CALIFORNIA ENERGY COMMISSION

California Energy Commission

Clean Transportation Program

**FINAL PROJECT REPORT**

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



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# California Energy Commission

Ghazal Razeghi
Kate Forrest
Michael Mac Kinnon
Scott Samuelsen
**Primary Authors**

University of California, Irvine
Advanced Power and Energy Program
221 Engineering Lab Facility, Bldg. 323
Irvine, CA 92697-3550
(916) 824-7302
Advanced Power and Energy Program Website (www.apep.uci.edu)

**Agreement Number: ARV-21-022**

Marc Perry
**Commission Agreement Manager**

Elizabeth John
**Branch Manager**
**COMMERCIAL AND INDUSTRIAL ZEV TECHNOLOGIES AND INFRASTRUCTURE BRANCH**

Hannon Rasool
**Director**
**FUELS AND TRANSPORTATION DIVISION**

Drew Bohan
**Executive Director**

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# PREFACE

Assembly Bill 118 (Núñez, Chapter 750, Statutes of 2007) created the Clean Transportation Program. The statute authorizes the California Energy Commission (CEC) to develop and deploy alternative and renewable fuels and advanced transportation technologies to help attain the state's climate change policies. Assembly Bill 8 (Perea, Chapter 401, Statutes of 2013) reauthorizes the Clean Transportation Program through January 1, 2024, and specifies that the CEC allocate up to $20 million per year (or up to 20 percent of each fiscal year's funds) in funding for hydrogen station development until at least 100 stations are operational.

The Clean Transportation Program has an annual budget of about $100 million and provides financial support for projects that:

- Reduce California's use and dependence on petroleum transportation fuels and increase the use of alternative and renewable fuels and advanced vehicle technologies.
- Produce sustainable alternative and renewable low-carbon fuels in California.
- Expand alternative fueling infrastructure and fueling stations.
- Improve the efficiency, performance, and market viability of alternative light-, medium-, and heavy-duty vehicle technologies.
- Retrofit medium- and heavy-duty on-road and nonroad vehicle fleets to alternative technologies or fuel use.
- Expand the alternative fueling infrastructure available to existing fleets, public transit, and transportation corridors.
- Establish workforce-training programs and conduct public outreach on the benefits of alternative transportation fuels and vehicle technologies.

To be eligible for funding under the Clean Transportation Program, a project must be consistent with the CEC's annual Clean Transportation Program Investment Plan Update. The CEC issued GFO-20-601 to accelerate the deployment of MDHD ZEVs and ZEV infrastructure with a holistic and futuristic view of transportation planning. In response to GFO-20-601, the recipient submitted an application that the CEC proposed for funding in its notice of proposed awards dated April 8, 2021, and the agreement was executed as ARV-21-022 on November 3, 2021.

# ABSTRACT

The project titled "A Comprehensive and Replicable Infrastructure Blueprint for Zero-Emission Medium- and Heavy-Duty Vehicles Operating at a Port Terminal" facilitates the deployment of zero-emission medium- and heavy-duty (MDHD) vehicles at port terminals and the specification of the required charging/fueling infrastructure. The project team developed a comprehensive blueprint for the vehicles and infrastructure by soliciting and including input from stakeholders. The project (1) assessed the benefits of zero-emission MDHD port vehicles to adjacent disadvantaged and low-income communities, (2) conducted community outreach for input, (3) developed a blueprint of the infrastructure required to support a port zero-emission MDHD fleet, and (4) conducted a technology assessment to optimize MDHD electric vehicle supply equipment and associated fueling infrastructure.

The project team partnered with International Transportation Service terminal at the Port of Long Beach and obtained the data associated with its cargo handling equipment (CHE) to develop a baseline for current fuel consumption. The project team estimated the future electricity and hydrogen demand of the CHE fleet with different combinations of battery-electric and hydrogen fuel cell CHE. The project team used the demand to estimate the fixed infrastructure needed to support the electric charging and hydrogen fueling for the fleet and the associated costs and the changes in operations and fueling protocols.

The project team used (1) the Community Multi-Scale Air Quality model to model atmospheric chemistry and transport to assess the air quality impacts of transitioning to zero-emission CHE, and (2) the United States Environmental Protection Agency's Benefits Mapping and Analysis Program—Community Edition to quantify and value the health benefits that result from the reduced levels of ozone and particulate matter smaller than 2.5 microns in diameter.

**Keywords**: Port Electrification, Zero-Emission CHE, Charging Infrastructure, Hydrogen Fueling, Air Quality Impacts, Health Impacts

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# 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 supply. Currently, seaports and marine terminals are working to balance global and local economic viability and sustainability. While vital to global and regional economies, port entities 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 emissions. The sources of emissions from ports include ocean-going vessels, heavy-duty drayage trucks, harbor crafts, railroad locomotives and cargo handling equipment. A key strategy to reduce criteria pollutant and greenhouse gas emissions from port terminals, is to replace medium- and heavy-duty vehicles and cargo handling equipment with zero-emission options such battery-electric and hydrogen fuel cell options. With the electrification of cargo handling equipment, alternative marine power, and port vehicles, port electricity and hydrogen demand will increase significantly. The reliance solely on electricity or hydrogen alone for terminal operations will increase the vulnerability of the port to power outages or hydrogen supply respectively. Thus, it is necessary to consider impacts on reliability and resiliency, and to provide solutions to enhance reliability and resiliency. Furthermore, new infrastructure is required to support battery charging and hydrogen fueling needs of the new zero-emission medium- and heavy-duty vehicle fleet. Thus, it is necessary to develop a plan for electric charging and hydrogen fueling infrastructure at marine terminals to support zero-emission medium- and heavy-duty vehicles and cargo handling equipment. To this end, the Advanced Power and Energy Program at the University of California, Irvine, has developed a comprehensive and replicable infrastructure blueprint to support zero-emission medium- and heavy-duty vehicles and cargo handling equipment at a marine terminal.

## Project Purpose

To address the infrastructure needs of zero-emission medium- and heavy-duty vehicles and cargo handling equipment at the ports, the goals of the project were (1) to develop a comprehensive and replicable infrastructure blueprint to support zero-emission medium- and heavy-duty vehicles and cargo handling 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, the Advanced Power and Energy Program:

- Assessed the benefits of zero-emission medium- and heavy-duty vehicles operating at a port terminal to disadvantaged and low-income communities.
- Conducted community outreach for input.
- Developed a replicable and comprehensive blueprint for the infrastructure necessary to support the zero-emission medium- and heavy-duty vehicle fleet operating at a marine terminal by defining the blueprint parameters and boundaries, including technical, economic and environmental goals.
- Conducted a technology assessment in order to optimize medium- and heavy-duty electric vehicle supply equipment and hydrogen fueling infrastructure.

## Project Approach

The project approach systematically evaluated the deployment of zero-emission cargo handling equipment at ports with a specific focus on the International Transportation Service, Inc. terminal at the Port of Long Beach. First, the Advanced Power and Energy Program conducted a detailed literature and background review in order to compile applicable energy and environmental goals at the state, local and city levels. While the state of California has stringent energy and greenhouse gas reduction goals and regulations to accelerate transition to zero-emission medium- and heavy-duty vehicles and cargo handling equipment, the San Pedro Bay Ports have set their own greenhouse gas reduction targets detailed in the San Pedro Clean Air Action Plan, which requires all terminal equipment, including cargo handling equipment and on-road drayage trucks, to be transitioned to zero-emission options by 2030 and 2035, respectively. To determine the constraints and boundaries of the blueprint and assess the current status of zero-emission technologies, the Advanced Power and Energy Program used data, survey results and lessons learned from these demonstrations and leveraged discussions and meeting with terminal staff.

The Advanced Power and Energy Program used data from emissions inventories from the Port of Long Beach and the Port of Los Angeles, as well as data received from the International Transportation Service, Inc. terminal, to identify the cargo handling equipment types contributing most to emissions and to determine the average daily operating hours and maximum daily operating hours (associated with particularly busy days) for each type of cargo handling equipment.  These data were then used to establish a baseline for the operational needs of the future zero-emission cargo handling equipment fleet.

The research team established scenarios, each with a different mix of battery-electric and hydrogen fuel cell options, to (1) compare costs, complexity, and impact on operations, and (2) encompass options for terminals with different needs, funding, and targets.

For some commercially available cargo handling equipment, the Advanced Power and Energy Program used data from existing vehicles and previous and current demonstrations to estimate the electricity demand and hydrogen requirements based on operating hours, energy demand, and battery size. For other cargo handling equipment that are not yet commercial and due to lack of available operational data, the Advanced Power and Energy Program estimated the electricity and hydrogen demand using the diesel demand, accounting for the higher efficiencies of battery-electric and hydrogen fuel cell counterparts.

Using the estimated charging needs of the battery-electric cargo handling equipment, and focusing on use of direct current fast charging, the Advanced Power and Energy Program determined the infrastructure required to support the battery-electric cargo handling equipment charging, which includes electric vehicle supply equipment, electric grid upgrades, layout changes to existing cargo handling equipment parking lots, and additional space to accommodate installation of charging and grid equipment. The analysis included multiple charging opportunities during the day and between shifts to ensure that battery-electric cargo handling equipment can perform the required tasks. The detailed analysis considered both average and worst-case operation days, and determining the percentage of charging of battery-electric cargo handling equipment associated with each charging opportunity. This percentage was then used to determine the cost of electricity and demand charges. The research team developed a delayed and smart (i.e., controlled) charging strategy for battery-electric cargo handling equipment, and assessed the impact of delayed and smart charging on reducing peak electricity demand and costs.

The infrastructure and selected strategy for hydrogen fueling was assumed similar to the existing diesel fueling strategy on the terminal. The infrastructure included hydrogen storage at the terminal and a mobile hydrogen fueler to drive to and refuel hydrogen fuel cell cargo handling equipment once a day. Based on the hydrogen need of each scenario, the Advanced Power and Energy Program determined the size of required hydrogen storage. For the scenarios with a mix of both battery-electric and hydrogen fuel cell cargo handling equipment, the Advanced Power and Energy Program estimated infrastructure costs as well as overall fuel costs based on the required electric charging and hydrogen fueling infrastructure.

In order to reduce energy costs and increase the reliability and resiliency of terminal operations, and based on available footprint and space on the terminal, the Advanced Power and Energy Program determined the capacity of the terminal for hosting photovoltaic solar energy generation, battery energy storage, and stationary fuel cells. Leveraging previous the Advanced Power and Energy Program experience and projects, the blueprint includes a discussion on microgrids and nanogrids, including hydrogen grids, at the ports.

## Conclusions and Recommendations

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

- Implement strategies with varying levels of battery-electric and hydrogen fuel cell cargo handling equipment.
- Implement two options, 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 cargo handling equipment and required charging/hydrogen fueling infrastructure.
- Deploy battery-electric and grid-tied options in the short-term and deploy fuel cell options in the medium-term to long-term as they become commercially available.
- Battery-electric options will require slight modifications in the operation of the terminals.
- With the addition of communication infrastructure, delayed and smart charging can help reduce electricity costs and demand charges.
- Deployment of battery-electric cargo handling equipment requires substantial grid upgrades and will require substantial space on the terminals.
- Hydrogen fuel cell options are more suitable for terminal operations than diesel cargo handling equipment and should be deployed in the medium-term to long-term.
- Substantial investment is required to accommodate deployment of zero-emission cargo handling equipment at the ports.
- Operational costs, especially fuel costs, can be reduced by switching to zero-emission cargo handling equipment.
- Technologies currently being demonstrated might play a major role in facilitating deployment of zero-emission cargo handling equipment and the required infrastructure.

- Deploying zero-emission cargo handling equipment has substantial environmental and public health benefits to benefit disadvantaged communities.

The blueprint is designed to facilitate the adoption of zero-emission medium- and heavy-duty cargo handling equipment at ports by reducing uncertainty regarding the required infrastructure and reliability, and by providing pathways and recommendations to achieve the State energy and environmental goals. The anticipated benefits to the region include, but not limited to:

- Greenhouse gas reduction of more than 315,000 tons per year.
- Criteria pollutant reduction of more than one ton per day.
- Air quality improvement, including ground-level ozone and particulate matter.
- Health benefits valued at saving $2 million to $7 million per month.
- Job creation.
    - Through collaboration with Saddleback College, the Advanced Power and Energy Program developed a workforce curriculum as well as a list of degrees and certificates relevant to workforce training in this area. Jobs related to the deployment of zero-emission cargo handling equipment include manufacturing, installation, operation, and maintenance of the charging/fueling infrastructure.

# CHAPTER 1: Introduction

The seaports (commonly known as ports) in California are responsible for handling 40 percent of container imports into the United States. Cargo that enters the ports are generally transferred from ships at terminals using cargo handling equipment (CHE) such as cranes, and forklifts. From there, drayage trucks transport the goods across the region to distribution centers. Thus, ports play a critical role in the global and local economy and need to retain their economic competitiveness while increasing efficiencies of operation, and improving the resiliency, reliability, and security of their operations. Port operations are also 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. At the Port of Long Beach (POLB) alone, diesel-powered rubber tire gantry cranes (RTG) comprise only 5 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 equipment inventory and a significant percentage of overall port emissions. In addition, more than 3,200 pieces of CHE operate at both POLB and the Port of Los Angeles (POLA), comprising 6 percent of the port's overall diesel particulate matter emissions, 7 percent of oxides of nitrogen (NOx) emissions and 17 percent of greenhouse gas (GHG) emissions (Port of Long Beach and Port of Los Angeles, 2017).

Thus, a key strategy to reduce environmental impacts from a marine terminal operation is to reduce emissions from medium- and heavy-duty (MDHD) off-road port vehicles, which are mostly comprised of CHE, including yard tractors, top handlers, side handlers, reach stackers, forklifts, and RTGs. To facilitate transitioning to and deploying zero-emission CHE at marine terminals, the Advanced Power and Energy Program (APEP) at the University of California, Irvine (UCI) developed the document *A Comprehensive and Replicable Infrastructure Blueprint for Zero-Emission Medium- and Heavy-Duty Vehicles Operating at a Port Terminal*[1] (blueprint), funded by a grant from the California Energy Commission (CEC) to determine the infrastructure required to support zero-emission CHE at port terminals. POLB was an advisory partner in the project in order to coordinate the blueprint with its overall goals and existing plans and to ensure that the blueprint is complementary to existing efforts by POLB to de-carbonize port operations.

Another project partner was the International Transportation Service, Inc. (ITS) terminal at POLB that served as the case study for the blueprint. The UCI Institute of Transportation Studies facilitated surveys and Saddleback College partnered in workforce development and training. Project partners that provided input and overall review of the findings included FirstElement Fuel, Toyota, ChargePoint, Southern California Edison, South Coast Air Quality Management District (SCAQMD), Air Liquide, Air Products, and Hyundai America Technical Center, Inc.

[1] "A Comprehensive and Replicable Infrastructure Blueprint for Zero-Emission Medium- and Heavy-Duty Vehicles Operating at a Port Terminal." (http://www.apep.uci.edu/WhitePapers/PortTerminalBlueprint2023.html)

## Project Goals and Objectives

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

1. Assess the benefits of zero-emission MDHD vehicles operating at a port terminal to disadvantaged and low-income communities.
2. Conduct community outreach for input.
3. Develop a replicable and comprehensive blueprint for the infrastructure necessary to support the zero-emission MDHD fleet operating at a marine terminal by defining the blueprint parameters and boundaries, including technical, economic and environmental goals.
4. Conduct a technology assessment in order to optimize MDHD electric vehicle supply equipment (EVSE) and hydrogen fueling infrastructure.

## Approach

To achieve the goals and objectives of the project, the project team developed and addressed the following tasks:

- Task 1: Administration
  - This task included all the activities required for project management and included the preparation and submission of the required reports, including the final report.
- Task 2: Define technical, economic, and environmental goals of the blueprint
  - The goal of this task was to gather data and information from the marine terminal to define the parameters, goals, and boundaries of the blueprint. APEP accomplished this by:
    a. Reviewing previous CEC efforts for zero-emission MDHD vehicles and the actions taken and adopted by local jurisdictions to deploy those vehicles.
    b. Defining the economic and environmental goals of the port.
    c. Identifying diesel-powered MDHD vehicles and CHE that can be replaced by zero-emission options.
    d. Identifying fueling and charging operating constraints specific to a marine terminal.
- Task 3: Technology assessment and charging and fueling infrastructure optimization
  - The goal of this task was to assess and optimize EVSE and hydrogen fueling infrastructure needed to meet needs of future zero-emission MDHD operating at a marine terminal, as well as assessing the impact of the infrastructure on the electrical grid, electricity costs, and overall electrical resiliency of the community. APEP accomplished this by:
    a. Identifying the best zero-emission technologies for various MDHD use cases at the terminal.
    b. Determining charging and fueling requirements based on operational data and driving and usage patterns.

c. Assessing various technologies to support charging and fueling needs at the terminal.
d. Assessing impacts on the electrical grid, electricity rates, and energy resiliency.
e. Developing strategies to take advantage of synergies between hydrogen fueling and battery charging infrastructure.
f. Identifying additional tools to further improve infrastructure planning.

- Task 4: Community outreach and knowledge/technology transfer
  - The goal of this task was to develop a plan for outreach efforts and knowledge transfer to ensure that the blueprint was shared with the community and stakeholders, and that their inputs were considered in the blueprint. APEP accomplished this by:

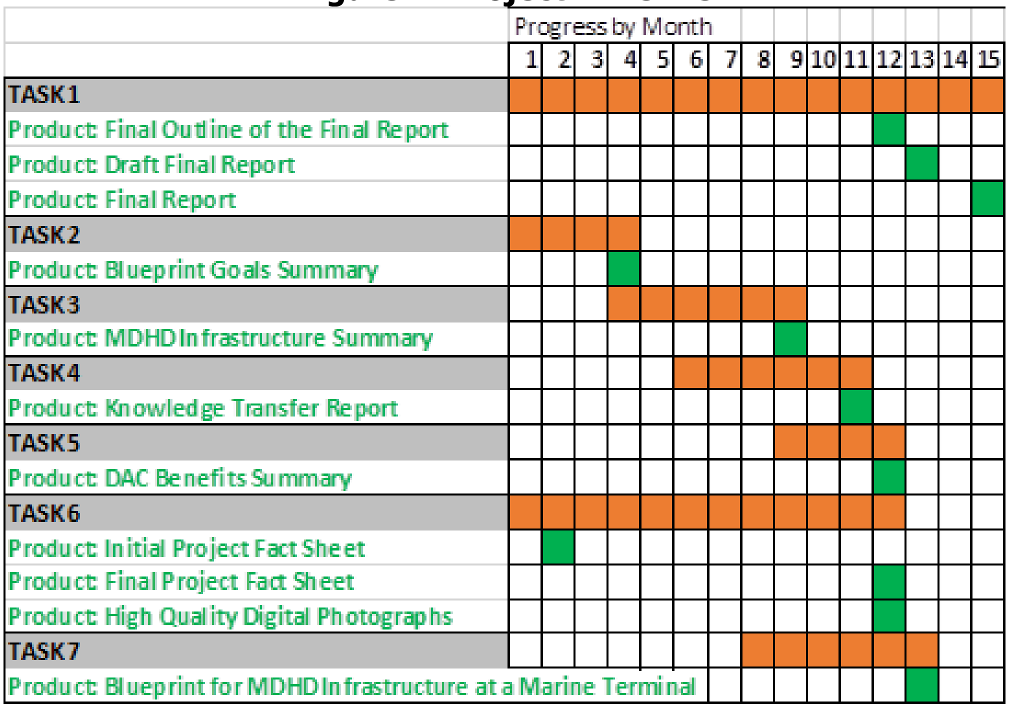
    a. Engaging stakeholders, including local businesses, financial institutions, and community-based organization through a series of meeting summits.
    b. Conducting surveys to get inputs from aforementioned stakeholders.
    c. Summarizing jobs that will be created.
    d. Transferring knowledge and lessons learned from the project through presentations and community outreach.
    e. Developing workforce curricula in collaboration with Saddleback College and deploy it throughout the region.
- Task 5: Assess benefits to disadvantaged and low-income communities
  - The goal of this task was to assess the benefits of the project on disadvantaged and low-income communities near the port, and specifically the deployment of zero-emission MDHD vehicles and their supporting charging and fueling infrastructure at a terminal. APEP accomplished this by:

    a. Identifying low-income and disadvantaged communities that are impacted.
    b. Determining economic and environmental benefits to these communities including reduction in criteria pollutant emissions, improved air quality and reduced GHGs.
- Task 6: Project Fact sheet
  - The goal of this task was to develop an initial and final project fact sheet that described the CEC funded project and the benefits resulting from the project for the public and key decision makers.
- Task 7: Blueprint
  - The goal of this task was to compile the information and results of the previous tasks into a comprehensive blueprint planning document for the MDHD infrastructure at a marine terminal.

## Project Schedule

Figure 1 shows the project schedule and important deliverables from Month 1 (September 2021) to Month 15 (December 2022).

**Figure 1: Project Timeline**




Credit: Advanced Power and Energy Program

# CHAPTER 2: Infrastructure Blueprint for Zero-Emission Cargo Handling Equipment

## Framing the Blueprint

POLB and POLA are the largest fixed sources of emissions and air pollutants in Southern California, emitting more 100 tons per day of particulate-forming NOx, more than the cars in the area. To reduce emissions from the ports and their operations, the San Pedro Bay Ports have set targets to reduce emissions and transition to zero-emission CHE and drayage trucks. The SCAQMD Clean Port Initiative[2] includes four guiding principles and seven action items outlining the steps that SCAQMD, along with federal and state agencies and local and international ports, can take to help reduce port pollution in the region. Additionally, the two ports have agreed to the San Pedro Clean Air Action Plan (CAAP) as a pathway to zero-emission ports and reduce emissions from port operations from every source. Both POLB and POLA adopted the 2017 CAAP, which places the ports on a pathway to become zero-emission goods movement hubs. The 2017 CAAP requires that all terminal equipment and on-road trucks transition to zero-emission options by 2030 and 2035, respectively. Thus, the blueprint adopts the timeframe of 2023 to 2030 to achieve zero-emission CHE at the ITS port terminal and delineates the required infrastructure to support electric charging and hydrogen fueling of the zero-emission CHE. In addition to the CAAP, several other state level programs and targets encourage or mandate transition to zero-emission MDHD and the overall reduction of emissions from these sources. The blueprint includes these state level programs as well as some local and city level programs.

To meet the goals of the CAAP and achieve zero-emission operations, multiple projects demonstrating zero-emission and near-zero emission technologies have occurred or are occurring at POLB and POLA. The San Pedro Bay Ports *2020 Annual Report and 2021 Priorities* (Port of Long Beach and Port of Los Angeles, 2021) includes a summary of some of these projects and demonstrations of zero-emission CHE including electric yard tractors, fuel cell yard tractors, electric forklifts, electric top handlers, and electric RTG cranes. The blueprint includes the details of these projects and additional demonstration projects at POLB, POLA, and other ports across the state and nation.

To further establish the boundaries, constraints, and barriers for the blueprint, APEP conducted a detailed literature review in addition to interviewing ITS terminal staff and leveraging surveys conducted previously by POLB (Port of Long Beach, 2019). APEP identified major constraints such as vehicle range, limited space, and time for charging and fueling, as well as the capital cost of installing new infrastructure.

Freight terminals prefer to operate CHE for two shifts without charging or fueling in between. This presents a challenge for existing battery-electric CHE, which mostly require charging more than once a day to support the operation of the terminal especially on busy days. To resolve

[2] South Coast Air Quality Management District Clean Ports Initiative website (https://www.aqmd.gov/nav/about/initiatives/clean-port)

this issue, APEP discussed several other timeframes for charging the battery-electric CHE with ITS terminal staff. The blueprint includes analyses of these charging opportunities. Additionally, a longshore worker is required to plug in the battery-electric CHE and thus robotic arms for automated hands-free EVSE are preferrable. For hydrogen fueling, the preference is to keep the infrastructure and operations as similar to the existing diesel refueling as possible.

Other barriers include lack of standardization of MDHD charging and hydrogen fueling, lack of skilled workforce and the required training for the zero-emission CHE, the cost associated with charging/hydrogen fueling, the lifetime of batteries, and the need for mobile hydrogen fueling. The blueprint includes a detailed discussion of these barriers.

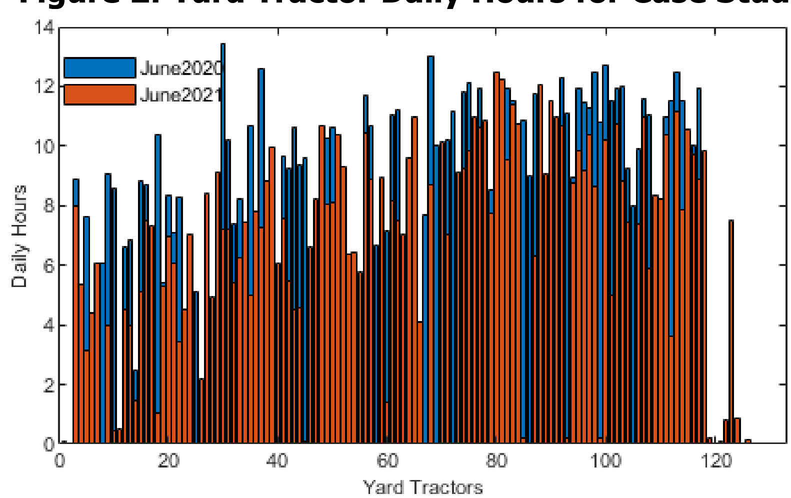
## Establishing a Baseline

To estimate future electricity and hydrogen need of a zero-emission CHE fleet, APEP established a baseline associated with current operations. The first step was to establish a baseline in order to identify the CHE to be replaced with zero-emission options. To this end, APEP used the emissions signature for different CHE at the ports. The data from POLA and POLB emissions inventories indicated that the highest emissions are from yard tractors, top handlers, RTG cranes, and forklifts. Replacing these four types of CHE with zero-emission options will reduce emissions approximately of 90 percent (Agrawal, *et al.* and Port of Long Beach, 2021), (Agrawal, *et al.* and Port of Los Angeles, 2021).

The research team analyzed the operational needs of these four CHE types using two years of monthly operating hours data from the terminal under study. Using these data, APEP determined the average need of the fleet of each type of CHE, as well as a maximum case where the demand is significantly higher than the average. This was undertaken to ensure that the zero-emission CHE fleet can not only handle the average day operations but also extreme and busy days.

Around 120 yard tractors operate on the terminal under study. Figure 2 shows the daily hours of operation for each yard tractor on this terminal for June 2020 and June 2021.

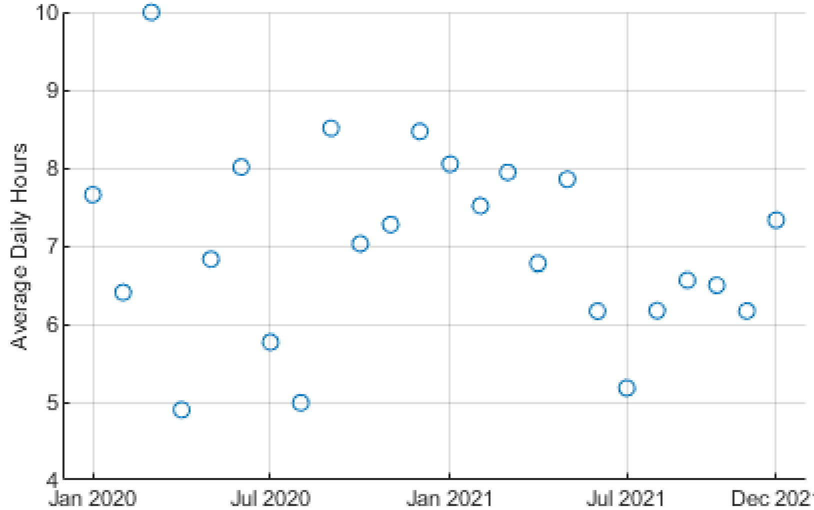
**Figure 2: Yard Tractor Daily Hours for Case Study**




Credit: Advanced Power and Energy Program

Figure 3 shows the average daily hours for the yard tractor fleet for each month (January 2020 to December 2021). This figure shows that the average daily hours range from five hours to 10 hours with an average of seven hours for this terminal, which is consistent with the overall yard tractor fleet at POLB. For analysis of other types of CHE, refer to the blueprint.

**Figure 3: Average Daily Hours for the Yard Tractor Fleet**




Credit: Advanced Power and Energy Program

With the operational baseline established, the commercially established and evolving zero-emission technologies were then identified as capable of meeting the operational requirements of the CHE. The two major categories of zero-emission options are battery-electric CHE and hydrogen fuel cell CHE. Table 1 presents examples of demonstration programs (and the pros and cons) for some of these technologies. The San Pedro Bay Ports conducted several feasibility studies and surveys on the status and technology readiness of these technologies for deployment and determined that the battery-electric options are ahead of HFC options in terms of commercialization and maturity (Port of Long Beach and Port of Los Angeles, 2019) (Port of Long Beach and Port of Los Angeles, 2022). As a result, battery-electric options are more likely to be used in the short term transition to zero-emission. As hydrogen fuel cell options become commercial in the medium-term, they will accelerate the transition to zero-emission. In the short-term, bridging commercial near-zero-emission hybrid product is available with low-NOx diesel generation that can be designed to be replaced by fuel cell power prior to 2030. The blueprint includes infrastructure for varying mixes of battery-electric and hydrogen fuel cell options and thereby the opportunity to compare costs, complexity, and impact on operations depending on terminal needs, funding, and targets.

**Table 1: Pros and Cons of CHE Battery-Electric and Fuel Cell-Electric Technologies**

| | **Pros** | **Cons** |
|---|---|---|
| **Battery Electric Options** | • High TRL<br>• Reliable | • Battery size<br>• Need to be charged more than once<br>• Fueler is needed to plug-in between shifts<br>• Cost and footprint of charging infrastructure<br>• Lack of standardization for chargers |
| **Fuel Cell-Electric Options** | • Comparable range to diesel<br>• Refueled once a day<br>• Similar fueling infrastructure and procedures to existing diesel<br>• Lower vulnerability to grid outages | • Low TRL<br>• Lack and cost of hydrogen infrastructure<br>• Space required for the refueling infrastructure |

Source: Advanced Power and Energy Program

## Forecast Future Electricity and Hydrogen Need

To determine the future charging needs of battery-electric CHE and the fueling needs of hydrogen fuel cell CHE, a variety of scenarios were assessed, from a 100 percent battery-electric CHE fleet to a 100 percent hydrogen fuel cell CHE fleet. These scenarios help understand cases with a mixed fleet. For some of the commercially viable battery-electric CHE, APEP derived the operation and energy demand from existing vehicles and demonstrations. For other CHE, including hydrogen fuel cell CHE, APEP estimated the demand using the diesel usage and taking into account the higher efficiencies of battery-electric and hydrogen fuel cells. The blueprint includes the details of the approach to estimate electricity and hydrogen demand, and Table 2 provides a brief summary of the average electricity and hydrogen demand of any zero-emission CHE fleet, as well as the demand associated with a busy day during which the hours of operation are significantly higher than the average.

**Table 2: Summary of Electricity and Hydrogen Demand for All Scenarios**

| 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 | 83,00 | 4,900 | 1,580 | 0 |
| | **Avg H2 (kg/day)** | 0 | 148 | 355 | 600 | 753 | 915 | 1,090 | 1,230 | 1,380 | 1,500 | 1,550 |
| | **Max H2 (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 |
| | **Avg H2 (kg/day)** | 0 | 61 | 241 | 393 | 644 | 870 | 1,100 | 1,350 | 1,540 | 1,660 | 1,690 |
| | **max H2 (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 H2 (kg/day)** | 0 | 10 | 18 | 52 | 86 | 103 | 133 | 166 | 198 | 229 | 260 |
| | **Max H2 (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 H2 (kg/day)** | 0 | 5 | 5 | 17 | 17 | 26 | 26 | 29 | 29 | 32 | 32 |
| | **Max H2 (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 H2 (kg/day)** | 0 | 1.2 | 2 | 3.6 | 4 | 4.2 | 4.8 | 5 | 6 | 6.5 | 7 |
| | **Max H2 (kg/day)** | 0 | 1.9 | 3 | 5 | 5.9 | 6 | 6.7 | 7 | 9 | 9.5 | 10 |

Source: Advanced Power and Energy Program

## Charging Infrastructure

Using the daily electricity demand discussed in the previous section, APEP determined the required infrastructure. Most terminals operate in two shifts: Shift 1 is 8:00 a.m. to 5:00 p.m., and Shift 2 is 6:00 p.m. to 3:00 a.m. The ideal time to charge the battery-electric CHE is at the end of the second shift between the hours of 3:00 a.m. to 8:00 a.m. in order to not disrupt the terminal operations. As Table 3 shows, some of the battery-electric CHE need to be charged at least twice per day, and for some of those vehicles, five hours of charging might not be sufficient. To address this, APEP discusses the possibility of other charging opportunities with the terminal. The 5:00 p.m. to 6:00 p.m. timeframe occurs during peak time; thus, this timeframe has the lowest priority in order to reduce electricity costs.

**Table 3: 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** | N/A | 2,600 | 5,200 | 8,000 | 10,600 | 13,200 | 15,800 | 18,400 | 21,200 | 23,800 | 26,400 |
| | **Stacked Stalls** | N/A | 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** | | N/A | 7.3 | 21 | 37 | 54 | 72 | 91 | 111 | 134 | 155 | 180 |
| **Charging Time at each Interval (%)** | **3:00 a.m.-8:00 a.m.** | N/A | 100 | 100 | 100 | 100 | 100 | 95.5 | 91.8 | 89 | 87 | 82 |
| | **12:00 p.m.-1:00 p.m.** | N/A | 0 | 0 | 0 | 0 | 0 | 4.5 | 8.2 | 11 | 13 | 15 |
| | **5:00 p.m. -6:00 p.m.** | N/A | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **10:00 p.m.-11:00 p.m.** | N/A | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 |
| | | | | | | | | | | | | |
| **Worst Case Fleet Total Hours of Charging per Day** | | N/A | 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.** | N/A | 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.** | N/A | 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.** | N/A | 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.** | N/A | 18.8 | 30.1 | 31.6 | 32.7 | 33.4 | 34.4 | 35.1 | 35.6 | 35.4 | 35.5 |

Source: Advanced Power and Energy Program

For yard tractors, a battery size of 240 kWh is assumed, with a 200 kW direct current fast charger (DCFC). Based on a survey conducted by POLB, APEP assumed one charger per CHE. Table 3 summarizes the results and suggest that a 100 percent battery-electric yard tractor fleet can increase the daily electricity demand of a terminal by 15 percent to 37 percent and increase the peak demand by 1.70 to 2.70 times.

APEP assumed a battery size of 931 kWh combined with a 150 kWh DCFC charger for top handlers, smaller chargers of 10 kW to 30 kW for small forklifts, and either 163 kWh, 245 kWh, or 392 kWh batteries with a 50 kW to 350 kW charger for large forklifts. The blueprint includes the results of the analyses for these CHE (similar to those in Table 3). Moreover, the research team developed delayed and smart charging strategies, the details of which are included in the blueprint. The results show that these charging strategies can significantly reduce peak demands and demand during peak hours and, as a result, reduce both the energy costs and demand charges. The blueprint also includes a brief discussion of other charging strategies such as alternating current (AC) chargers, wireless charging, and on-route charging.

Electrified RTG cranes are different from battery-electric CHE that APEP has discussed so far, and the existing zero-emission options are grid-tied. To manage the peaks, some electrified RTG cranes include a battery. The electrified RTG cranes demonstrated at the San Pedro Bay Ports each required a 4 kilovolt connection to the utility. APEP estimated 180 kW of peak power for a 250 horsepower RTG crane based on existing data and literature review. Note that this peak excludes any battery storage that might accompany the RTG crane that would reduce the peak demand charges. The blueprint includes the detailed analyses and results.

## Hydrogen Fueling Infrastructure

The infrastructure for hydrogen fueling at a terminal needs to be very similar to existing diesel and gasoline options, and plans to develop hydrogen stations should include hydrogen storage on the terminal and mobile hydrogen fuelers that will drive around the terminal to refuel the hydrogen fuel cell CHE once per day. The ITS terminal 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 CHE, the terminal will eventually replace the diesel tanks with hydrogen storage. Assuming that the hydrogen storage tanks are filled once or twice per week, APEP determined the storage size. Table 4 includes the results of the analyses.

**Table 4: Hydrogen Storage Size for Fuel Cell-Electric CHE**

| | Fuel Cell %: | 0 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **UTR** | **Min. 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** | **Min. 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** | **Min. 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** | **Min. 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: Advanced Power and Energy Program

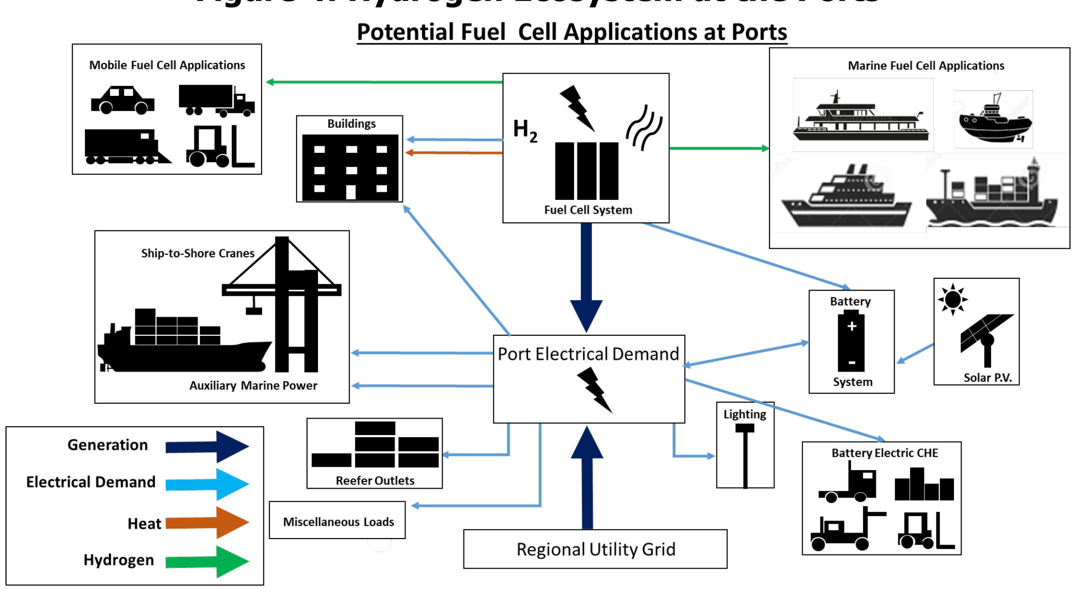
Once the hydrogen demand reaches a threshold of 1,400 kilograms per day (kg/day), the terminal can remove and replace one of the 12,000 gallon diesel storage tanks with hydrogen storage, the size of which depends on the hydrogen demand associated with the number of hydrogen fuel cell CHE. In the meantime, and during the transition, temporary hydrogen storage solutions, such as tube trailer, can be driven off the site to resupply. The footprint of hydrogen storage tanks is greater compared to that of diesel storage tanks. This is an important factor since space is limited on port terminals. For example, an 18,000-gallon liquid hydrogen storage deployed by the Orange County Transportation Authority has a 300 square meter footprint. To save space, hydrogen storage tanks can be vertically installed.

While some mobile hydrogen fuelers with very low capacity are available, several companies are now developing options suitable for port operations with demonstrations planned in the near future.

## Resiliency Considerations

As previously discussed, deploying battery-electric CHE has the potential to significantly increase the electricity demand at the terminal and major upgrades are necessary both on the utility and customer sides. To address this, one approach is to deploy distributed energy resources (DER) and take advantage of possible synergies. Using the available footprint at the ITS terminal, APEP determined the capacity of the terminal to host photovoltaic (PV) energy technologies (commonly known as solar power) based on the available rooftop space, energy storage, and stationary fuel cells. Figure 4 depicts a hydrogen ecosystem at the port. Stationary fuel cells, battery energy storage, and other DERs can supply the electricity need of the port, including charging the battery-electric CHE. Having a reversible fuel cell helps capture excess PV energy and produce hydrogen, which can be used to support hydrogen fuel cell CHE or marine fuel cells.

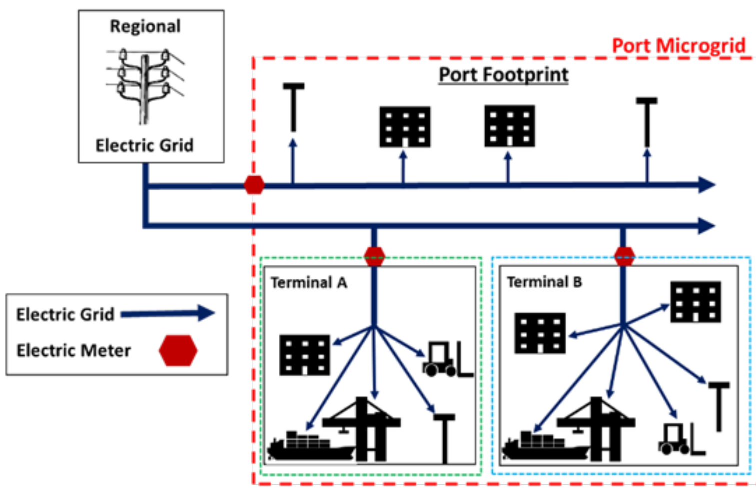
**Figure 4: Hydrogen Ecosystem at the Ports**




Credit: Mac Kinnon, *et al.*, 2021

It is also important to consider resiliency when determining the mix of zero-emission CHE fleet for a terminal. Due to increased frequency of extreme weather events, the grid resiliency and reliability are impacted, resulting in more frequent and longer outages. 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. Figure 5 shows one of the possible microgrid configurations at the ports with each terminal serving as a nanogrid. During grid outages, the terminals require 100 percent operation for outages lasting less than 48 hours. For outages more than 48 hours, they can continue operation with some vehicles at 50 percent capacity (such as CHE). Electrification of CHE significantly increases the size of the DERs on the microgrid and there is not sufficient space on the terminal to deploy enough DERs to support a 100 percent electric 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 options. A mixed fleet (1) has hydrogen as a source of energy in addition to electricity, resulting in not all operations being dependent on the grid and the DERs, and (2) reduces the size of the required DERs to support a microgrid during outages.

**Figure 5: Port Microgrid with Nested Nanogrid**




Credit: Advanced Power and Energy Program

## Environmental Impacts and Impacts on Disadvantaged Communities

The research team used an integrated modeling approach to characterize and quantify the air quality and public health impacts of emission reduction from CHE and port sources in general (e.g., drayage trucks, ocean-going vessels, harborcraft, trains, etc.) relative to a business-as-usual reference case to provide relative insight into the co-benefits that could be achieved in 2035. APEP projected the criteria pollutant emissions for 2035 using California Air Resources Board's California Emissions Projection Analysis Model Standard Emissions Tool pollutant emissions inventory[3], and spatially and temporally resolved the emissions using the Sparse

[3] California Emissions Projection Analysis Model 2019 v1.03
(https://ww2.arb.ca.gov/applications/cepam2019v103-standard-emission-tool)

Matrix Operator Kernels Emissions[4] model. For the two cases (CHE and port sources in general), all emissions were removed from relevant sources to develop cases of completely clean CHE and ports sectors to establish a zero emissions case. Next, emission changes were translated into impacts on atmospheric pollution levels, including ground-level ozone and fine particulate matter, via an advanced photochemical air quality model called the Community Multiscale Air Quality[5] (CMAQ) model that accounts for atmospheric chemistry and transport. Given the highly computational nature of CMAQ, APEP used an episodic air quality modeling approach, including the evaluation of the differences in ground-level ozone and fine particulate matter for the months of July 2035 and January 2035 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[6], which provides a quantitative estimate of the incidence and value of avoided harmful health outcomes associated with air pollution in each scenario. Finally, APEP analyzed the health impact results through an environmental justice framework to quantify the benefits that occur specifically within socially and economically disadvantaged communities that are identified using California Communities Environmental Health Screening Tool 4.0 (more commonly known as CalEnviroScreen)[7].

The blueprint provides details associated with the air quality and health impact analysis and shows that deploying zero-emission CHE at the San Pedro Bay Ports can result in a 13 percent to 18 percent reduction in GHG emissions, the extent of which depends on the sources of electricity and hydrogen. Additionally, deploying zero-emission CHE at the ports results in one ton per day reduction in NOx emissions, improved air quality and health benefits valued at up to $7 million per month, with $1 million dollar per month alone in the disadvantaged communities surrounding the ports.

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4 Sparse Matrix Operator Kernels Emissions Model v4.7 (https://www.cmascenter.org/smoke/documentation/4.0/manual_smokev40.pdf)

5 Community Multiscale Air Quality v5.3.2 (https://www.epa.gov/cmaq)

6 Environmental Benefits Mapping and Analysis Program v1.5.8 (https://www.epa.gov/benmap/benmap-downloads)

7 California Communities Environmental Health Screening Tool 4.0 (https://oehha.ca.gov/calenviroscreen/report/calenviroscreen-40)

# CHAPTER 3: Knowledge Transfer Activities

The goal of knowledge transfer activities was to develop a plan to ensure that the blueprint is shared with the industry stakeholders and workforce stakeholders and that their inputs were considered in the blueprint development. To this end, the following were achieved:

- Engaging stakeholders,
- Reviewing existing surveys and conducting survey interviews,
- Assessing jobs that will be created,
- Transferring knowledge and lessons learned from the project, and
- Workforce training through collaboration with Saddleback college.

To ensure stakeholder input on the blueprint, a series of meetings were held with them and with Saddleback College to coordinate workforce training efforts. The project team developed a questionnaire and conducted several interviews.

## Engaging Stakeholders

APEP held two meetings over the last year covering MDHD zero-emission vehicle infrastructure standardization. Each meeting included two sessions: (1) a battery-electric vehicle charging infrastructure session, and (2) a hydrogen refueling infrastructure session. At the meetings, APEP provided initial findings regarding the crucial infrastructure standardization gaps and technology limitations that need to be addressed in order to achieve widescale deployment of MDHD zero-emission vehicles, as well as early insights into an industry-driven trajectory on standards for the MDHD zero-emission market. Representatives from more than 30 industry partners attended the sessions (Table 5).

**Table 5: Meeting Attendees**

| First Meeting - October 2021 | Second Meeting - June 2022 |
|---|---|
| 2050 Partners | AC Transit |
| AC Transit | Air Liquide |
| Air Products | Air Products |
| Argonne National Laboratory | Argonne National Laboratory |
| BYD Motors | BYD Motors |
| California Energy Commission | California Energy Commission |
| California Fuel Cell Partnership | California Fuel Cell Partnership |
| California Air Resources Board | California Public Utilities Commission |
| California Department of Food and Agriculture | California Air Resources Board |
| ChargePoint, Inc. | California Department of Food and Agriculture |
| Center for Transportation and the Environment | Daimler Trucks North America |
| Department of Energy | First Element Fuel |
| Electric Power Research Institute | Flex Power |
| First Element Fuel | General Motors |

| | |
|---|---|
| Governor's Office of Business and Economic Development | Governor's Office of Business and Economic Development |
| Hyzon Motors | Gas Technologies, Inc. |
| Iwatani | Hyzon Motors |
| National Renewable Energy Laboratory | National Renewable Energy Laboratory |
| New Flyer | Nikola Motors |
| Nikola Motors | Nuvve |
| Nuvve | Proterra |
| Pacific Gas and Electric | Rhombus Energy Solutions |
| Port of Los Angeles | South Coast Air Quality Management District |
| Port of Long Beach | San Francisco Municipal Transportation Agency |
| Proterra | Siemens |
| Rhombus Energy Solutions | Southern California Edison |
| South Coast Air Quality Management District | Toyota |
| San Francisco Municipal Transportation Agency | United States Environmental Protection Agency |
| Shell | Veloce Energy |
| Siemens | Zen Energy Solutions |
| Southern California Edison | |
| Sunline Transit | |
| Toyota | |
| United States Environmental Protection Agency | |
| Veloce Energy | |
| Wireless Advanced Vehicle Electrification | |
| Xos Trucks | |
| Zen Energy Solutions | |

Source: Advanced Power and Energy Program

## Interviews

The ports have conducted several surveys to identify the port community and terminals' understanding of zero-emission options, uncertainties, and risks (Port of Long Beach, 2019), as well as to determine the feasibility of achieving zero-emission goals of the CAAP (Port of Long Beach and Port of Los Angeles, 2022). POLB conducted one of these surveys as a part of the *Port Community Electric Vehicle Blueprint* project funded by the CEC (Moilanen, *et al.* 2021). APEP used the results and insights from this and other surveys to determine the constraints and boundaries of the blueprint.

To further assess the current status of infrastructure and availability of zero-emission CHE, the project team developed three sets of questions for original equipment manufacturers (OEM), EVSE providers, and hydrogen providers (Table 6). The project team conducted several interviews in addition to many other informal meetings/interviews to garner the current status of the zero-emission CHE and the related infrastructure and the business and viability of these technologies.

## Table 6: Questionnaire for OEMs

| Research questions related | Main questions | Follow-up questions |
|---|---|---|
| Q1 (CHE in the market) | • What type(s) of CHE does your company provide?<br>• Of those, are there any zero-emission cargo handling equipment that are commercially available in the market?<br>• If so, what specific zero-emission equipment do you provide? | • Would you please let us know the approximate price of each of [the zero-emission CHE mentioned]?<br>• Approximately, how much cost would be needed for the maintenance of [the zero-emission CHE mentioned]?<br>• Would you compare the maintenance costs of [the zero-emission CHE mentioned] with a diesel counterpart?<br>• Do you have any estimation of total cost of ownership (TCO) of the zero-emission CHE?<br>• For the TCO estimation, what assumption do you make for fuel [electricity or hydrogen] price?<br><br>Note: TCO is the total cost (in $ or $/mile) of the equipment throughout its life, including purchase cost, cost of fueling infrastructure, maintenance costs, fuel costs, driver and labor costs and other operation costs, midlife cost (e.g., battery replacement), cost of disposal, etc. |
| Q1 (CHE in demonstration) | • Is your company participating in any demonstration projects for zero-emission CHE at ports? | • (General) Would you please elaborate more about the demonstration? (e.g., name of the port, types of zero-emission CHE, etc.) |
| Q1 (Repower) | • Do you have plans to re-power your existing [the CHE mentioned]?<br>• [In case they provide multiple types of CHE] If so, what equipment do you plan to repower (e.g., RTG cranes)? | |
| Q1 (Demand observed) | • Have you been contacted by any port terminals or drayage fleets for an inquiry about zero-emission CHE or vehicles? | • If so, would you mind explaining what they asked you about (e.g., availability, specifications, costs, launch timelines, etc.)?<br>• In general, do you think the demand for zero-emission CHE has been increasing in California? |
| Q2 (Charging or hydrogen | • For charging [the battery-electric CHE mentioned], do you have any | • [For battery-electric CHE] Between AC or DC charging, which one would you recommend? |

| | | |
|---|---|---|
| fueling of zero-emission CHE) | recommendation on a charging rate?<br>• What is the pressure at which hydrogen is dispensed (or the max pressure of the tank, e.g., 350 or 700 bar)? How long does it take to fully refuel [the zero-emission CHE mentioned]? | • [For battery-electric CHE] Do you have any approximate on the amount of charging time with each charging option?<br>• [For battery-electric CHE] Do you expect that increased charging rates will be available to meet terminal's operation requirements and duty cycles?<br>• [For battery-electric CHE] Do you have any plans to develop equipment with a larger battery size?<br>• [For battery-electric CHE] What do you think about battery swapping option?<br>• [For battery-electric CHE] What about wireless charging or on-route charging? Are there any changes required for the vehicles? |
| Q3 (Barriers / support) | • What do you think are the barriers to developing and producing zero-emission CHE from a manufacturer's point of view?<br>• Are there any programs providing financial incentives or other support that you have used before?<br>• What additional support do you think could be provided to alleviate such difficulties?<br><br>Note: programs include state or federal level funding, incentives, demonstration/pilot projects. | • Would you elaborate more financial or non-financial barriers, if any?<br>• How important is the government support for your company to develop/produce zero-emission CHE? |

Source: Advanced Power and Energy Program

## Job Creation

There are numerous jobs associated with the manufacturing, sale, and maintenance of zero-emission vehicles, in addition to the manufacturing, installation, operation, and maintenance of the related fueling infrastructure.[8] Examples include:

- Research: materials scientists, chemists, engineers
- Design and Development: regional planners, electrical power-line technicians, electricians, engineers
- Manufacturing: machinists, machine tool operators, assemblers, production managers
- Sales and support: salespersons, customer service representatives

[8] United States Bureau of Labor Statistics Careers in Electric Vehicles (https://www.bls.gov/green/electric_vehicles)

- Maintenance: automotive service technicians, mechanics, electric infrastructure technicians, electricians completed the Electric Vehicle Infrastructure Training Program certification

## Knowledge Transfer

The knowledge, experience, and results derived from this project have the potential to inform and benefit policy makers, ports and terminals, utilities, students, engineers, energy professionals, and investors.

As shown in Figure 6, the strategy for transferring knowledge and information about this project to the public is based on a five-point platform: journal publications, APEP website, Bridging Magazine articles, Conferences, and APEP outreach.

**Figure 6: Technology/Knowledge Transfer Overview**


Credit: Advanced Power and Energy Program

# CHAPTER 4: Conclusions and Recommendations

The project team conducted detailed analyses to determine the future electricity demand and hydrogen need of a zero-emission CHE fleet for different scenarios using different mix of battery-electric and hydrogen fuel cell CHE at a port terminal. APEP conducted the analyses based on operational hours and data from the POLB ITS terminal and used the results to determine the required infrastructure to support electric vehicle charging and hydrogen fueling of a zero-emission CHE fleet on a terminal. Subsequently, APEP addressed costs associated with deployment of zero-emission CHE and the infrastructure including overall fuel costs of the fleet.

Based on the analyses conducted to prepare and develop the 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, statuses of commercially available zero-emission CHE, and demonstrations at the ports, APEP 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 contact with the utility companies for the necessary infrastructure planning and upgrades.
- **Battery-electric options should be deployed in the short-term, followed by hydrogen fuel cell options in the medium- and long-term.**
  Since battery-electric and grid-tied options are more mature compared to hydrogen fuel cell options, terminals should deploy battery-electric and grid-tied options in the short-term and then 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 options should be deployed in the medium- to long-term as they become commercially available. Two implementation strategies with varying levels of battery-electric and hydrogen fuel cell CHE are recommended in the blueprint.
- **Multiple options are available for the terminals to meet 2030 targets.**
  Based on available funding and investments for each terminal for purchasing zero-emission CHE and deploying the required charging and hydrogen fueling infrastructure, multiple options are available. The blueprint presents two implementation options, 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 for an evolving implementation plan for the selection of both the CHE and required charging and hydrogen fueling infrastructure.
- **Battery-electric options require slight 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 of the yard tractor fleet and 13 percent of the top handler fleet 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 longshore worker 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 about 50 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 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 options are more suitable for terminal operations and should be deployed in the medium- to long-term.**
  Hydrogen fuel cell options, due to range and fueling process, are similar to their diesel counterparts and thus will 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 of these technologies are currently being demonstrated at POLA and POLB. Additionally, mobile refuelers suitable for the ports are also being developed. As a result, hydrogen fuel cell options are viable in the medium- and long-term when both hydrogen fuel cell CHE and mobile fuelers become commercially available.
- **The number of hydrogen fuel cell CHE and hydrogen demand should reach a threshold to maximize benefits.**
  For the ITS terminal, the analysis shows that when the hydrogen demand reaches 1,400 kg/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/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 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 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 is 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 fleet, a hydrogen price of more than $12.50 per kg results in an increase in fuel costs.
- **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 yard tractors, and hydrogen fuel cell RTG cranes. While these technologies were included in the blueprint, it is currently difficult to compare these emerging technologies with currently available solutions due to the lack of operational data and cost data. 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 have substantial environmental benefits and also benefit disadvantaged communities.**
  Deploying zero-emission CHE results in GHG reduction of up to 315,000 tons per year, a NOx reduction of one ton per day and health benefits of up to $7 million per month, with $1 million of that associated with disadvantaged communities.

# GLOSSARY

ADVANCED POWER AND ENERGY PROGRAM (APEP)—A program at the University of California, Irvine that addresses the development and deployment of efficient, environmentally sensitive, sustainable power generation and energy conversion worldwide.[9]

ALTERNATING CURRENT (AC)—Flow of electricity that constantly changes direction between positive and negative sides. Almost all power produced by electric utilities in the United States moves in current that shifts direction at a rate of 60 times per second.

BATTERY ELECTRIC VEHICLE (BEV)—Also known as an "All-electric" vehicle (AEV), BEVs utilize energy that is stored in rechargeable battery packs. BEVs sustain their power through the batteries and therefore must be plugged into an external electricity source in order to recharge.

BLUEPRINT—The planning document titled "A Comprehensive and Replicable Infrastructure Blueprint for Zero-Emission Medium- and Heavy-Duty Vehicles Operating at a Port Terminal" that was written to educate, inform, showcase and demonstrate the value of zero-emission vehicles to decarbonizing the concrete industry.[10]

CALIFORNIA ENERGY COMMISSION - The state's primary energy policy and planning agency. The agency was established by the California Legislature through the Warren-Alquist Act in 1974. It has seven core responsibilities:

- Developing renewable energy
- Transforming transportation
- Increasing energy efficiency
- Investing in energy innovation
- Advancing state energy policy
- Certifying thermal power plants
- Preparing for energy emergencies

CARGO HANDLING EQUIPMENT (CHE)—Any motorized vehicle used to handle cargo or perform routine maintenance activities at ports, freight distribution centers, and intermodal rail yards. The type of equipment includes yard trucks, rubber-tired gantry cranes, container handlers, forklifts, etc.[11]

CLEAN AIR ACTION PLAN (CAAP)—The Clean Air Action Plan at the Ports of San Pedro Bay (the combined Ports of Los Angeles and Long Beach) is an air quality plan that establishes the

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[9] Advanced Power and Energy Program (https://www.apep.uci.edu/)

[10] "A Comprehensive and Replicable Infrastructure Blueprint for Zero-Emission Medium- and Heavy-Duty Vehicles Operating at a Port Terminal." (http://www.apep.uci.edu/WhitePapers/PortTerminalBlueprint2023.html)

[11] California Air Resources Board (https://ww2.arb.ca.gov/our-work/programs/cargo-handling-equipment)

most comprehensive, far-reaching strategy for reducing port-related air pollution and related health risks, while allowing port development, job creation and economic activity associated with that development to continue.[12]

COMMUNITY MULTISCALE AIR QUALITY (CMAQ)—An active open-source development project of the United States Environmental Protection Agency that consists of a suite of programs for conducting air quality model simulations.[13]

DIRECT CURRENT (DC)—A charge of electricity that flows in one direction and is the type of power that comes from a battery.

DISTRIBUTED ENERGY RESOUCES (DER)—Small-scale power generation technologies (typically in the range of 3 kilowatts to 10,000 kilowatts) located close to where electricity is used (for example, a home or business) to provide an alternative to, or an enhancement of, the traditional electric power system.

ELECTRIC VEHICLE SUPPLY EQUIPMENT (EVSE)—Commonly known as electric vehicle charging stations, EVSE supplies electric energy for the charging of plug-in electric vehicles.

GREENHOUSE GAS (GHG)—Any gas that absorbs infrared radiation in the atmosphere. Greenhouse gases include water vapor, carbon dioxide, methane, oxides of nitrogen, halogenated fluorocarbons, ozone, perfluorinated carbons, and hydrofluorocarbons.

INTERNATIONAL TRANSPORTATION SERVICE, INC. (ITS)—A container terminal company at the Port of Long Beach that deals with the receipt and shipment of containerized cargo in domestic and foreign trade.[14]

KILOGRAM (kg)—A unit of mass that measures 1,000 grams.

KILOWATT (kW)—A unit of energy measurement equal to 1,000 watts. A watt is equal to one ampere under a pressure of one volt.

KILOWATT-HOUR (kWh)—The unit of measure telling the amount of kilowatts consumed over the course of one hour.

MEDIUM- AND HEAVY-DUTY (MDHD) - Vehicles that have a gross vehicle weight rating of more than 10,000 pounds and includes vans, buses, trucks, and off-road cargo handling equipment.

MEGAWATT (MW)—A unit of energy measurement equal to one million watts. A watt is equal to one ampere under a pressure of one volt.

NITROGEN OXIDES (OXIDES OF NITROGEN, NOx)—A general term pertaining to compounds of nitric oxide (NO), nitrogen dioxide ($NO_2$), and other oxides of nitrogen. Nitrogen oxides are typically created during combustion processes and are major contributors to smog formation

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[12] San Pedro Bay Ports Clean Air Action Plan (https://cleanairactionplan.org)

[13] United States Environmental Protection Agency Community Multiscale Air Quality Modeling System (https://www.epa.gov/cmaq)

[14] International Transportation Services, Inc. (https://www.itslb.com)

and acid deposition. $NO_2$ is a criteria air pollutant and may result in numerous adverse health effects.

ORIGINAL EQUIPMENT MANUFACTURER (OEM)—A company that provides the original design and materials for manufacture and engages in the assembly of vehicles. The OEM is directly responsible for manufacturing, marketing, and providing warranties for the finished product.[15]

PHOTOVOLTAIC (PV)—Devices that absorb energy from sunlight and convert it into electrical energy through semiconducting materials. More commonly known as solar panels.[16]

PORT OF LONG BEACH (POLB)—The Port of Long Beach, also known as the Harbor Department of the City of Long Beach, is a commercial port in Southern California.[17]

PORT OF LOS ANGELES (POLA)—The Port of Los Angeles, also known as the City of Los Angeles Harbor Department, is a commercial port in Southern California.[18]

RUBBER TIRE GANTRY (RTG)—A wheeled, mobile crane used to ground or stack intermodal containers.[19]

SOUTH COAST AIR QUALITY MANAGEMENT DISTRICT (SCAQMD)

TOTAL COST OF OWNERSHIP (TCO) - A calculation of all the costs involved in buying and using a product over time.[20]

UNIVERSITY OF CALIFORNIA, IRVINE (UCI)

ZERO-EMISSION VEHICLE (ZEV)—Vehicles which produce no emissions from the on-board source of power (e.g., an electric vehicle)

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[15] United States Energy Information Administration Glossary (https://www.eia.gov/tools/glossary)

[16] United States Department of Energy (https://www.energy.gov/eere/solar/photovoltaics)

[17] Port of Long Beach (https://polb.com)

[18] Port of Los Angeles (https://www.portoflosangeles.org)

[19] Wikipedia (https://en.wikipedia.org/wiki/Rubber_tyred_gantry_crane)

[20] Corporate Finance Institute Glossary (https://dictionary.cambridge.org/us/dictionary/english/total-cost-of-ownership)

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