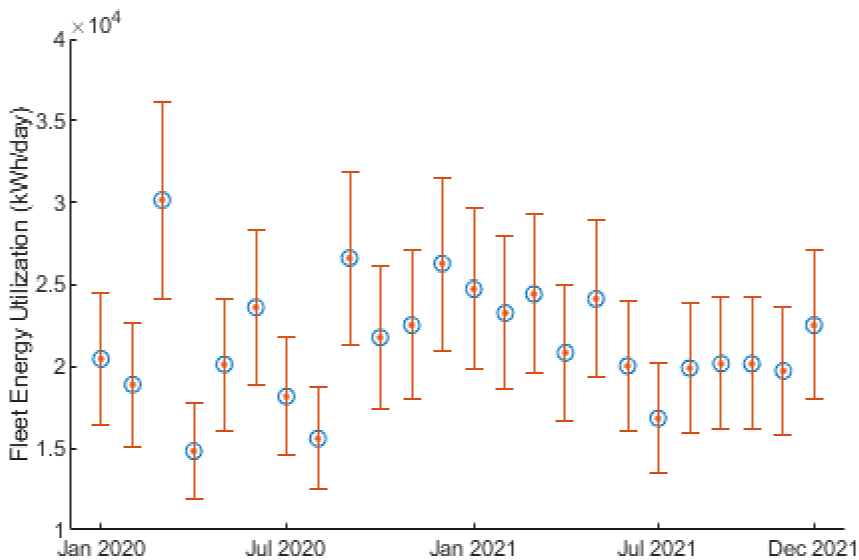
Figure 23. Energy Utilization of Battery-Electric Yard Tractor Fleet (June 2021)



Credit: APEP

The daily energy utilization for the entire fleet of yard tractors (100 percent battery-electric) is shown in Figure 24. To fully transition the entire yard tractor fleet at a terminal, an average of 21 MWh of electricity per day is required to charge them. In Chapter 4, the infrastructure required to provide required charging to the fleet will be discussed.

Figure 24. Electric Yard Tractor Fleet Daily Energy Utilization



Credit: APEP

3.1.2 Top Handler

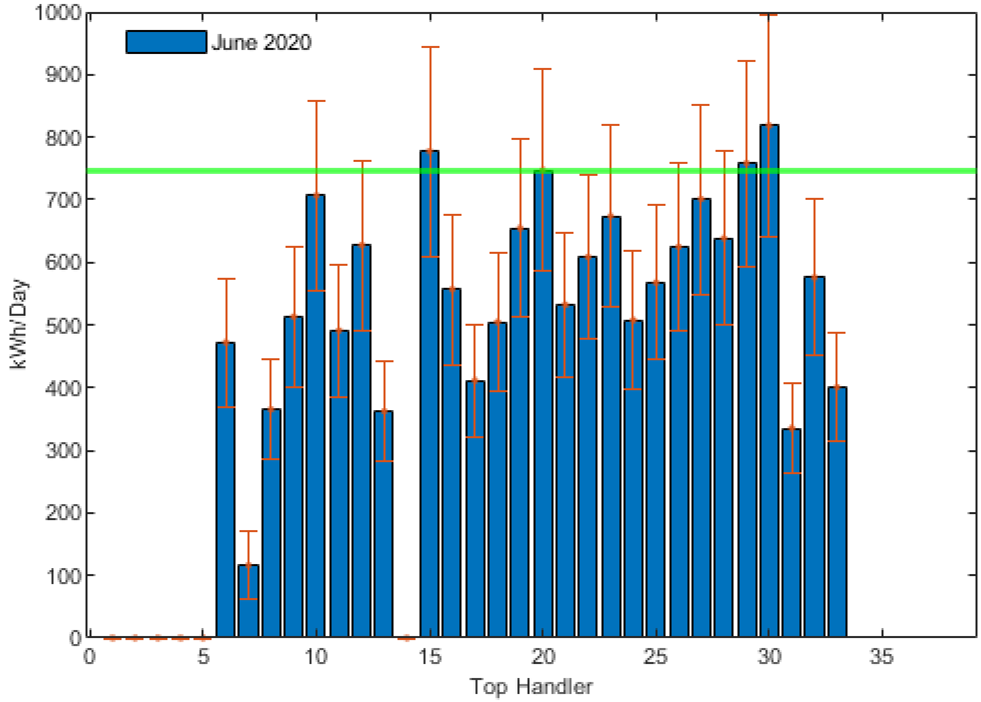
As discussed in the previous chapter, battery-electric top handlers are not yet considered commercially available; however, several have been demonstrated at the San Pedro Bay Ports. In the C-PORT project [48], three battery-electric top handlers were demonstrated (by Taylor Machine and BYD), and in the Everport Advanced Cargo Handling Equipment Demonstration Project, two battery-electric top handlers were demonstrated [47]. The top handlers demonstrated had a 931 kWh battery and were deployed along with 200 kW chargers.

The result published from the C-Port demonstration show that, for two of the battery-electric top handlers that were operated five to seven hours per day, the energy utilization was 60±13 kWh/hr. The third battery-electric top handler was used less (and with a milder duty cycle) for 2.8±2.2 hours per day. For this top handler, the energy utilization was 28±13 kWh/hr [50]. Using the daily hours of operation for a battery-electric top handler in the ITS terminal under study detailed previously in Figure 7, the energy utilization was calculated as follows: if the daily hours of operation were less than five hours, 28 kWh/hr was used, and for daily hours of five or greater, 60 kWh/hr was used. The results for June 2020 and June 2021 are shown in Figure 25 and Figure 26, respectively. The vertical line represents the maximum energy on one charge. battery-electric top handlers requiring more energy than this maximum will need to be charged at least twice a day.

Based on this analysis, each day, 13 percent of the battery-electric top handler fleet on average need to be charged at least twice per day. This percentage ranges from 0.0 percent to 55 percent. Thus, there are days that the battery-electric top handler fleet can operate on one charge, and there will be days where more than half of the fleet will need to be plugged in and charged at least twice. Thus, it is necessary to record better data from the operation of the existing fleets, and especially their duty cycle, to get a better estimate of the required energy and the required infrastructure.

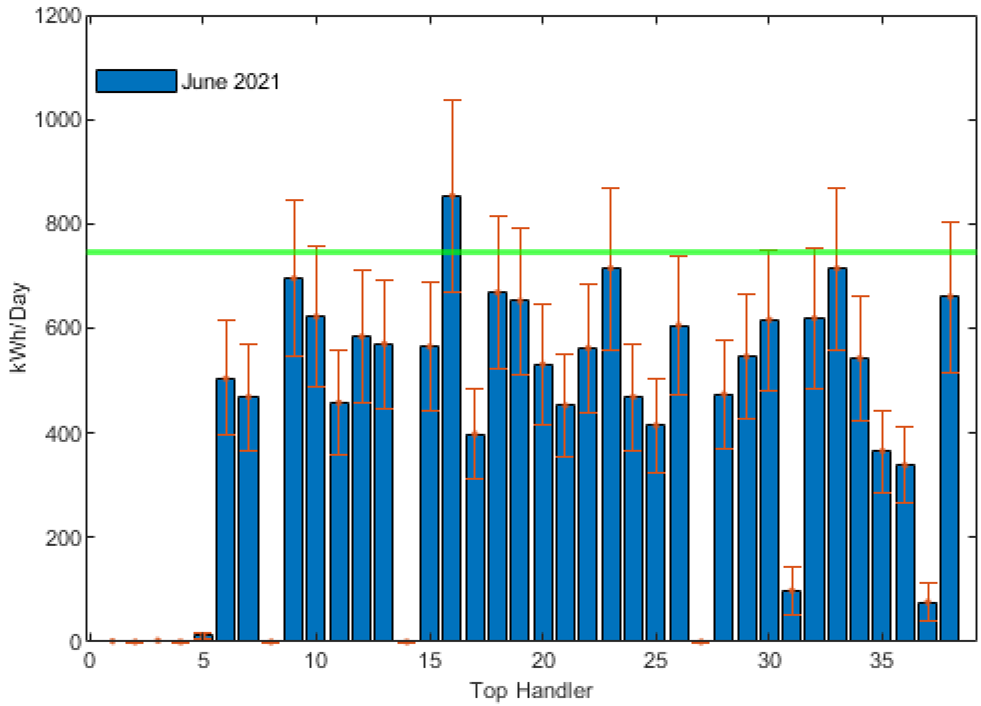
The daily energy utilization for the entire fleet of battery-electric top handlers (100 percent battery-electric) is shown in Figure 27. To fully transition the entire battery-electric top handler fleet on a terminal, an average of 16.5 MWh of electricity per day is required to charge them. In Chapter 4, the infrastructure required to charge this fleet will be discussed.

Figure 25. Energy Utilization of Battery-Electric Top Handler Fleet (June 2020)



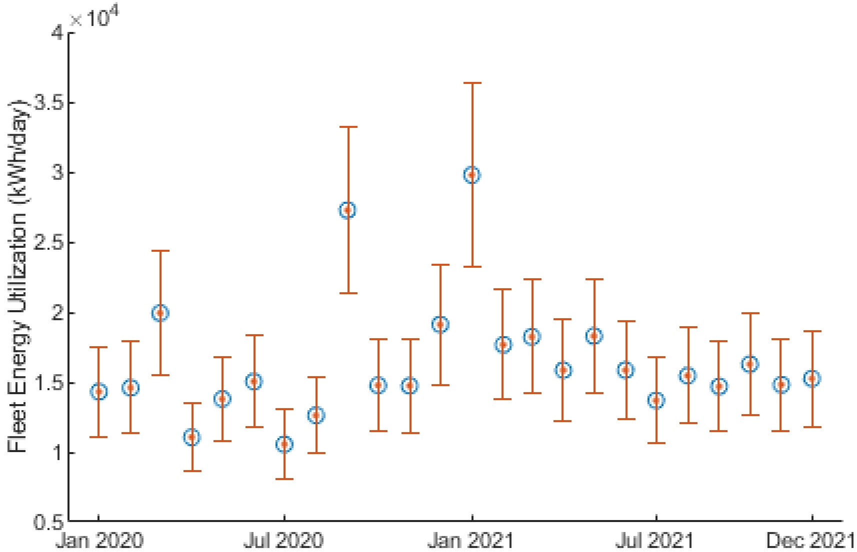
Credit: APEP

Figure 26. Energy Utilization of Battery-Electric Top Handler Fleet (June 2021)



Credit: APEP

Figure 27. Electric Top Handler Fleet Daily Energy Utilization

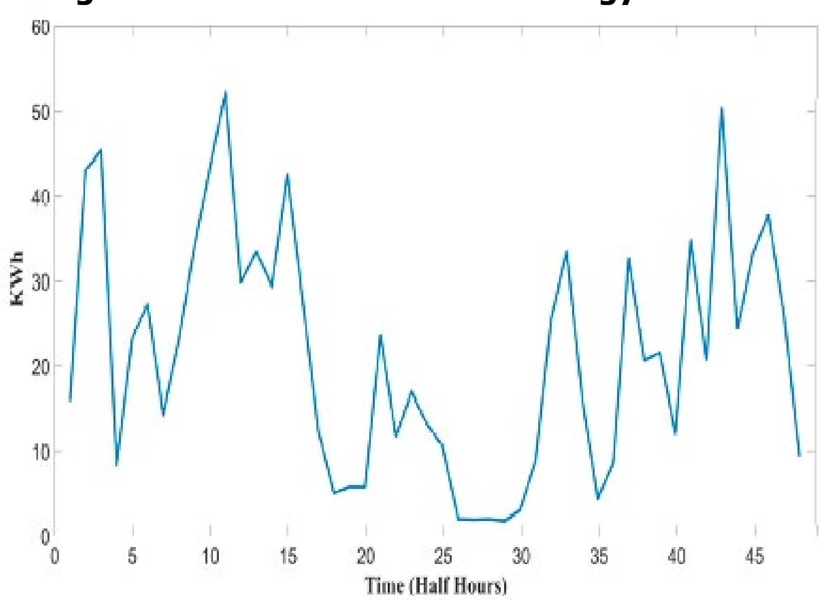


Credit: APEP

3.1.3 RTG Crane

RTG cranes can be replaced with, or repowered to, zero-emission or near-zero-emission options. The full zero-emission electric option has no diesel engine, and the electric drive is directly connected to the grid. Alternatively, the diesel engine can be replaced with a small diesel engine complemented by battery power, making a hybrid-electric RTG (near-zero-emission, since there is still a diesel engine). Grid-tied RTG cranes are commercially available from OEMs such as Kalmar, but detailed data on the duty cycle and energy utilization are not yet available. Several studies such as the study conducted by Alasali et al. have focused on grid-tied RTG cranes, their electricity usage and how to avoid or mitigate peaks [52]. Figure 28 shows the energy utilization of a grid-tied RTG crane for a specific day, and it ranges from 10 kWh/hr to 50 kWh/hr.

Figure 28. Electric RTG Crane Energy Demand



Credit: Alasali et al. [52]

In the absence of operational or demonstration data, the following method was used to estimate the energy requirement of zero-emission CHE such as grid-tied RTG cranes. First, fuel utilization of diesel CHE was estimated using the Brake-specific fuel utilization (BSFC)[6] and the load factor[7] associated with the specific CHE. It is typically used for comparing the efficiency of internal combustion engines with shaft output. The BSFC for several fuels is shown in Table 8. The rated power of the CHE and the hours of operation were derived from the data obtained from the ITS terminal.

Table 8. BSFC for Several Fuels

Fuel	BSFC in lb/(hp·h)
Diesel	0.33
Gasoline	0.407
LPG	0.411

Source: Shao et al. [53]

The load factor for each type CHE at the San Pedro ports is provided in San Pedro Bay Ports *Emission Inventory Methodology Report* and it is used in this study [54]. The load factor used are shown in Table 9.

Table 9. Cargo Handling Equipment Engine Load Factors

CHE Type	Load Factor
Cone vehicle	0.51
RTG crane	0.20
Crane	0.43
Excavator	0.55
Forklift	0.30
Loader, backhoe	0.55
Top handler, side pick, reach stacker	0.59
Truck, other with off-road engine	0.51
Truck, other with on-road engine	0.51
Straddle carrier	0.20
Sweeper	0.68
Yard tractor with off-road engine	0.39
Yard tractor with on-road engine	0.39

Source: San Pedro Bay Ports Emissions Inventory Methodology Report [54]

6 BSFC is a measure of the fuel efficiency of any prime mover that burns fuel and produces rotational, or shaft power.

7 Portion of the rated power engine that is utilized during operation.

After determining the fuel usage for the existing fleet, the electricity or hydrogen equivalent is calculated using *Fuel Conversion Factors to Gasoline Gallon Equivalents* report published by the U.S. EPA [55]. To determine the electricity usage of battery-electric CHE or hydrogen usage of hydrogen fuel cell-electric CHE, it is necessary to also take into account fuel efficiencies since battery-electric and hydrogen fuel cell-electric options are overall more efficient than diesel and gasoline internal combustion engines.

In a study conducted by Burnham et al. fuel economy (miles per diesel gallon equivalent (DGE)) of various MD/HD vehicles (diesel, battery-electric, and hydrogen fuel cell-electric) in 2020 and 2025 are provided [56],and shown in Table 10.

Table 10. Fuel Economy for MD/HD Vehicles (miles per DGE)

		ICE-CI[8]	**FCEV**	**BEV**
Tractor - Sleeper	MY20	6.66	6.70	11.59
	MY25 – low	7.17	7.18	12.60
	MY25 – high	8.27	8.34	14.67
Tractor - Day cab	MY20	6.14	6.29	11.90
	MY25 – low	6.65	6.81	12.91
	MY25 – high	7.78	8.19	15.41
Class 8 Vocational	MY20	7.01	9.31	17.46
	MY25 – low	7.49	10.10	18.92
	MY25 – high	8.56	11.48	21.40
Class 6 - Pickup/Delivery	MY20	10.18	14.37	27.41
	MY25 – low	10.93	15.80	29.72
	MY25 – high	13.20	18.30	34.06
Class 4 - Pickup/Delivery	MY20	12.85	22.73	43.18
	MY25 – low	13.76	25.07	47.18
	MY25 – high	15.79	28.87	54.36
Transit Bus	MY20	7.08	9.88	18.79
Class 8 Refuse	MY20	5.39	No Data	18.04

Data Source: Burnham et al. [56]

Additionally, fuel economy of different classes of MD/HD vehicles are provided for diesel, battery-electric and hydrogen fuel cell-electric options in a study conducted by Brown et al. [57] and are summarized and compared to gasoline gallon equivalents (GGE) in Table 11.

[8] diesel-fueled compression-ignition internal combustion engine (ICE-CI)

Table 11. Fuel Economy of Different Types of MD/HD Vehicles (miles per GGE)

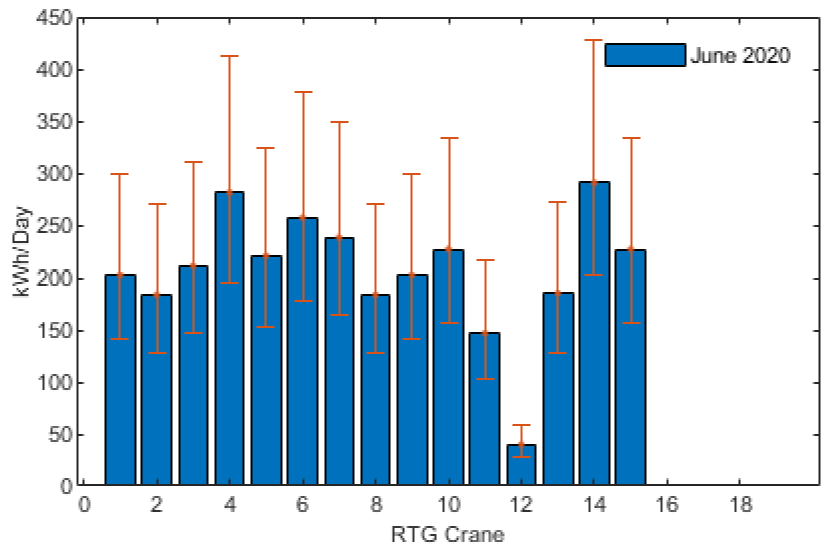
Vehicle		2010	2015	2020	2025	2030	2035	2040	2045	2050
Light Truck	DSL	29.8	32.3	34.7	35.3	35.9	37.0	38.2	39.6	39.6
	EV100	88.4	103.3	110.5	107.8	105.1	105.7	106.2	106.7	106.7
	EV200	88.5	96.6	104.6	103.6	102.6	103.2	103.7	104.3	104.3
	FC	42.9	45.4	50.7	50.5	50.3	51.1	51.8	52.6	52.6
Long haul	Diesel	4.8	5.3	6.0	7.4	7.9	8.2	8.6	9.0	9.4
	BEV	12.8	14.3	15.8	16.3	16.8	17.2	17.7	18.1	18.6
	Fuel Cell	5.7	6.4	7.1	8.8	9.5	9.9	10.3	10.8	11.3
Short Haul	Diesel	4.6	4.9	5.2	6.2	6.5	6.8	7.0	7.3	7.6
	BEV 200	14.8	15.7	16.6	20.0	20.9	21.7	22.5	23.4	24.3
	Fuel Cell	9.7	10.3	10.9	13.1	13.7	14.2	14.7	15.3	16.0
MD Delivery	Diesel	7.2	7.6	7.9	9.3	9.7	10.0	10.3	10.7	11.1
	BEV 200	27.5	28.8	30.0	35.4	36.7	38.0	39.3	40.8	42.3
	Fuel Cell	15.2	15.9	16.6	19.6	20.3	21.0	21.7	22.5	23.4
Transit Bus	Diesel	4.0	4.0	4.2	4.9	5.1	5.3	5.5	5.7	5.9
	BEV	12.7	12.9	13.4	15.7	16.4	16.9	17.5	18.2	18.8
	Fuel Cell	8.7	8.9	9.2	10.8	11.3	11.7	12.1	12.5	13.0
Other Bus	Diesel	6.1	6.3	6.6	7.8	8.1	8.4	8.7	9.0	9.4
	BEV	19.5	20.2	21.2	25.0	26.0	26.8	27.8	28.8	29.9
	Fuel Cell	13.4	13.9	14.6	17.2	17.8	18.5	19.1	19.8	20.6
HD vocational	Diesel	3.8	3.8	4.0	4.7	4.9	5.1	5.3	5.4	5.6
	BEV	12.2	12.3	12.9	15.1	15.7	16.3	16.8	17.4	18.1
	Fuel Cell	8.4	8.5	8.9	10.4	10.8	11.2	11.6	12.0	12.4
MD vocational	Diesel	7.0	7.3	7.6	9.3	9.8	10.2	10.5	11.0	11.4
	BEV	26.5	27.9	28.9	35.4	37.3	38.6	40.1	41.6	43.3
	Fuel Cell	14.7	15.4	16.0	19.6	20.6	21.3	22.1	23.0	23.9
HD pickup	Diesel	15.1	15.7	17.9	20.0	22.9	23.8	24.7	25.8	26.9
	BEV 200	57.3	59.7	68.2	76.0	86.8	90.3	93.9	98.0	102.3
	Fuel Cell	33.2	34.6	39.5	44.0	50.3	52.3	54.4	56.7	59.2

Data Source: Brown et al. [57]

Data from Table 11 and Table 12 indicate that battery-electric MD/HD fuel economies are 1.7 to 3.6 times more efficient (with an average of 2.5 times more efficient) than that of their diesel counterparts.

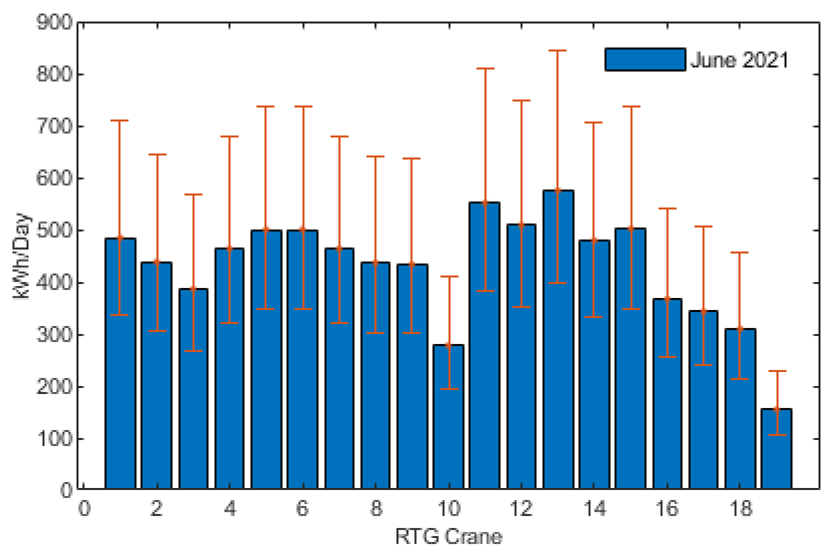
This methodology of using diesel utilization to estimate electricity and hydrogen demand taking into account higher efficiencies of battery-electric and fuel cell-electric counterparts, was used to estimate the electricity utilization of RTG cranes for the ITS terminal. Note that the operation hours were previously discussed and it was assumed that all the existing RTG cranes are 250 hp. Results for grid-tied RTG cranes are shown in Figure 29 and in Figure 30 for June 2020 and June 2021, respectively. The daily utilization results are consistent with published research such as the one conducted by Alasali et al. [58].

Figure 29. Energy Utilization of Grid-Tied RTG Crane Fleet (June 2020)



Credit: APEP

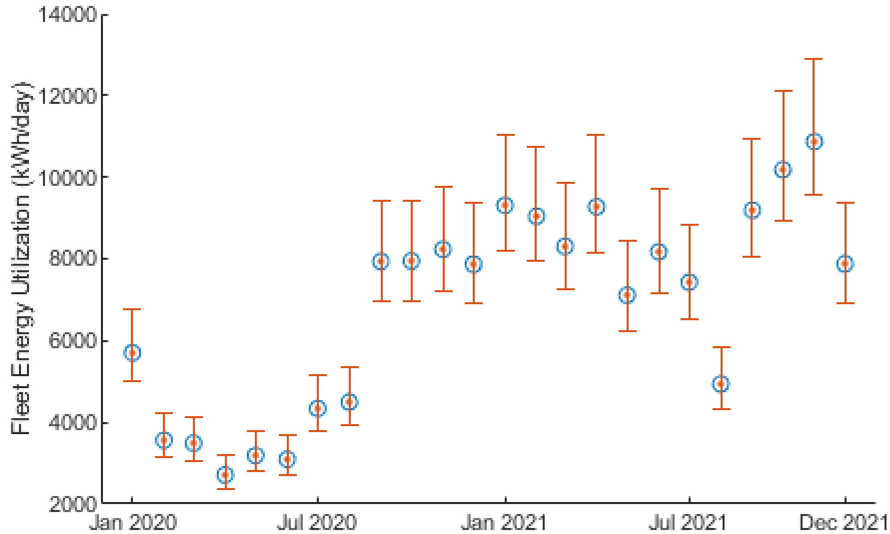
Figure 30. Energy Utilization of Battery-Electric RTG Crane Fleet (June 2021)



Credit: APEP

The daily energy utilization for the entire fleet of 100 percent grid-tied RTG cranes is shown in Figure 31. To fully transition the entire fleet on a terminal, an average of 7 MWh of electricity per day will be required. However, the peak demand depends strongly on the duty cycle and the dynamics of operation should be taken into account while determining the required infrastructure and impacts on costs.

Figure 31. Grid-Tied Electric RTG Crane Fleet Daily Energy Utilization

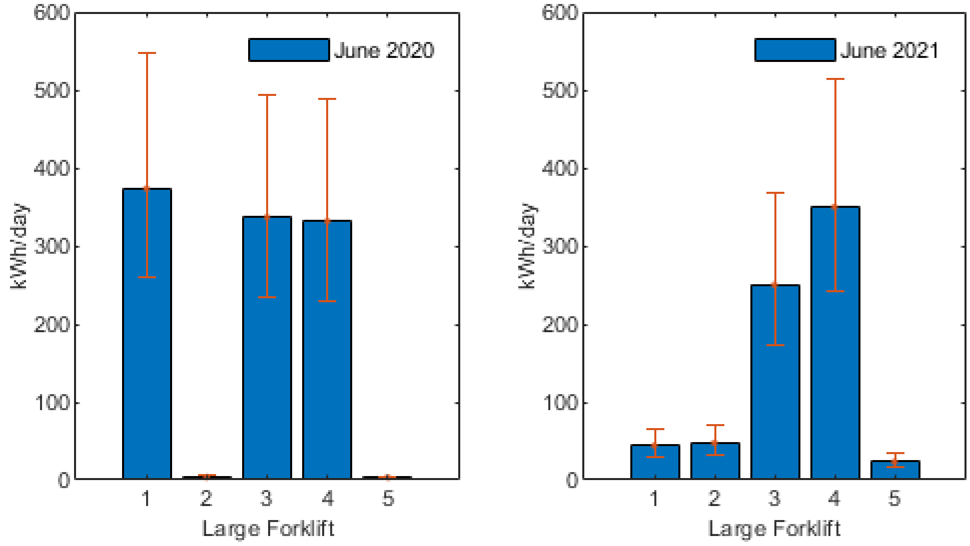


Credit: APEP

3.1.4 Forklifts

Battery-electric forklifts (both lithium-ion and lead acid) have been commercially available for small forklifts for the past 10-15 years, and while the large battery-electric forklifts used at the port are not considered commercial, three 21-ton forklifts that have been repowered from diesel to battery-electric are being demonstrated at POLA [44]. Due to lack of detailed operational data, duty cycle and energy demands, the energy utilization of the battery-electric forklift fleet were estimated using estimates of diesel utilization, load factor and taking into account that battery-electric options are more efficient that their diesel counterparts (the details were included in previous Section 3.1.3). Results for battery-electric large forklifts are shown in Figure 32 for June 2020 and June 2021, respectively.

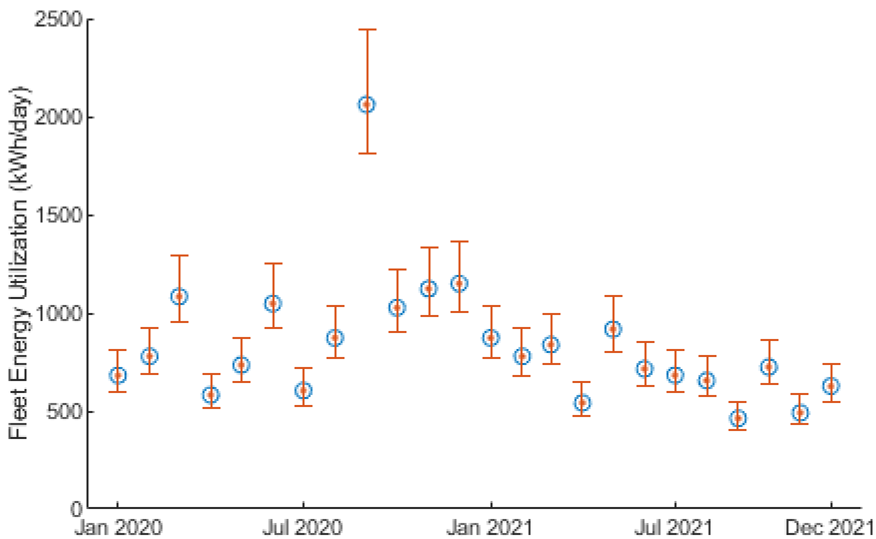
Figure 32. Energy Utilization of Battery-Electric Large Forklift Fleet (June 2020 and June 2021)



Credit: APEP

The daily energy utilization for the entire fleet of large battery-electric forklifts (100 percent battery-electric) is shown in Figure 33. The average daily energy utilization for the large battery-electric forklift fleet is around 835 kWh, although there are days when 2 MWh is required for the large battery-electric forklifts.

Figure 33. Battery-Electric Large Forklift Fleet Daily Energy Utilization

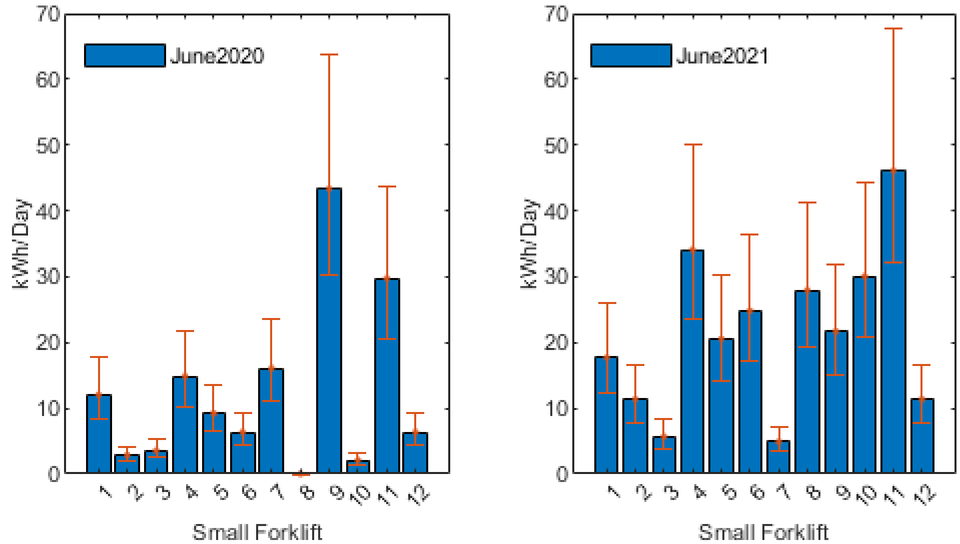


Credit: APEP

The analysis is repeated for small battery-electric forklifts. Results for small battery-electric forklifts are shown in Figure 34 for June 2020 and June 2021, respectively. The daily energy utilization for the entire fleet of small battery-electric forklifts (100 percent electric) is shown in Figure 35. The average daily energy utilization for the large battery-electric forklift fleet is around 177 kWh per day. Note that small battery-electric forklifts have lower horsepower and that their daily hours of operation is less than large battery-electric forklifts (compare Figure

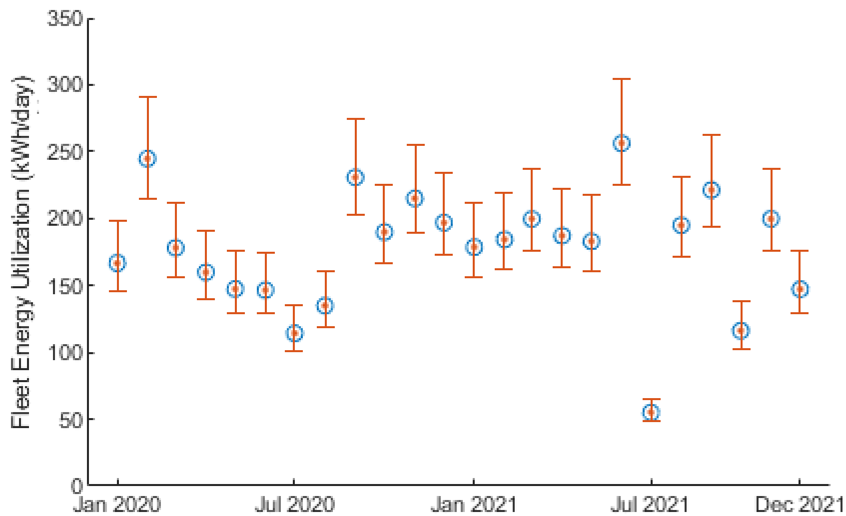
15 and Figure 17). Thus, their energy and fuel utilization is less than the large battery-electric forklifts fleet, despite the number of vehicles in each fleet.

Figure 34. Energy Utilization of Battery-Electric Small Forklift Fleet (June 2020 and 2021)



Credit: APEP

Figure 35. Small Battery-Electric Forklift Fleet Daily Energy Utilization

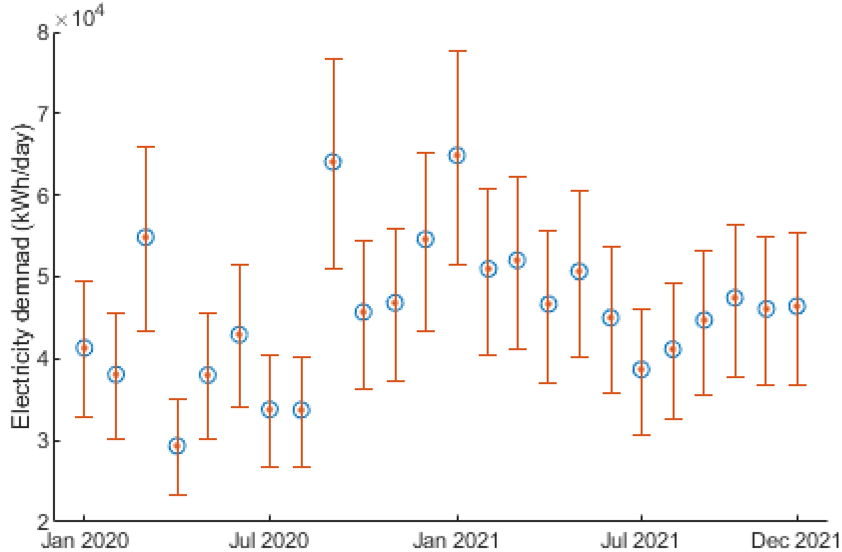


Credit: APEP

3.1.5 Summary of Scenario I

Using the data and analysis provided in previous sections, the daily energy utilization for the Scenario I, a 100 percent battery-electric or grid-tied CHE fleet for the ITS terminal under study, is shown in Figure 36, with an average of 45 MWh per day, which is a significant amount of electricity and does not include the peaks and the required power to support the peaks, which will be further discussed in the next chapter.

Figure 36. Daily Electricity Demand of a Fully Battery-Electric CHE Fleet for the Terminal under Study



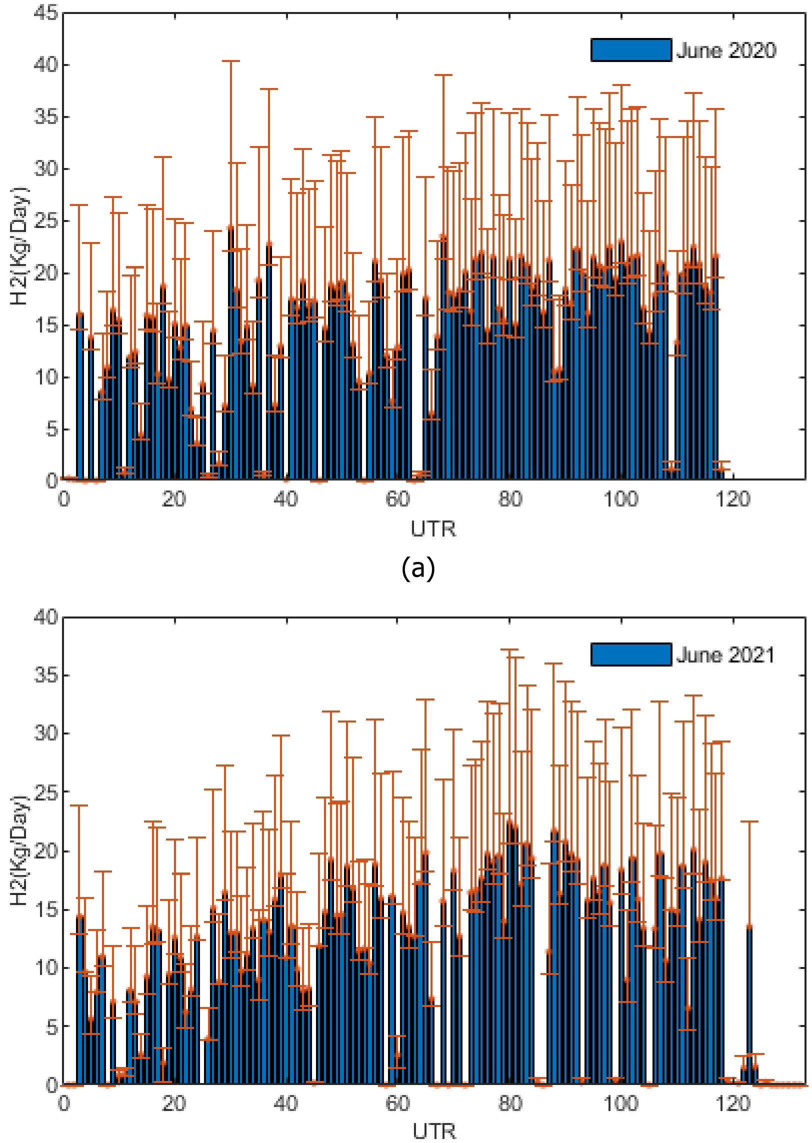
Credit: APEP

3.2 Scenario II: Hydrogen Fuel Cell Fleet

As previously mentioned, a 100 percent hydrogen fuel cell-electric CHE fleet is highly unlikely since battery-electric options are more mature and expected to be deployed first on the terminal, with some already deployed. This scenario is used to understand the upper bound of hydrogen demand and the related infrastructure in support of the mixed fleet analyses presented in the next section. Among the hydrogen fuel cell-electric CHE previously mentioned, only small forklifts are commercially available. There are two hydrogen fuel cell-electric hybrid yard tractors being demonstrated at POLA with 10-20 kg of onboard hydrogen storage at 350-bar [41]. And as mentioned previously in Section 2.3, a battery-electric top handler with hydrogen fuel cell range extender is being demonstrated and a hydrogen fuel cell-electric RTG crane is under development.

Since hydrogen fuel cell-electric CHE are not commercially available, public data on the performance of these vehicles have not been published. As a result, the methodology introduced in Section 3.1.3 which uses estimates of diesel utilization and load factors and takes into account the fact that hydrogen fuel cell-electric CHE are more efficient than their diesel counterparts, was used to estimate the hydrogen utilization of a fuel cell-electric CHE. Using the data in Table 10 and Table 11, it is concluded that hydrogen fuel cell-electric MD/HD options are on average expected to have a fuel economy two times that of their diesel counterparts (from 1.2 to 2.2 times the fuel economy, with an average of 2.0). Using this improvement in the fuel economy, and CHE hours of operation, the hydrogen demand is estimated. The results are shown Figure 37 to Figure 46.

Figure 37. Hydrogen Need of Fuel Cell-Electric Yard Tractors

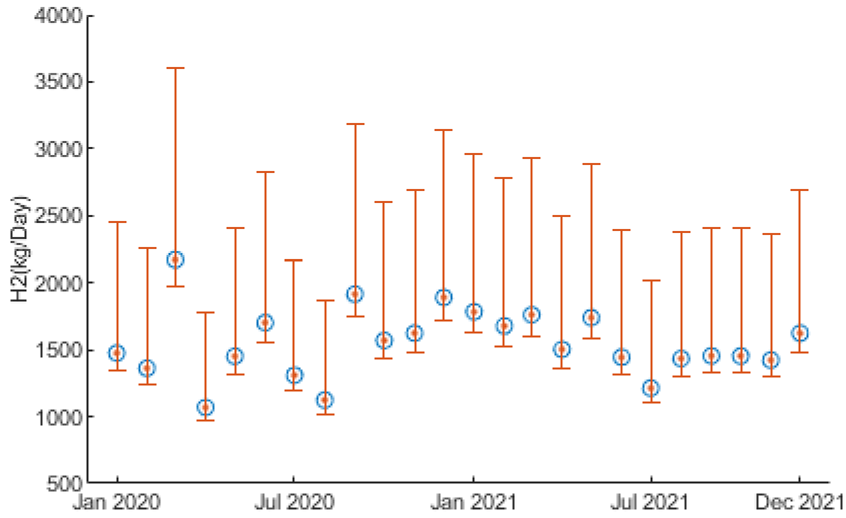


(a)

(b)

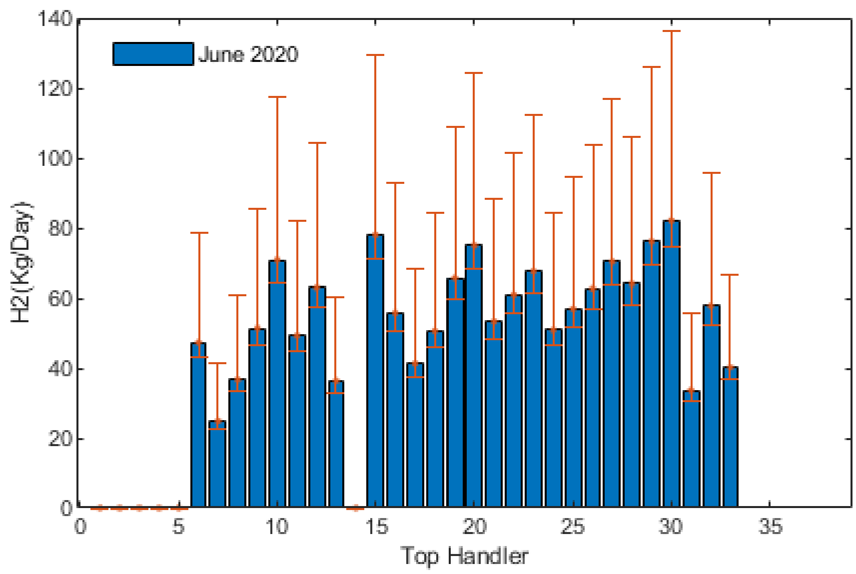
Credit: APEP

Figure 38. Hydrogen Need of a 100% Fuel Cell-Electric Yard Tractor Fleet

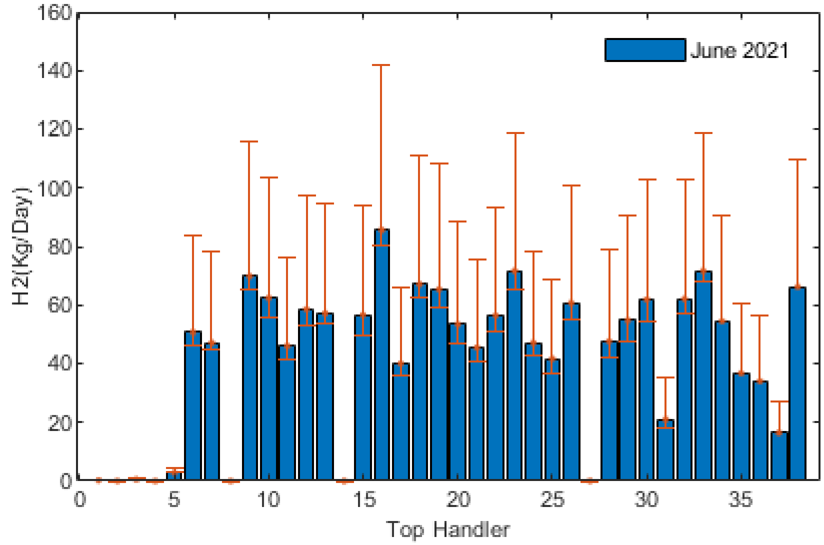


Credit: APEP

Figure 39. Hydrogen Need of Fuel Cell-Electric Top Handlers



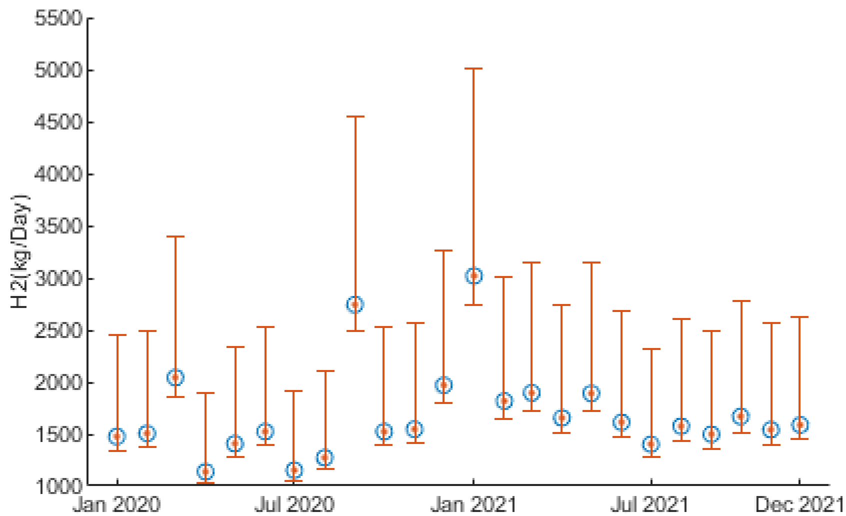
(a)



(b)

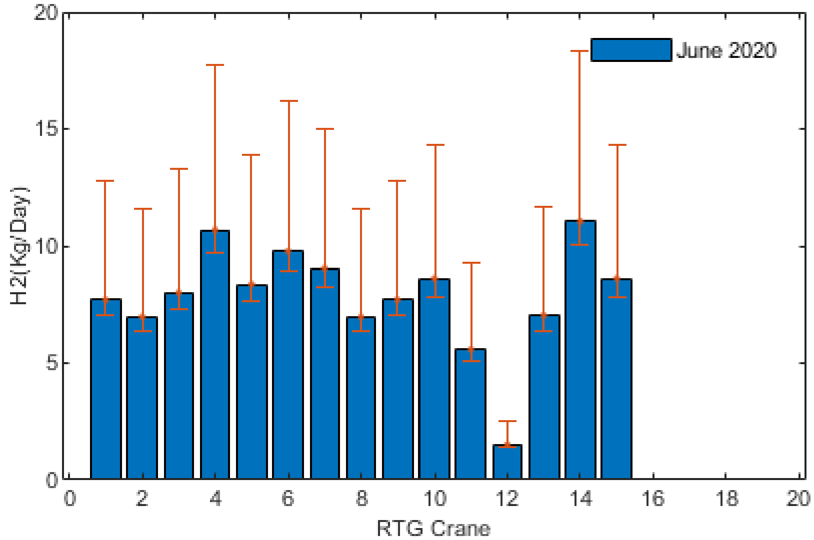
Credit: APEP

Figure 40. Hydrogen Need of a 100% Fuel Cell-Electric Top Handler Fleet

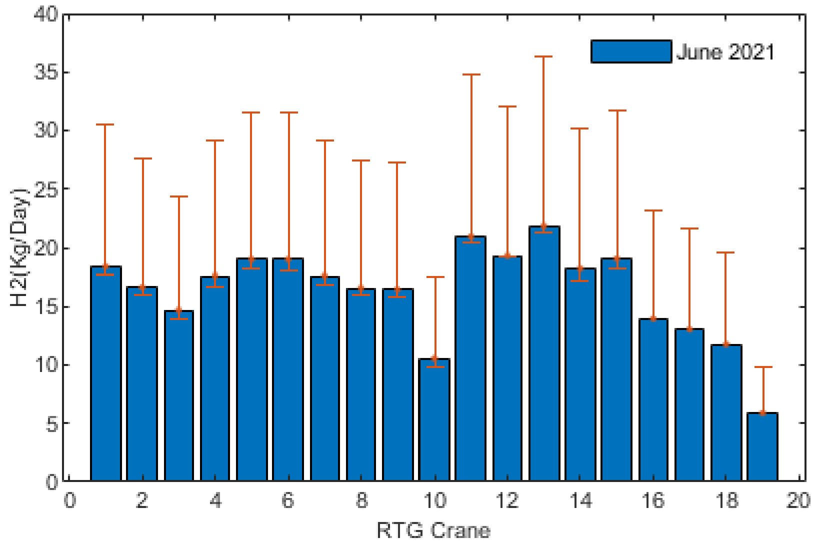


Credit: APEP

Figure 41. Hydrogen Need of Fuel Cell-Electric RTG Crane



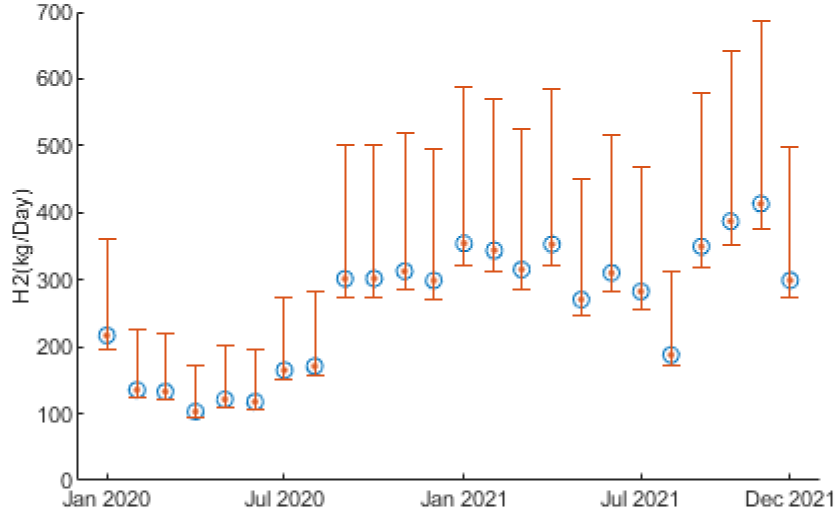
(a)



(b)

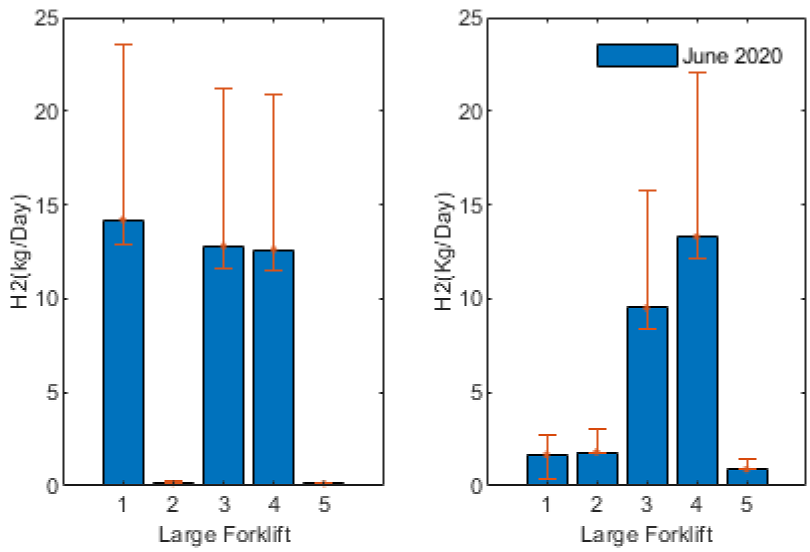
Credit: APEP

Figure 42. Hydrogen Need of a 100% Fuel Cell-Electric RTG Crane Fleet



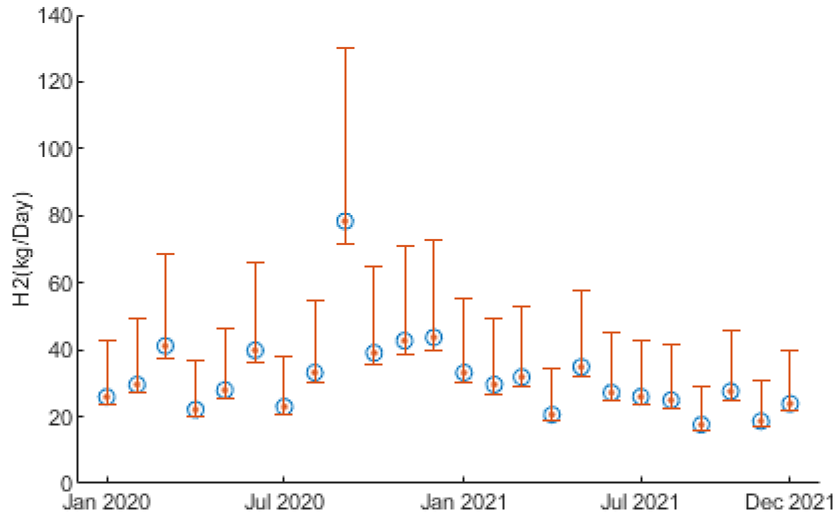
Credit: APEP

Figure 43. Hydrogen Need of Fuel Cell-Electric Large Forklift



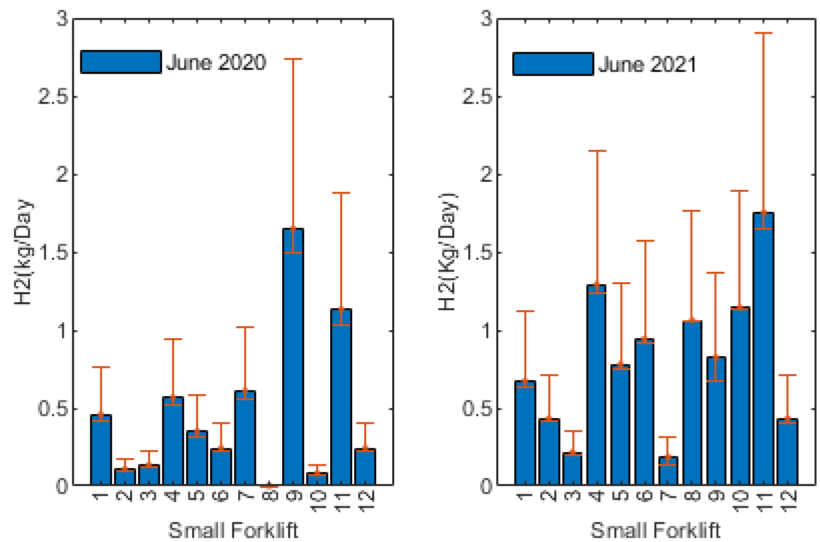
Credit: APEP

Figure 44. Hydrogen Need of a 100% Fuel Cell-Electric Large Forklift Fleet



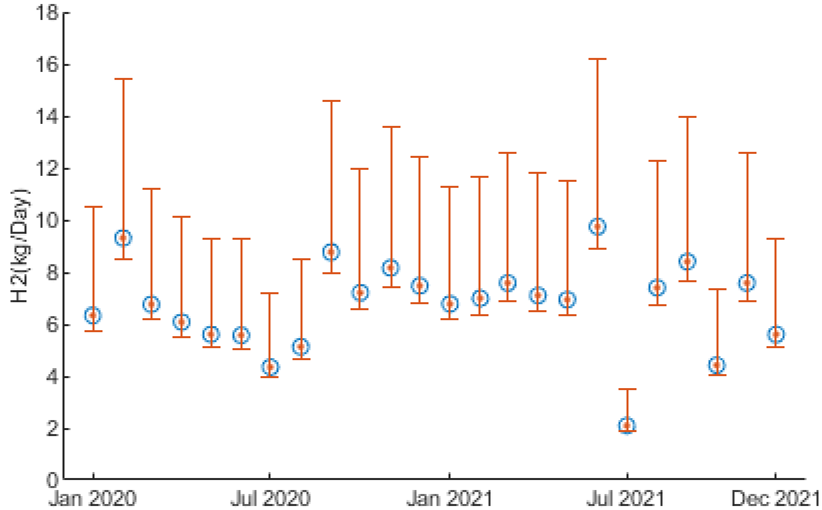
Credit: APEP

Figure 45. Hydrogen Need of Small Fuel Cell-Electric Forklift



Credit: APEP

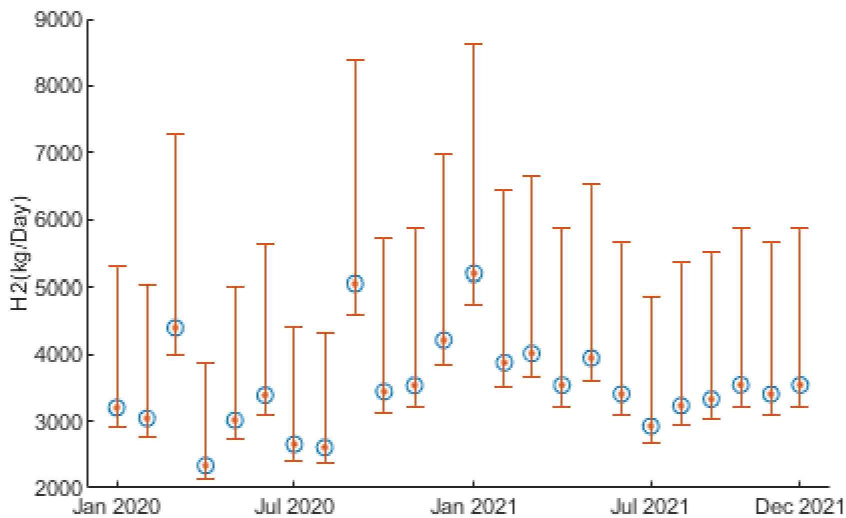
Figure 46. Hydrogen Need of a 100% Small Fuel Cell-Electric Forklift Fleet



Credit: APEP

The overall hydrogen demand of a 100 percent hydrogen fuel cell-electric CHE fleet on the ITS terminal under study is shown in Figure 47. The average daily hydrogen demand of a 100 percent fuel cell-electric CHE is 3,500 kilograms per day (kg/day) with a maximum of 5,000 kg/day. A study by the Pacific Northwest National Laboratory and Oak Ridge National Laboratory estimates hydrogen demand of fuel cell-electric CHE (shown in Table 12) [59]. Using these estimates, and number of each CHE type on the terminal, the daily hydrogen demand of a fully fuel cell-electric CHE fleet will be about 5,000 kg/day. Note that this estimate does not take into account the different operational hours of individual CHE in each fleet and their day-to-day changes.

Figure 47. Daily Hydrogen Demand of a Fully Fuel Cell-Electric CHE Fleet for the Terminal



Credit: APEP

Table 12. Estimated Hydrogen Utilization

CHE	H2 (kg/Day)
Yard Tractor	21
Top Handler	33-56
RTG Crane	45
Forklift	4

Source: Steel et al. [59]

3.3 Mixed Fleet

The two extreme scenarios, 100 percent battery-electric and 100 percent hydrogen fuel cell-electric CHE, were discussed in Section 3.1 and Section 3.2. The same methodology described in those previous sections is also used to determine the electricity demand of the battery-electric fleet (kWh/day) and hydrogen demand (kg/day) of hydrogen fuel cell-electric fleet. The scenarios studied include 100% zero-emission CHE fleet with varying fleet mix spanning 0.0 percent to 100 percent of battery-electric fleet (100 percent to 0.0 percent hydrogen fuel cell) in 10 percent steps. Since battery-electric options are more mature, it is assumed that the older equipment will be retired and replaced first, followed by CHE that have the lowest daily average operating hours. This is to ensure that at the beginning of the transition, the number of battery-electric CHE that need to be charged more than once a day is reduced. After the CHE with battery-electric options are selected, it is assumed that the rest will be hydrogen fuel cell-electric options in order to achieve a 100 percent zero-emission CHE fleet. The results are presented in Table 13 for each type of CHE discussed. Table 13 also shows the percentage of the fleet that needs to be charged at least twice in a day for yard tractors and top handlers assuming a battery size of 240 kWh and 931 kWh, respectively and 80 percent useful SOC.

Table 13. Mixed Fleet Electricity Demand and Hydrogen Demand

Battery-Electric %		100	90	80	70	60	50	40	30	20	10	0
Fuel Cell %		**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
UTR	**Avg. Electricity (kWh/day)**	21,500	19,400	16,600	13,700	11,000	8,800	6,500	4,400	2,400	565	0
	Max. Electricity (kWh/day)	30,100	26,400	23,600	20,800	18,100	15,800	12,200	8,300	4,900	1,580	0
	Charge multiple times (%)	43[9] (13-67)	38 (12-60)	31 (12-54)	24 (8-45)	18 (5-37)	14 (4-31)	9 (2-26)	6 (1-18)	2 (0-11)	~0 (0-2)	0
	Avg. H_2 (kg/day)	0	148	355	600	753	915	1,090	1,230	1,380	1,500	1,550
	Max. H_2 (kg/day)	0	290	495	700	876	1,080	1,300	1,570	1,820	2,110	2,170
Top Handler	**Avg. Electricity (kWh/day)**	16,400	15,900	14,100	12,600	10,200	7,900	5,700	3,100	1,330	143	0
	Max. Electricity (kWh/day)	29,800	29,700	25,500	22,900	18,400	14,000	10,500	5,900	2,560	803	0
	Charge multiple times (%)	13 (0-55)	12 (0-55)	11 (0-53)	10 (0-47)	9 (0-37)	7 (0-26)	6 (0-18)	2 (0-10)	1 (0-5)	0	0
	Avg. H_2 (kg/day)	0	61	241	393	644	870	1,100	1,350	1,540	1,660	1,690
	Max. H_2 (kg/day)	0	198	987	1,300	1,590	1,900	2,200	2,500	2,800	2,970	3,020
RTG Crane	**Avg. Electricity (kWh/day)**	6,850	6,580	6,380	5,470	4,580	4,140	3,370	2,490	1,630	807	0
	Max. Electricity (kWh/day)	10,900	9,600	9,310	7,970	6,680	6,100	5,000	3,760	2,590	1,390	0
	Avg. H_2 (kg/day)	0	10	18	52	86	103	133	166	198	229	260
	Max. H_2 (kg/day)	0	48	88	134	176	200	243	282	323	368	413
Large Forklift	**Avg. Electricity (kWh/day)**	835	691	691	387	387	137	137	59	59	0	0
	Max. Electricity (kWh/day)	2,060	1,390	1,390	713	713	377	377	373	373	0	0
	Avg. H_2 (kg/day)	0	5	5	17	17	26	26	29	29	32	32
	Max. H_2 (kg/day)	0	26	26	52	52	70	70	77	77	78	78
Small Forklift	**Avg. Electricity (kWh/day)**	177	145	122	82	72	64	50	35	13	6	0
	Max. Electricity (kWh/day)	256	210	188	153	142	114	80	62	24	14	0
	Avg. H_2 (kg/day)	0	1.2	2	3.6	4	4.2	4.8	5	6	6.5	7
	Max. H_2 (kg/day)	0	1.9	3	5	5.9	6	6.7	7	9	9.5	10

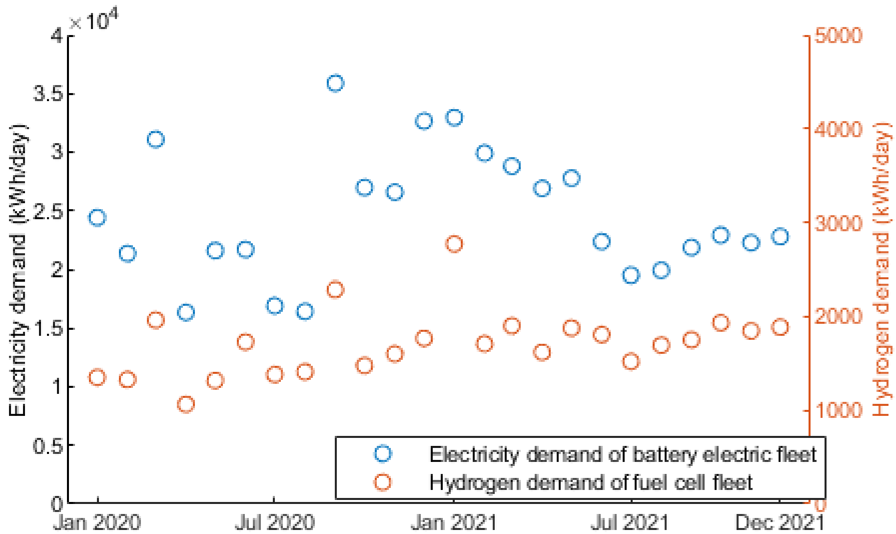
Source: APEP

9 The top shows the average percentage of the fleet than needs to be charged at least twice a day, the bottom shows (min-max) percentage based on the specific day and duty cycle.

Note that not all CHE types need to have the same market penetration of battery-electric or hydrogen fuel cell-electric options. For example, 100 percent of the forklift fleet can be hydrogen fuel cell-electric while other CHE types have a mix of battery-electric and hydrogen fuel cell-electric options with different penetrations. The results presented in Table 13 cover these cases as well. For example, the overall electricity and hydrogen demands for a mix of battery-electric and hydrogen fuel cell-electric CHE can be inferred from Table 13 and more detailed results of this case are provided in Figure 48.

- Yard tractor: 60 percent battery-electric, 40 percent hydrogen fuel cell-electric
- Top handler: 50 percent battery-electric, 50 percent hydrogen fuel cell-electric
- RTG crane: 70 percent electric, 30 percent hydrogen fuel cell-electric
- Large forklift: 50 percent battery-electric, 50 percent hydrogen fuel cell-electric
- Small forklift: 100 percent hydrogen fuel cell-electric

Figure 48. Electricity and Hydrogen Demand of a Mixed CHE Fleet for a Terminal



Credit: APEP

4 Infrastructure and Technologies to Support Electric Charging and Hydrogen Fueling

In the previous chapter, electricity and hydrogen demand of a 100 percent zero-emission CHE fleet was determined for a variety of scenarios with different penetration and mix of battery-electric and hydrogen fuel cell-electric options. In this chapter, using the results previously presented, the infrastructure that will be required to support the charging of battery-electric CHE and hydrogen fueling of fuel cell-electric CHE, is discussed.

4.1 Charging and EVSE Infrastructure

The daily electricity demand of battery-electric CHE, determined in the previous chapter, is used to determine the required charging infrastructure. Most terminals operate in two shifts (some three): Shift 1 typically works from 8:00 a.m. to 5:00 p.m. and Shift 2 works from 6:00 p.m. to 3:00 a.m. The ideal time to charge the battery-electric CHE is at the end of the day, from 3:00 a.m. to 8:00 a.m. As discussed in the previous chapter, some of the battery-electric CHE need to be charged at least twice per day, and five hours might not be sufficient. To address this, other charging opportunities include: 12:00 p.m. to 1:00 p.m., 5:00 p.m. to 6:00 p.m., and 10:00 p.m. to 11:00 p.m. While between the two shifts (5:00 p.m. to 6:00 p.m.) might appear to be a good time for charging, this period is during peak times when terminals are on an elevated time-of-use (TOU) tariff and more expensive to charge battery-electric CHE. As a result, charging during this period was avoided as much as possible in the upcoming analysis.

In this section, necessary EVSE, grid upgrades (utility side and terminal side), and other considerations, such as rearranging the parking spaces, are discussed.

4.1.1 Yard Tractors

Since the equipment on the terminal are being used at the same time, it is preferred to have one charger per equipment. This assumption was confirmed by a survey conducted by POLB [19]. In the battery-electric yard tractor demonstrations, the chargers for battery-electric yard tractors were DCFC at 70 kW, 100 kW, and 200 kW. During the demonstration on the ITS terminal under study with seven battery-electric yard tractors, six 200 kW DCFC BYD chargers were deployed along with a 100 kW Cavotec automated charger. In this section, it is assumed that 200 kW DCFC chargers are deployed and, for the purpose of determining maximum power for grid planning and infrastructure, 200 kW per charger is adopted.

Data from the demonstration and published reports show that the average charging power was 80 kW to 100 kW when only one charging port on the vehicle was used [15]. When two ports of the vehicle were used, the charging power average was 140 kW, with a maximum of 185 kW. A charging rate of 140 kW is used to determine the duration of charging sessions. To determine maximum power during charging of the fleet (1) 185 kW is used per charger, and (2) in the absence of any charging control, the entire electric fleet is assumed to be connected to the EVSE with charging starting at 3:00 a.m. when the second shift ends. Delayed and controlled charging strategies are discussed later in this chapter.

To determine charging needs, it is assumed that all battery-electric yard tractors have a 240 kWh battery with 200 kWh usable energy. Using the results presented in the previous chapter, all battery-electric yard tractors with less than 200 kWh daily energy demand can be charged only once per day, between 3:00 a.m. and 8:00 a.m. For the equipment with more than 200 kWh energy demand, first priority charging is 12:00 p.m. to 1:00 p.m. since (1) it is off-peak, and (2) it can take advantage of solar photovoltaic (PV) if deployed at the terminal. The second option is 10:00 p.m. to 11:00 p.m., since some TOU tariffs can be mid-peak, and the last option is 5:00 p.m. to 6:00 p.m., because it is during peak pricing and avoided as much as possible. Moreover, it is assumed that during the day (12:00 p.m. to 1:00 p.m., 5:00 p.m. to 6:00 p.m., and 10:00 p.m. to 11:00 p.m.), if the equipment is connected to the EVSE, the charging stops if the battery is full or the one-hour session is completed, whichever comes first. Additionally, it is assumed that the operation of the equipment is spread out evenly throughout the day and the two shifts since data providing the operation of CHE at each hour of the day are not available.

Based on assumptions and inputs discussed above, as well as the results of the two previous chapters, the number of chargers, the maximum power for grid infrastructure planning, the maximum fleet charging power, the total daily charging hours for the battery-electric yard tractor fleet, and the percentage of charging that occurs during each charging opportunity are determined and provided in Table 14. For the latter two, both the average and worst case observed are provided. The average case uses the average operating hours of a specific piece of equipment and the worst uses the maximum daily operating hours of that equipment observed in two years of data. The worst case has a low probability of occurring.

To accommodate DCFC equipment, including the cabinets and dispensers, the CHE parking lots need to be rearranged. POLB estimated that, for lane parking, 400 square feet per yard tractor is dedicated, and accommodating DCFC equipment will increase that by 50 percent [37]. For stacked parking, POLB estimated that an additional 50 square feet will be required per electric yard tractor. The results are included in Table 14.

Grid infrastructure on both the utility-side and customer (terminal) side should be upgraded. On the utility side, the infrastructure needs to be upgraded to accommodate the addition of a significant load. This includes addition or upgrade of pad-mounted equipment, capacitor banks, transformers, distribution conduit and cables, and switchgear. On the terminal side, parking spots need to be rearranged and DCFC equipment installed.

Note that the grid upgrade requirements depend on the existing infrastructure as well as the number of battery-electric yard tractor and other equipment. The ITS terminal under study has a monthly electricity demand of 88 MWh to 138 MWh per day. Therefore, a 100 percent battery-electric yard tractor fleet can add 15 percent to 37 percent to the daily electricity usage. On the other hand, a study conducted by Matulka et al. concluded that largest terminals have a 10 MW to 15 MW peak demand [60]; thus, the addition of chargers for battery-electric yard tractors has the potential to increase the peak demand 1.7 to 2.7 times (see Table 14), especially in absence of any charging strategy and control.

Table 14. Summary of Infrastructure Considerations for Battery-Electric Yard Tractor Deployment

Battery-Electric %		0	10	20	30	40	50	60	70	80	90	100
Number of Chargers		0	13	26	40	53	66	79	92	106	119	132
Max Power for Grid Planning (MW)		0	2.6	5.2	8	10.6	13.2	15.8	18.4	21.2	23.8	26.4
Max Fleet Charging Power (MW)		0	2.4	4.8	7.4	9.8	12.2	14.6	17	19.6	22	24
Additional Space for DCFC Equipment	**Lane Parking**	NA	2,600	5,200	8,000	10,600	13,200	15,800	18,400	21,200	23,800	26,400
	Stacked Stalls	NA	650	1,300	2,000	2,650	3,300	3,950	4,600	5,300	5,950	6,600
Average Fleet Total Hours of Charging per Day		NA	7.3	21	37	54	72	91	111	134	155	180
Charging Time at each Interval (%)	**3:00 a.m. - 8:00 a.m.**	NA	100	100	100	100	100	95.5	91.8	89	87	82
	12:00 p.m. - 1:00 p.m.	NA	0	0	0	0	0	4.5	8.2	11	13	15
	5:00 p.m. - 6:00 p.m.	NA	0	0	0	0	0	0	0	0	0	0
	10:00 p.m. - 11:00 p.m.	NA	0	0	0	0	0	0	0	0	0	3
Worst Case Fleet Total Hours of Charging per Day		NA	20.7	51.6	88	121	156	188	220	256	291	326
Charging Time at each Interval (%)	**3:00 a.m. - 8:00 a.m.**	NA	57.4	44	40.2	38.5	36.6	36	35.5	35.1	34.4	34.6
	12:00 p.m. - 1:00 p.m.	NA	19.5	22.8	23.7	24.1	24.2	24.4	24.5	24.5	24.6	24.7
	5:00 p.m. - 6:00 p.m.	NA	4.3	3.1	4.5	4.7	5.8	5.2	4.9	4.8	5.6	5.2
	10:00 p.m. - 11:00 p.m.	NA	18.8	30.1	31.6	32.7	33.4	34.4	35.1	35.6	35.4	35.5

Source: APEP

4.1.2 Top Handler

The battery-electric top handlers that were demonstrated have a battery size of 931 kWh and 200 kW DCFC chargers. There is currently a demonstration of a hybrid top handler (battery-electric with hydrogen fuel cell range extender) that uses 250 kW wireless charging [43]. In this section, 200 kW DCFC was assumed. In the absence of available data, an average of 150 kW charging rate was assumed for the charging of the top handler fleet. Other assumptions are similar to battery-electric yard tractors in the previous section and are presented in Table 15. The infrastructure upgrade and space consideration are similar to battery-electric yard tractors previously discussed.

Table 15. Summary of Infrastructure for Battery-Electric Top Handler Deployment

Battery-Electric %		0	10	20	30	40	50	60	70	80	90	100
Number of Chargers		0	4	8	11	15	19	23	27	30	34	38
Max. Power for Grid Planning (MW)		0	0.8	1.6	2.2	3	3.8	4.6	5.4	6	6.8	7.6
Max. Fleet Charging Power (MW)		0	0.74	1.48	2.03	2.78	3.52	4.26	5	5.55	6.29	7.03
Average Fleet Total Hours of Charging per Day		NA	1.47	11.51	23.5	50	55.7	70.8	87.5	97.7	110.1	118
Charging Time at each Interval (%)	3:00 a.m. - 8:00 a.m.	NA	100	100	100	100	100	100	100	100	100	100
	12:00 p.m. - 1:00 p.m.	NA	0	0	0	0	0	0	0	0	0	0
	5:00 p.m. - 6:00 p.m.	NA	0	0	0	0	0	0	0	0	0	0
	10:00 p.m. - 11:00 p.m.	NA	0	0	0	0	0	0	0	0	0	0
Worst Case Fleet Total Hours of Charging per Day		NA	7.86	28.23	53.4	81	108.2	137.6	168.8	192.8	217.5	235.5
Charging Time at each Interval (%)	3:00 a.m. - 8:00 a.m.	NA	100	89.4	76.6	72.9	71.3	69.5	68	67.3	66.9	68.7
	12:00 p.m. - 1:00 p.m.	NA	0	7.1	9.7	11.1	12	12.4	12.4	12.4	12.4	12
	5:00 p.m. - 6:00 p.m.	NA	0	0	5.9	6.2	6.5	7.2	8.3	8.9	9.2	8.6
	10:00 p.m. - 11:00 p.m.	NA	0	3.5	7.8	9.8	10.2	10.9	11.3	11.4	11.5	10.7

Source: APEP

4.1.3 RTG Crane

Electrified RTG cranes are different from yard tractors and top handlers that have been discussed so far. They are grid-tied[10] (although some have energy storage to offset peaks). Since it is grid-tied, the operation of this equipment will not have to be modified for zero

---

[10] Having a direct and constant connection to the grid

emission. On the other hand, electricity demand peaks are harder to manage and will require deployment of distributed energy resources (DER)[11] on the terminal [52].

A demonstration at POLB with Southern California Edison is in the process of deploying nine grid-tied RTG crane conversions. To charge these electric RTG cranes, a 4kV (kilovolt) grid-connection was adopted. The infrastructure includes new 12 kV circuits, a pad-mounted capacitor bank, four new 12 kV/4 kV distribution substation, four 500 kilovolt-ampere (kVA) 12 kV/4 kV transformers, switches, and conduits and cables. The necessary infrastructure is specific to the terminal, the existing infrastructure, and the horsepower of the RTG crane.

For a 250 hp RTG crane and the efficiencies observed, the peak demand is estimated to be about 180 kW. (Note, the average demand is lower, see Section 3.1.3). The results for the maximum power required are presented in Table 16.

Table 16. Summary of Infrastructure for Grid-Tied RTG Cranes

Battery-Electric %	0	10	20	30	40	50	60	70	80	90	100
Number of 4 kV Connections to Utility	0	2	4	6	8	10	11	13	15	17	19
Max. Power of the Electric RTG Crane Fleet (MW)	NA	0.4	0.7	1.1	1.4	1.8	2	2.3	2.7	3.1	3.4

Source: APEP

4.1.4 Forklift

Small battery-electric forklifts have 10 kW chargers (some can be up to 30 kW). Since there are only 12 small battery-electric forklifts at the terminal, and their charging rate is relatively low, they comprise a small load when compared to the other CHE. It is expected that little to no changes to the grid infrastructure will be required to deploy small battery-electric forklifts.

For large forklifts, battery-electric options are available between 18 tons to 33 tons. These forklifts have 163 kWh, 245 kWh, or 392 kWh batteries, and the chargers range between 50 kW to 350 kW [61]. For this analysis, a 392 kWh battery is chosen with a charging rate of 200 kW (since the other electric equipment have a 200 kW charger and the lower charging rate might not meet the operational needs of the equipment). The results are shown in Table 17. The analysis is repeated with 350 kW chargers, which results in fewer charging sessions during the day, but might increase the peak load (Table 18). Note that the load and peak of the large battery-electric forklift fleet is much smaller than the demand and peak of battery-electric electric yard tractors or top handlers.

[11] Resources (resources include generation, storage and controllable loads) that are connected to the distribution system (66 kV and lower) and close to the loads they serve.

Table 17. Summary of Infrastructure for Battery-Electric Large Forklift (200 kW charger)

Battery-Electric %		0	20	40	60	80	100
Number of Chargers		0	1	2	3	4	5
Max Fleet Charging Power (MW)		0	0.2	0.4	0.6	0.8	1
Average Fleet Total Hours of Charging per Day		NA	0.32	0.71	2	3.5	4.3
Charging Time at each Interval (%)	3:00 a.m. - 8:00 a.m.	NA	100	100	100	88.9	90.8
	12:00 p.m. - 1:00 p.m.	NA	0	0	0	11.1	9.2
	5:00 p.m. - 6:00 p.m.	NA	0	0	0	0	0
	10:00 p.m. - 11:00 p.m.	NA	0	0	0	0	0
Worst Case Fleet Total Hours of Charging per Day		NA	1.87	3.2	5.7	9.1	12.5
Charging Time at each Interval (%)	3:00 a.m. - 8:00 a.m.	NA	75	85.6	63.4	49	42.5
	12:00 p.m. - 1:00 p.m.	NA	25	14.4	18.9	21.2	22.2
	5:00 p.m. - 6:00 p.m.	NA	0	0	0	20.4	21.7
	10:00 p.m. - 11:00 p.m.	NA	0	0	17.7	9.4	13.6

Source: APEP

Table 18. Summary of Infrastructure for Battery-Electric Large Forklift (350 kW charger)

Battery-Electric %		0	20	40	60	80	100
Number of Chargers		0	1	2	3	4	5
Max. Fleet Charging Power (MW)		0	0.35	0.7	2.25	1.4	1.75
Average Fleet Total Hours of Charging per Day		NA	0.18	0.4	1.1	2	2.5
Charging Time at each Interval (%)	3:00 a.m. - 8:00 a.m.	NA	100	100	100	88.8	90.8
	12:00 p.m. - 1:00 p.m.	NA	0	0	0	11.2	9.2
	5:00 p.m. - 6:00 p.m.	NA	0	0	0	0	0
	10:00 p.m. - 11:00 p.m.	NA	0	0	0	0	0
Worst Case Fleet Total Hours of Charging per Day		NA	1.1	1.9	3.2	5.2	7.1
Charging Time at each Interval (%)	3:00 a.m. - 8:00 a.m.	NA	75	85.6	81.1	60	50.5
	12:00 p.m. - 1:00 p.m.	NA	25	14.4	18.9	21.2	22.2
	5:00 p.m. - 6:00 p.m.	NA	0	0	0	0	0
	10:00 p.m. - 11:00 p.m.	NA	0	0	0	18.8	27.3

Source: APEP

4.1.5 Controlled Charging

So far, in this section for battery-electric options, uncontrolled charging was assumed. Uncontrolled charging means that the charging starts when the vehicle/equipment is connected to EVSE and it stops when the battery is fully charged or when the charging session ends, whichever comes first. While this approach is the simplest one to implement, it might result in high peak demand and, consequently, high demand charges. To mitigate high peak demand, one approach is to use delayed charging. In the case of a delayed charging, the charging does not start right away, and instead starts at a set time after the equipment is connected. The delayed charging is only implemented for the 3:00 a.m. to 8:00 a.m. intervals and not for the other three charging windows. The reason is that the other charging windows are short (1 hour). For battery-electric yard tractor (assuming a 240 kWh battery, 140 kW average charging rate, and 185 kW maximum charging rate), the fleet is divided into three groups. The first group starts charging right away, the second starts charging with a delay of 1.5 hours and the third with a delay of 3.0 hours. The same strategy is implemented for large forklifts (with 392 kWh and 200 kW charging rate). For battery-electric top handlers with a battery size of 931 kWh and charging rate of 150 kW to 200kW, not all of the fleet can be fully charged in less than five hours, and thus a simple delayed charging does not guarantee that all the fleet will be fully charged at 8:00 a.m. A smart charging strategy, discussed next, is appropriate for this situation. The results of the delayed charging are provided in Table 19 for both the average and worst cases.

A smart charging strategy can be used to minimize the peak load during each charging opportunity. To this end, an optimization is used. The objective of the optimization is to minimize peak load with the following constraints: (1) all equipment be fully charged at 8:00 a.m., and (2) for charging during the day, the equipment should have enough SOC to perform its task until next charging session. Note that implementation of the smart charging strategy requires communication with the vehicle and the EVSE. Based on the SOC at the time the vehicle is connected to EVSE and forecasted operation of the equipment, a charging profile was determined for each vehicle. The results of smart charging are shown in Table 19.

Results associated with the battery-electric yard tractor fleet show that delayed charging can help reduce the peak demand (in MW) by up to 70 percent for 3:00 a.m. to 8:00 a.m., and smart charging can result in an average of 10 percent to 20 percent more reduction in peak demand compared to delayed charging. Additionally, smart charging can help reduce the peak demand during other charging opportunities as shown in Table 19.

For battery-electric top handlers, smart charging can reduce the peak demand between 45 percent to 62 percent compared to uncontrolled charging. Similar results are observed for large forklifts.

Table 19. Peak Load (MW) for Delayed and Smart Charging Strategies

Battery-Electric %			0	10	20	20	40	50	60	70	80	90	100
UTR Peak Demand Average Case (MW)	**3:00 a.m. - 8:00 a.m.**	Uncontrolled	NA	2.4	4.8	7.4	9.8	12.21	14.61	17.02	19.6	22.02	24.42
		Delayed	NA	0.92	1.67	2.59	3.33	4.07	5	5.74	6.66	7.4	8.14
		Smart	NA	0.37	0.93	1.48	2.04	2.78	3.33	3.89	4.44	5.18	5.55
	12:00 p.m. - 1:00 p.m.	Uncontrolled	NA	0	0	0	0	0	2.04	4.44	7.03	9.44	11.84
		Smart	NA	0	0	0	0	0	0.93	1.85	2.78	3.89	5
	5:00 p.m. - 6:00 p.m.	Uncontrolled	NA	0	0	0	0	0	0	0	0	0	0
		Smart	NA	0	0	0	0	0	0	0	0	0	0
	10:00 p.m. - 11:00 p.m.	Uncontrolled	NA	0	0	0	0	0	0	0	0	0	11.1
		Smart	NA	0	0	0	0	0	0	0	0	0	11.1
UTR Peak Demand Worst Case	**3:00 a.m. - 8:00 a.m.**	Uncontrolled	NA	2.4	4.8	7.4	9.8	12.21	14.61	17.02	19.6	22.02	24.42
		Delayed	NA	0.92	1.67	2.59	3.33	4.07	5	5.74	6.66	7.4	8.14
		Smart	NA	0.55	0.93	1.48	1.85	2.22	2.59	2.96	3.33	3.7	4.26
	12:00 p.m. - 1:00 p.m.	Uncontrolled	NA	1.29	3.7	6.29	8.7	11.1	13.51	15.91	18.5	20.91	23.31
		Smart	NA	0.93	2.22	3.89	5.55	7.03	8.51	10	11.66	13.3	14.99
	5:00 p.m. - 6:00 p.m.	Uncontrolled	NA	0.19	0.37	0.93	1.3	2.04	2.22	2.41	2.78	3.7	3.89
		Smart	NA	0.19	0.37	0.93	1.11	1.85	1.85	2.04	2.41	3.15	3.15
	10:00 p.m. - 11:00 p.m.	Uncontrolled	NA	0.74	2.96	5.37	7.59	9.99	12.4	14.8	17.39	19.8	22.2
		Smart	NA	0.74	2.96	5.18	7.4	9.62	12.03	14.43	17.02	19.24	21.46
Top Handler Peak Demand Average Case (MW)	**3:00 a.m. - 8:00 a.m.**	Uncontrolled	NA	0.74	1.48	2.03	2.78	3.52	4.26	5	5.55	6.29	7.03
		Smart	NA	0.19	0.56	0.93	1.67	2.22	2.78	3.33	3.7	4.26	4.44
	12:00 p.m. - 1:00 p.m.	Uncontrolled	NA	0	0	0	0	0	0	0	0	0	0
		Smart	NA	0	0	0	0	0	0	0	0	0	0
	5:00 p.m. - 6:00 p.m.	Uncontrolled	NA	0	0	0	0	0	0	0	0	0	0
		Smart	NA	0	0	0	0	0	0	0	0	0	0
	10:00 p.m. - 11:00 p.m.	Uncontrolled	NA	0	0	0	0	0	0	0	0	0	0
		Smart	NA	0	0	0	0	0	0	0	0	0	0

Battery-Electric %			0	10	20	20	40	50	60	70	80	90	100
Top Handler Peak Demand Worst Case (MW)	**3:00 a.m. - 8:00 a.m.**	Uncontrolled	NA	0.74	1.48	2.03	2.78	3.52	4.26	5	5.55	6.29	7.03
		Smart	NA	0.37	1.11	1.11	1.48	2.22	2.78	2.96	2.96	3.15	3.7
	12:00 p.m. - 1:00 p.m.	Uncontrolled	NA	0	0.37	0.93	1.67	2.41	3.15	3.89	4.44	5	5.18
		Smart	NA	0	0.37	0.56	0.93	1.67	2.22	2.59	2.59	2.59	2.78
	5:00 p.m. - 6:00 p.m.	Uncontrolled	NA	0	0	0.56	0.93	1.3	1.85	2.59	3.15	3.7	3.7
		Smart	NA	0	0	0.19	0.19	0.56	0.93	1.3	1.3	1.3	1.3
	10:00 p.m. - 11:00 p.m.	Uncontrolled	NA	0	0.19	0.74	1.48	2.04	2.78	3.52	4.07	4.63	4.63
		Smart	NA	0	0.19	0.37	0.74	1.3	1.85	2.22	2.22	2.22	2.22
Large Forklift Peak Demand Average Case	**3:00 a.m. - 8:00 a.m.**	Uncontrolled	NA	-	0.2	0.2	0.4	0.4	0.6	0.6	0.8	0.8	1
		Delayed	NA	-	0.2	0.2	0.2	0.2	0.2	0.2	0.4	0.4	0.4
		Smart	NA	-	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	12:00 p.m. - 1:00 p.m.	Uncontrolled	NA	-	0	0	0	0	0	0	0.2	0.2	0.2
		Smart	NA	-	0	0	0	0	0	0	0.2	0.2	0.2
	5:00 p.m. - 6:00 p.m.	Uncontrolled	NA	-	0	0	0	0	0	0	0	0	0
		Smart	NA	-	0	0	0	0	0	0	0	0	0
	10:00 p.m. - 11:00 p.m.	Uncontrolled	NA	-	0	0	0	0	0	0	0	0	0
		Smart	NA	-	0	0	0	0	0	0	0	0	0
Large Forklift Peak Demand Worst Case	**3:00 a.m. - 8:00 a.m.**	Uncontrolled	NA	-	0.2	0.2	0.4	0.4	0.6	0.6	0.8	0.8	1
		Delayed	NA	-	0.2	0.2	0.2	0.2	0.2	0.2	0.4	0.4	0.4
		Smart	NA	-	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.4
	12:00 p.m. - 1:00 p.m.	Uncontrolled	NA	-	0.2	0.2	0.2	0.2	0.4	0.4	0.6	0.6	0.8
		Smart	NA	-	0.2	0.2	0	0	0.4	0.4	0.4	0.4	0.6
	5:00 p.m. - 6:00 p.m.	Uncontrolled	NA	-	0	0	0	0	0	0	0.2	0.2	0.4
		Smart	NA	-	0	0	0	0	0	0	0.2	0.2	0.4
	10:00 p.m. - 11:00 p.m.	Uncontrolled	NA	-	0	0	0	0	0.2	0.2	0.4	0.4	0.6
		Smart	NA	-	0	0	0	0	0.2	0.2	0.4	0.4	0.6

Source: APEP

Considerations

The delayed charging strategy is relatively easy to implement since most vehicles have the option. The driver at the end of the day (3:00 a.m.) needs to enable the delayed charging; however, for equipment that need to be charged during the day, the driver should remember to turn off the delay, otherwise failure to do so might result in the equipment not being able to perform the required tasks. For smart charging, communication between the vehicle and the EVSE is required, and while it eliminates the intervention of the driver, it will add to the overall costs.

4.1.6 Alternative Charging Approaches

In this section so far, it was assumed that DCFC is used to charge the battery-electric CHE. While using alternating current (AC) chargers might reduce the cost and size of the charging equipment and overall complexity of the required infrastructure, the industry and OEMs are moving toward a CCS standard charging interface. AC and DC connector markets are shown in Table 20 [62]. Notably, battery-electric options can be complemented with a hydrogen fuel cell. Several companies are offering battery-electric yard tractors with hydrogen fuel cell range extenders.

At the ports, a gearman needs to plug in the vehicle and not the driver. This hinders the capability to charge the vehicles during the day (at 12:00 p.m. to 1:00 p.m., 5:00 p.m. to 6:00 p.m., and 10:00 p.m. to 11:00 p.m.). As a result, an automatic charger is preferred that will connect to the vehicle without intervention. As previously mentioned, one of these chargers has already been demonstrated at POLB.

Another option is wireless (inductive) charging. Several projects are currently demonstrating wireless charging at the San Pedro Bay Ports. Implementation of wireless charging requires significant subsurface work and retrofit of the vehicle and will thus increase costs; however, the analysis should be updated once additional data and information becomes available from demonstrations of these technologies at the ports.

Table 20. Status of MD/HD Connectors and Standards

AC Connector Charging								
	Current Standards							**In Development**
Connector	GB/T 20234.2	e	IEC 62196.2 (Type 2 - Mennekes)	IEC 62196.2 (Type 3 - Scame)	SAE J1772 (Type 1)	SAE J3068	SAE J2954	SAE J2954-2
Current Type	AC	AC	AC[1]	AC	AC/DC[1]	AC	Inductive	Inductive
Power (kW)	14	10	Up to 33-43	Type 3A – 19.2 Type 3C – 43.6	AC: Up to 19.2 DC: Lvl 1- 80 kW Lvl 2 – 400 kW	Up to 133-166 kW	3.7, 7.7, 11, & 22 kW	Up to 500 kW
Voltage (V)	250/440	230	400/480 3/1ϕ	Type 3A – 230/240 Type 3C – 400	120/240 1ϕ, 208 3ϕ	480/600	N/A	N/A
Current (A)	16/32 (Rated 63)	15	63/70 3/1ϕ (Rated 300)	Type 3A – 32 1ϕ Type 3C – 63 3ϕ	80	160 3ϕ (Rated 300)	N/A	N/A
V2X						✓		
Markets	China	India	Europe	Europe (Now Deprecated)	North America, Japan	North America	North America	North America

DC EVSE Connector Market								
	Current Standard						In Development	
Connector	CHAdeMO	GB/T 20234.3	CCS1	CCS2	Tesla	SAE J3105[1]	SAE J3271 (MCS[12])	ChaoJi
Current Type	DC	DC	AC/DC	AC/DC	AC/DC	DC	DC	DC
Power (kW)	6 – 400	187.5	Up to 350, Planned 450	Up to 350, Planned 450	AC: up to 19.2 DC: 250, 350 Planned	L1: up to 350 kW L2: up to 1.2 MW	Up to 3.75 MW	50-900 kW (Expandable)
Voltage (V)	1,000	750	920, Planned 1,000	920, Planned 1,000	AC: 240 DC: 1,000	Up to 1,000	1,250	1,500
Current (A)	400	250	380 (Rated 500)	380 (Rated 500)	AC: 80A DC: 250, 350 Planned	Up to 1,200	3,000	600
V2X	✓		WIP	WIP			✓	✓
Markets	Japan, Sporadic	China	North America	Europe	North America	North America, Europe	North America, Europe	China, Japan

Data Source: Forrest et al. [62]

4.2 Hydrogen Fueling Infrastructure

The infrastructure for hydrogen fueling at a terminal was assumed to be very similar to existing diesel and gasoline options, namely hydrogen storage at or adjacent to the terminal and mobile hydrogen fuelers to drive around the terminal and fuel the hydrogen fuel cell-electric CHE once per day. The ITS terminal under study has two 12,000 gallon diesel and one 12,000 gallon gasoline storage tank. These tanks are filled once or twice per week, depending on the usage. It is expected that with the deployment of hydrogen fuel cell-electric CHE, these tanks will be replaced by hydrogen storage. Assuming that the hydrogen storage tanks will also be filled once or twice per week, the storage size was determined and the results are shown in Table 21. For a 100% hydrogen fuel cell-electric CHE (Scenario II in Section 3.2), a 25,000 gallon liquid hydrogen storage tank is required[13]. The storage size decreases as the frequency of refills increases per week. Nevertheless, the availability of hydrogen delivery and its frequency depends on the overall hydrogen ecosystem at the ports (see Section 4.3).

Once the hydrogen demand reaches a certain threshold (1,400 kg per day for this analysis), one of the 12,000 gallon diesel storage tanks can be removed and replaced with a permanent hydrogen storage size of which depends on the hydrogen demand and the number of hydrogen fuel cell-electric CHE. In the meantime, and during the transition, temporary hydrogen storage solutions, such as tube trailers are available and can be driven off of the site.

12 Megawatt Charging System

13 Existing liquid hydrogen storage are 1,500-25,000 gallons

The footprint of hydrogen storage tanks is greater compared to that of diesel storage tanks. This is an important factor since space is limited at port terminals. For example, an 18,000-gallon (4,000 kg) liquid hydrogen storage deployed by the Orange County Transportation Authority has a 300 square meter (m^2) footprint. To save space, some hydrogen storage tanks can be installed vertically; however, permitting of the vertical storage options might be more complicated and take more time.

Currently, the ITS terminal has two gearmen to refuel the CHE before and between shifts. While mobile hydrogen fuelers are available, their capacity is currently low and more than two might be needed to fuel the hydrogen fuel cell-electric fleet. Note that since the hydrogen fuel cell-electric CHE options are not yet commercial, it is difficult to estimate their fueling needs.

Table 21. Hydrogen Storage Size for Fuel Cell-Electric CHE

Fuel Cell %		0	10	20	30	40	50	60	70	80	90	100
UTR	Minimum Size of Hydrogen Storage (gal.)	0	2,000	4,000	5,000	6,000	8,000	9,000	11,000	12,000	14,000	15,000
Top Handler	Minimum Size of Hydrogen Storage (gal.)	0	1,500	7,000	9,000	11,000	13,000	15,000	17,000	19,000	20,000	20,000
RTG Crane	Minimum Size of Hydrogen Storage (gal.)	0	400	600	1,000	1,200	1,400	1,600	1,900	2,200	2,500	2,900
Large Forklift	Minimum Size of Hydrogen Storage (gal.)	0	200	200	350	350	500	500	500	500	500	500
Small Forklift	Size of Hydrogen Storage (gal.)	0	15	20	35	40	40	45	45	60	60	70

Source: APEP

When a customer hydrogen demand is 5,000 kg/day or higher, hydrogen providers will design and develop a dedicated supply chain[14] which will be more reliable. For Scenario II (a 100 percent hydrogen fuel cell CHE fleet discussed in Section 3.2), the hydrogen demand was estimated to be on average 3,500 kg/day, with a maximum of 5,000 kg/day, thus the hydrogen demand of a terminal will be less than 5,000 kg/day. However, if several of the terminals deploy hydrogen fuel cell-electric CHE, and with increased use and deployment of light-duty hydrogen fuel cell-electric vehicles and hydrogen fuel cell drayage trucks, the port hydrogen demand may exceed the threshold of 5,000 kg/day.

4.3 Distributed Energy Resources and Synergies

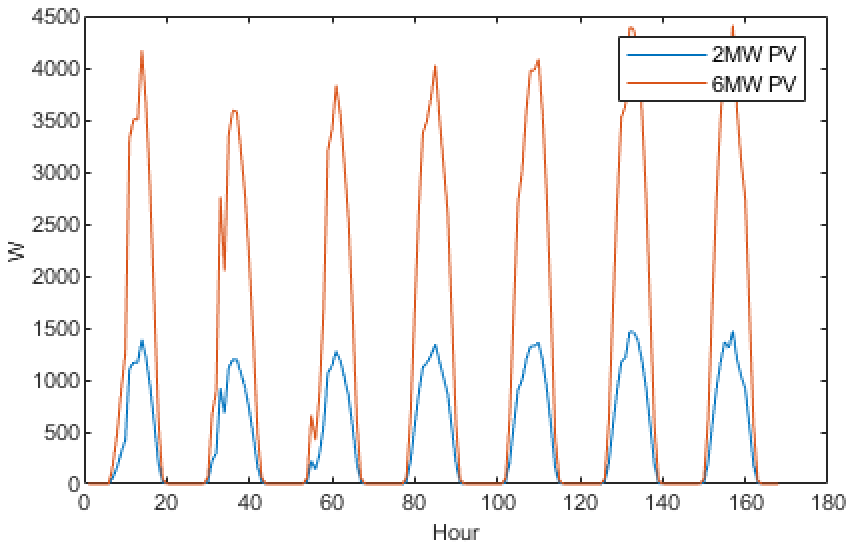
As demonstrated in Table 13 and Table 19 of this report, replacing the existing CHE with battery-electric options increased the electricity demand of the terminal. This increase will result in higher electricity costs and demand charges and possibly the overall cost of operation. One approach to address this increase in electricity demand is to deploy DER, such as solar PV or fuel cells.

---

[14] Based on discussions and interviews with several hydrogen providers

Using Google Earth[15], the area of the existing building rooftops on the ITS terminal is determined, and assuming a 150 W of PV power per m^2, almost 2 MW of PV panels can be installed on the existing buildings. Assuming that all CHE parking areas on the terminal can be covered in PV panels, 6 MW of PV panels can be installed on the terminal. Using NREL's PVWatts[16] calculator, the PV energy generation is determined and the results for a week in August are shown in Figure 49.

Figure 49. PV Generation



Credit: APEP

Additionally, the terminal can accommodate 15 MWh of energy storage and can further reduce electricity demand during peak or mid-peak hours. Stationary fuel cells are another DER option that have high efficiency, no criteria pollutant emissions and, most importantly, can be a source of 24/7 electricity. Existing fuel cell installations of 3.7 MW, 15 MW, and 59 MW have a footprint of 1,000 m^2, 6,000 m^2, and 20,000 m^2, respectively[17]. If the terminal can provide one acre for stationary fuel cell electricity generation, then 10 MW to 12 MW of stationary fuel cell resources can be deployed.

With the deployment of zero-emission CHE at the ports and the need to deploy DERs, it is necessary to discuss synergies. A hydrogen ecosystem at the port is shown in Figure 50. Stationary fuel cells, battery energy storage, and other DERs can supply the electricity need of the port, including electric CHE. Having an electrolyzer or reversible fuel cell[18] can capture excess PV energy and produce hydrogen, which can be used to support hydrogen fuel cell-electric CHE or fuel cells powered marine vehicles.

---

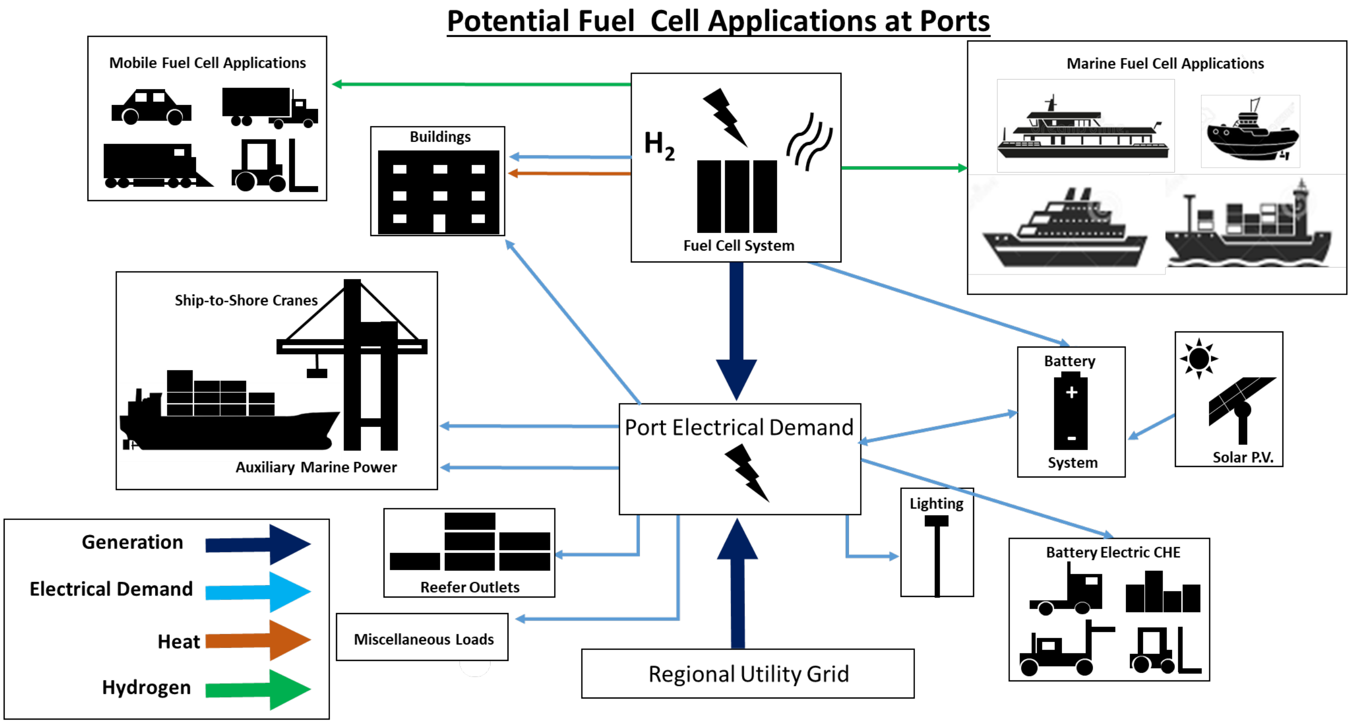
15 https://earth.google.com

16 https://pvwatts.nrel.gov/

17 https://www.fuelcellenergy.com/products/

18 A reversible or regenerative fuel can run in reverse mode, consume electricity and produce hydrogen.

Figure 50. Hydrogen Ecosystem at the Ports



Credit: Adapted from Mac Kinnon et al. [63]

4.4 Resiliency Considerations

When considering the mix of the zero-emission CHE fleet, resiliency is important to consider. The increased frequency of extreme weather events such as hurricanes, wildfires, and winter storms have impacted the resiliency of the electric grid and resulted in outages, including planned outages as occurs during a Public Safety Power Shutoff. The development and implementation of microgrid structures within port electrical infrastructure can facilitate different energy management goals, including the ability to maintain business continuity during emergencies or other unplanned grid disruption and to reduce the environmental footprint of operations. During grid outages, the terminals require 100 percent operation for outages lasting less than 48 hours. For outages longer than 48 hours, terminals can continue operation with some (such as CHE) at 50 percent capacity. Electrification of CHE increases the DER sizes on the microgrid significantly, and there is not sufficient space on the terminal to deploy enough DERs to support the 100 percent battery-electric and grid-tied CHE and other terminal loads (such as ship to shore demand). Thus, it is important to consider a mixed fleet of battery-electric and hydrogen fuel cell-electric options. A mixed fleet has several sources of energy for resiliency, including (1) electricity and hydrogen to ensure that not all vehicle operations are dependent on the grid and the DERs, and (2) reducing the amount of required DERs to support a microgrid during outages.

4.4.1 Microgrids

Microgrids provide local generation of electricity to complement the utility grid and thereby provide economic benefits for the ports and port tenants, enhancing both reliability and resiliency of port operations and providing the energy resources required to serve critical loads should the utility grid experience an outage. While internal combustion sources (e.g., gas turbines, diesel engines) have traditionally provided this capability, stationary fuel cells offer a clean alternative with zero tailpipe emissions that meet both port energy demands and environmental goals. Given the unique and diverse energy requirements of port operations and the flexibility of fuel cell systems, a broad range of applications exist for fuel cells at ports (Figure 50) including both stationary power generation and motive power for port vehicles and vehicles serving the ports (e.g., locomotives, ocean going vessels, and CHE). Using fuel cells for both port electricity resources and mobile power supports the port conversion from conventional fossil fuels (e.g., natural gas, diesel) to hydrogen.

The operational and technical constraints at ports require specific considerations for microgrid deployment that may differ from more common applications and thus require further information and assessment. The development and implementation of microgrid structures within port electrical infrastructure can facilitate different energy management goals, including the ability to maintain business continuity during emergencies or other unplanned grid disruption and to reduce the environmental footprint of operations. The importance of a microgrid infrastructure to support and manage future port energy requirements is reflected in the POLB Energy Island Initiative [64] and Resiliency in a Zero Emissions Future project funded by the California Energy Commission [65].

The benefits of using a microgrid approach to port energy management include the ability to:

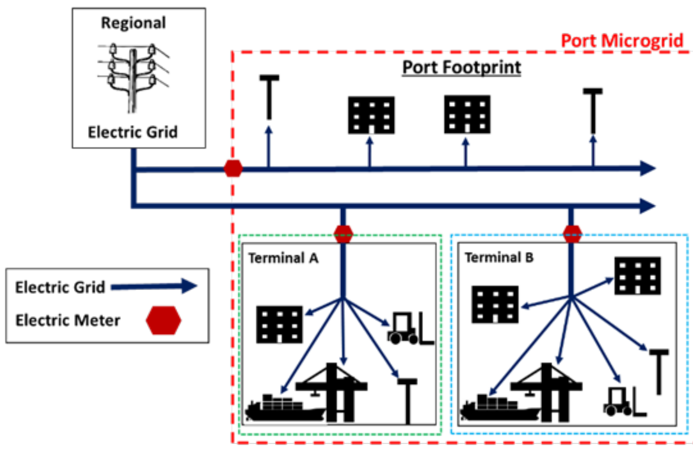
- Protect critical port infrastructure from power loss.
- Sustain port operations during grid outages.
- Facilitate integration of renewable energy and distributed generation.
- Manage resources better, resulting in higher efficiency and lower costs.
- Provide services to the grid, as well as adjacent critical facilities in case of an emergency or unforeseen occurrence.

The use of on-site 24/7 DER to meet base-load, peak, and backup/emergency power can provide reliable, high-quality power to the ports and support critical loads in the event of a grid outage. Commonly considered DER include energy storage, such as battery and hydrogen storage, thermal systems, and renewable power generation technologies such as wind turbines and solar PV. The self-generation can achieve economic benefits to the consumer, including peak-shaving, a decrease in the cost of energy, and protection from increasing utility rates and other changes.

The ports include a parent organization (the port) managing a collection of individual tenants (terminals). Each terminal is leased from the port and operated by a distinct company with different cargoes handled, berth specifications, and special equipment. The port has meters that service various loads (e.g., pumping stations, sewer stations, buildings, irrigation, traffic signals, streetlights). The terminals are fed from one or more utility circuits, each with a separate utility meter and collection of electrical loads (e.g., wharf cranes, high-mast lighting, and buildings). In Figure 51, the meter serving Terminal A is managed between the operator of Terminal A and the utility. Similarly, the meter servicing the port electrical infrastructure is managed between the port and the utility.

The group of disparate utility customers represents a challenge for ports transitioning to a microgrid. One option is to have the port and each terminal be established as an independent microgrid. Another option is a port microgrid that is comprised of a collection of nanogrids[19] (e.g., individual terminals and the port). For this option, the terminals and port electrical infrastructure and management must be comprehensively integrated with the port and terminals each operating as a nanogrid and interacting with each other (if needed in the case of an emergency or critical need to share resources) at the point of connection with the utility.

Figure 51. Port Microgrid



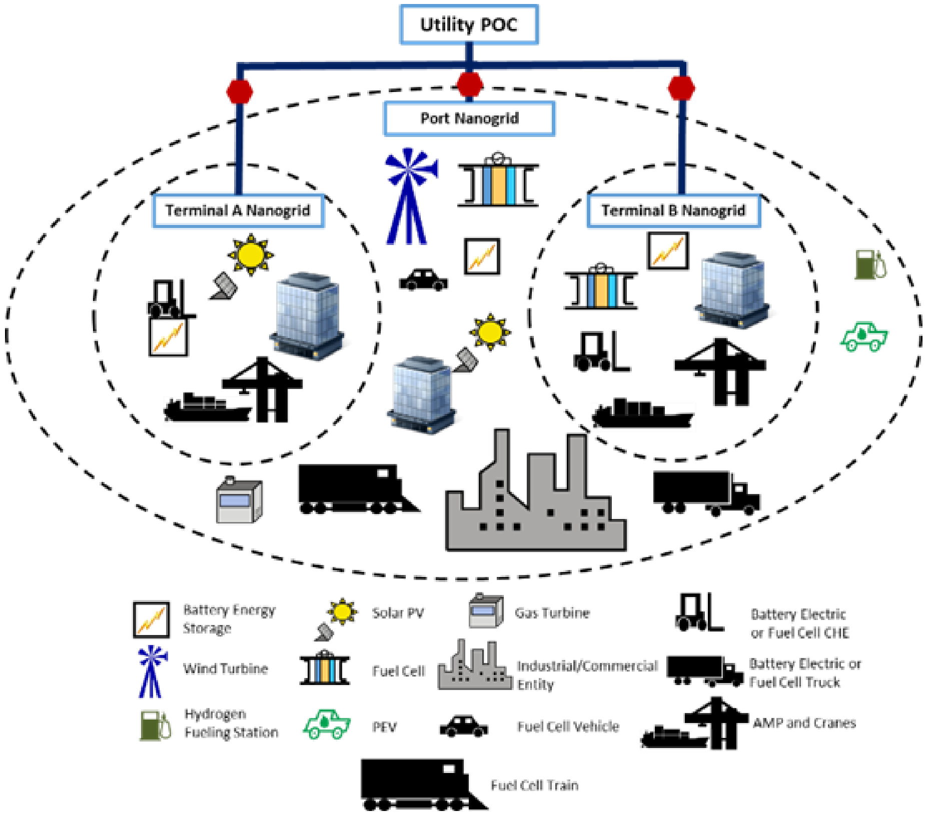
Credit: APEP

This configuration, nested (or fractal) microgrids[20], is especially suitable for the ports. Terminals can operate independently as they do today but, unlike today, they would be able to individually island in the event of a grid outage and form a nanogrid, and when required, cooperate as an ensemble. Thus, nanogrids can retain their autonomy while sharing resources for resiliency and reliability as needed. While the configuration provides the necessary resiliency and reliability of the microgrid as a whole, terminals can retain their independence and have the freedom to design and operate their own system independent of the port and the other terminals. A schematic of this configuration for a port nested microgrid is shown in Figure 52.

19 Nanogrid are smaller microgrids serving one building or load. They can also refer to smaller microgrids inside microgrids that can run independent of that microgrid.

20 Interconnection of several adjacent microgrids or nanogrids.

Figure 52. Future of Port Power System-Nested Microgrid



Credit: APEP

4.5 Costs

4.5.1 Vehicle and Infrastructure Costs

The price of a battery-electric yard tractor is estimated to be about $320,000 (compared to $100,000 for diesel and $150,000 for LNG). Maintenance costs of battery-electric yard tractors, though, are estimated to be lower at $15.50/hr compared to $22.15/hr for the diesel and near zero-emission options [37].

POLB estimates that the terminal costs for upgrading the electrical infrastructure to support DCFC for charging battery-electric yard tractors is about $50,000 per EVSE which is consistent with demonstrations to this date [37]. Additionally, the cost of installing each charger is more than $100,000 due to permits, construction costs, inspections, etc. Thus, it is estimated that installing DCFC infrastructure costs about $150,000 per battery-electric yard tractor, not including the utility-side costs, such as transformer and wiring upgrades to handle the increased energy requirements. Those are estimated to cost an additional $37,500 per charger, based on the demonstration done at POLB.

Results from Transportation Electrification Priority Review Projects [15] indicate that the infrastructure cost is about $1,930/kW for small battery-electric forklifts and $570/kW for RTG cranes. The infrastructure cost for RTG crane is based on a project currently being demonstrated at POLB, including nine electrified RTG cranes. The purchase cost of a grid-tied RTG crane is $1,800,000 (compared to $1,200,000 for the diesel) and maintenance costs are lower at about $24.09/hr (compared to $32.12 for diesel) [37].

For hydrogen fuel cell-electric CHE, estimating the purchase costs is more difficult since they are not yet sold commercially. Previous research shows that capital cost of retail-entry MD/HD hydrogen fuel cell options (specifically linehaul, drayage, and construction) are 1.2 to 1.5 times greater than their diesel counterpart [66]. The cost of hydrogen storage is $60 per gallon of storage and an addition of roughly 30 percent should be considered for the cost of installation and commissioning.

4.5.2 Fuel Costs

Southern California Edison offers the following time-of-use (TOU) tariffs[21] for EV charging: TOU-EV-7 for less than 50 kW, TOU-EV-8 for 50 kW to 500 kW, and TOU-EV-9 for a site with more than 500 kW of charging. For all these TOU rates, 4:00 p.m. to 9:00 p.m. is considered peak (or mid peak in winter) and they have demand charges or will in the future. Using results shown previously in Table 14, Table 15, and Table 17, the average cost for charging battery-electric yard tractors, top handlers, and forklifts was determined. Overall, an average of $0.20 to $0.26 per kWh is the result, which is consistent with previous demonstrations. To compare the overall fuel cost of a fully zero-emission fleet with existing diesel fleets, a price of $8.00 per kilogram was used for hydrogen and a price of $5.00/gallon was used for diesel. The price of hydrogen was based on projections for the cost of 100 percent renewable hydrogen in 2035 from *Roadmap for the Deployment and Buildout of Renewable Hydrogen Production Plants in California* [67]. The results are detailed in Table 22 and show that switching to zero-emission options results in a reduction in fuel costs compared to the existing diesel fleet. Note that the results are based on the price of hydrogen and diesel previously mentioned.

For diesel yard tractors and a diesel fuel price of $5.00 per gallon, the average reduction in fuel costs (summer) for scenarios with a fully zero-emission yard tractor fleet with 50 percent and 100 percent hydrogen fuel cell-electric CHE is shown in Figure 53. As can be inferred from this figure, for the scenario with 100 percent hydrogen fuel cell-electric yard tractors, hydrogen price of more than $9.00 per kilogram results in increase in overall fuel costs. For the scenario with 50 percent hydrogen fuel cell-electric yard tractors (and the other 50% battery-electric yard tractors), a hydrogen price of more than $12.50 per kilogram results in an increase in overall fuel costs.

---

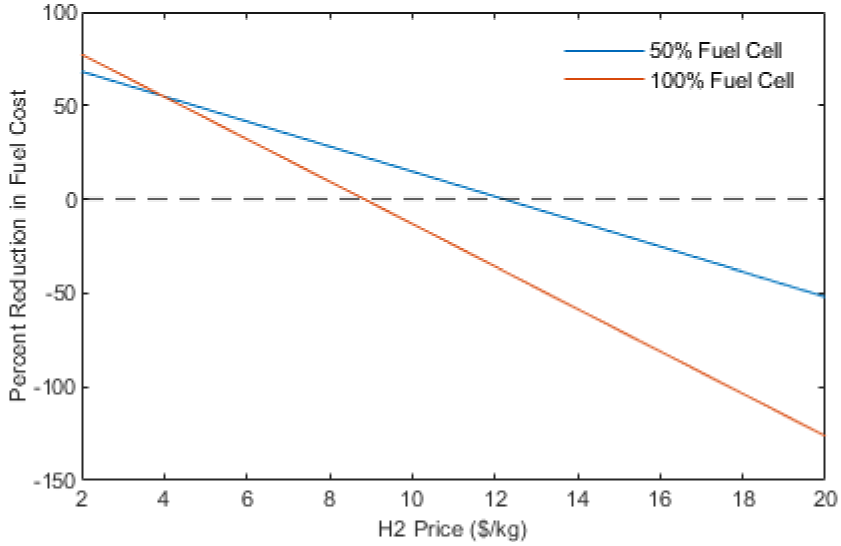
[21] Utility tariffs are a collection of electric rates and other charges that are applied to calculate a final utility bill, not to be confused with import tariffs.

Table 22. Electricity Cost and Overall Fuel Cost Reduction

Battery-Electric %			100	90	80	70	60	50	40	30	20	10	0
Fuel Cell %			0	10	20	30	40	50	60	70	80	90	100
UTR	Avg Electricity ($/kWh)	Summer	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	-
		Winter	0.11	0.11	0.11	0.12	0.12	0.12	0.12	0.12	0.12	0.12	-
	Avg Reduction in Fuel Cost ($/Day)	Summer	7,399	7,090	6,169	5,014	4,490	3,859	3,089	2,564	1,924	1,444	1,299
		Winter	10,864	10,052	8,711	7,098	6,175	5,170	4,072	3,238	2,306	1,577	1,299
	Max Electricity ($/kWh)	Summer	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26
		Winter	0.12	0.12	0.11	0.12	0.12	0.12	0.12	0.11	0.11	0.12	0.12
	Max Reduction in Fuel Cost ($/Day)	Summer	7,247	6,172	5,881	5,547	5,290	4,800	4,369	3,417	2,764	1,547	1,819
		Winter	13,910	12,129	11,099	10,034	9,128	7,992	6,831	5,203	3,801	1,961	1,819
Top Handler	Avg Electricity ($/kWh)	Summer	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	-
		Winter	1,982.	2,094	2,605	3,042	3,765	4,416	5,240	5795	6,353	6,665	-
	Avg Reduction in Fuel Cost ($/Day)	Summer	10,807	10,595	9,589	8,730	7,307	6,027	4,387	3,314	2,214	1,605	1,417
		Winter	12,954	12,599	11,367	10,323	8,595	7,041	5,297	3,742	2,423	1,632	1,417
	Max Electricity ($/kWh)	Summer	0.27	0.27	0.27	0.27	0.27	0.26	0.26	0.26	0.25	0.25	-
		Winter	0.13	0.13	0.13	0.13	0.12	0.12	0.12	0.12	0.12	0.12	-
	Max Change in Fuel Cost ($/Day)	Summer	17,825	16,879	11,519	9,952	8,850	7,488	6,102	4,725	3,303	2,656	2,532
		Winter	22,508	21,222	15,363	13,308	11,571	9,617	7,688	5,764	3,831	2,799	2,532
Large Forklift	Avg Electricity ($/kWh)	Summer	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	-	-
		Winter	0.12	0.11	0.11	0.12	0.12	0.12	0.12	0.12	0.12		
	Avg Reduction in Fuel Cost ($/Day)	Summer	132	120	120	77	77	50	50	40	40	27	27
		Winter	215	187	187	114	114	63	63	45	45	27	27
	Max Electricity ($/kWh)	Summer	0.30	0.29	0.29	0.25	0.25	0.25	0.25	0.25	0.25	-	-
		Winter	0.14	0.14	0.14	0.11	0.11	0.11	0.11	0.11	0.11	-	-
	Max Reduction in Fuel Cost ($/Day)	Summer	232	147	149	65	65	12	13	5	6	65	65
		Winter	487	437	439	390	389	357	358	351	352	377	377

Source: APEP

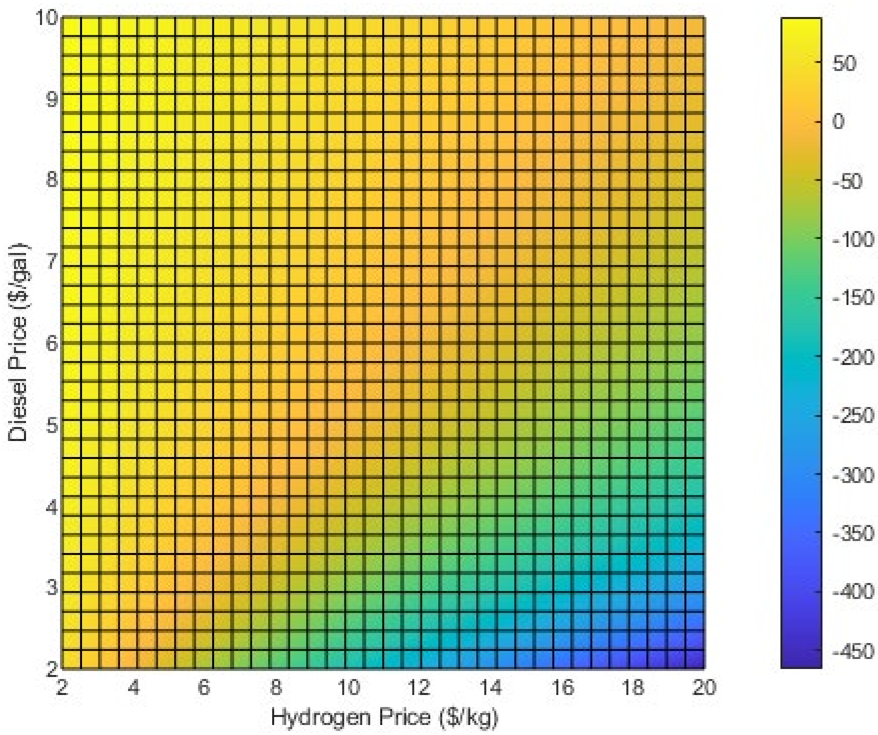
Figure 53. Fuel Cost Reduction Percentage for Yard Tractor ($5 per Gallon Diesel)



Credit: APEP

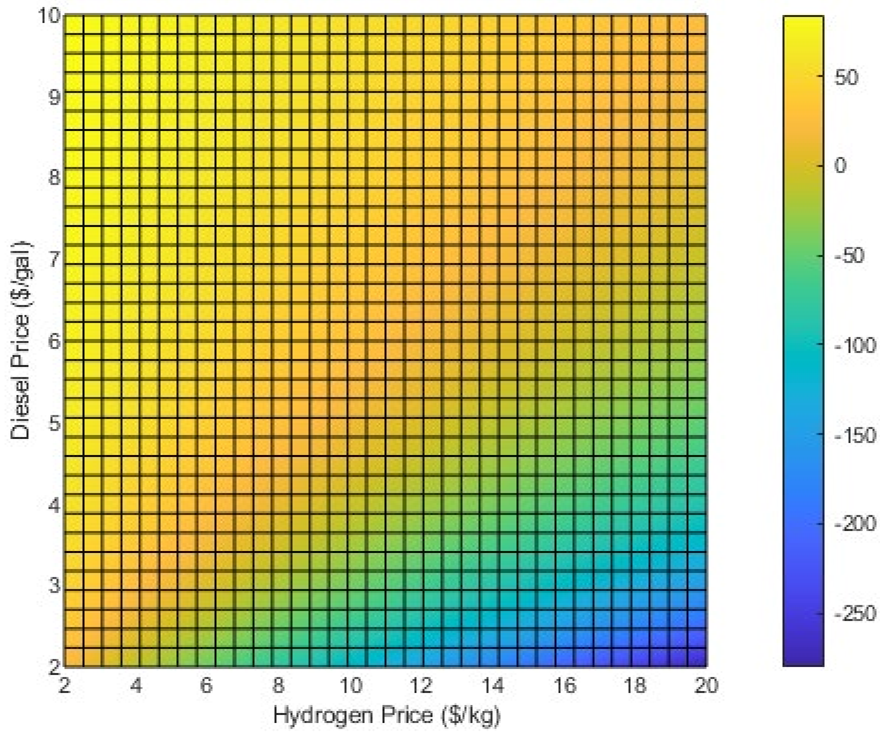
For a fully zero-emission yard tractor fleet with 100 percent and 50 percent hydrogen fuel cell-electric yard tractors, the impact of price of hydrogen and diesel is shown in Figure 54 and Figure 55, respectively.

Figure 54. Fuel Cost Reduction Percentage for 100% Fuel Cell-Electric Yard Tractor



Credit: APEP

Figure 55. Fuel Cost Reduction Percentage for 50% Fuel Cell-Electric Yard Tractor



Credit: APEP

Grid-tied electric RTG cranes will be on a different tariff and possibly subject to demand charges. For grid-tied electric RTG cranes and any future EV charging tariffs that includes demand charges, the results shown previously in Table 16 and Table 19 can be used to determine the demand charges.

4.5.3 Funding Sources, Incentives and Infrastructure Planning Tools

CARB's Clean Off-Road Equipment Voucher Incentive Project (CORE) provides incentives for purchasing zero-emission off-road equipment [46]. For zero-emission yard tractors, top handlers, small forklifts, and large forklifts, incentives of up to $120,000, $500,000, $15,000 and $500,000 is offered, respectively[22]. For the infrastructure, the CEC offers incentives through its Energy Infrastructure Incentives for Zero-Emission Commercial Vehicles (EnergIIZE)[23] project that is being administered by CALSTART, as well as several block grants for zero-emission MD/HD refueling infrastructure[24]. BAAQMD has partnered with CARB in the Goods Movement Emission Reduction Program for charging and hydrogen fueling infrastructure for equipment, including CHE, and also provides funding for infrastructure under AB 617. Moreover, local governments as well as utilities provide some incentives and funding for zero-emission refueling infrastructure. SB 350 authorizes utilities to accelerate transportation electrification. The CEC, CARB, and CPUC support this effort by directing the

22 Eligible Equipment Catalog https://californiacore.org/equipmentcatalog/

23 https://www.energy.ca.gov/proceedings/energy-commission-proceedings/energy-infrastructure-incentives-zero-emission-commercial

24 https://www.energy.ca.gov/solicitations/2020-07/gfo-20-603-block-grant-medium-duty-and-heavy-duty-zero-emission-vehicle

utilities to create programs and investments. The CPUC authorized SCE, SDG&E and PG&E to invest $41 million for 15 transportation electrification pilots and demonstrations.

Additionally, the CEC, CARB, and BAAQMD have funded several projects including blueprints like this one that address EV charging and hydrogen fueling. A comprehensive list of ZEV infrastructure resources is provided by CARB[25]. There are also many studies that address the feasibility of, and charging requirements and hydrogen needs of, a zero-emission MD/HD fleet [68]. NREL's EVI-X[26] is a modeling suite of tools for EV charging infrastructure analysis, including MD/HD[27]. NREL also provides several tools for hydrogen fueling and costs such as H2FAST[28] and H2FillS[29], as well as several tools for total cost of ownership (TCO). Moreover, several utilities provide distribution planning tools to facilitate deployment of battery-electric MD/HD vehicles, as such SCE's Charge Ready Transport Program.

25 https://ww2.arb.ca.gov/zero-emission-vehicle-zev-infrastructure-topics

26 https://www.nrel.gov/transportation/evi-x.html

27 https://www.nrel.gov/transportation/evi-x.html

28 https://www.nrel.gov/hydrogen/h2fast.html

29 https://www.nrel.gov/hydrogen/h2fills.html

5 Environmental Impacts

In this chapter, the impact on emissions, air quality, and associated health impacts from transitioning to a zero-emission CHE fleet is assessed at both the regional and local (disadvantaged) community levels in the near vicinity of the San Pedro Bay Ports.

5.1 Approach

As shown in Figure 56, an integrated modeling approach was used to characterize and quantify the air quality and public health impacts of reducing emissions for the following two cases in which sources are transitioned to zero-emission: (1) port-related CHE and (2) port sources in general e.g., ships, drayage trucks, CHE, and trains relative to a business-as-usual "Reference Case". The purpose of the Reference Case is to provide relative insight into the benefits that could be achieved in 2035 from the transition to zero-emission compared to no action.

For the Reference Case, criteria pollutant emissions were projected out to 2035 from a detailed base year using CARB's pollutant emissions inventory[30] and then spatially and temporally resolved using the Sparse Matrix Operator Kernels Emissions version 4.7 (SMOKE)[31] model. Then, for the two cases analyzed, all emissions were removed from relevant sources to develop cases of completely zero-emission CHE and ports sectors. Next, emission changes were translated into impacts on atmospheric pollution levels, including ground-level ozone and $PM_{2.5}$, via an advanced photochemical air quality model called the Community Multiscale Air Quality version 5.3.2 (CMAQ)[32] model that accounts for atmospheric chemistry and transport. Given the highly computational nature of CMAQ, an episodic air quality modeling approach was used, including the evaluation of the differences in ground-level ozone and $PM_{2.5}$ for the months of July and January relative to the Reference Case. Air quality changes were then used to conduct a health impact assessment using the Environmental Benefits Mapping and Analysis Program - Community Edition (BenMAP)[33], which provides a quantitative estimate of the incidence and value of avoided harmful health outcomes that are associated with air pollution in each case. Finally, the health impact results were analyzed through an environmental justice framework to quantify the benefits that occur specifically within socially and economically disadvantaged communities that were identified using CalEnviroScreen[34].

---

30 https://ww2.arb.ca.gov/applications/cepam2019v103-standard-emission-tool

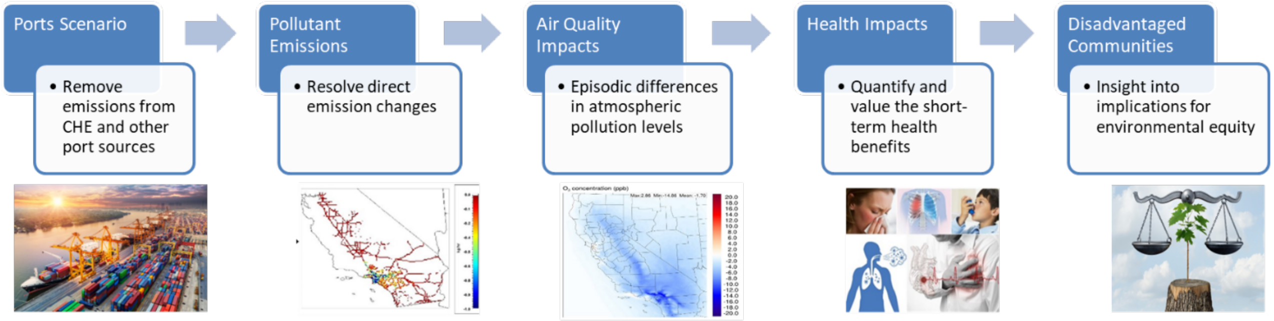
31 SMOKE v4.7: https://www.cmascenter.org/smoke/documentation/4.0/manual_smokev40.pdf

32 CMAQ v5.3.2: https://www.epa.gov/cmaq/latest-version-cmaqv533

33 BenMAP v1.5.8: https://www.epa.gov/benmap/benmap-downloads

34 CalEnviroScreen 4.0: https://oehha.ca.gov/calenviroscreen/report/calenviroscreen-40

Figure 56. Overview of the Air Quality and Public Health Assessment Approach



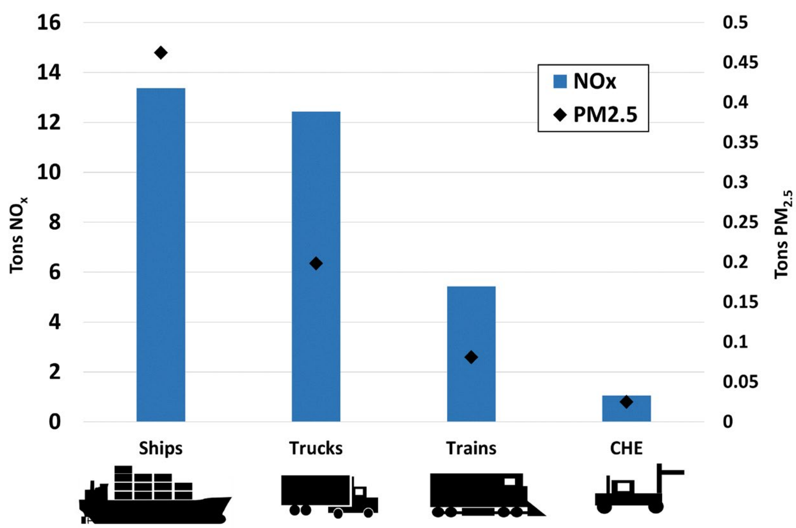
Credit: APEP

5.1.1 Case Assumptions

The assumptions in the case design were the complete removal of all emissions associated with 1) CHE and 2) CHE, heavy-duty drayage trucks, ships, and trains in Southern California, which was then compared to the business-as-usual Reference Case to determine emissions, air quality, and health benefits. Emissions from all other sources were held constant to the Reference Case.

Annual emissions of NO_X and $PM_{2.5}$ emanating from sources in the San Pedro Bay Ports are shown in Figure 57.

Figure 57. POLA/POLB Annual Emissions of NO_x and $PM_{2.5}$



Credit: APEP

5.1.2 Emissions

The baseline pollutant emissions represent a highly detailed emissions inventory developed by CARB, which includes total emissions by sector and source, as well as spatial and temporal information regarding source activity. The emissions were projected out to 2035 using output from the PATHWAYS [69] model[35] for technologies, fuels, and energy demand by AB 32 GHG Inventory sector [70]. The pollutant emissions inventory was then processed into air quality model-ready format using the SMOKE model, including resolving the location and timing of the emissions to correspond with the sources that are responsible for them (e.g., the location of refineries, the locations of residential and commercial buildings, the locations of major roadways and the traffic patterns for vehicles) [71]. On-road vehicle emissions were spatially resolved to the locations of vehicle activity using the Emissions Spatial and Temporal Allocator (ESTA) model developed by CARB [72].

5.1.3 Air Quality

Atmospheric chemistry and transport were modeled with CMAQ, which accounts for both primary (emitted) and secondary (formed) pollutant species, including ground-level ozone and $PM_{2.5}$ [73]. CMAQ was developed by the U.S. EPA and is widely used for various air quality assessment purposes [74], [75]. The SAPRC-07 chemical mechanism [76] was applied to account for gas-phase chemistry, and the AERO6 module [77] was used to resolve aerosol dynamics. The simulation domain included all of California at a 4 kilometer (km) by 4 km horizontal resolution. The Advanced Research Weather Research and Forecasting Mode [78] was used to provide meteorological conditions and the Community Atmosphere Model with Chemistry version 2.1 provided boundary conditions [79]. Biogenic emissions were produced using the Model of Emissions of Gases and Aerosols from Nature [80]. The air quality modeling tools and sources of data are shown in Table 23.

The months of January and July were selected to represent the seasonal variation in meteorology and emissions concentrations associated with the winter and summer months respectively. July was modeled because it includes conditions that are favorable to high ozone and $PM_{2.5}$, including elevated temperatures, strong sunlight, lack of natural scavengers, and the occurrence of inversion layers [81]. January was modeled because it often experiences high $PM_{2.5}$ in regions of California including the South Coast Air Basin and the Central Valley.

The CMAQ output has been validated using observational data from the U.S. EPA's Air Quality System [82] and is within the statistical parameters for acceptable model performance [83]. The two pollutants evaluated were $PM_{2.5}$ and tropospheric ozone as many regions of California experience ambient levels in excess of State and Federal health-based standards [84], and both are associated with harmful health outcomes in exposed populations [85]–[87]. For consistency with ambient air quality standards, ground-level concentrations are reported as maximum daily eight-hour average ozone (MD8H) and 24-hour average $PM_{2.5}$.

---

[35] https://www.ethree.com/tools/pathways-model/

Table 23. Overview of the Air Quality Modeling Tools and Sources of Data Inputs

	Model/Data Source
Base Year Inventory	2020 CARB v0018
Emissions Processing	SMOKE v4.7 and ESTA
Air Quality Model	CMAQ v5.3.2
Chemical Mechanism	SAPRC-07 and AERO6
Biogenic Emissions	MEGAN v2.1
Meteorological Files	WRF-ARW v3.9.1
Boundary Conditions	CESM v2.1/CAM-chem

Source: APEP

5.1.4 Health Impacts

BenMAP from the U.S. EPA was used to quantify and value the health benefits that result from reduced levels of ozone and $PM_{2.5}$ [88]. For inputs, the California population was projected to 2035 using data from GeoLytics [89]. The selection of inputs, including concentration-response functions (shown in Table 24 and Table 25), baseline incidence rates, and valuation functions generally follow those recommended by the U.S. EPA [88]. Additionally, the quantification of avoided incidence of premature mortality due to reduced short-term exposure to $PM_{2.5}$ was estimated using Atkinson et al. 2014 [90]. Impacts were estimated for ozone and $PM_{2.5}$ in July and $PM_{2.5}$ in January as ozone concentrations are generally below health-based standards in winter and share an inverse relationship with precursor emissions that prevents useful conclusions from being made from the results. Finally, the estimated health savings were quantified specifically within census tracts that have been identified as disadvantaged communities using CalEnviroScreen [91].

Table 24. Health Endpoints and Their Concentration-Response Function Reference Included in the BenMAP Analysis for Reduced Exposure to Ozone

Ozone Health Endpoints	Reference[36]
Avoided Mortality	Huang et al. 2005
Emergency Room Visits, Respiratory	Barry et al. 2018
Hospital Admissions, Respiratory	Katsouyanni et al. 2009
Asthma Symptoms	Lewis et al. 2013
Incidence, Asthma Onset	Tetreault et al. 2016

Source: APEP

36 Additional information on the studies the concentration-response functions used in BenMAP are derived from can be found in the BenMAP users manual.

Table 25. Health Endpoints and Their Concentration-Response Function Reference Included in the BenMAP Analysis for Reduced Exposure to $PM_{2.5}$

$PM_{2.5}$ Health Endpoints	Reference[36]
Avoided Premature Mortality	Atkinson et al. 2014
Hospital Admissions, Alzheimer's Disease	Kioumourtzoglou et al. 2016
Hospital Admissions, Parkinson's Disease	Kioumourtzoglou et al. 2016
Incidence, Lung Cancer	Gharibvand et al. 2016
Incidence, Asthma Onset	Tetreault et al. 2016
Acute Myocardial Infarction, Nonfatal	Zanobetti et al. 2009
Asthma Symptoms	Rabinovitch et al. 2006
Hospital Admissions, Cardiovascular	Bell et al. 2015
Emergency Room Visits, Cardiovascular	Ostro et al. 2016
Hospital Admissions, Respiratory	Bell et al. 2015
Emergency Room Visits, Respiratory	Krall et al. 2016

Source: APEP

5.1.4.1 Air Quality and Health Impact Assessment Caveats

This section provides the major assumptions and caveats associated with the health impact assessment that should be considered when interpreting the results.

Episodic modeling provides insight into the maximum impacts on air quality, but does not provide a comprehensive understanding of the air quality impacts. Due to the selection of modeling periods coinciding with high pollutant formation periods, the pollutant differences and the corresponding health impacts are also highest during those periods and may not be as large in other months. Therefore, the results of both the air quality and health benefit assessments represent two distinct months and cannot be used to estimate other periods (e.g., multiplying to determine annual changes).

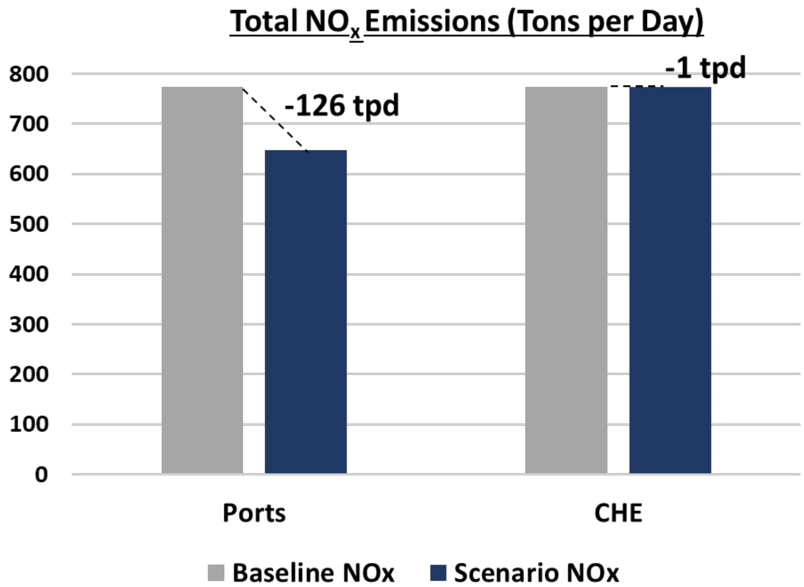
The health benefits are quantified and reported for reduced short-term exposure to $PM_{2.5}$ and ozone for two months in 2035. Therefore, the results do not provide a comprehensive accounting of the health benefits including what would be achieved annually or cumulatively. Further, though BenMAP can be used to estimate long-term health impacts such as those occurring from annual average $PM_{2.5}$ changes, impacts are reported here for short-term exposure to ozone and $PM_{2.5}$ as appropriate for the modeled episodes. It should be noted that the value of short-term exposure health benefits is significantly lower than those estimated for long-term exposure (generally 8 times to 12 times higher).

5.2 Results

5.2.1 Emissions

As shown in Figure 58, when compared to the Reference Case, removing emissions from CHE and other port sources results in a significant reduction in NO_X emissions, 126 tons per day or approximately 16 percent of the total statewide NO_X emissions in 2035. Removing emissions solely from CHE results in a reduction of approximately 1 ton per day.

Figure 58. Total NO_X Emissions for the Reference Case and for Cases Involving the Removal of All Emissions from CHE and Other Port Sources



Credit: APEP

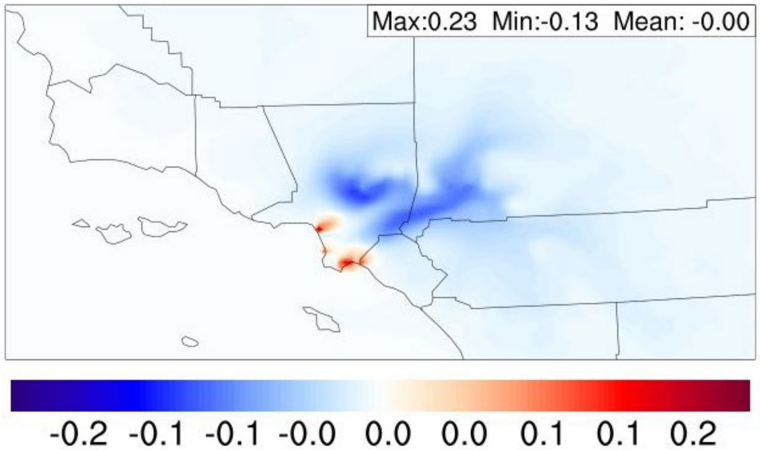
5.2.2 Air Quality

The emission reductions within the cases considered achieve improvements in air quality in California, including reductions in concentrations of ground-level ozone and $PM_{2.5}$. The following section provides the results of the air quality assessment for the modeling periods in 2035.

5.2.2.1 CHE Case

Improvements in air quality are relatively minor for the CHE-only case. Reductions in ground-level ozone for July 2035 relative to the Reference Case are shown in Figure 59. Improvements exceed 0.1 ppb, with the largest reductions occurring in Los Angeles and San Bernardino Counties. The spatial distribution of reductions in $PM_{2.5}$ in July 2035 are provided in Figure 60 and reach 0.02 ug/m^3 with the largest reductions at and immediately east of the San Pedro Bay Ports in Los Angeles County. Shown in Figure 61, in January, improvements in $PM_{2.5}$ reach 0.07 ug/m^3, with a spatial distribution similar to those that occur in summer.

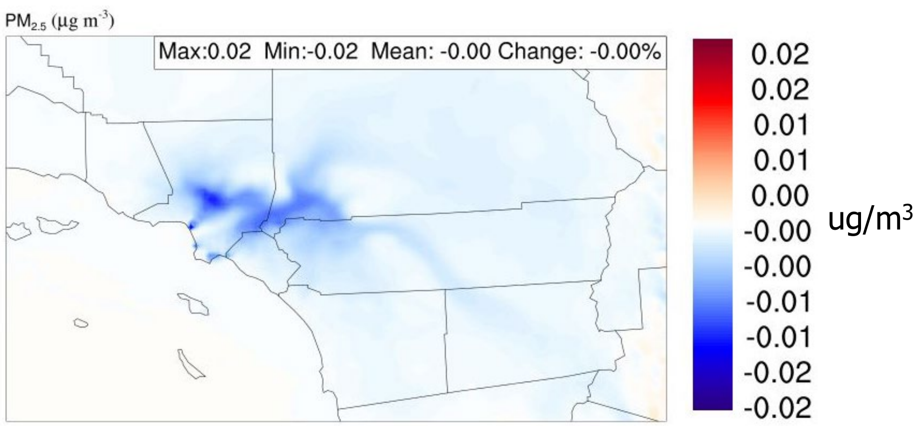
Figure 59. Improvements in Maximum Daily 8-Hour Average Ozone (ppb) in July 2035 for the CHE Case



Parts per billion

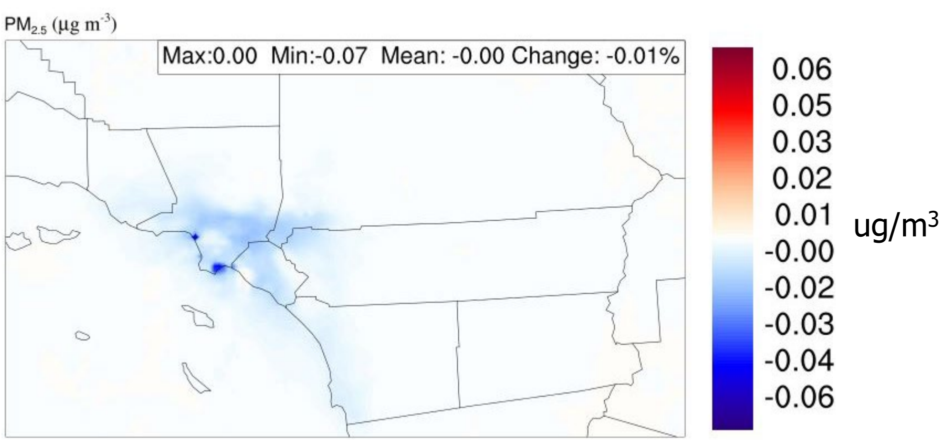
Credit: APEP

Figure 60. Improvements in 24-Hour Average PM2.5 (ug/m³) in July 2035 for the CHE Case



Credit: APEP

Figure 61. Improvements in 24-Hour Average $PM_{2.5}$ (ug/m³) in January 2035 for the CHE Case

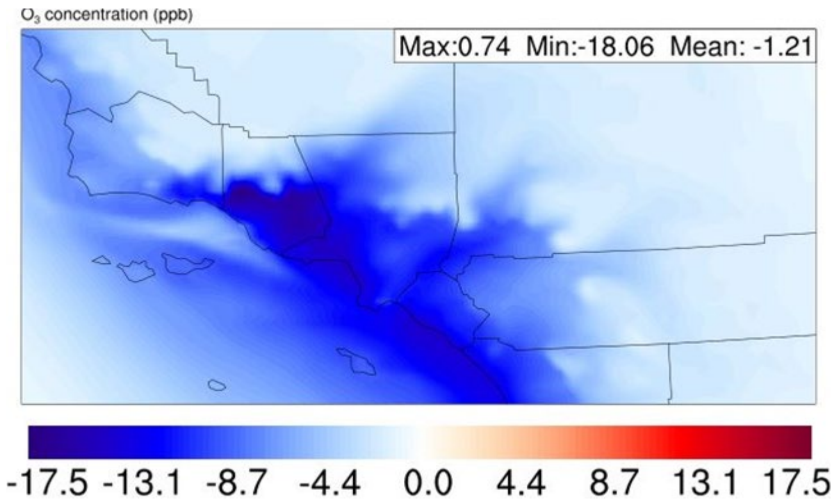


Credit: APEP

5.2.2.2 Port Sources Case

In contrast, the impacts of removing emissions from all port sources results in very large reductions in ozone and $PM_{2.5}$ and represents a major improvement in air quality. Improvements in ground-level ozone exceed 19 ppb as shown in Figure 62. The location and magnitude of the improvement is significant given that the region experiences the most degraded ozone air pollution in the U.S. [92], and the presence of a large population, including numerous disadvantaged communities according to CalEnviroScreen. Similarly, improvements in $PM_{2.5}$ are sizeable in both summer (Figure 63) and winter (Figure 64), and the locations coincide with dense urban populations.

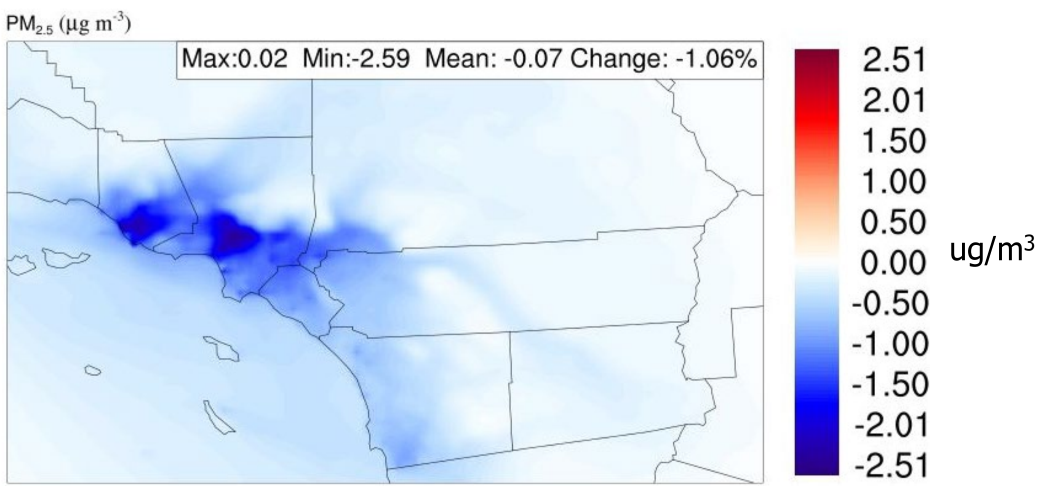
Figure 62. Improvements in Maximum Daily 8-Hour Average Ozone (ppb) in July 2035 for the Ports Case



Parts per billion

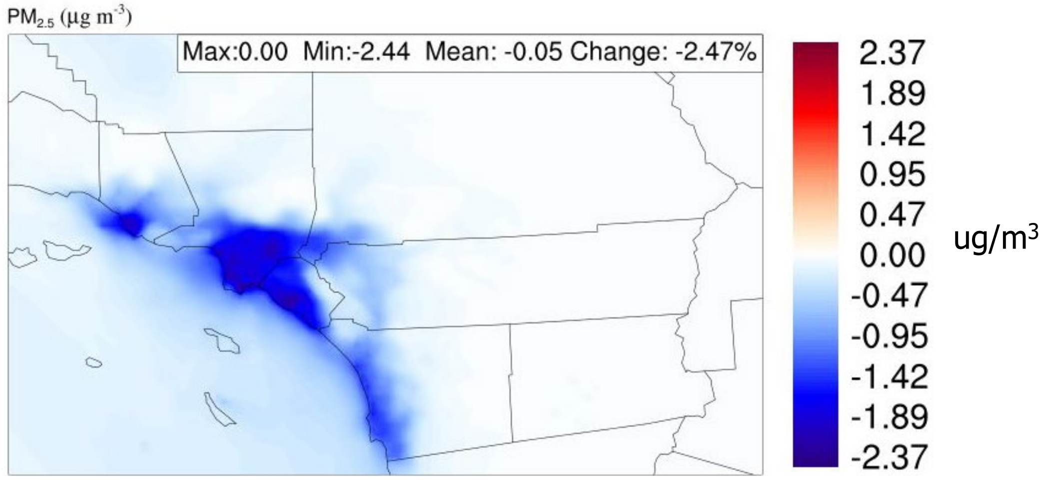
Credit: APEP

Figure 63. Improvements in 24-Hour Average $PM_{2.5}$ (ug/m^3) in July 2035 for the Ports Case



Credit: APEP

Figure 64. Improvements in 24-Hour Average $PM_{2.5}$ (ug/m^3) in January 2035 for the Ports Case



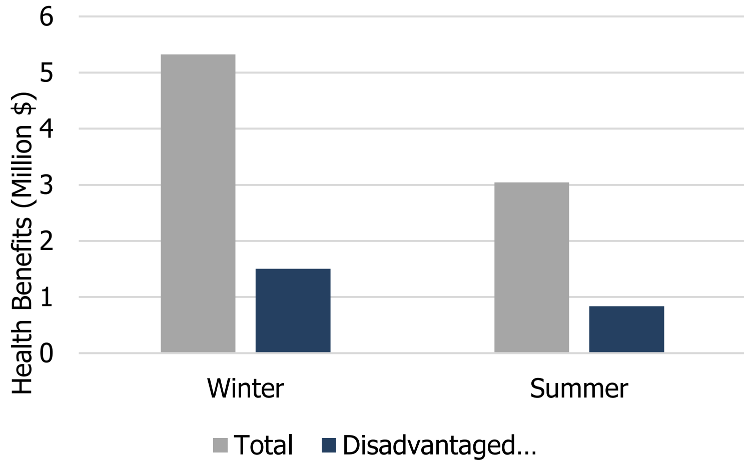
Credit: APEP

5.2.3 Health Impacts

The total health benefits for each month considered are shown in Figure 65 for the CHE-only case, and range from approximately $3 million for July 2035 to over $5 million for January 2035. In addition to the air quality-related health benefits that occur throughout southern California, those benefits occurring specifically within socially and economically disadvantaged communities are identified. The total health benefits that occur within disadvantaged communities that are identified by CalEnviroScreen range from over $800,000 to $1.5 million for those same months.

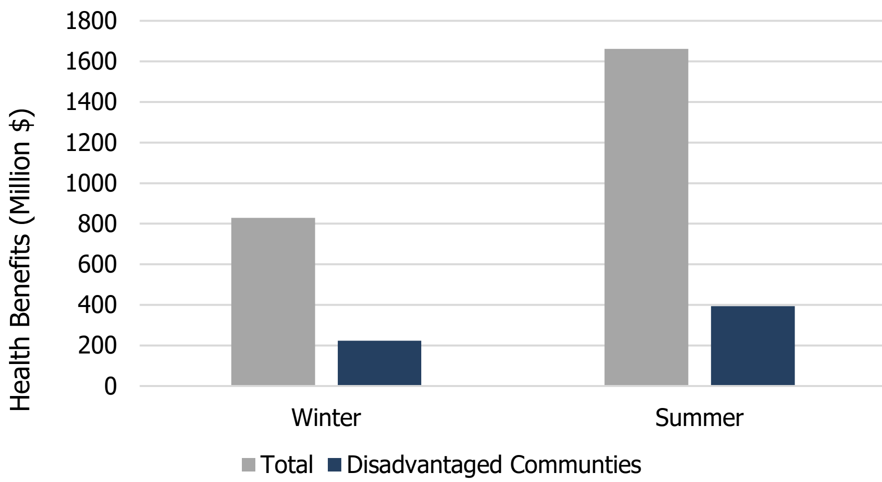
The total health benefits for each month for the ports case are shown in Figure 66 and range from $800 million to $1.6 billion per month in total and from $200 million to $400 million per month in disadvantaged communities. It should again be noted that these estimates are highly conservative given the episodic air quality modeling approach, and that the use of more comprehensive modeling, including annual air quality simulations, would report benefits that are generally orders of magnitude higher.

Figure 65. Valuation of the Total Health Benefits in the CHE Case



Credit: APEP

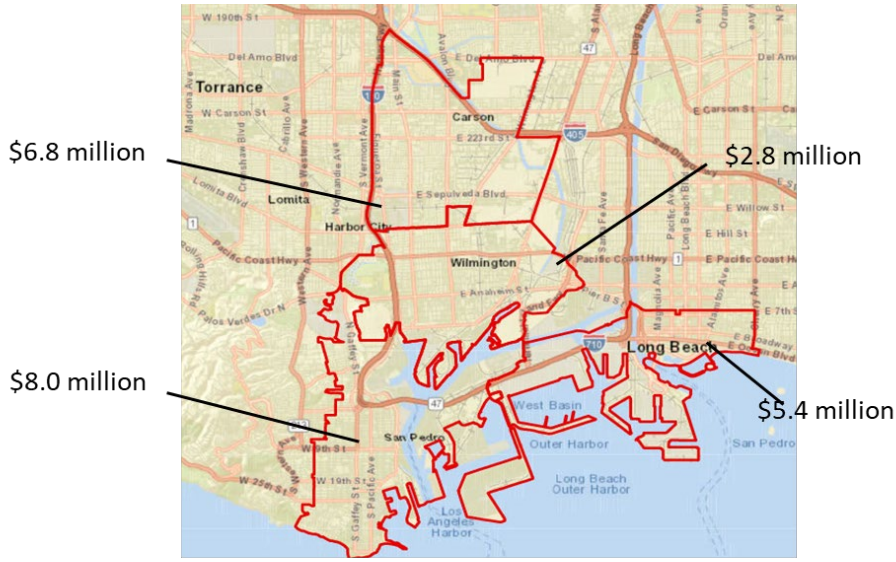
Figure 66. Valuation of the Total Health Benefits in the Ports Case



Credit: APEP

To further demonstrate the health benefits attained within disadvantaged communities, select communities were evaluated to provide an estimate of the benefits that an individual community may experience. The analysis included certain disadvantaged communities surrounding San Pedro Bay Ports (Figure 67). In total, for the two months that were assessed, the communities attain benefits ranging from $2.8 million to $8.0 million for the ports case and demonstrate the importance of the air quality benefits at the community level.

Figure 67. Total Health Benefits for the Two Months Modeled in the Ports Case



**Disadvantaged Communities Outlined in Red*

Credit: APEP

5.2.4 Results Summary

Based on the analysis and results presented, the following are the conclusions of air quality and health impact analyses:

- Electrifying port sources attains substantial air quality improvements (both ozone and $PM_{2.5}$) and health benefits in California.
    - Transitioning MD/HD vehicles and ships to zero-emission results in the largest benefits, more than a hundred-fold over the transition of CHE alone.
- Total California NO_X emissions could be reduced by approximately 11 percent in 2045 if all port sources transition to zero emission vehicles and equipment.
- A highly conservative estimate of the health benefits shows $1.7 billion for one month in 2035.
    - Benefits accrue disproportionally higher in disadvantaged communities surrounding the ports.

6 Implementation Options

Based on the data and information collected, results of models and analysis, as well as commercial availability and TRL of zero-emission CHE, the following two implementation options are recommended to achieve a 100 percent zero-emission CHE fleet by 2030. As previously mentioned in the blueprint, 2023-2025 is designated as short-term, 2025-2030 as medium-term, and beyond 2030 as long-term.

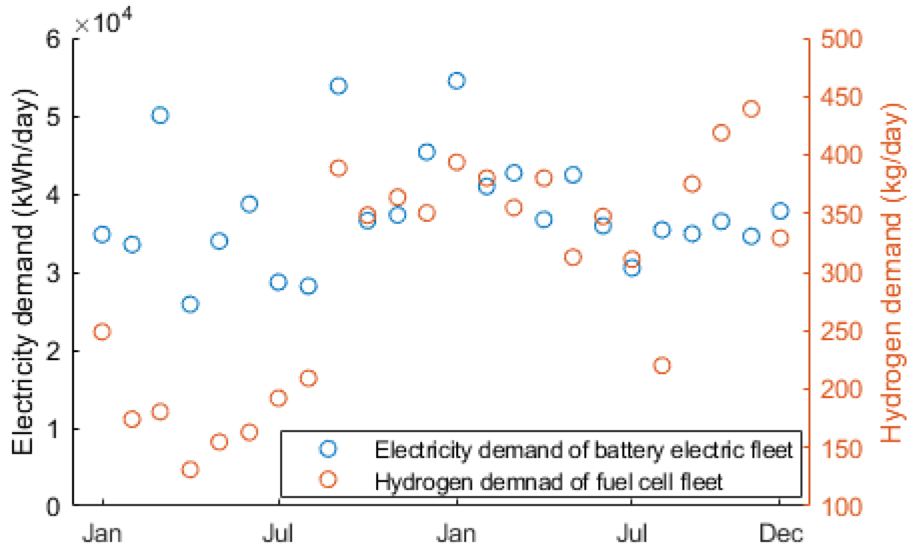
Option 1:

This option focuses on ordering commercially available options as much as possible in the short-term. Because battery-electric technology for yard tractors and top handlers are more mature and commercially viable than fuel cell-electric technology, in this option the yard tractors and top handlers are replaced with battery-energy technology. This transition should start in short-term and continue in the medium-term since the number of specially yard tractors on the terminals are significant. In contrast, RTG cranes and forklifts are replaced with hydrogen fuel cell-electric technology equipment which is being demonstrated and at the threshold of commercial viability. Small forklifts can be replaced in the short-term and large forklifts and RTG cranes in the medium-term. Alternatively, for RTG cranes, they can first be replaced with low-NO_X, near-zero-emission combustion hybrid technology (a so-called "bridging" strategy) in the short-term, which can later be transformed to zero-emission by replacing the diesel engine with a hydrogen fuel cell engine. Thus, the zero-emission CHE fleet in this option consists of:

- Yard tractor: 100 percent battery-electric
- Top handler: 100 percent battery-electric
- RTG crane: 100 percent hydrogen fuel cell-electric
- Large forklift: 100 percent hydrogen fuel cell-electric
- Small forklift: 100 percent hydrogen fuel cell-electric

The average electricity and hydrogen demand, determined using the analysis outlined in this blueprint, are presented in Figure 68 for a 24-month analysis. For this fleet, the average daily electricity utilization is 37.9 MWh (with a maximum of 55 MWh) and the daily hydrogen demand is 300 kg (with a maximum of 450 kg per day).

Figure 68. Electricity and Hydrogen Demand for Option 1



Credit: APEP

For this fleet, 170 chargers are required for the ITS terminal with a 33 MW requirement, as well as a significant rearrangement of CHE parking spaces. During days with high daily operational hours, up to 67 percent and 55 percent of the battery-electric yard tractors and top handlers, respectively, need to be at least charged twice, and for this fleet 5.0 percent to 8.0 percent of charging occurs at peak time, which is undesirable. For the hydrogen demand, a storage of 3,000 gallons (~800 kg) to 4,000 gallons (~1,100 kg) is sufficient.

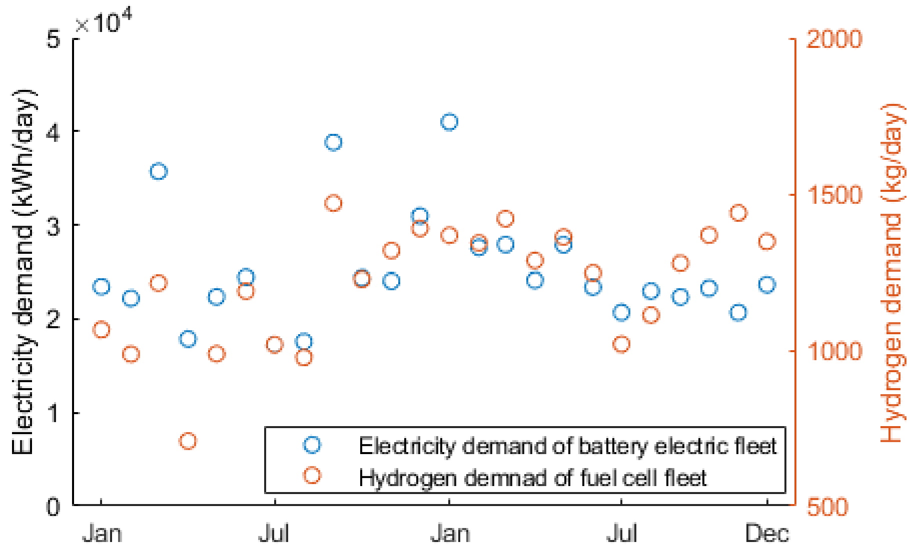
Option 2:

This option focuses on resiliency and leveraging technologies that are currently under demonstration and will become commercial soon. This option is similar to the previous option, except that the yard tractors are 50 percent battery-electric and 50 percent hydrogen fuel cell-electric. Since the number of yard tractors on the terminal is high compared to other CHE, they will not be replaced all at once. First, they will be replaced with battery-electric options in the short-term and the rest will be replaced with hydrogen fuel cell-electric options in the medium- to long-term. Deployment of forklifts and RTG cranes is similar to Option 1. The zero-emission CHE fleet in this option consists of:

- Yard tractor: 50 percent battery-electric, 50 percent hydrogen fuel cell
- Top handler: 100 percent battery-electric
- RTG crane: 100 percent hydrogen fuel cell-electric or 100% bridging hybrid
- Large forklift: 100 percent hydrogen fuel cell-electric
- Small forklift: 100 percent hydrogen fuel cell-electric

The results are summarized in Figure 69. The average daily electricity utilization is 25.2 MWh, with a maximum of 41 MWh. The average hydrogen requirement is 1,200 kg/day, with a maximum of 1,500 kg/day.

Figure 69. Electricity and Hydrogen Demand for Option 2



Credit: APEP

For this fleet, 105 chargers are required for the terminal under study, with a 21 MW requirement. During days with high daily operational hours, up to 31 percent and 55 percent of the battery-electric yard tractors and top handlers, respectively, need to be charged at least twice, and for this fleet 5.0 percent to 8.0 percent of charging occurs at peak time, which is undesirable. For the hydrogen demand a storage of 11,000 gallons (~2,900 kg) to 12,000 gallons (~3,200 kg) is appropriate. This option, due to lower electricity demand (both energy and power) is more amenable to microgrid design and deployment compared to Option 1; however, still significant DER need to be deployed to support this terminal in an outage but the required DER sizes are much smaller than those in Option 1 since hydrogen plays a bigger role in this option.

7 Recommendations and Summary

By assessing CHE inventories of POLB, POLA, and a marine terminal, this blueprint is established to meet the timeframe and environmental goals of the San Pedro Bay Ports CAAP. To achieve 100 percent zero-emission at the terminal by year 2030, the timeframe of the infrastructure blueprint is 2023-2030, using 2020 (or 2021, when available) as the baseline for existing zero-emission CHE. Yard tractors, top handlers, RTG cranes, and forklifts are the first to transition to zero-emission, which by themselves will reduce emissions by 90 percent.

Using POLB data and data associated with the terminal used as the case study, a detailed analysis of infrastructure needs to transition to a zero-emission CHE fleet was performed. To this end, the operation of existing CHE was first assessed to establish a baseline. The future electricity and hydrogen requirements were projected based on the operations and hours of operation of CHE types, the electricity demand of electric options was determined, and the hydrogen demand of fuel cell options was established using data from current and previous demonstrations and, in the absence of such data, a model that was developed for this purpose. Using the electricity demand and the hydrogen requirements of a zero-emission CHE fleet, the infrastructure required to support charging and hydrogen fueling was determined. Additionally, for charging of battery-electric options, impacts of delayed and smart charging on reducing peak demand were identified and assessed, followed by alternatives to DCFC.

Next, deployment of DERs was addressed by determining the amount of solar PV, energy storage, and stationary fuel cells the ITS terminal can accommodate. This was followed by a description of a possible port hydrogen ecosystem to achieve zero emission not only in CHE at the port, but in other sectors of the port, such as marine applications and drayage. The importance of resiliency in selecting an optimum fleet mix for CHE was established followed by the costs associated with vehicles, infrastructure, and fuel. Available incentives and tools to facilitate the transition to zero-emission CHE were summarized.

Overall, based on the analysis and discussions provided in this report, it is concluded that a mix of battery-electric and hydrogen fuel cell-electric options is ideal. Charging infrastructure can be costly and will most likely require a significant grid upgrade. Moreover, battery-electric CHE require changes to current operation since many need to be charged multiple times a day and, in the absence of automatic or wireless charging, personnel are required to plug in the equipment, which might delay the start of a charging session (which is limited especially during the day to between shifts 1 and 2). Hydrogen infrastructure, while expensive, does require a change in neither operations nor behavior, as it similar to the existing diesel fueling strategy.

Since battery-electric technologies are today more mature than fuel cell-electric technologies, battery-electric CHE are projected to be deployed in the short-term for yard tractors and top handlers. To avoid reliance on one source of energy, and to increase the resiliency of operation and capture a more optimal fit to certain CHE applications, hydrogen fuel cell-electric powered CHE are projected to be deployed as they become commercially viable in long-term. In the meantime, near-zero-emission options will serve as a bridging option. For example, hybrid RTG cranes can be deployed to reduce emissions and can later be repowered with hydrogen fuel cell-electric (the fuel cell will replace the existing diesel engine in the hybrid RTG). Two implementation options were discussed in the blueprint, one focused on early transition to zero-emission CHE and the other on resiliency. In both options, battery-electric CHE are deployed in short-term and fuel cell-electric CHE in the medium- to long-term.

Based on the analysis conducted to prepare and develop this blueprint, the conclusions and recommendations of the projects are:

- **Meeting zero-emission CHE targets by 2030 is feasible.**
  Based on the literature and background review, status of commercially available zero-emission CHE, and demonstrations at the ports, we concluded that the 2030 CAAP target can be met. However, due to long lead times it is necessary that terminals plan and place orders as soon as possible for the CHE that are commercially available and initiate the necessary infrastructure planning and upgrades. Two implementation strategies with varying levels of battery-electric and hydrogen fuel cell-electric CHE are recommended in the blueprint.
- **Multiple options are available for the terminals to meet 2030 targets.**
  Based on available funding/investment for each terminal for purchasing zero-emission CHE and deploying the required charging and hydrogen fueling infrastructure, multiple options are available. In the blueprint, two implementation options are presented, one focusing on early transition to zero-emission in short-term and the other on resiliency. The blueprint can be used to support the development of an implementation plan from scratch, or an evolving implementation plan for the selection of both the CHE and required charging/hydrogen fueling infrastructure.
- **Battery-electric options should be deployed in the short-term followed by hydrogen fuel cell-electric options in the medium- to long-term.**
  Since battery-electric and grid-tied options are more mature compared to hydrogen fuel cell-electric options, terminals should deploy battery-electric and grid-tied options in the short-term as well as near-zero emission options such as hybrid rubber-tired gantry (RTG) cranes designed for transformation to zero -emission hydrogen fuel cell power in the medium-term. To avoid reliance on one source of energy and increase the resiliency of operation, as well as take advantage of possible future hydrogen ecosystem at the ports, fuel cell-electric options should be deployed in the medium- to long-term as they become commercially available.
- **Battery-electric options require modifications in the operation of the terminals.**
  While it is preferred that the battery-electric CHE be charged only once per day and only after the second shift, the analysis in this project shows that, on average, 30 percent and 13 percent of the yard tractor and top handler fleet respectively need to be charged at least twice per day. For busy days, this percentage can be up to 60 percent and 50 percent, respectively. Thus, it is necessary to select other charging opportunities to ensure that the battery-electric CHE fleet are capable of performing the required tasks. The additional charging opportunities at the terminals include 12:00 p.m. to 1:00 p.m., 5:00 p.m. to 6:00 p.m., and 10:00 p.m. to 11:00 p.m. with the 5:00 p.m. to 6:00 p.m. slot during peak hours being undesirable. During these times, the operators need

to drive the battery-electric CHE to charging stations and a gearman needs to be present to plug in the equipment for charging.

- **With the addition of communication infrastructure, delayed and smart charging can help reduce electricity costs and demand charges.**
  Deployment of battery-electric CHE can result in an increase in terminal electricity demand up to 51 percent depending on the fleet mix, and the peak terminal demand can increase by three times, substantially impacting costs. Results of the modeling and analyses show that delayed and smart charging can substantially reduce terminal peak electricity demand and also help avoid charging during on-peak times. Depending on the number of battery-electric CHE in the fleet, smart charging can help reduce the peak demand by 85 percent and electricity usage during on-peak times by up to 19 percent.
- **Deployment of battery-electric CHE requires substantial grid upgrades, and requires substantial space on the terminals.**
  Considering the operations of the terminal and surveys conducted by POLB, one charger is required per equipment. As the penetration of battery-electric options in the fleet mix increases, this requirement results in the deployment of a substantial number of chargers which will require large grid upgrades both on the utility and the customer (terminal) sides of the meter. Additionally, DCFC equipment requires substantial space and will require rearranging the CHE parking spaces and increasing the space dedicated to CHE parking on the terminal by up to 50 percent.
- **Hydrogen fuel cell-electric options are particularly suitable to replace diesel powered CHE.**
  Hydrogen fuel cell-electric options, due to range and fueling process, are similar to their diesel counterparts and will, as a result, require minimal changes to the terminal operations and procedures. However, these technologies are less commercially mature compared to the battery-electric options. Substantial progress has been made in the recent years and many fuel cell-electric technologies are being demonstrated at the San Pedro Bay Ports. Additionally, mobile refuelers suitable for the ports are also being developed. As a result, hydrogen fuel cell-electric options are viable in the medium- and long-term when both hydrogen fuel cell-electric CHE and mobile fuelers become commercially available. In the meantime, near zero-emission CHE such as hybrid RTG cranes (with a low-NO_X diesel generator) can be deployed to immediately reduce emissions, and then transformed to zero-emission hydrogen fuel cell power when commercially viable (perhaps as soon as March 2023).
- **The number of hydrogen fuel cell-electric CHE and hydrogen demand should reach a threshold to maximize benefits.**
  For the ITS terminal, the analyses show that when the hydrogen demand reaches 1,400 kg per day, one of the diesel storage tanks can be removed. The footprint of hydrogen storage tanks is greater compared to that of diesel storage tanks, and thus removing one of the diesel storage tanks frees valuable space on the terminal for hydrogen. Additionally, discussions with hydrogen providers indicate that when hydrogen demand reaches at least 5,000 kg per day, they plan to build dedicated hydrogen infrastructure to increase the reliability of hydrogen delivery. Analyses show that even with a 100 percent hydrogen fuel cell-electric CHE fleet, the terminal hydrogen demand reaches

3,500 kg/day to 5,000 kg/day. If multiple terminals at the port deploy hydrogen fuel cell-electric CHE, the threshold of 5.000 kg/day can be readily met.

- **Substantial investment is required to accommodate deployment of zero-emission CHE at the ports.**
  Results of the analyses show that a substantial upfront investment is required to purchase zero-emission CHE. The zero-emission CHE that is currently commercially available are substantially more expensive than their diesel counterparts (despite having lower maintenance costs), and it is expected that the future offerings will follow this trend.
- **Operational costs, especially fuel costs, can be reduced by switching to zero-emission CHE.**
  Results of the analyses show that transitioning to zero-emission CHE can reduce the overall cost of fuel for the terminal (cost of electricity plus hydrogen compared to diesel) but the extent of reduction highly depends on the price of hydrogen and diesel. With current diesel prices, and for a 50 percent hydrogen fuel cell-electric fleet, a hydrogen price of more than $12.50/kg results in an increase in fuel costs. (Note that previous APEP studies project that the delivered price of 100 percent renewable hydrogen will be $8.00/kg in 2035.) In this project, a detailed sensitivity analysis was conducted on the price of hydrogen and diesel.
- **Technologies currently being demonstrated might play a major role in facilitating deployment of zero-emission CHE and the required infrastructure.**
  Many technologies are being demonstrated (or will be demonstrated) at the ports, including wireless charging, on-route charging, hydrogen fuel cell-electric yard tractors, and hydrogen fuel cell-electric RTG cranes. While these technologies were included in the blueprint, due to lack of data including operational data and cost data, it is currently difficult to compare these emerging technologies with currently available solutions. However, these technologies provide solutions to several issues and constraints that current technologies face related to operations on a port terminal.
- **Deploying zero-emission CHE has substantial climate, air quality, and public health benefits, especially to disadvantaged communities.**
  Deploying zero-emission CHE results in GHG reduction of 13 to 18 percent, NO_x reductions of 1 ton/day, and health benefits of $2 million to $ 7 million per month, $1 million of which is associated with disadvantaged communities.

8 References

[1] California Air Resources Board, "AB 32 Global Warming Solutions Act of 2006," 2018. [Online]. Available: https://ww2.arb.ca.gov/resources/fact-sheets/ab-32-global-warming-solutions-act-2006.

[2] Office of Governor, "Governor Brown Establishes Most Ambitious Greenhouse Gas Reduction Target in North America." [Online]. Available: https://www.ca.gov/archive/gov39/2015/04/29/news18938/index.html.

[3] California Air Resources Board, "Proposed Fiscal Year 2019-20 Funding Plan for Clean Transportation Incentives For Low Carbon Transportation Investments and the Air Quality Improvement Program," Sep. 2019.

[4] 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," Sep. 2018.

[5] California Energy Commission, "Clean Energy and Pollution Reduction Act - SB 350." [Online]. Available: https://www.energy.ca.gov/rules-and-regulations/energy-suppliers-reporting/clean-energy-and-pollution-reduction-act-sb-350#:~:text=What Does SB 350 Do,to 50 percent by 2030.&text=SB 350 also requires the,gas end uses by 2030.

[6] California Air Resources Board, "Advanced Clean Trucks." [Online]. Available: https://ww2.arb.ca.gov/our-work/programs/advanced-clean-trucks.

[7] "Executive Order N-79-20." [Online]. Available: https://www.gov.ca.gov/wp-content/uploads/2020/09/9.23.20-EO-N-79-20-Climate.pdf.

[8] California Air Resources Board, "Implementation Manual for the Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP) and Low NOx Engine Incentives Implemented through HVIP," Jan. 2018.

[9] California Air Resources Board, "Hybrid and Zero-Emission Truck and Bus Voucher Incentive Program (HVIP)." .

[10] "L.A.'s Green New Deal. Sustainable City pLAn," 2019. [Online]. Available: https://plan.lamayor.org/sites/default/files/pLAn_2019_final.pdf.

[11] Clean Air Action Plan, "No Title." [Online]. Available: https://cleanairactionplan.org/strategies/.

[12] Port of Long Beach and Port of Los Angeles, "San Pedro Bay Ports Technology Advancement Program. 2020 Annual Report and 2021 Priorities," 2021. [Online]. Available: https://cleanairactionplan.org/documents/2020-tap-annual-report.pdf/.

[13] U.S. Environmental Protection Agency, "Case Study of the San Pedro Bay Ports' Clean Air Action Plan 2006–2018. Best Practices and Lessons Learned," 2021. [Online]. Available: https://www.epa.gov/sites/default/files/2021-03/documents/420r21011.pdf.

[14] San Pedro Bay Ports Clean Air Action Plan, "2018 FEASIBILITY ASSESSMENT for CARGO HANDLING EQUIPMENT," 2019. [Online]. Available:

https://cleanairactionplan.org/documents/final-cargo-handling-equipment-che-feasibility-assessment.pdf/.

[15] Cadmus Group, National Renewable Energy Laboratory, Idaho National Laboratory, and DAV Energy Solutions, "California Transportation Electrifiaction Priority Review Project, Final Evaluation Report," 2021. [Online]. Available: https://www.cpuc.ca.gov/-/media/cpuc-website/divisions/energy-division/documents/sb-350-te/california-te-prp-final-evaluation-report-presentation.pdf.

[16] P. Margalef, T. M. Brown, J. Brouwer, and S. Samuelsen, "Efficiency comparison of tri-generating HTFC to conventional hydrogen production technologies," *Int. J. Hydrogen Energy*, vol. 37, no. 12, pp. 9853–9862, 2012.

[17] "Port of Los Angeles Preliminarily Awarded $41 Million from California Air Resources Board to Launch Zero Emissions Hydrogen-Fuel-Cell-Electric Freight Project | Port of Los Angeles." .

[18] Port of Long Beach, "Our Zero Emission Future." [Online]. Available: https://polb.com/environment/our-zero-emissions-future/#program-details.

[19] R. Moilanen *et al.*, "Port Community Electric Vehicle Blueprint," 2021. .

[20] Port of Long Beach, "The making of state-of-the-art terminal," 2021. [Online]. Available: https://polb.com/port-info/news-and-press/the-making-of-a-state-of-the-art-terminal-08-26-2021/.

[21] Port of San Diego, "Climate Action Plan." [Online]. Available: https://www.portofsandiego.org/environment/energy-sustainability/climate-action-plan.

[22] California Energy Commission, "San Diego Port Sustainability Freight Demonstration Project." [Online]. Available: https://www.energy.ca.gov/showcase/driving-cleaner-transportation/san-diego-port-sustainability-freight-demonstration-project.

[23] Port of San Diego, "Tenth Ave. Marine Terminal Microgrid." [Online]. Available: https://www.portofsandiego.org/environment/energy-sustainability/energy.

[24] Bay Area Air Quality Management District, "West Oakland Community Action Plan," 2019. [Online]. Available: https://www.baaqmd.gov/community-health/community-health-protection-program/west-oakland-community-action-plan.

[25] Port of Oakland, "Seaport Air Quality 2020 and Beyond Plan. The Pathway to Zero Emissions," 2019. [Online]. Available: https://www.portofoakland.com/files/PDF/Volume I.pdf.

[26] The Port of Virginia, "2065 Master Plan: Executive Summary." [Online]. Available: https://www.portofvirginia.com/wp-content/uploads/2016/02/TPOV-master-plan-2065-final-020316.pdf.

[27] Port Houston, "Sustainability Action Plan," 2021. [Online]. Available: https://porthouston.com/wp-content/uploads/SAT-Workshops-Final-Report_20210830_V2.pdf.

[28] U.S. Environmental Protection Agency, "Georgia Ports Authority Reduces Diesel Emissions, Improves Efficiency, and Saves Costs." [Online]. Available:

https://www.epa.gov/ports-initiative/georgia-ports-authority-reduces-diesel-emissions-improves-efficiency-and-saves.

[29] Port of Tacoma, "Northwest Ports Clean Air Strategy," 2021. [Online]. Available: https://www.portoftacoma.com/environment/air-climate/northwest-ports-clean-air-strategy.

[30] M. Moultak, N. Lutsey, and D. Hall, "Transitioning to Zero-Emission Heavy-Duty Freight Vehicles," 2017. [Online]. Available: https://theicct.org/sites/default/files/publications/Zero-emission-freight-trucks_ICCT-white-paper_26092017_vF.pdf.

[31] "Charging Outlet Standards for Cargo-Handling Equipment at the Port of Long Beach and Port of Los Angeles," 2017. [Online]. Available: https://cleanairactionplan.org/documents/charging-outlet-standards-cargo-handling-equipment.pdf/.

[32] Port of Long Beach, "Charging Ahead: The Port Community Electric Vehicle Equipment," 2019. [Online]. Available: https://sustainableworldports.org/wp-content/uploads/Port-Community-Electric-Blueprint-Port-of-Long-Beach.pdf#page=57&zoom=100,93,725.

[33] "J2601/2 Fueling Protocol for Gaseous Hydrogen Powered Heavy Duty Vehicles," 2014. [Online]. Available: https://www.sae.org/standards/content/j2601/2_201409/.

[34] "J2601/3 Fueling Protocol for Gaseous Hydrogen Powered Industrial Trucks," 2013. [Online]. Available: https://www.sae.org/standards/content/j2601/3_201306/.

[35] "J2799 Hydrogen Surface Vehicle to Station Communications Hardware and Software," 2014. [Online]. Available: https://www.sae.org/standards/content/j2799_201404/.

[36] M. Infusino, D. Friez, and M. Boehm, "Zero-Emission Port Equipment Workforce Assessment." [Online]. Available: https://polb.com/environment/our-zero-emissions-future/#program-details.

[37] San Pedro Bay Ports Clean Air Action Plan, "2021 Update: Feasibility Assesement for Cargo-Handling Equipment," 2022. [Online]. Available: https://polb.com/port-info/news-and-press/ports-invite-comment-on-second-cargo-handling-equipment-assessment-03-03-2022/.

[38] Port of Long Beach and L. Starcrest Consulting Group, "Port of Long Beach 2020 Air Emissions Inventory," 2021. [Online]. Available: https://polb.com/environment/air/#emissions-inventory.

[39] Port of Los Angeles and L. Starcrest Consulting Group, "Inventory of Air Emissions for Calendar Year 2020," 2021. [Online]. Available: https://www.portoflosangeles.org/environment/air-quality/air-emissions-inventory.

[40] S. William and G. Ron, "Port of Long Beach Zero Emmission Terminal Equipment Demonstration Projects at Piers C, E, F, G, J, and T," *Ports 2019*. pp. 369–379, 30-Oct-2020.

[41] California Air Resources Board, "Zero Emissions for California Ports (ZECAP)." [Online]. Available: https://ww2.arb.ca.gov/sites/default/files/movingca/pdfs/zecap.pdf.

[42] Advanced Clean Transportation Expo, "2022 Display Vehicles." [Online]. Available: https://www.actexpo.com/vehicles.

[43] California Air Resources Board, "LCTI: Demonstration of Zero-Emission Technologies for Freight Operations at Ports," 2022. [Online]. Available: https://ww2.arb.ca.gov/lcti-demonstration-zero-emission-technologies-freight-operations-ports.

[44] California Air Resources Board, "LCTI: Multisource Green Omni Terminal Project." [Online]. Available: https://ww2.arb.ca.gov/lcti-multisource-green-omni-terminal-project.

[45] Port of Los Angeles, "Advanced Yard Tractor Deployment and Eco-FRATIS Drayage Truck Efficiency Project." [Online]. Available: https://sustainableworldports.org/wp-content/uploads/CEC_2015_Factsheet_final.pdf.

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

[47] Port of Los Angeles, "Everport Advanced Cargo Handling Demonstration Project." [Online]. Available: https://kentico.portoflosangeles.org/getmedia/a374b9ef-59bf-4862-ab66-9b8f69c62315/fact_sheet_cec_2017.

[48] California Air Resources Board, "LCTI: The Commercialization of POLB Off-Road Technology 'C-PORT' Demonstration." [Online]. Available: https://ww2.arb.ca.gov/lcti-commercialization-polb-road-technology-c-port-demonstration.

[49] CAVOTEC, "Service for Ports & Maritime." [Online]. Available: https://www.cavotec.com/en/your-applications/ports-maritime/service-for-ports-maritime.

[50] C. Frederickson *et al.*, "Performance and Activity Characteristics of Zero Emission Battery-Electric Cargo Handling Equipment at a Port Terminal," in *WCX SAE World Congress Experience*, 2022.

[51] California Public Utilities Commissions, "Transportation Electrification Activities Pursuant to Senate Bill 350."

[52] F. Alasali, S. Haben, V. Becerra, and W. Holderbaum, "Optimal Energy Management and MPC Strategies for Electrified RTG Cranes with Energy Storage Systems," *Energies* , vol. 10, no. 10. 2017.

[53] Z. Shao, "Non-road emission inventory model methodology," *Interantional Counc. Clean Transp.*, 2016.

[54] Port of Los Angeles and Port of Long Beach, "San Pedro Bay Ports Emissions Inventory Methodology Report." [Online]. Available: https://www.portoflosangeles.org/environment/air-quality/air-emissions-inventory.

[55] Department of Energy, "Fuel Conversion Factors to Gasoline Gallon Equivalents." [Online]. Available: https://epact.energy.gov/fuel-conversion-factors.

[56] A. Burnham *et al.*, "Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains," United States, 2021.

[57] A. L. Brown, D. Sperling, B. Austin, J. DeShazo, L. Fulton, and T. Lipman, "Driving California's Transportation Emissions to Zero," *UC Off. Pres. Univ. Calif. Inst. Transp. Stud.*, 2021.

[58] E. Alasali, S. Haben, V. Becerra, and W. Holderbaum, "A Peak Shaving Solution For Electrified RTG Cranes," in *Proceedings of the International Conference on Recent Innovations in Engineering and Technology*, 2017.

[59] L. M. Steele and C. Myers, "Hydrogen Fuel Cell Applications in Ports: Feasibility Study at Multiple U.S. Ports," 2019. [Online]. Available: https://www.energy.gov/sites/prod/files/2019/10/f68/fcto-h2-at-ports-workshop-2019-viii3-steele.pdf.

[60] R. Matulka, J. R. DeShazo, and C. Callahan, "Moving Towards Resiliency: An Assessment of the Costs and Benefits of Energy Security Investments for the San Pedro Bay Ports," UCLA Luskin Center for Innovation, Los Angeles, CA. Available: http://innovation.luskin.ucla.edu/sites/default/files/Port%20Report.pdf (Accessed 2/8/2016), 2013.

[61] Kalmar, "Electric Heavy Forklift Truck." [Online]. Available: https://www.kalmarglobal.com/equipment-services/forklift-trucks/electric-heavy-forklift/.

[62] K. Forrest and S. Samuelsen, "Medium- and Heavy-Duty Zero-Emission Vehicle Fueling and Charging Standardization Assessment (Interim Report #2)," 2022.

[63] M. Mac Kinnon, G. Razeghi, and S. Samuelsen, "The role of fuel cells in port microgrids to support sustainable goods movement," *Renew. Sustain. Energy Rev.*, vol. 147, p. 111226, 2021.

[64] Port of Long Beach, "Port of Long Beach Energy Island Initiative."

[65] Port of Long Beach, "Port of Long Beach Microgrid —Resilience for Critical Facilities."

[66] B. Lane, M. MacKinnon, B. Shaffer, and S. Samuelsen, "Deployment planning tool for environmentally sensitive heavy-duty vehicles and fueling infrastructure," *Energy Policy*.

[67] J. Reed *et al.*, "Roadmap for the Deployment and Buildout of Renewable Hydrogen Production Plants in California," 2020.

[68] K. Forrest, M. Mac Kinnon, B. Tarroja, and S. Samuelsen, "Estimating the technical feasibility of fuel cell and battery electric vehicles for the medium and heavy duty sectors in California," *Appl. Energy*, vol. 276, p. 115439, 2020.

[69] Energy+Environmental Economics, "California PATHWAYS Model," https://ethree.com/public_projects/energy_principals_study.php (Accessed 11/3/2015), 2015.

[70] California Air Resources Board, "PATHWAYS Scenario Modeling,2022 Scoping Plan Update." [Online]. Available: https://ww2.arb.ca.gov/sites/default/files/2021-12/Revised_2022SP_ScenarioAssumptions_15Dec.pdf.

[71] "SMOKE v4.0 User's Manual," Community Modeling and Analysis System . Available: https://www.cmascenter.org/smoke/documentation/4.0/manual_smokev40.pdf , 2016.

[72] California Air Resources Board, "ESTA Documentation," 2022. .

[73] U.S. Environmental Protection Agency, "Community Multiscale Air Quality Modeling System (CMAQ)," 2022. .

[74] S. Zhu, M. Mac Kinnon, B. P. Shaffer, G. S. Samuelsen, J. Brouwer, and D. Dabdub, "An uncertainty for clean air: Air quality modeling implications of underestimating VOC emissions in urban inventories," *Atmos. Environ.*, vol. 211, pp. 256–267, 2019.

[75] M. Mac Kinnon, B. Shaffer, M. Carreras-Sospedra, D. Dabdub, G. S. Samuelsen, and J. Brouwer, "Air quality impacts of fuel cell electric hydrogen vehicles with high levels of renewable power generation," *Int. J. Hydrogen Energy*, vol. 41, no. 38, pp. 16592–16603, 2016.

[76] W. P. L. Carter, "Development of the SAPRC-07 chemical mechanism," *Atmos. Environ.*, vol. 44, no. 40, pp. 5324–5335, 2010.

[77] H. O. T. Pye *et al.*, "On the implications of aerosol liquid water and phase separation for organic aerosol mass," *Atmos. Chem. Phys.*, vol. 17, no. 1, pp. 343–369, 2017.

[78] W. C. Skamarock *et al.*, "A Description of the Advanced Research WRF Version 3," *Tech. Rep.*, no. June, p. 113, 2008.

[79] G. Danabasoglu *et al.*, "The community earth system model version 2 (CESM2)," *J. Adv. Model. Earth Syst.*, vol. 12, no. 2, p. e2019MS001916, 2020.

[80] A. B. Guenther *et al.*, "The Model of Emissions of Gases and Aerosols from Nature version 2.1 (MEGAN2. 1): an extended and updated framework for modeling biogenic emissions," 2012.

[81] M. Carreras-Sospedra, D. Dabdub, M. Rodriguez, and J. Brouwer, "Air quality modeling in the south coast air basin of California: What do the numbers really mean?," *J. Air Waste Manage. Assoc.*, vol. 56, no. 8, pp. 1184–1195, 2006.

[82] U.S. Environmental Protection Agency, "Air Quality System (AQS)," 2019. .

[83] C. Emery, Z. Liu, A. G. Russell, M. T. Odman, G. Yarwood, and N. Kumar, "Recommendations on statistics and benchmarks to assess photochemical model performance," *J. Air Waste Manage. Assoc.*, vol. 67, no. 5, pp. 582–598, Apr. 2017.

[84] CARB, "Area Designation Maps / State and National. California Air Resources Board," 2017. .

[85] D. W. Dockery *et al.*, "An association between air pollution and mortality in six US cities," *N. Engl. J. Med.*, vol. 329, no. 24, pp. 1753–1759, 1993.

[86] M. Jerrett *et al.*, "Long-term ozone exposure and mortality," *N. Engl. J. Med.*, vol. 360, no. 11, pp. 1085–1095, 2009.

[87] C. A. Pope III and D. W. Dockery, "Health effects of fine particulate air pollution: lines that connect," *J. Air Waste Manage. Assoc.*, vol. 56, no. 6, pp. 709–742, 2006.

[88] U.S. EPA, "Environmental Benefits Mapping and Analysis Program - Community Edition," 2022.

[89] GeoLytics, "GeoLytics Demographic Data," 2020. .

[90] R. W. Atkinson, S. Kang, H. R. Anderson, I. C. Mills, and H. A. Walton, "Epidemiological time series studies of PM2.5 and daily mortality and hospital admissions: A systematic review and meta-analysis," *Thorax*, vol. 69, no. 7, pp. 660–665, 2014.

[91] OEHHA, "CalEnviroScreen 4.0 Available at:," 2021. .

[92] American Lung Association, "State of the Air 2022," 2022.