Project 2347 | July 2025

SJSU SAN JOSÉ STATE UNIVERSITY

MTI MINETA TRANSPORTATION INSTITUTE

Hydrogen Fuel Cell Application for Port Drayage Truck: Integrated Transportation and Energy Modeling

Shams Tanvir, PhD, PE

Emu Ghosh

CSUTC California State University Transportation Consortium

CALIFORNIA STATE UNIVERSITY LONG BEACH

MINETA TRANSPORTATION INSTITUTE

Founded in 1991, the Mineta Transportation Institute (MTI), an organized research and training unit in partnership with the Lucas College and Graduate School of Business at San José State University (SJSU), increases mobility for all by improving the safety, efficiency, accessibility, and convenience of our nation's transportation system. Through research, education, workforce development, and technology transfer, we help create a connected world. MTI leads the Mineta Consortium for Emerging, Efficient, and Safe Transportation (MCEEST) funded by the U.S. Department of Transportation, the California State University Transportation Consortium (CSUTC) funded by the State of California through Senate Bill 1 and the Climate Change and Extreme Events Training and Research (CCEETR) Program funded by the Federal Railroad Administration. MTI focuses on three primary responsibilities:

Research

MTI conducts multi-disciplinary research focused on surface transportation that contributes to effective decision making. Research areas include: active transportation; planning and policy; security and counterterrorism; sustainable transportation and land use; transit and passenger rail; transportation engineering; transportation finance; transportation technology; and workforce and labor. MTI research publications undergo expert peer review to ensure the quality of the research.

Education and Workforce Development

To ensure the efficient movement of people and goods, we must prepare the next generation of skilled transportation professionals who can lead a thriving, forward-thinking transportation industry for a more connected world. To help achieve this, MTI sponsors a suite of workforce development and education opportunities. The Institute supports educational programs offered by the Lucas Graduate School of Business: a Master of Science in Transportation Management, plus graduate certificates that include High-Speed and Intercity Rail Management and Transportation Security Management. These flexible programs offer live online classes so that working transportation professionals can pursue an advanced degree regardless of their location.

Information and Technology Transfer

MTI utilizes a diverse array of dissemination methods and media to ensure research results reach those responsible for managing change. These methods include publication, seminars, workshops, websites, social media, webinars, and other technology transfer mechanisms. Additionally, MTI promotes the availability of completed research to professional organizations and works to integrate the research findings into the graduate education program. MTI's extensive collection of transportation-related publications is integrated into San José State University's world-class Martin Luther King, Jr. Library.

Report 25-17

Hydrogen Fuel Cell Application for Port Drayage Truck: Integrated Transportation and Energy Modeling

Shams Tanvir, PhD, PE

Emu Ghosh

July 2025

A publication of the
Mineta Transportation Institute
Created by Congress in 1991

College of Business
San José State University
San José, CA 95192-0219

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
25-17		

4. Title and Subtitle	5. Report Date
Hydrogen Fuel Cell Application for Port Drayage Truck: Integrated Transportation and Energy Modeling	July 2025
	6. Performing Organization Code
7. Authors	**8. Performing Organization Report**
Shams Tanvir - https://orcid.org/0000-0003-1675-9647 Emu Ghosh - https://orcid.org/0000-0001-8126-7935	CA-MTI-2437
9. Performing Organization Name and Address	**10. Work Unit No.**
Mineta Transportation Institute College of Business San José State University San José, CA 95192-0219	**11. Contract or Grant No.** SB1-SJAUX_2023-26
12. Sponsoring Agency Name and Address	**13. Type of Report and Period Covered**
State of California SB1 2017/2018 Trustees of the California State University Sponsored Programs Administration 401 Golden Shore, 5th Floor Long Beach, CA 90802	**14. Sponsoring Agency Code**

15. Supplemental Notes

10.31979/mti.2025.2437

16. Abstract

This report investigates the viability of hydrogen Fuel Cell Electric Vehicles (FCEVs) for port drayage applications, focusing on both energy modeling and economic feasibility. Port drayage—trucking operations that move goods a short distance to and from ports—is a key part of freight logistics and the critical movement of goods in American communities. This project developed a microscopic energy consumption model using second-by-second activity data from 38 Class 8 diesel drayage trucks operating in Southern California. The model emulated FCEV operations and determined an average hydrogen fuel consumption of 0.15 kg/mile across 749 trips. This data informed a levelized cost of hydrogen (LCOH) analysis under various production methods, station capacities, and fleet adoption rates. In other words, the analysis helps show conditions under which hydrogen FCEVs could become a cost-competitive and sustainable option for port drayage fleets. The project used two economic modeling approaches: a general parametric study and a comprehensive analysis using established spreadsheet tools (H2A-Lite and HDSAM-4.5). Results from the parametric study showed a concave relationship between hydrogen station capacity utilization and LCOH. Higher fleet conversion rates (e.g., 25%) significantly reduced LCOH (as low as $1.4/kg for blue hydrogen) but strained infrastructure, highlighting the need for strategic station deployment. Conversely, underutilized stations led to elevated hydrogen costs, especially with green hydrogen. This means that as station utilization increases, LCOH initially drops quickly—because more trucks using the station spreads out fixed costs, making each kilogram of hydrogen cheaper, but after a certain point, the rate of cost savings slows down—and, eventually, adding more demand may even introduce new costs (such as the need for upgrades). The comprehensive analysis reinforced these findings and showed that while grey hydrogen remains the cheapest to produce, green hydrogen—particularly from hybrid solar-wind PEM electrolysis—becomes competitive at scale. Delivery methods also impacted cost: liquid hydrogen delivery proved more cost-efficient at low utilization, while gaseous delivery was better suited for high-demand scenarios. The study concludes that achieving cost-effective hydrogen adoption for port drayage trucks hinges on optimizing station utilization, scaling infrastructure, and supporting green hydrogen technologies through policy and investment. Given the critical role of port drayage in transportation networks, this study helps lay the path forward toward decarbonizing a high-impact sector through hydrogen technology.

17. Key Words	18. Distribution Statement
Hydrogen refueling, energy consumption, economic analysis, fuel cell vehicles, drayage	No restrictions. This document is available to the public through The National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	38	

Form DOT F 1700.7 (8-72)

DOI: 10.31979/mti.2025.2437

Mineta Transportation Institute
College of Business
San José State University
San José, CA 95192-0219
Tel: (408) 924-7560
Fax: (408) 924-7565
Email: mineta-institute@sjsu.edu

transweb.sjsu.edu/research/2437

Acknowledgments

The authors thank the University of California, Riverside, College of Engineering, Center for Environmental Research and Technology (CE-CERT) for sharing the initial data for this research. Dr. Kanok Boriboonsomsin at CE-CERT laid out the initial ideas for this project for battery electric trucks and collected the microscale vehicle activity information. The authors are thankful to the College of Engineering at California State University, Long Beach for providing tuition support for students working on this project.

Contents

LIST OF FIGURES

List of Tables

Executive Summary

Hydrogen Fuel Cell Electric Vehicles (FCEVs) offer a promising solution for the decarbonization of medium- and heavy-duty vehicles (MHDVs), particularly in port drayage applications. In this report, a microscopic energy model was developed from second-by-second drayage truck activity data collected from a group of 38 Class 8 diesel trucks in Southern California. In order to emulate the operation of electric trucks, vehicle mass and drivetrain efficiencies were converted to hydrogen FCEV truck equivalents. Utilizing this model, average fuel rate consumption from 749 trips was found to be 0.15 kg H_2/mile. This average fuel economy was then further integrated into an economic analysis, and the levelized cost of hydrogen (LCOH) at dispensing was evaluated to compare economic viability for different hydrogen production technology, delivery method, station capacity, and utilization rate. The economic analysis framework followed a two-step analysis: (i) general parametric study and (ii) comprehensive study with existing spreadsheet modeling.

General Parametric Study

The Advanced Clean Fleets Regulations established by the California Air Resources Board (CARB) aimed to convert at least 1,000 drayage trucks to ZEVs by the year 2025. For this reason, this report assumed a drayage truck fleet of 1,000 vehicles seeking to transition to ZEVs in 2025. Five different scenarios were developed with varying percentages of port truck conversion to HFCVs from the assumed 1,000 truck fleets, ranging from 5% to 25%, with a 5% increment. Also, each truck was assumed to travel 185 miles per day (derived from the truck fleet data) with a total operation of 112 times annually (as mentioned in the CARB report).

Four hydrogen refueling stations (HRS) were assumed to be solely dedicated for these truck fleets, each having the same capacity. In order to grasp how the levelized cost of hydrogen varies with the capacity of hydrogen refueling station (HRS,), four scenarios were developed with varying capacities of HRS (4,000 kg/day, 6,000 kg/day, 8,000 kg/day, and 10,000 kg/day). In this approach, the capital cost for hydrogen refueling stations was estimated through a cost function developed by Melaina and Penev (2013), and all other expenses were considered as a percentage of the capital cost for simplification. This cost function combined capital cost estimates with data from the Hydrogen Station Cost Calculator (HSCC) and station capacity projections beyond 2016, which consider the size of the station and aggregated installed station capacity as input parameters. To configure the levelized cost of H_2, this study considered two different cases of HRSs: (i) blue H_2 production from steam methane reforming and (ii) green H_2 production from electrolysis.

Findings suggested that there exists a concave down relationship between the capacity of HRS and the conversion rate of port trucks, indicating that increasing demand of H_2 has the potential to reduce the levelized cost of hydrogen. At a 5% conversion rate, the highest levelized costs observed in the 10,000 kg/day capacity scenarios (blue H_2: \$13.9/kg, green H_2: \$17.4/kg) suggest that under-utilization of HRSs is a key driver of high hydrogen fuel costs. This highlights the necessity of accurately forecasting the future demand of hydrogen correctly to ensure maximum utilization of refueling stations. At a 25% conversion rate, the lowest levelized costs are observed across all conversion rates for both blue hydrogen ($1.4–$2.8/kg) and green hydrogen ($1.8–$3.5/kg). However, the demand-to-supply ratio significantly increases at this conversion level, ranging from 8.7 at 5% conversion to 3.5 at 25% conversion. This suggests that the current capacity, with only four refueling stations, is insufficient to meet the increased demand for Hydrogen Fuel Cell Vehicles (HFCVs) at higher conversion rates. Addressing this shortcoming will require expanding the refueling infrastructure to support wider adoption of HFCVs and ensuring that supply can match demand. The LCOH of blue hydrogen remains lower than that of green hydrogen across all conversion levels due to its lower production costs (e.g., steam methane reforming with carbon capture is currently cheaper than electrolysis powered by renewable energy). However, as more port drayage trucks convert to HFCVs, the gap between blue hydrogen and green hydrogen narrows, suggesting that green hydrogen becomes more competitive at higher adoption rates.

Comprehensive Study with Existing Spreadsheet Modeling:

This approach considers (i) levelized cost at the production level and (ii) levelized cost for hydrogen delivery and dispensing at refueling stations. To understand how LCOH varies from production level to the dispensing site, two different spreadsheet models were utilized. Production level LCOH was evaluated with the Hydrogen Analysis Lite Production (H2A-lite) Model developed by National Renewable Energy Laboratory (NREL). For the levelized cost at the delivery and dispensing level, the Hydrogen Delivery Scenario Analysis Model (HDSAM-4.5) of Argonne National Laboratory was used.

In this method, we have assumed three types of central production plants: (i) grey H_2 produced from natural gas in a Steam Methane Reformer (SMR), (ii) blue H_2 produced from natural gas in a SMR with carbon capture and sequestration technology, and (iii) green H_2 produced from proton exchange membrane (PEM) with renewable energy. Two types of delivery methods were considered: (i) liquid truck delivery and (ii) gaseous pipeline delivery.

The California Air Resources Board (CARB, 2022) reported that the Port of Los Angeles/Long Beach (POLA) has a drayage truck inventory of 17,830 trucks. We have assumed that 25% of these drayage trucks will convert to fuel cell vehicles and evaluated the daily hydrogen demand incorporating the energy efficiency computed from the microscopic modeling. In this analysis, we have used three types of refueling station capacity—4,000 kg/day, 8,000 kg/day, and 12,000 kg/day. These station capacities were chosen based on the sizes of existing and planned medium- and heavy-duty FCEV hydrogen refueling stations (HRS) as reported by the California Energy Commission in its Senate Bill 643 Staff Report (2023).

Findings reveal that LCOH at the production level doubles for blue hydrogen ($2.73/kg H_2) and is 3–6 times higher for green hydrogen ($3.94–$6.65/kg H_2) compared to grey hydrogen production ($1.30/kg H_2) using natural gas. Furthermore, LCOH at the downstream (delivery and dispensing) level suggests that a lower utilization rate is causing a jump in the levelized cost at the refueling station across all station capacity for each delivery method. At gaseous hydrogen refueling stations (HRS), the downstream levelized cost of hydrogen (LCOH) escalates by 50%–60% as utilization declines from 80% to 40%. Conversely, liquid HRS stations exhibit a comparatively smaller maximum increase of 36% at the 4,000 kg/day capacity, highlighting the economic benefit of liquid hydrogen infrastructure in low-utilization scenarios. When the impact of different green renewable energy on the total LCOH at dispensing was assessed, findings revealed that LCOH is highest for wind-gaseous ($14.18/kg at 4,000 kg/day) and lowest for hybrid-liquid ($9.56/kg at 12,000 kg/day), with larger station capacities consistently reducing costs across all cases. This emphasizes that the combined use of solar and wind electricity for green hydrogen production can substantially reduce the price of hydrogen in future.

The findings emphasize that hydrogen adoption remains cost-prohibitive at low conversion rates, necessitating higher FCEV penetration to reduce LCOH. This report highlights the importance of optimizing HRS utilization, as underutilized stations lead to a higher unit price of hydrogen. Liquid hydrogen delivery systems prove more cost-efficient at lower utilization rates, whereas gaseous hydrogen is more viable under high-demand scenarios. The study also confirms that the current refueling infrastructure is inadequate for large-scale FCEV adoption, requiring strategic expansion and demand-driven station deployment. Policymakers should support green hydrogen incentives and optimize HRS placement to ensure cost-effective hydrogen adoption. Despite these insights, several challenges remain, including a limited dataset based on 38 trucks, potential biases from uniform HRS capacity assumptions, and logistical complexities such as permitting and stakeholder coordination for infrastructure deployment. Additionally, the risk of overbuilding HRS before widespread adoption must be carefully managed to avoid inefficiencies. Finally, a proactive approach to scaling hydrogen production and refueling infrastructure is crucial for enabling a cost-effective transition toward zero-emission trucking.

1. Introduction

According to 2021 statistics from the US Energy Information Administration, commercial and freight trucks were the second largest portion of the transportation energy use at 24.5%. This number is only exceeded by light vehicles at 30%, yet passes up all cars and motorcycles which sit at 23% (EIA, 2021). This is a surprising statistic considering that these trucks account for less than 5% of registered vehicles in the US but use such a large share of energy (Bureau of Transportation Statistics, 2021). With this large share of energy going to this small population, any changes will have larger effects, making them a good focus to lower emissions.

Fuel Cell Electric Vehicle (FCEV) technology provides a viable pathway for the decarbonization of medium- and heavy-duty vehicles (MHDV). The primary reasons for the attractiveness of FCEV over other zero-emissions vehicles (ZEV) are that they are lightweight, fast refueling, and low maintenance. FCEVs take significantly less time to refuel compared to battery electric vehicles (BEV). Also, the FCEV does not need to carry a bulky and heavy-weight battery similar to BEVs. The byproduct of a hydrogen-based FCEV is water which provides a significant environmental improvement over greenhouse gas-emitting Internal Combustion Engine vehicles (ICEV).

The Bipartisan Infrastructure Law (IIJA) provided $7 billion to establish 6–10 regional clean hydrogen hubs across the United States. These hydrogen hubs involve the production, processing, delivery, storage, and end-use of clean hydrogen. One of the end-uses for a hydrogen hub is the port drayage application since 4% of US energy consumption occurs at ports (Energy Information Administration). In addition, ports are the most suitable location for hydrogen FCEVs due to the transportation equipment being operated at a localized or central space, i.e., "clusters," and access to other end-uses such as buildings and industry nearby. Kopasz and Krause (2019) studied 19 US ports and found that 88.66% of the total hydrogen demand in a port is coming from drayage trucks. In 2017, Toyota demonstrated a proof-of-concept prototype of a hydrogen FCEV for drayage application for the Port of Los Angeles (Voelcker, 2017). However, questions remain as to whether the existing energy demand models can effectively predict the hydrogen demand for HFCEV drayage fleets and whether the current HRS stations have the capacity for promoting a gradual and smooth transition for decarbonization of port drayage trucks.

In this study, we aim to acknowledge these questions by developing a microscopic energy demand model for fuel cell drayage trucks. For this purpose, the FCEV-relevant information has been incorporated into the second-by-second drayage truck activity dataset collected from the literature of Tanvir et al. (2021). Additionally, site-related information for HRS planning has been collected aiming to extend the demand modeling to the estimation of LCOH. Various scenarios have been simulated related to the application of hydrogen fuel cells for drayage vehicles utilizing a novel dataset of second-by-second transportation activities of the drayage trucks.

The following section provides a review of relevant literature and highlights the key research questions. Subsequently, we outline the data collection process and detail the methodology used for the analysis, followed by results obtained from simulating various scenarios in energy demand modeling. Finally, we conclude by summarizing the findings and discussing potential directions for future research.

1.1 Literature Review

The variety of port drayage activities requires a personalized approach to refueling hydrogen. The ownership structure and operational characteristics of drayage trucks vary significantly from one drayage operator to another. Greene et al. (2020) described four types of hydrogen refueling stations (HRS) for drayage trucks: (a) gaseous hydrogen delivered via truck or pipeline, (b) liquid hydrogen delivered by truck, (c) distributed hydrogen production via small scale electrolysis, and (d) distributed hydrogen production via small-scale steam methane reforming. The dispensed levelized cost of hydrogen (LCOH), which combines cost of production, delivery, and refueling stationing costs, can be minimized if the selection of refueling technique is matched with appropriate demand. Greene et al. (2020) also stressed understanding both the "supply" (e.g., station technology performance and cost) and "demand" (e.g., where and how often refueling needs will occur) for hydrogen refueling station (HRS) design.

Stephens-Romero et al. (2010) developed the STREET model to estimate the spatial distribution of demand for hydrogen refueling using existing traffic flows and locations of early FCEV adopters. Park et al. (2022) aimed to predict the hydrogen demand for HFCVs to address the significance of a robust hydrogen supply plan to support HFCV adoption in South Korea. In this study, Bass, logistic, and Gompertz models were employed to project the demand for HFCV in 2040 under three scenarios (conservative, standard, and optimistic) based on three different diffusion rates. This study predicted that daily hydrogen demand for each station would increase to 1–2.3 tons by 2040, suggesting insufficient capacity of current hydrogen stations to support such demand in South Korea. However, the HRS design for drayage trucks is significantly different from light-duty transportation. Drayage heavy-duty trucks have limited daily mileage. In addition, drayage trucks return to the home base at least once per day during operation and spend a significant portion of their trips in creeping and transient modes. These conditions provide opportunities for refueling at the home base and regeneration of energy from frequent braking events. These nuances require specialized and integrated modeling of transportation and energy demands for hydrogen FCEVs.

For medium- and heavy-duty vehicles, inadequate HRS infrastructure is a major drawback for the commercialization of hydrogen FCVs. However, there is a limited number of studies conducted in this regard (Tsuda et al., 2014; Yaïci and Longo, 2022; Rose and Neumann, 2020). Yaïci and Longo (2022) assessed the techno-economic viability of implementing a nationwide hydrogen refueling infrastructure in Canada to assist the conversion of long-haul, heavy-duty trucks (LHHDs) from diesel to hydrogen. This literature evaluated various delivery methods, including truck delivery, pipeline-fed fuel, and onsite production, while considering factors such as traffic flow, station spacing, and technology integration. It was observed that the lowest capital costs would occur from a liquid hydrogen truck delivery method, while pipeline delivery is cost-effective at higher traffic rates and technology integration levels. However, this study only assumed four different cases with varying traffic flow and distances between HRS stations, which may not represent the actual situation. Rose and Neumann (2020) explored the connection between HDV hydrogen refueling stations and the power system by integrating an infrastructure location planning model and an electricity system optimization model that considers grid expansion options. The study assumed two scenarios: one where refueling stations were designed to back the power system and another where they were sized independently, focusing on Germany as a case study. These scenarios were evaluated for their impact on yearly electricity system expenses, the LCOH, and regional integration. The levelized cost of hydrogen differs regionally, influenced by electricity production costs, ranging from €4.83 to €5.36 per kg. Finally, the authors concluded that co-optimizing various energy sectors is highly necessary for investment planning and can enhance coordinated efforts.

Previous literature for modeling fuel demands for MHDV FCEVs was predominantly based on assumed truck fleet information and FCEV truck performances. Moreover, the energy demand modeling in the reported literature is macroscopic. For example, Li et al. (2021) assumed that all FCEVs travel a fixed 150 miles per day and HD drayage trucks have a fixed fuel efficiency of 15 MPkgH2. Zhao et al. (2024) investigated the applicability of zero-emission medium- and heavy-duty vehicles (ZEVs) in California by employing a macroscopic dynamic discrete choice model developed based on market penetration and consumer behavior. The analysis used aggregated fleet behaviors and average consumer preferences to forecast market shares under multiple scenarios, reflecting macroscopic trends rather than individual-level dynamics. These macroscopic models are not capable of capturing the variety of activities that the drayage trucks are performing over the day and the variety of transportation operating conditions that will unfold in future years.

Based on the limitations discussed in this section, the following research questions have been identified:

1) How can a microscopic energy simulation model be developed for estimating hydrogen Fuel Cell Electric Vehicle (FCEV) energy demand based on real-world operating conditions of drayage trucks?

2) What are the key operational characteristics of drayage trucks that should be incorporated into a microscopic energy demand model for hydrogen FCEVs?

3) How can an economic analysis framework be crafted considering the dispensed levelized cost of hydrogen (LCOH) under various technology types, numbers, locations, sizes, and utilization of hydrogen refueling stations (HRS)?

4) How can future hydrogen demand for drayage trucks be predicted under varying scenarios of adoption, fleet sizes, and refueling infrastructure deployment?

2. Data Description

Activity data for vehicles and engines were gathered from a group of 38 Class 8 trucks operating at a drayage company in Southern California. The port of Los Angeles is about 1 mile away from the truck fleet's home base. The truck fleet mainly operates at the San Pedro Bay port complex which not only includes the port of Los Angeles and the port of Long Beach but also covers some other areas in the Greater Los Angeles Metropolitan area and the Inland Empire area. Sometimes the truck fleets provide service to several areas in the Central Valley and Northern California's inland. According to a 2013 survey on drayage truck operations in the region, around 60% of the tours covered distances of less than 40 miles (Papson & Ippoliti, 2013). The drayage operator from whom activity data was collected for this study did not have a storehouse facility. Thus, every tour included at least one loading (pick-up) and one unloading (drop-off) outside the home base.

Data collection was conducted for each truck over a period of 1 to 2 months when the trucks were available for installing and retrieving data loggers. This endeavor led to the formation of a novel dataset containing more than 130,000 mi and 15,000 h of real-world operation data.

The data collection was conducted through an integrated approach by combining global positioning system (GPS) and engine control unit data loggers. These data loggers were set up to record the GPS data (such as latitude, longitude, timestamp, and speed) alongside over 170 engine control unit parameters at a frequency of 1 Hz. At the end of data collection, data processing involved multiple steps, including (i) conversion of formats, (ii) quality assurance through identification and correction of inaccurate data, (iii) identification of trips by splitting trips from data string, and (iv) confidentiality protection of the fleet by origin-destination cloaking of trip. Details of each data processing step can be found in Scora et al. (2019).

3. Methodology

The methodology includes an analysis of the microscopic FCEV energy consumption model and the development of an economic analysis framework at the drayage operator level.

3.1 Hydrogen Truck Energy Consumption Model

A second-by-second microscopic energy consumption model was proposed for drayage trucks based on data collected for truck activities of conventional diesel trucks. In order to emulate the operation of electric trucks, vehicle mass and drivetrain efficiencies were converted to hydrogen FCEV truck equivalents. Therefore, the values of mass and efficiency for diesel truck components were used alongside the values for FCEV. For each time instance, t, the tractive power $P(t)$ is calculated as:

$$P(t) = m_{f_{cev}} v_t a_t + 0.5 \rho C_d A v_t^3 + c_{rr} g m_{f_{cev}} v_t \quad (1)$$

where v is truck velocity and a is acceleration ρ, C_d, c_{rr} and $m_{f_{cev}}$ are air density, coefficient of drag, coefficient of rolling resistance, and the mass of FCEV truck, respectively. The m_{fcev} is defined as:

$$m_{fcev} = m_v - m_e - m_{gb} + m_{fc} + m_{ft} + m_m \quad (2)$$

where, m_v, m_e, m_{gb}, m_{fc}, m_{ft}, and m_m stand for vehicle mass, engine mass, gearbox mass, fuel cell mass, fuel tank mass, and the motor mass, respectively. The algorithm designed for this analysis can consider the change in loaded vehicle mass, m_v, with each trip as the truck loads and unloads. Now, the consumed energy over the entire operating period, E_{consumed} can be calculated as:

$$E_{consumed} = \int (Discharge + Regeneration + Accessory\ Load)\, dt \quad (3)$$

This leads to the HR calculation for each time instance, t, as:

$$HR\ (t) = HR\ (t-1) - \frac{E_{consumed}(t)}{TEC} \quad (4)$$

Here, HR is the amount of hydrogen remaining. TEC stands for the tank energy capacity of the FCEV for the given truck technology. The velocity is at the core of the HR calculation, as each time the truck moves, the hydrogen level is depleted to provide tractive power. Table 1 refers to the information on the parameters employed for energy model consumption.

Table 1. Values for Input Parameter Estimations for Energy Demand Modeling

Parameter	Value
C_d	0.65
c_{rr}	0.008
ρ (kg/m^{-3})	1.161
g (ms^{-2})	9.8
m_v(kg)	34545
m_e(kg)	558
m_{gb}(kg)	180
m_m(kg)	432

3.2 Economic Analysis Framework

Different HRS pathways exist as described in the previous section. In addition, the state of California and the federal government have many pathways for the adoption of green hydrogen. Therefore, an economic analysis framework is needed at the drayage operator level to understand the economic implication of adopting one pathway over another. In this study, the levelized cost of hydrogen (LCOH) (Equation 5) was used to compare economic viability for onsite hydrogen production and promoting sustainable energy practices.

$$LCOH = \frac{NPV\ of\ Total\ Expenses\ (\$)}{NPV\ of\ Hydrogen\ Utilization} \quad (5)$$

The denominator in Equation 5 represents the supply side of the HRS operation. However, the demand aggregated from an energy consumption model such as Equation 4 will enable the researchers to accurately estimate the supply of hydrogen. The total expenses are also dictated by the demand, as higher utilization of the fixed-cost infrastructure will significantly lower the LCOH.

In this report, we have conducted two types of economic analysis: (i) general parametric study and (ii) comprehensive study with existing spreadsheet modeling.

3.2.1 General Parametric Study

Infrastructure costs are a critical factor in the economic feasibility of hydrogen refueling stations (HRS). Accurate capital cost estimation is essential for planning and optimizing HRS deployment, especially in scenarios involving large-scale adoption of fuel cell electric vehicles (FCEVs). Melaina and Penev (2013) established a capital cost function by combining capital cost estimates with data from the Hydrogen Station Cost Calculator (HSCC) and station capacity projections beyond 2016, which consider the size of the station and the aggregated installed station capacity as input parameters. The LCOH estimation for this study followed a parametric procedure in which the above-mentioned cost function was employed to determine the capital cost for the refueling station; all other expenses were considered as a percentage of the capital cost for simplification. The cost function is defined as:

$$C' = C^o \left(\frac{Q'}{Q^0}\right)^{\alpha} \left(\frac{V'}{V^0}\right)^{\beta} \qquad (6)$$

Where C' and C^o refer to the station capital cost and base capital cost in \$/station, Q' and Q^0 represent station capacity and base station capacity, and α and β refer to the scaling and learning factor. Also, V' and V^o refer to aggregate capacity and cumulative capacity at cost status of base station in kg/day, respectively. The value of these input parameters can be found in Melaina and Penev (2013).

According to CARB (2023), about 33,500 drayage trucks operate at California's seaports and intermodal railyards each year, with 28,700 of them visiting these facilities an average of two or more times per week, totaling 112 visits annually. In addition, the Advanced Clean Fleets Regulations established by CARB aimed to convert at least 1,000 drayage trucks to ZEVs. For this reason, this study assumed a drayage truck fleet of 1,000 vehicles seeking to transition to ZEVs in 2025. Thus, this study considered five different percentages of port truck conversion to HFCVs, ranging from 5% to 25%, with a 5% increment. Also, each truck was assumed to travel 185 miles per day (derived from the truck fleet data) with a total operation of 112 times annually (as mentioned in the CARB report). This study assumed that four hydrogen refueling stations having the same capacity of H_2 production were solely dedicated for these truck fleets. To configure the levelized cost of H_2, this study considered two different cases of HRS stations: (i) blue H_2 production from steam methane reforming and (ii) green H_2 production from electrolysis. These two processes are important from the perspective of sustainability as blue H_2 has some greenhouse effect in terms of CO2 emissions, whereas green H_2 is produced without any emissions directly through the electrolysis of water. Table 2 summarizes the HRS stations data. Here, the average efficiency of trucks was assumed in such a way so that the average fuel economy could match the average fuel efficiency computed from the energy demand modeling.

Table 2. Assumption on HRS Stations

Refueling Stations	Drayage Trucks in Each Station for 1,000 Truck Fleets	Average Efficiency of Trucks in Each Stations (kg H_2/mile)
HRS-1	30%	0.12
HRS-2	35%	0.17
HRS-3	10%	0.20
HRS-4	25%	0.14

Specific application scenarios for the hydrogen refueling station (HRS), based on the type of technology and production capacity ranging from (4,000–10,000) kg/day, were considered based on the demand as stated in Figure 1. The utilization capacity in each station was presumed to be 75%.

Figure 1. Cases Considered for LCOH Computation by Varying Technology Type and Capacity

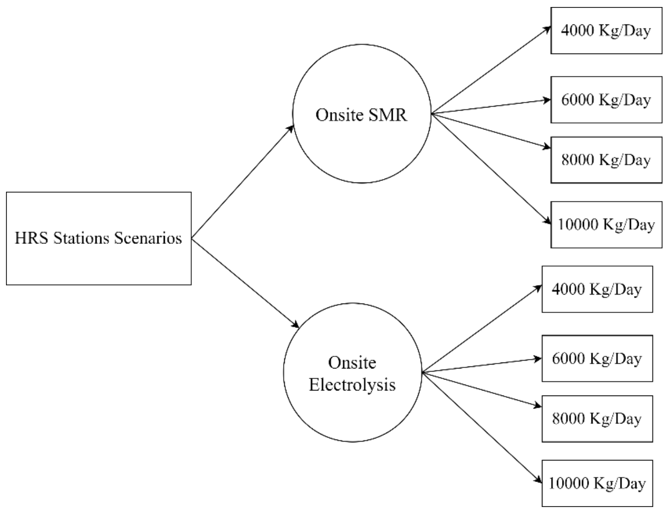


Table 3 below represents the considerations for estimating Net Present Value of Expenses for each station. Also, a factor of 1.2 was assumed in Equation 6 when computing the capital cost for onsite electrolysis to account for the additional cost in green hydrogen production.

Table 3. Assumptions for the HRS Cost Estimation

Assumptions	Onsite SMR	Onsite Electrolysis
Operational Costs	10% of Capital Expenditure	15% of Capital Expenditure
Maintenance Cost	2% of Capital Expenditure	2.5% of Capital Expenditure
Labor Cost	2% of Capital Expenditure	2.5% of Capital Expenditure
Discount Rate	5%	5%

3.2.2 Comprehensive Study with Existing Spreadsheet Modeling

This approach considers (i) the levelized cost at production level and (ii) the levelized cost for hydrogen delivery and dispensing at refueling station. To understand how LCOH varies from production level to the dispensing site, two different spreadsheet models were utilized. Production level LCOH was evaluated with the Hydrogen Analysis Lite Production Model (H2A-lite developed by National Renewable Energy Laboratory (NREL, 2023)). For the levelized cost at delivery and dispensing level, the Hydrogen Delivery Scenario Analysis Model (HDSAM-4.5) of the Argonne National Laboratory (2023) was used.

3.2.2.1 Levelized Production Cost Analysis with H2A-Lite

NREL's Hydrogen Analysis Lite Production (H2A-Lite) model offers a user-friendly, high-level techno-economic assessment of various hydrogen production technologies. The main advantage of using H2A-lite is the ease of using this model to evaluate levelized cost of production with a limited number of inputs. Users also can override default values and set up their own assumptions for conducting their own assessment for different technology scales. The design assumptions employed in this model are based on case studies and reports which are available on their website.

In our analysis, we have assumed three types of central hydrogen production plant:

Grey H_2: Natural gas is fed into the steam methane reformer (SMR) via a pipeline at 450 psia without any carbon capture and sequestration (CCS) process. We will refer to this plant technology type as "grey-SMR."

Blue H_2: In this H2A production plant, natural gas is fed into the steam methane reformer (SMR) via a pipeline at 435 psia with CCS where the carbon capture rate is 96%. We will refer to this plant technology type as "blue-SMR."

Green H_2: Hydrogen is produced utilizing renewable energy in a standalone proton exchange membrane electrolyzer (PEM) with a baseline power rating of 400 MW. Three types of renewable energy-based PEM were assumed: (a) solar PEM, (b) wind PEM, and (c) hybrid PEM (electricity produced with a combination of solar and wind).

Table 4 represents assumptions utilized in the H2A-lite production plant.

Table 4. Key assumptions for hydrogen production plant

Analysis Inputs	Key Assumptions
Production utilization capacity [kg/day]	500,000
Desired startup year	2024
System life [years]	40
Electricity usage per kg H_2 [kWh]	0.13 (grey), 1.5 (blue), 55.5 (green)
Natural gas per kg H_2 [MMBtu HHV]	0.175 (grey), 0.186 (blue)
Water per kg H_2 [gal]	4.3 (grey), 8.1 (blue), 3.8 (green)
Real return on equity	10.20%
Debt/equity	0.62
Interest rate	4.40%
Depreciation type	MACRS
MACRS depreciation period [years]	7
Total income tax rate	25.70%
Cash on hand [month of OpEx]	3
Dollar basis	2022
Per-kilogram incentives [$/kg H_2]	3 (green only)

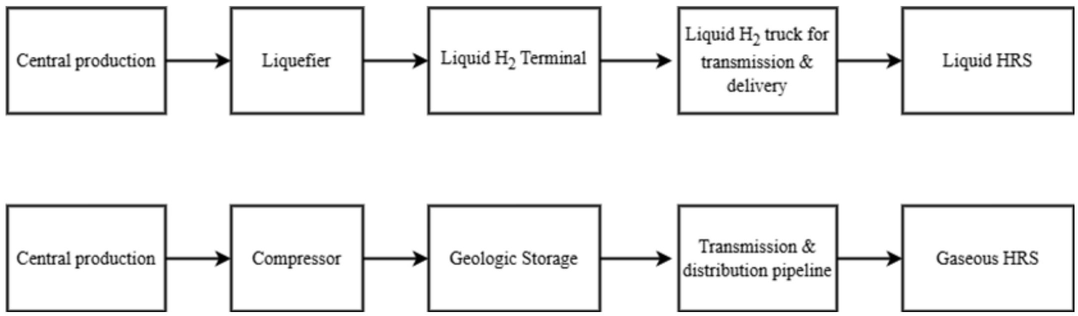
The utilization capacity of grey-SMR and blue-SMR was assumed to be 90%, whereas utilization capacity for green H_2 was varied with the type of renewable energy used. We take utilization rates of 29.4%, 26.4% and 60% for solar-PEM, wind-PEM and hybrid-PEM, respectively.

3.2.2.2 Levelized Cost Estimation for Delivery and Dispensing with HDSAM

In this economic analysis, we have applied HDSAM version 4.5 spreadsheet modeling for assessing the delivery and dispensing cost of hydrogen at the refueling station. In our analysis, we considered that hydrogen is dispensed at 700 bar and that two types of hydrogen delivery systems are available from the central production plant: (i) liquid hydrogen delivery via liquid tanker trucks and (ii) gaseous hydrogen delivery via pipeline. Although alternative dispensing methods, such as 350-bar dispensing and liquid hydrogen dispensing, are being explored in the industry and may potentially reduce hydrogen costs, 700-bar dispensing was modelled due to its ability to support longer driving ranges (up to 750 miles) and its higher level of commercial readiness compared to liquid hydrogen fills (Bracci et al., 2024). For the pipeline delivery system, transmission length and distribution length were assumed to be 150 km and 50 km, respectively.

Figure 2 represents the general configuration of liquid hydrogen delivery and pipeline delivery systemd used in the HDSAM model according to the Argonne National Laboratory.

Figure 2. Delivery Pathways for Liquid Hydrogen Delivery and Gaseous Hydrogen Delivery



The California Air Resources Board (CARB, 2022) reported that the Port of Los Angeles/Long Beach (POLA) has a drayage truck inventory of 17,830 trucks. We have assumed that 25% of these drayage trucks will convert to fuel cell vehicles and evaluated the daily hydrogen demand incorporating the energy efficiency computed from the microscopic modeling. In this analysis, we have used three types of refueling station capacity: 4,000 kg/day, 8,000 kg/day, and 12,000 kg/day. These station capacities are chosen based on the sizes of existing and planned medium- and heavy-duty FCEV hydrogen refueling stations (HRS) as reported by the California Energy Commission in its Senate Bill 643 Staff Report (Villareal, 2023).

Table 5 represents the general parameters assumed in the HDSAM Modeling for LCOH estimation at the delivery and dispensing levels.

Table 5. Assumed Parameters for Hydrogen Delivery and Dispensing

Key Parameters	Analysis Input	Value
Refueling station parameters	Max. Dispensed Amount per Vehicle (kg)	1
	Vehicle Fill Time (min)	40
	Number of Hoses Installed	10
	Station Precooling	-10
	Assumed Start-up Year	2020
General economic assumptions	Construction Period (year)	1
	Desired Year Dollars for Cost Estimates	2022
	Real After-tax Discount Rate (%)	0.1
	Refueling Station Analysis Period (Years)	15
	Other Components Analysis Period (Years)	30
	Debt Ratio (of total capital investment)	0.62
	Debt Interest (nominal)	0.07
	Debt Period	10

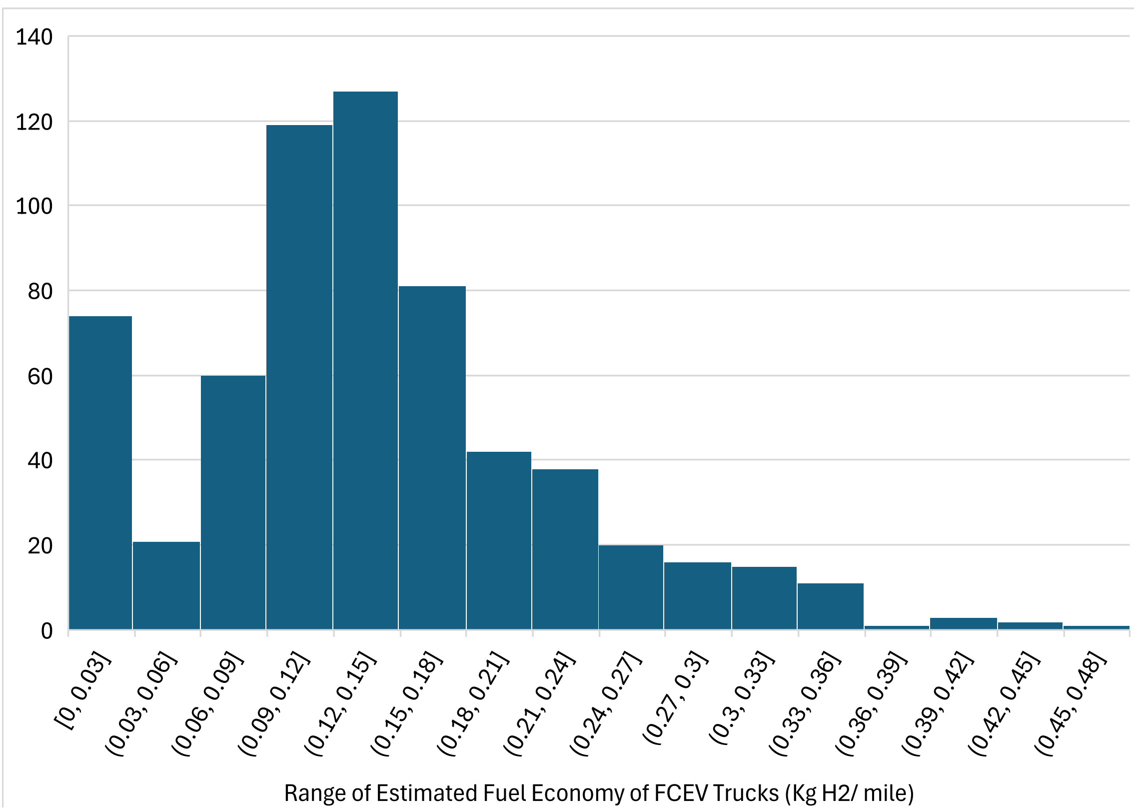
4. Results & Conclusions

The following section describes the findings of our analysis, which were observed from the energy demand modeling and levelized cost of hydrogen estimation.

4.1 Fuel Economy for Port Drayage Trucks

The microscopic energy consumption model for the FCEV truck resulted in fuel consumption rate estimations for each trip taken by the port drayage trucks. Figure 2 summarizes the fuel consumption rate estimations for 749 trips collected during the data collection period.

Figure 3. Histogram of Estimated Fuel Consumption Rate (kg H_2/mile)



The average fuel economy of the FCEV trucks for this study was 0.15 kg H_2/mile. The fuel economy showed a concave relationship with trip average speed. Fuel economy was the highest near trip average speed of 50 miles per hour and decreased at lower and higher speeds.

4.2 Hydrogen Refueling Economics: LCOH Insights from Parametric Study

To better understand how the levelized cost varies across different levels of FCEV truck conversion, Figure 4 illustrates the variation in average levelized cost per kilogram of H_2 based on conversion percentages, starting from 5% to 25% in increments of 5%, for a 4,000 kg/day H_2 production capacity across all stations (for blue H_2). It is evident that LCOH is high at lower demand levels, but with higher conversion to fuel cell electric trucks, LCOH has the potential to decrease significantly. Although the LCOH decreases to a lower value of $1.4 at 25% conversion to FCEVs, the demand/supply ratio becomes very high (close to 7), indicating that only four stations with a 4,000 kg/day H_2 capacity are insufficient to support this transition.

Figure 4. Variation of LCOH at Different Transition Levels for Onsite SMR Comparison for 4,000 kg/H_2 Capacity

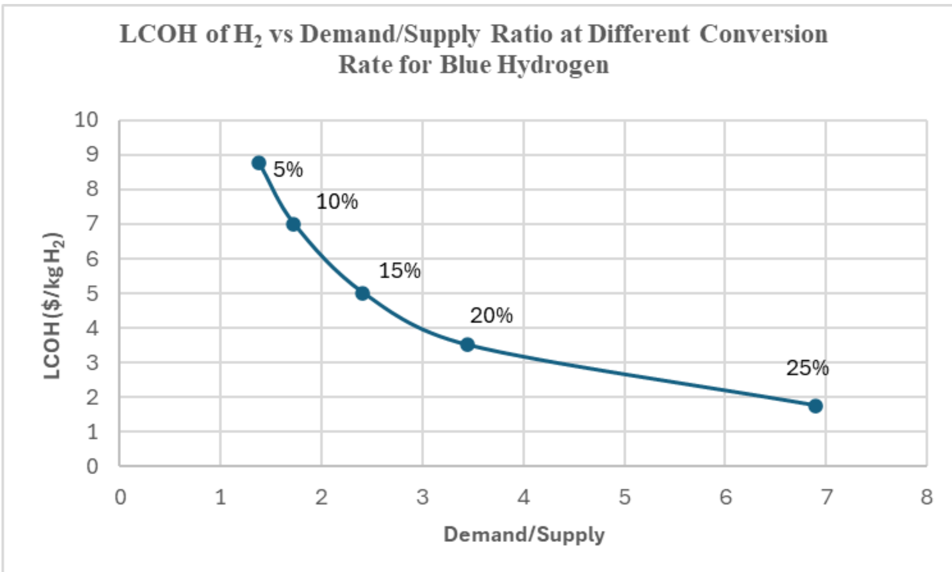
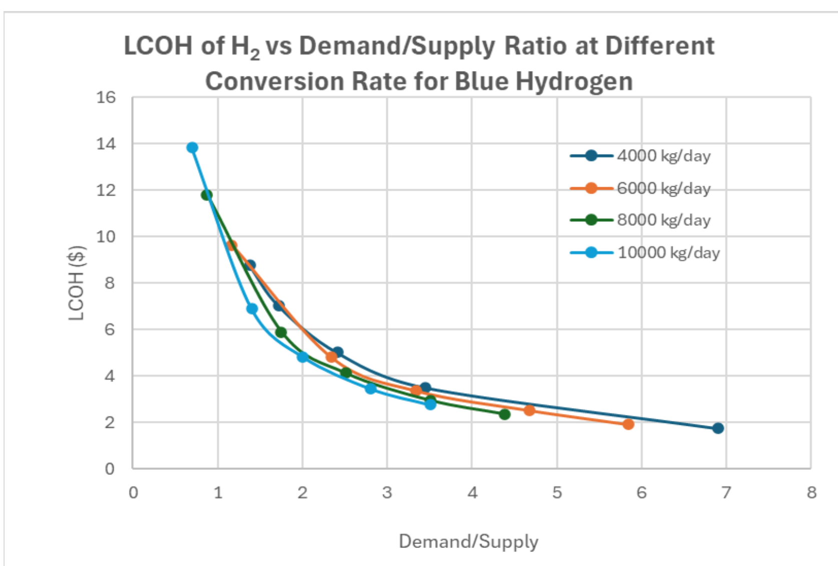
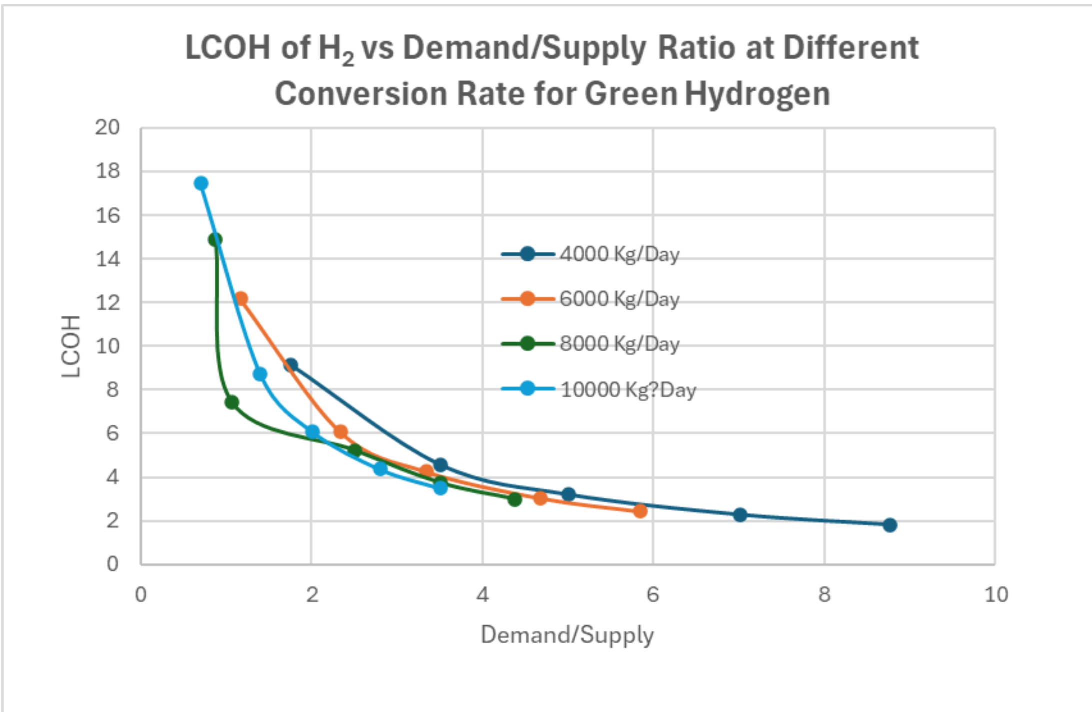


Figure 5. Comparison of LCOH at Different Transition Levels for Onsite SMR for All Capacity Levels



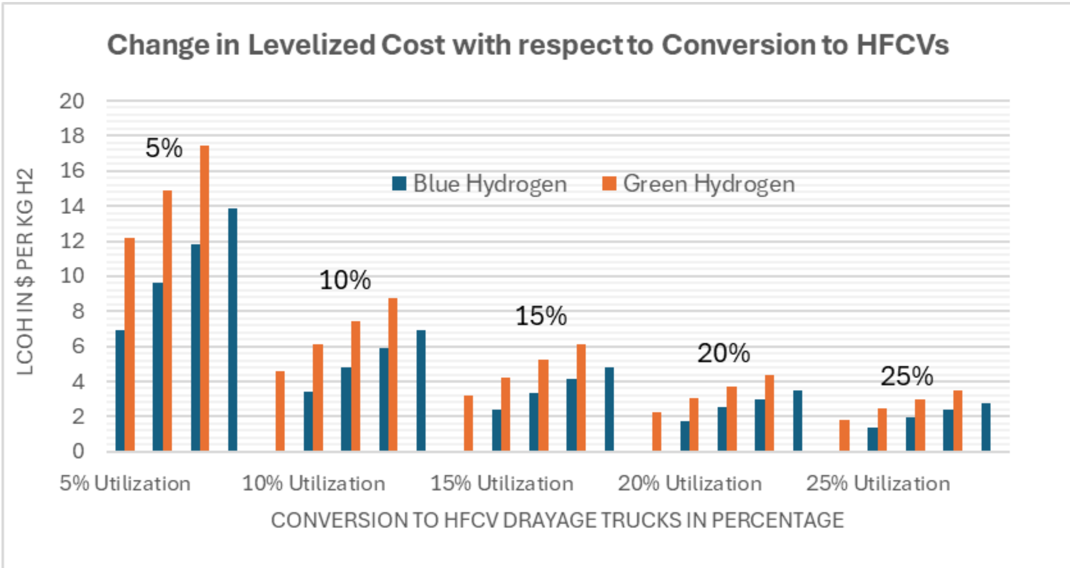
The same trend is also observed in Figures 5 and 6, which present a similar comparison of LCOH across various levels of capacity for blue and green hydrogen, respectively. Figure 7 highlights that the LCOH of blue hydrogen remains lower than that of green hydrogen across all conversion levels due to its lower production costs (e.g., steam methane reforming with carbon capture is currently cheaper than electrolysis powered by renewable energy). However, as more port drayage trucks convert to HFCVs, the gap between blue hydrogen and green hydrogen narrows, suggesting that green hydrogen becomes more competitive at higher adoption rates.

Figure 6. Comparison of LCOH with Varying Transition and Capacity Levels for Onsite Electrolysis



The decreasing trend of LCOH with the increase in demand for each case can be attributed to the distribution of infrastructure and production costs across a larger demand base which reduces the per-unit hydrogen cost. Nevertheless, a higher demand-to-supply ratio is not always practical, as it can overstretch the infrastructure. Overutilization of hydrogen refueling stations (HRS) may lead to long wait times, reduced service reliability, and logistical challenges. Therefore, optimization is needed not only to minimize costs but also to ensure that the hydrogen supply network remains sustainable from both economic and operational perspectives. This underscores the importance of strategically balancing the expansion of refueling infrastructure by optimizing both the number of stations and the production capacity of each to effectively accommodate increasing hydrogen demand.

Figure 7. LCOH Variation for Blue and Green HRS for All Capacity Levels

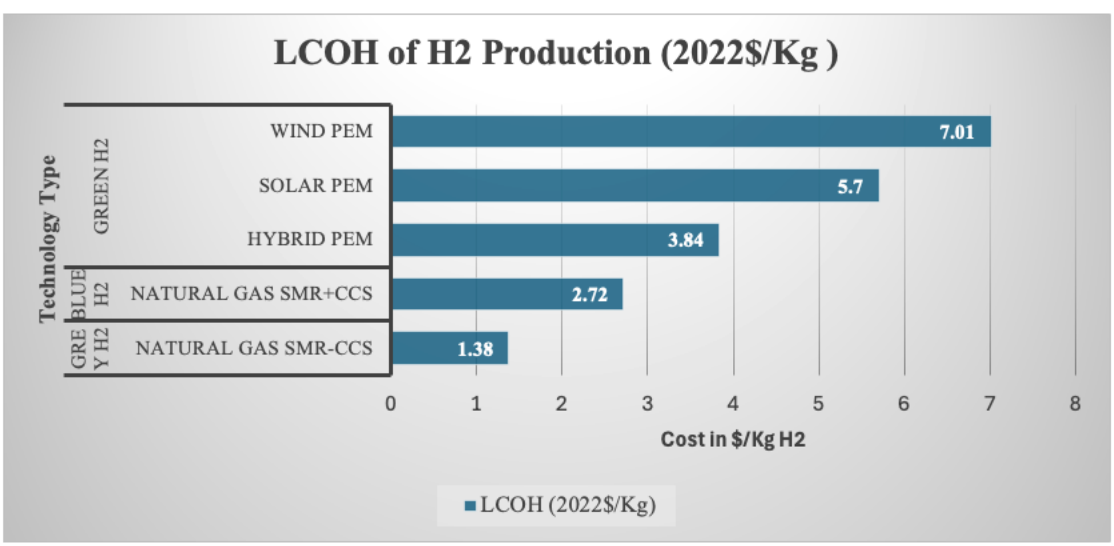


4.3 Economic Analysis from Production to Delivery with Existing Spreadsheet Modeling

4.3.1 Levelized Cost of Hydrogen at Production Level

Figure 8 demonstrates how levelized cost of hydrogen production varies with production technology in the Southern California Region. It is evident that LCOH at the production level doubles for blue hydrogen (\$2.73/kg H_2) and is 3–6 times higher for green hydrogen (\$3.94–\$6.65/kg H_2) compared to grey hydrogen production (\$1.30/kg H_2) using natural gas.

Figure 8. Variation of Levelized Cost of Hydrogen Production with Various Technology Types



Among the different green hydrogen production options, hybrid-PEM has the highest potential to compete with the lower price of grey and blue hydrogen due to its higher utilization rate (60%) compared to the efficiency of solar-PEM (29.4%) and wind-PEM (26.4%) plants.

4.3.2 LCOH of H_2 at Delivery and Dispensing

Our computed average energy efficiency (0.15 kg H_2/mile) was integrated into the assumption that 25% of port drayage trucks will convert to HFCV vehicles in the Southern California region. From the estimation, the daily demand for hydrogen was found to be 37.96 MTPD. Taking this market demand into account, we have calculated the delivered levelized cost of hydrogen for each station.

Figure 9. Change in Downstream LCOH with Utilization Rate for Gaseous Refueling Station

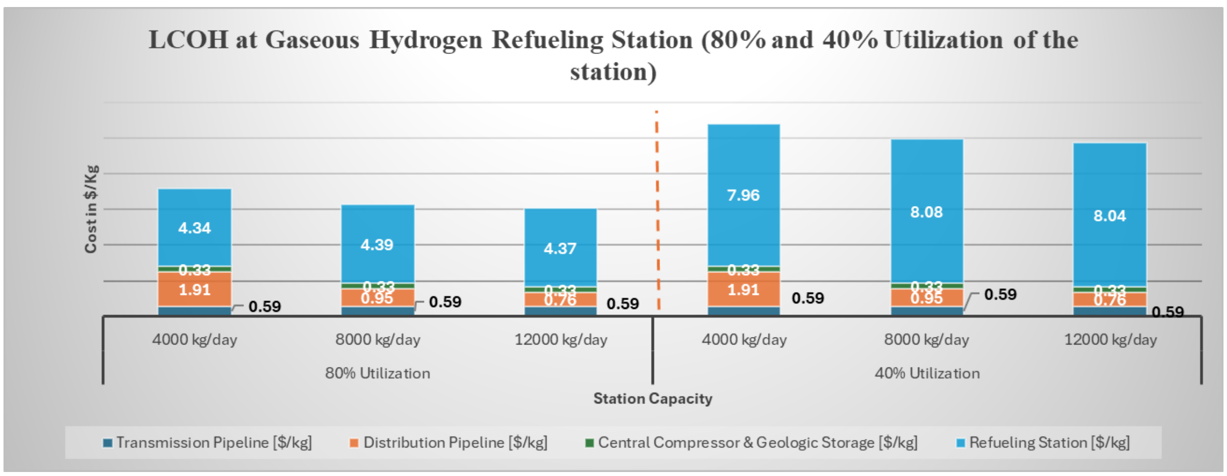
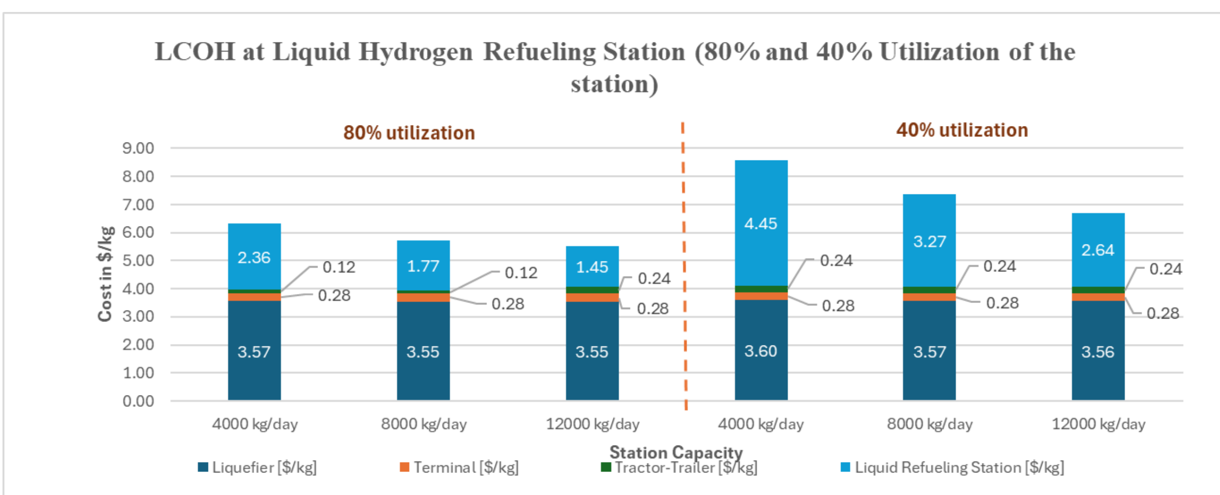


Figure 10. Change in Downstream LCOH with Utilization Rate for Liquid Refueling Station

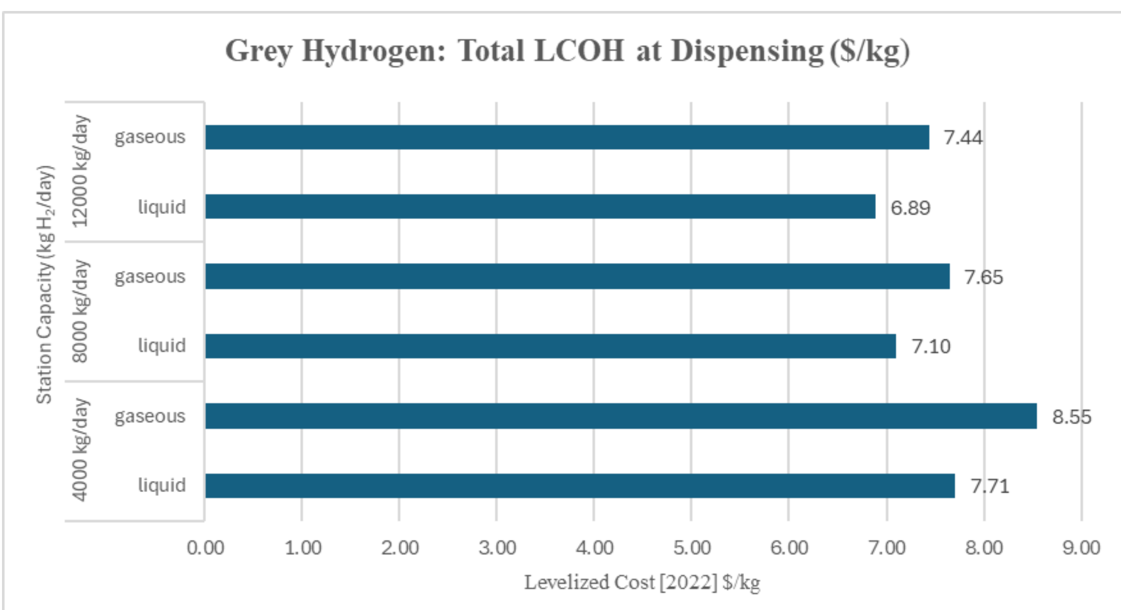


Figures 9 and 10 illustrate how downstream levelized costs (comprising delivery and dispensing components) vary with utilization rates for different station capacities. Figure 9 corresponds to gaseous hydrogen refueling stations, while Figure 10 represents liquid hydrogen refueling stations. It can be observed that a lower utilization rate causes a jump in the levelized cost at the refueling station across all station capacities for each delivery method. At gaseous hydrogen refueling stations (HRS), the downstream Levelized Cost of Hydrogen (LCOH) escalates by 50%–60% as utilization declines. Conversely, liquid HRS stations see a comparatively smaller maximum increase of 36% at the 4,000 kg/day capacity, highlighting the economic benefit of liquid hydrogen infrastructure in low-utilization scenarios. It is also observed that the delivery components of LCOH remain nearly constant across station capacities, except for distribution pipeline length in gaseous HRS and tractor-trailer costs in liquid HRS, which vary with transport distance. This highlights the importance of strategically locating central production plants to minimize transportation-related delivery costs in the future.

4.3.3 Variation in Total Levelized Cost across Station Capacity, Delivery Method and Production Technology

Figures 11, 12, and 13 illustrate the total levelized cost from upstream to downstream for each station capacity, considering an 80% utilization rate across three hydrogen production technologies (grey-SMR, blue-SMR, and green-PEM) and two delivery types (gaseous and liquid). The LCOH at dispensing for grey-SMR decreases as station capacity increases, with gaseous hydrogen experiencing a 12.98% reduction and liquid hydrogen a 10.64% reduction from 4,000 kg/day to 12,000 kg/day, demonstrating cost efficiency at larger stations (Figure 11).

Figure 11. Total LCOH from Production to Dispensing by Delivery Method and Station Capacity (Grey-SMR Production) at 80% HRS Utilization Rate



It can be inferred from Figure 12 that the LCOH at dispensing for blue hydrogen follows a similar trend, where gaseous hydrogen experiences an 11.22% cost reduction, while liquid hydrogen decreases by 9.06%, reinforcing the economic advantage of scaling up station capacity. Figure 13 demonstrates that for green-PEM using hybrid renewable energy, the LCOH at dispensing is the highest among the three production methods, but gaseous hydrogen still experiences a 10.08% decrease and liquid hydrogen an 8.06% decrease, indicating that higher station capacities help mitigate costs even for more expensive production pathways.

Figure 12. Total LCOH from Production to Dispensing by Delivery Method and Station Capacity (Blue-SMR Production) at 80% HRS Utilization Rate

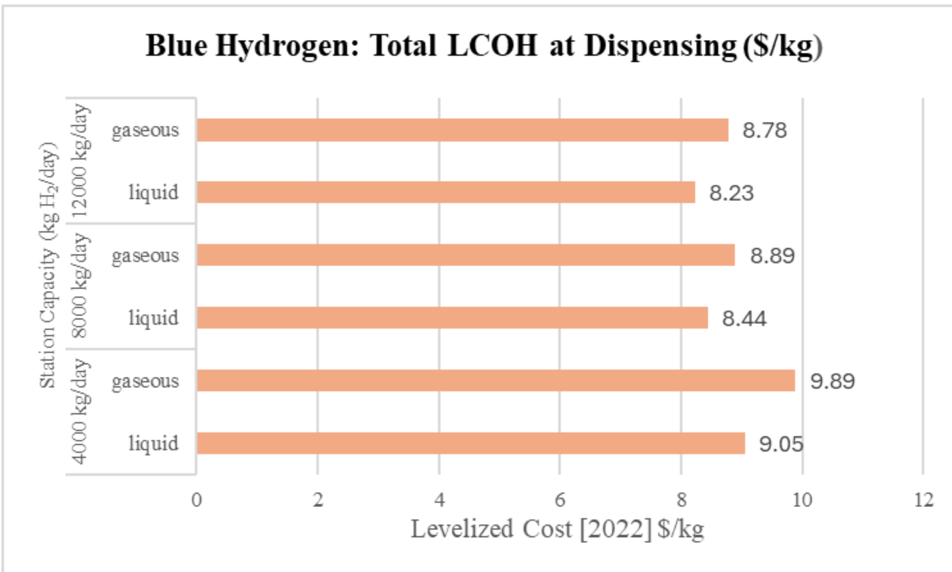
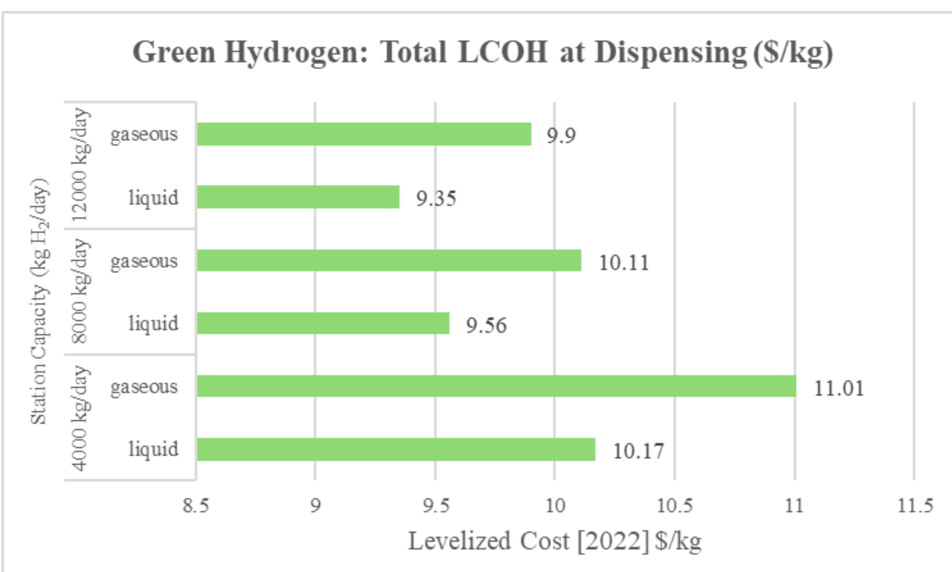
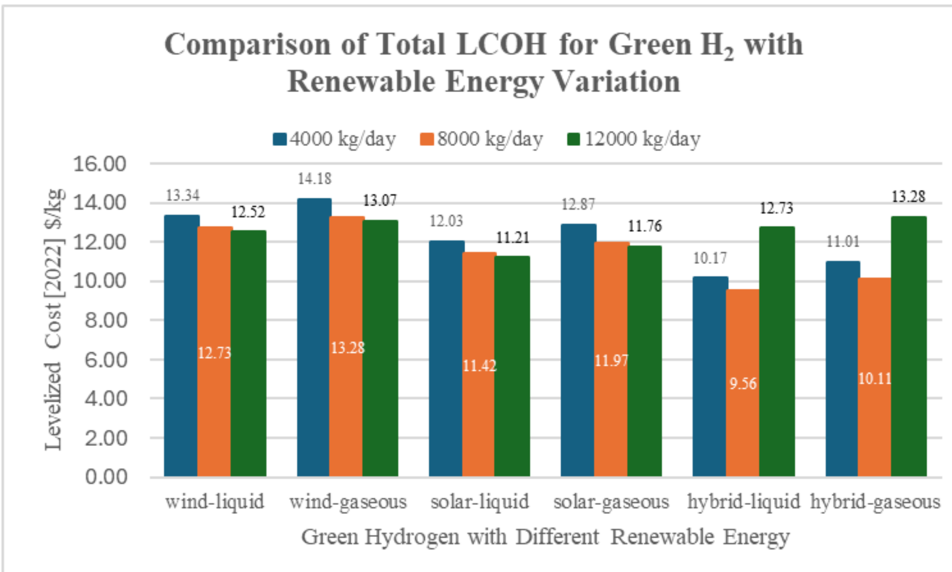


Figure 13. Total LCOH from Production to Dispensing by Delivery Method and Station Capacity (Green-PEM-hybrid Production) at 80% HRS Utilization Rate



In Figure 13, LCOH variation with station capacity and delivery type was shown for only hybrid-PEM as they have a higher potential to compete with the grey-SMR and blue-SMR technology types from the perspective of pricing. Figure 14 illustrates the impact of renewable energy variation on the total levelized cost for green hydrogen across different renewable sources (wind, solar, and hybrid) and delivery methods (liquid and gaseous). LCOH is highest for wind-gaseous ($14.18/kg at 4,000 kg/day) and lowest for hybrid-liquid ($9.56/kg at 12,000 kg/day), with larger station capacities consistently reducing costs across all cases. This emphasizes that the combined use of solar and wind electricity for green hydrogen production can substantially reduce the price of hydrogen in the future.

Figure 14. Impact of Types of Renewable Energy in Total LCOH for All Station Capacities at 80% Utilization for Green Hydrogen Production Technology



Bibliography

Argonne National Laboratory. (2023). *Hydrogen delivery scenario analysis model (HDSAM)*. U.S. Department of Energy. https://hdsam.es.anl.gov/index.php?content=hdsam

Bracci, J., Koleva, M., & Chung, M. (2024). *Levelized cost of dispensed Hydrogen for heavy-duty vehicles* (No. NREL/TP-5400-88818). National Renewable Energy Laboratory (NREL), Golden, CO (United States).

Bureau of Transportation Statistics. (2021). *Number of U.S. aircraft, vehicles, vessels, and other conveyances.* Retrieved October 24, 2022, from https://www.bts.gov/content/number-us-aircraft-vehicles-vessels-and-other-conveyances

California Air Resources Board. (2023). *Advanced clean fleets regulation: Detailed drayage truck requirements*. https://ww2.arb.ca.gov/resources/fact-sheets/advanced-clean-fleets-regulation-detailed-drayage-truck-requirements

Energy Information Administration. (2022). *Use of energy for transportation in depth.* U.S. Energy Information Administration (EIA). https://www.eia.gov/energyexplained/use-of-energy/transportation-in-depth.php

Environmental Protection Agency. (n.d.). *Sources of greenhouse gas emissions.* EPA. Retrieved February 2, 2022, from https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

Greene, D. L., Ogden, J. M., & Lin, Z. (2020). Challenges in the designing, planning, and deployment of hydrogen refueling infrastructure for fuel cell electric vehicles. *ETransportation*, *6*, 100086. https://doi.org/10.1016/j.etran.2020.100086

Halder, P., Babaie, M., Salek, F., Haque, N., Savage, R., Stevanovic, S., Bodisco, T. A., & Zare, A. (2024). Advancements in hydrogen production, storage, distribution and refuelling for a sustainable transport sector: Hydrogen fuel cell vehicles. *International Journal of Hydrogen Energy*, *52*(2024), 973–1004.

International Energy Agency. (n.d.). *Improving the sustainability of passenger and freight transport.* IEA. Retrieved February 2, 2022, from https://www.iea.org/topics/transport

Kopasz, J., & Krause, T. (2019). *H2@PORTS Workshop Summary Report* (No. ANL-20/12). Argonne National Laboratory (ANL). https://doi.org/10.2172/1608332

Lee, B., Tanvir, S., & Awwad, M. (2023). Planning and design for wireless enroute charging infrastructure. In *International Conference on Transportation and Development 2023* (pp. 449–464). https://doi.org/10.1061/9780784484729.045

Li, G., Ogden, J., & Miller, M. (2021). Hydrogen infrastructure requirements for zero-emission freight applications in California. *Energy Policy*, *147*, 111788. https://doi.org/10.1016/j.enpol.2020.111788

National Renewable Energy Laboratory. (2023). *H2A-Lite model*. U.S. Department of Energy. Retrieved December 10, 2025, from https://www.nrel.gov/hydrogen/h2a-lite.html

Papson, A., & Ippoliti, M. (2013). *Key performance parameters for drayage trucks operating at the Ports of Los Angeles and Long Beach*. CALSTART. https://calstart.org/wp-content/uploads/2018/10/I-710-Project_Key-Performance-Parameters-for-DrayageTrucks.pdf

Park, C., Lim, S., Shin, J., & Lee, C.-Y. (2022). How much hydrogen should be supplied in the transportation market? Focusing on hydrogen fuel cell vehicle demand in South Korea. *Technological Forecasting & Social Change*, *181*, 121750. https://doi.org/10.1016/j.techfore.2022.121750

Rose, P. K., & Neumann, F. (2020). Hydrogen refueling station networks for heavy-duty vehicles in future power systems. *Transportation Research Part D: Transport and Environment*, *83*, 102358.

Scora, G., Boriboonsomsin, K., Durbin, T. D., Johnson, K., Yoon, S., Collins, J., & Dai, Z. (2019). Variability in real-world activity patterns of heavy-duty vehicles by vocation. *Transportation Research Record: Journal of the Transportation Research Board*, *2673*, 51–61.

Stephens-Romero, S. D., Brown, T. M., Kang, J. E., Recker, W. W., & Samuelsen, G. S. (2010). Systematic planning to optimize investments in hydrogen infrastructure deployment. *International Journal of Hydrogen Energy*, *35*(10), 4652–4667. https://doi.org/10.1016/j.ijhydene.2010.03.057

Tanvir, S., Un-Noor, F., Boriboonsomsin, K., & Gao, Z. (2020). Feasibility of operating a heavy-duty battery electric truck fleet for drayage applications. *Transportation Research Record*, *2674*(9), 1–12. https://doi.org/10.1177/0361198120957325

Tsuda, K., Kimura, S., Takaki, T., Toyofuku, Y., Adaniya, K., Shinto, K., et al. Design proposal for hydrogen refueling infrastructure deployment in the Northeastern United States. *Int J Hydrogen Energy*. 2014;39:7449e59

Voelcker, J. (2023). Toyota "Project Portal" hydrogen fuel cell heavy-duty semi tractor as proof of concept. *Green Car Reports*. https://www.greencarreports.com/news/1109999_toyota-project-portal-hydrogen-fuel-cell-heavy-duty-semi-tractor

Yaïci, W., & Longo, M. (2022). Feasibility investigation of hydrogen refuelling infrastructure for heavy-duty vehicles in Canada. *Energies*, *15*(8), 2848. https://doi.org/10.3390/en15082848

Zhao, J., Burke, A. F., Miller, M. R., & Fulton, L. M. (2024). Vehicle choice modeling for emerging zero-emission medium- and heavy-duty vehicle markets in California. *Transportation Research Interdisciplinary Perspectives*, *26*, 101169. https://doi.org/10.1016/j.trip.2024.101169

About the Authors

Shams Tanvir, PhD, PE

Dr. Shams Tanvir is an Assistant Professor in the Department of Civil Engineering and Construction Engineering Management (CECEM) at California State University, Long Beach (CSULB). His research aims to develop and characterize transportation technologies that minimize energy consumption and emissions while enhancing mobility efficiency and equity. Dr. Tanvir has published extensively on energy and emissions modeling of transportation systems, including zero and near-zero emissions transportation, as well as the unintended consequences of transportation technologies. He is a member of the Transportation Research Board committee on Highway Capacity and Quality of Service, and Transportation Air Quality and Greenhouse Gas Mitigation. He chairs the Sustainable Transportation committee at the American Society of Civil Engineers (ASCE). Dr. Tanvir received his PhD in Transportation Systems Engineering from North Carolina State University. He received B.S. and M.S. in Civil Engineering from BUET.

Emu Ghosh

Emu Ghosh is a graduate student in Civil Engineering at CSULB. She earned her Bachelor of Science degree in civil engineering from Bangladesh University of Engineering and Technology in 2023. With a passion for research, Emu has always aspired to contribute to ensuring sustainability and mobility in the transportation sector. Currently, Emu serves as a Research Assistant at the Sustainable Mobility Laboratory under Dr. Shams Tanvir. The laboratory's primary focus is to reduce energy consumption and emissions, thereby enhancing mobility and achieving sustainability in the transportation sector.

MTI FOUNDER

Hon. Norman Y. Mineta

MTI BOARD OF TRUSTEES

Directors