Executive Summary - Hydrogen Powered Trucks 2025

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As a truck fleet, you are likely grappling with the fate of the diesel engine, dominant in trucks for over 100 years. Alternative fuels have challenged diesel, but none have bested it. The most recent contender, hydrogen, is both interesting and mysterious. In this guide, *Hydrogen Powered Trucks 2025*, you will discover that hydrogen is a unique and versatile gas, offering great potential despite certain challenges. We explore the technical aspects of hydrogen power trains, hydrogen fueling, the state of commercial rollout and ways fleets might begin to deploy hydrogen trucks.

Across the United States, there are pockets of significant interest in hydrogen as a transportation fuel, notably California, Texas, and the Pacific Northwest extending into Canada, driven by energy security, corporate sustainability and/or the need to reduce local air pollution.

Hydrogen is recognized by engine manufacturers and truck OEMs as a preferred decarbonization option due to diesel-like truck refueling, range, and cargo capacity and its versatility, either as a bridge fuel -burned in internal combustion engines- or as an electromotive drivetrain energy source. However, hydrogen fueled trucking recently moved from R&D, into an early-commercial Class 8 truck market. Commercial demonstration projects are needed to enable market pull. These demonstrations will require vertical deployment of hydrogen fueling and trucks in an iterative fashion to de-risk this early market and set it up for growth.

Despite tremendous momentum to create hydrogen corridors, the early hydrogen truck market has not yet fully emerged. Given these factors *Hydrogen Powered Trucks 2025* is offered as a primer to arm Class 8 truck fleets with the minimum knowledge to be conversant around the topic of hydrogen fuel and its use in trucking, noting that much of this information is applicable to hydrogen fueled vehicles of all classes.

In trucking and heavy freight, recognition of a need for corporate environmental stewardship creates pressure to proactively adopt sustainability best practices, with a move to zero-emission vehicles (ZEV). In some cases, the actions of individual corporations are ahead of public policy and regulation. Corporations like Ikea, DHL, Sysco, Maersk and PepsiCo are testing business models for decarbonizing their freight logistics.

This increased activity in sustainability best practice exerts pressure on the supply chain to reduce carbon dioxide air pollution (commonly referred to as “carbon”). Truck OEMs are taking note and investing heavily into hydrogen as a transportation fuel because of its potential to meet these needs. Now the federal government and regions across the country are implementing policy that create the market conditions for hydrogen’s success. California, Oregon, Washington, Texas are states taking a regional approach to hydrogen market creation.

Layered on this are the national standards to reduce air pollution and improve conditions in and around cities. These federal air pollution improvement requirements are tied to federal highway funding.

Congress implemented two major tools that is stimulating the hydrogen marketplace. In 2021, through the Infrastructure Investment and Jobs Act, $8 billion was earmarked by US DOE to stimulate the development of seven clean hydrogen production hubs. Additionally, the Inflation Reduction Act of 2022, includes energy- and climate-related provisions, which will influence energy consumption, production and trade in the US which will directly and indirectly benefit trucking and hydrogen.

Introduction

Introduction

Economic growth is the cornerstone of the US economy. This growth is fueled by increased consumption of raw materials and energy. The results are increases in both production and waste (pollution), which has given rise to corporate sustainability efforts geared towards maximizing production and minimizing waste. These solutions, such as process efficiency improvements, adoption of technologies with lower environmental impact and a shift to renewable energy sources, require investment and may come at a higher cost than business-as-usual.

For example, the commercial truck sector is dependent on diesel engines and fuel, energy and economically efficient with the support of a mature oil & gas market; good for economic growth but with air pollution consequences. There is increasing recognition that burning petroleum-based diesel fuel is unsustainable due to the adverse health and carbon dioxide impacts. Enter hydrogen, a fuel that contains no carbon, and therefore no carbon particulate or carbon dioxide pollution impacts. In fact, the major exhaust of hydrogen fuel consumption is pure water, exemplifying hydrogen’s potential to both decarbonize transportation and reduce other forms of air pollution.

Today, the hydrogen truck fueling market is nascent and exists only in California, however federal and state policy around hydrogen opens doors to commercial rollout in a way that is aligns energy growth with air pollution reduction, and economic growth. The trifecta.

California and the Role of Hydrogen Trucks

California and the Role of Hydrogen Trucks

California has long stood at the forefront of air quality and climate action in the United States, establishing some of the most stringent environmental policies in the world. These mandates have not only shaped vehicle emissions standards for decades but have now become the primary engine driving the rapid adoption of zero-emission vehicles (ZEVs) — across passenger, commercial, and especially heavy-duty sectors. Hydrogen fuel cell electric trucks (FCETs) have emerged as a key solution in California’s strategy to achieve deep decarbonization while addressing persistent air quality disparities in frontline communities.

Air Quality as a Foundational Driver

The foundation of California’s ZEV market lies in its commitment to public health. State agencies, led by the California Air Resources Board (CARB), have documented for decades the disproportionate pollution burden borne by communities near freight corridors, railyards, ports, and industrial centers; topping the list are Southern California’s South Coast Air Basin and the San Joaquin Valley. In these regions, heavy-duty diesel trucks are among the largest contributors to localized smog-forming pollutants (NO_x) and toxic diesel particulate matter (PM), both of which are directly linked to respiratory illness, cardiovascular disease, and cancer.

This enduring public health imperative has shaped a policy framework that does not treat zero-emission technology as optional, but as a necessity for compliance with federal and state air quality standards. Many regions in California are still in nonattainment with federal ozone and particulate matter limits under the Clean Air Act. Thus, California treats ZEV adoption as not just a climate solution, but a regulatory necessity.

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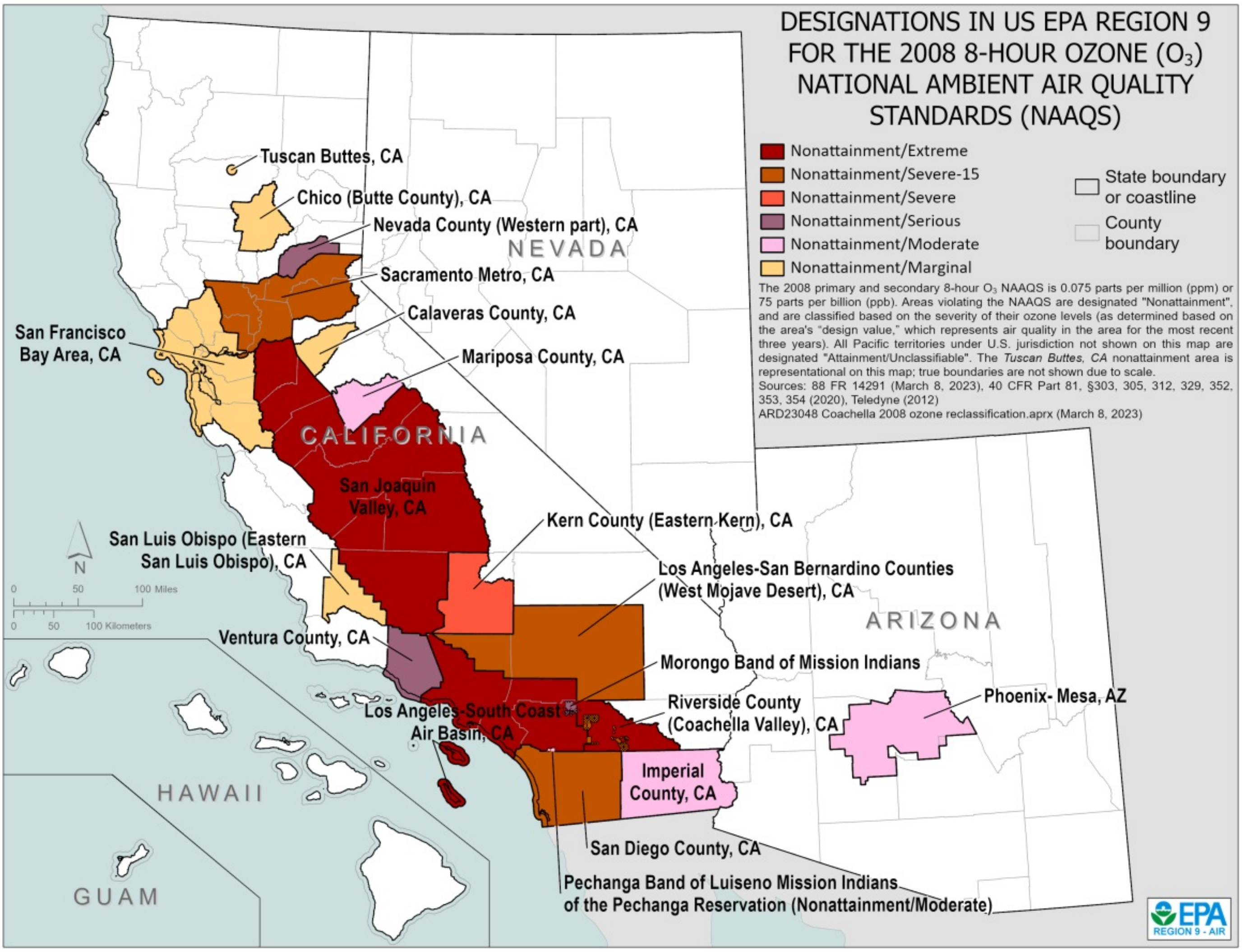

Texas and Hydrogen Trucking

[Texas and Hydrogen Trucking]

Texas is a Hydrogen State

Texas has the resources and desire to implement hydrogen as a transportation fuel. In 2023, HyVelocity, Inc., was awarded one of seven US DOE grants, valued at $1.2 billion, to establish a clean hydrogen production hub centered in Houston. This will supplement Texas' existing, 38% share of domestic US hydrogen production capacity. Texas produced hydrogen, primarily used in crude oil refining, has potential to be used directly as a transportation fuel, which is a use case that is rapidly emerging in the truck market, particularly Class 8 tractors.

Texas salt domes are an additional resource which are highly complementary to the emerging hydrogen industry. These impermeable geologic reservoirs from which oil and gas have been extracted, can be repurposed to store pressurized hydrogen gas, as demonstrated by the Beaumont, TX hydrogen storage cavern that holds on the order of 4.5 billion cubic feet of hydrogen.

Furthermore, the Texas Gulf Coast hosts a portion of the largest dedicated hydrogen pipeline network in the US. Pipeline is the lowest cost method for hydrogen transmission and distribution.

All of these Texas factors mesh well with the 2024US National Zero-Emission Freight Corridor Strategy, which prioritizes electric truck infrastructure, including hydrogen. Factors for prioritizing this network of electromotive infrastructure include freight volume, port tonnage, freight activity and air pollution burden. These bring Texas to the forefront as a priority state. In fact funds are already flowing; FHWA has awarded $70 million to develop hydrogen truck fueling stations in the Texas Triangle and US DOE has funded development of the nation's first interstate hydrogen freight corridor along Interstate 10, connecting the Texas Triangle to Los Angeles.

Given these opportunities, hydrogen has potential to take the Texas trucking world by the horns.

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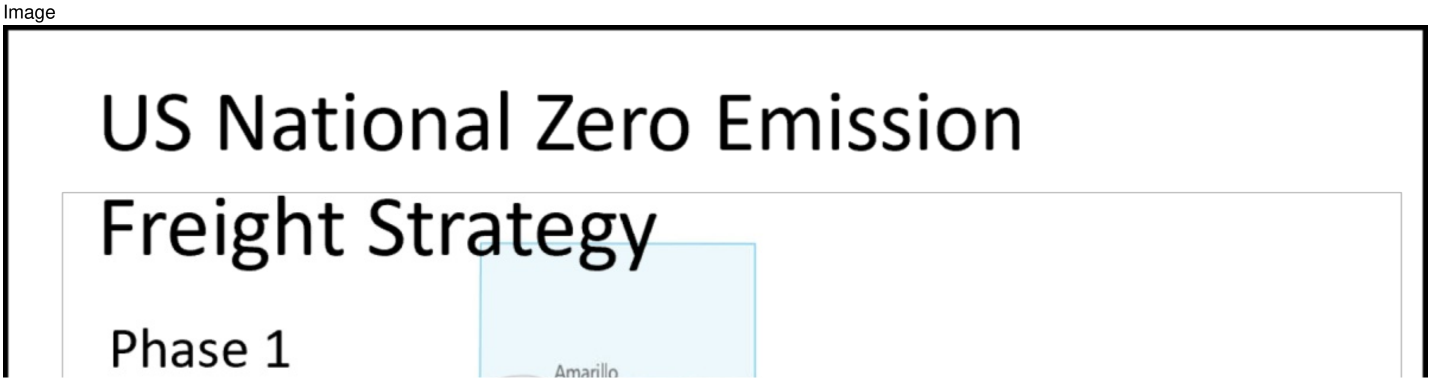

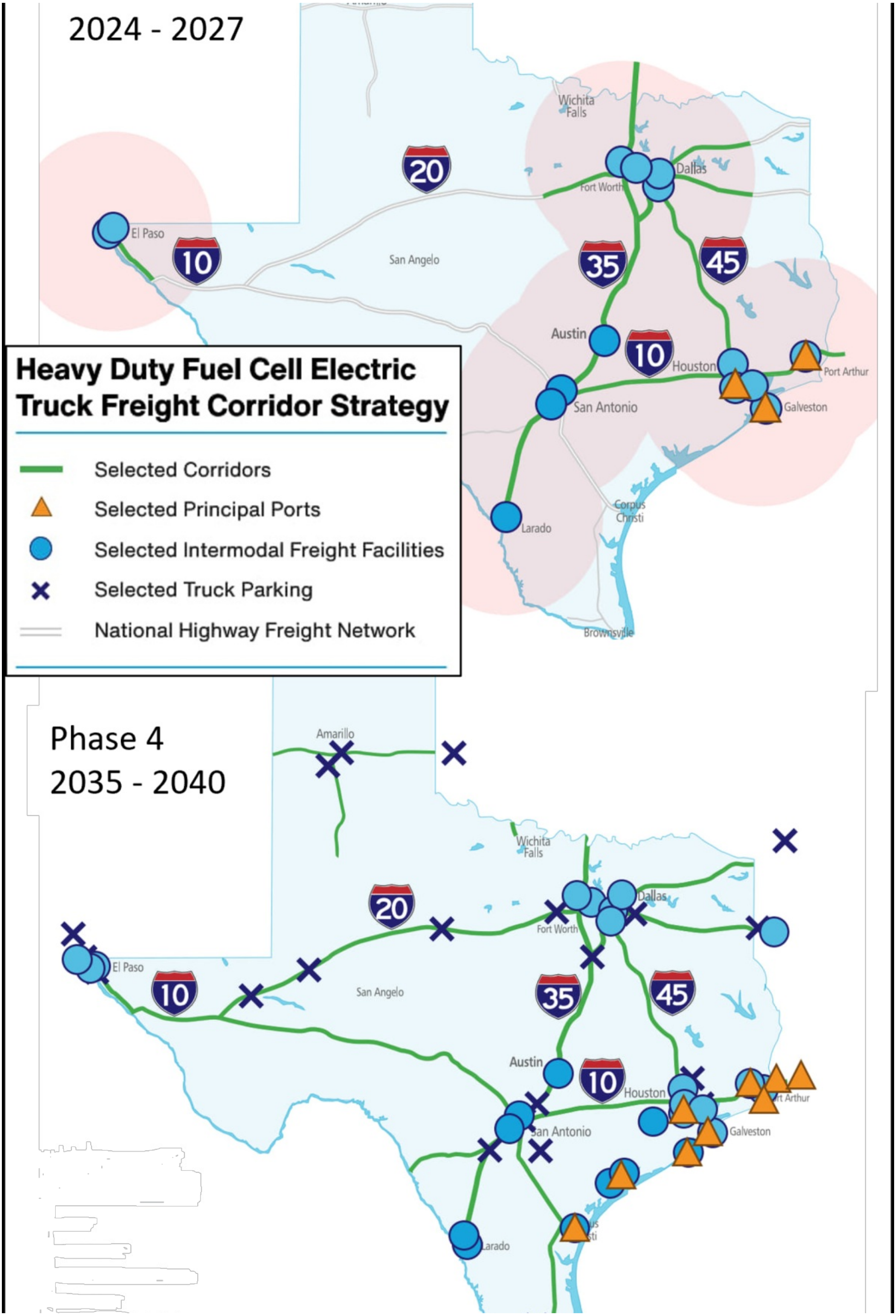

2024 - 2027
Heavy Duty Fuel Cell Electric Truck Freight Corridor Strategy
Selected Corridors
Selected Principal Ports
Selected Intermodal Freight Facilities
Selected Truck Parking
National Highway Freight Network
Phase 4
2035 - 2040
20
10
35
45
El Paso
San Angelo
Wichita Falls
Fort Worth
Dallas
Austin
Houston
Port Arthur
San Antonio
Galveston
Larado
Corpus Christi
Brownsville
Amarillo

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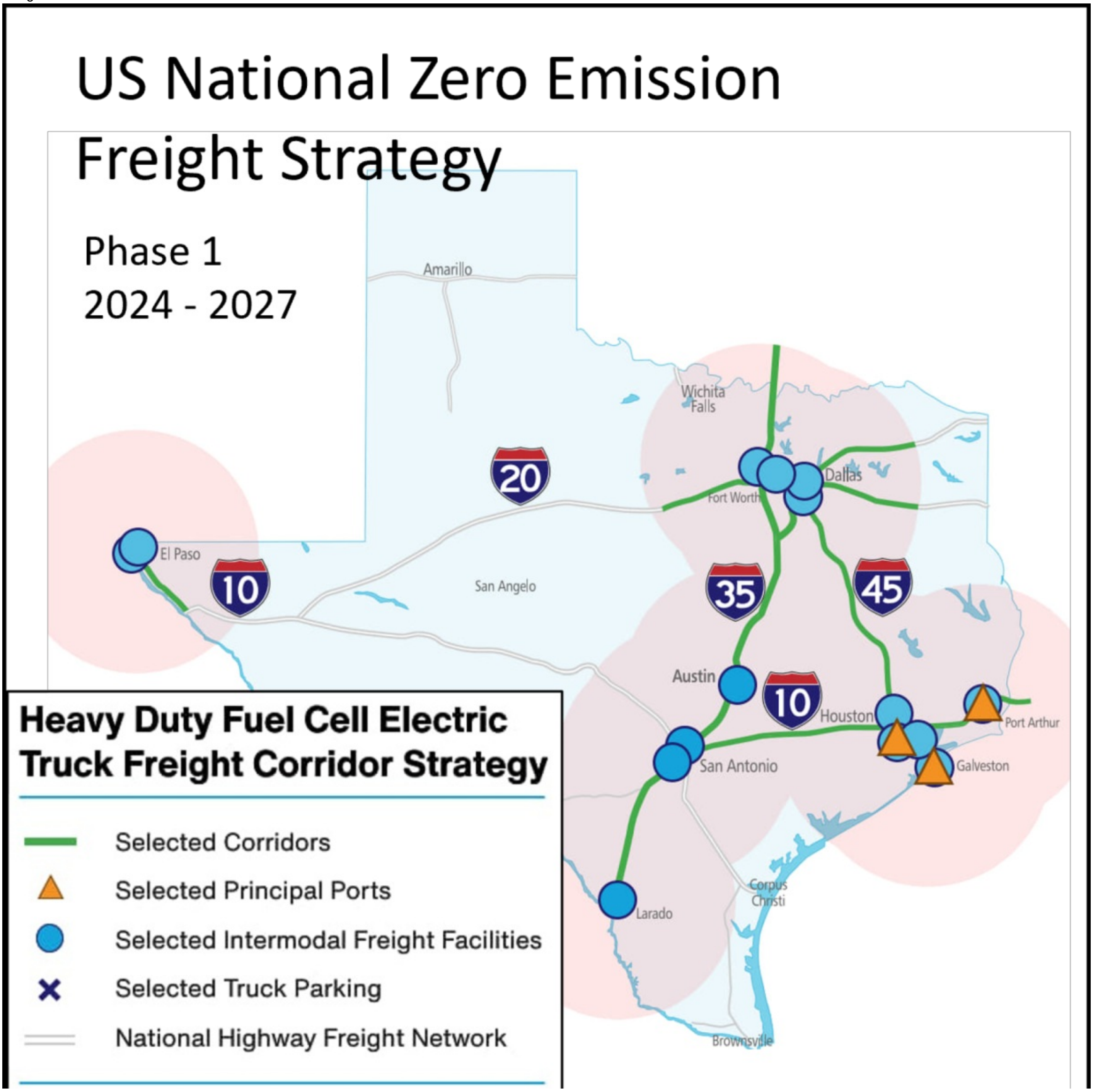

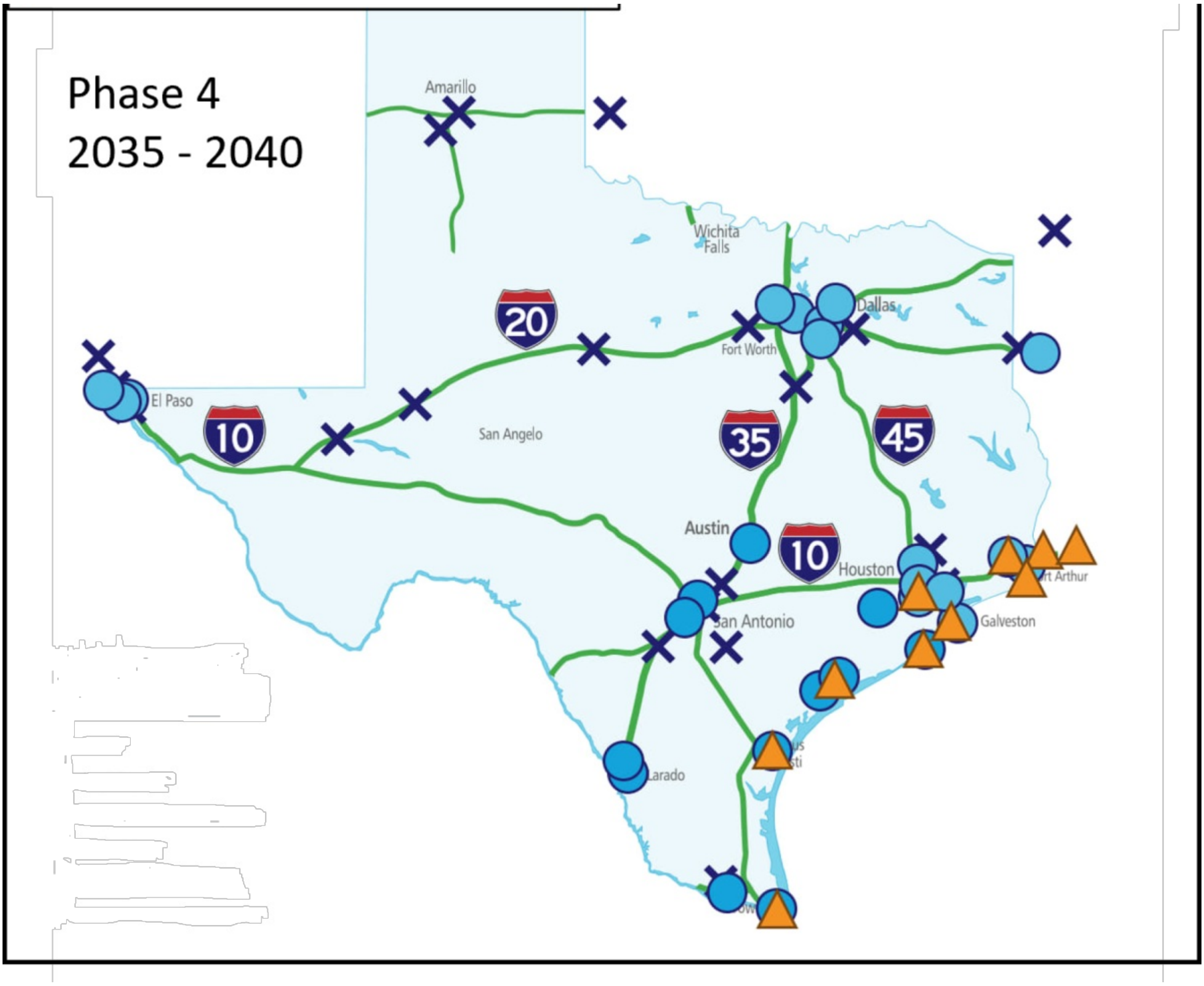

State and Federal Support

[State and Federal Support]()

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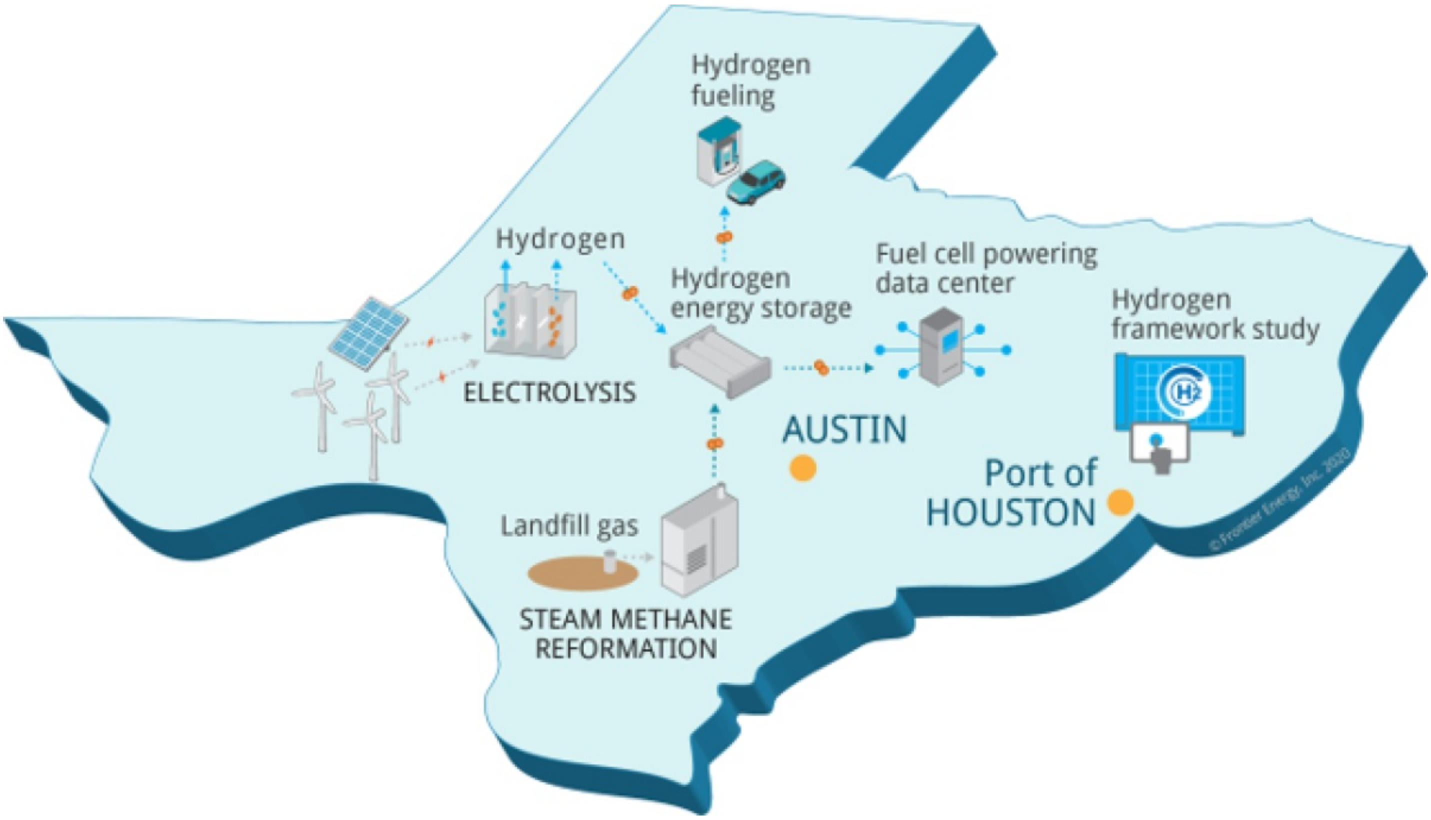
Hydrogen fueling
Hydrogen
Hydrogen energy storage
Fuel cell powering data center
Hydrogen framework study
ELECTROLYSIS
AUSTIN
Port of HOUSTON
Landfill gas
STEAM METHANE REFORMATION

Image


GTI ENERGY
Expanding the Nation's Hydrogen Fueling Infrastructure
Los Angeles
10
Houston
H2LA
Houston to Los Angeles: I-10 Hydrogen Corridor

Image

Support of Hydrogen Projects in Texas

Texas is a major hydrogen producing state in the US and hosts a portion of the Gulf Coast dedicated hydrogen pipeline network, the largest in the US. The following are examples of funding that is or is expected to enter the state in support of hydrogen truck implementation projects.

1. HyVelocity, an industry-led, public/private collaboration focused on developing a Gulf Coast Hydrogen Production Hub. HyVelocity was awarded a US DOE grant of up to $1.2billion in October 2023. Seven core industry partners, AES Corporation, Air Liquide, Chevron, ExxonMobil, Mitsubishi Power Americas, Ørsted, and Sempra Infrastructure collaborated to create this Hub.

2. H2@Scale is a US DOE project, bookended at UT Austin and the Port of Houston, with a focus on demonstrating that renewable hydrogen can be a cost-effective fuel for multiple end-use applications, including FCEV, when coupled with large, baseload consumers that use hydrogen for clean, reliable stationary power, including commercial hydrogen production, distribution, storage, and use.

3. Inflation Reduction Act (IRA) The federal IRA provides an investment tax credit (ITC) for the development of advanced industrial facilities such as hydrogen production facilities, and resulted in the IRS § 45V tax credit, which provides a production tax credit (PTC) of up to $3/kg for the production of low-carbon hydrogen. These federal policies will benefit Texas hydrogen production projects.

4. H2LA- Houston to Los Angeles I-10 Hydrogen Corridor Project This project will develop a flexible and scalable blueprint plan for an investment-ready hydrogen fueling and heavy-duty freight truck network from Houston to LA (H2LA) along I-10, including the Texas Triangle region. The methodology developed for H2LA will inform future hydrogen corridor plans across the country.

5. Texas Hydrogen Infrastructure, Vehicle and Equipment Grant Program (THIVE) This program will fund acquisition of hydrogen powered heavy-duty vehicles and accompanying hydrogen fueling infrastructure. It was established under Texas Health and Safety Code (THSC), Chapter 386, by House Bill 4885 and will be administered by the TCEQ.

6. Port of Houston The Port of Houston Clean Air Strategy includes pursuit of state and federal funding to reduce truck emissions, including grants from US EPA, US DOT, TCEQ, Harris County, and the Houston-Galveston Area Council.

7. IH 45 Corridor Zero Emission Vehicle Plan The North Central Texas Council of Governments (NCTCOG), which serves the Dallas-Fort Worth Clean Cities Coalition (DFWCC), has outlined recommendations for build-out of new fueling infrastructure to support ZEV project deployment hydrogen FCEVs, along IH 45. This corridor carries a large amount of freight and is key to advancing air quality efforts in Dallas-Fort Worth and Houston, which have ozone air pollution challenges substantially impacted by heavy-duty diesel trucks. The plan was developed under an award by the Federal Highway Administration.

8. Texas Triangle, FHWA Truck Hydrogen Fueling Station Grant The North Central Texas Council of Governments was awarded a $70 million Federal Highway Administration (FHWA) grant to build five medium-/heavy-duty hydrogen fueling stations to serve the Dallas-Fort Worth, Houston, Austin and San Antonio freight corridors.

9. Railroad Commission Hydrogen Authority H.B. 2847 authorizes the Texas Railroad Commission (Commission) jurisdiction over the production, pipeline transportation, and storage of hydrogen. The Commission is directed to establish a hydrogen production policy council to study the development of Texas Hydrogen industries, monitor the development of a Texas hydrogen hub, coordinate activities of other state agencies in supporting the regional hydrogen hub, develop a state plan for hydrogen production, and make recommendations to the Texas legislature regarding hydrogen industry regulation.

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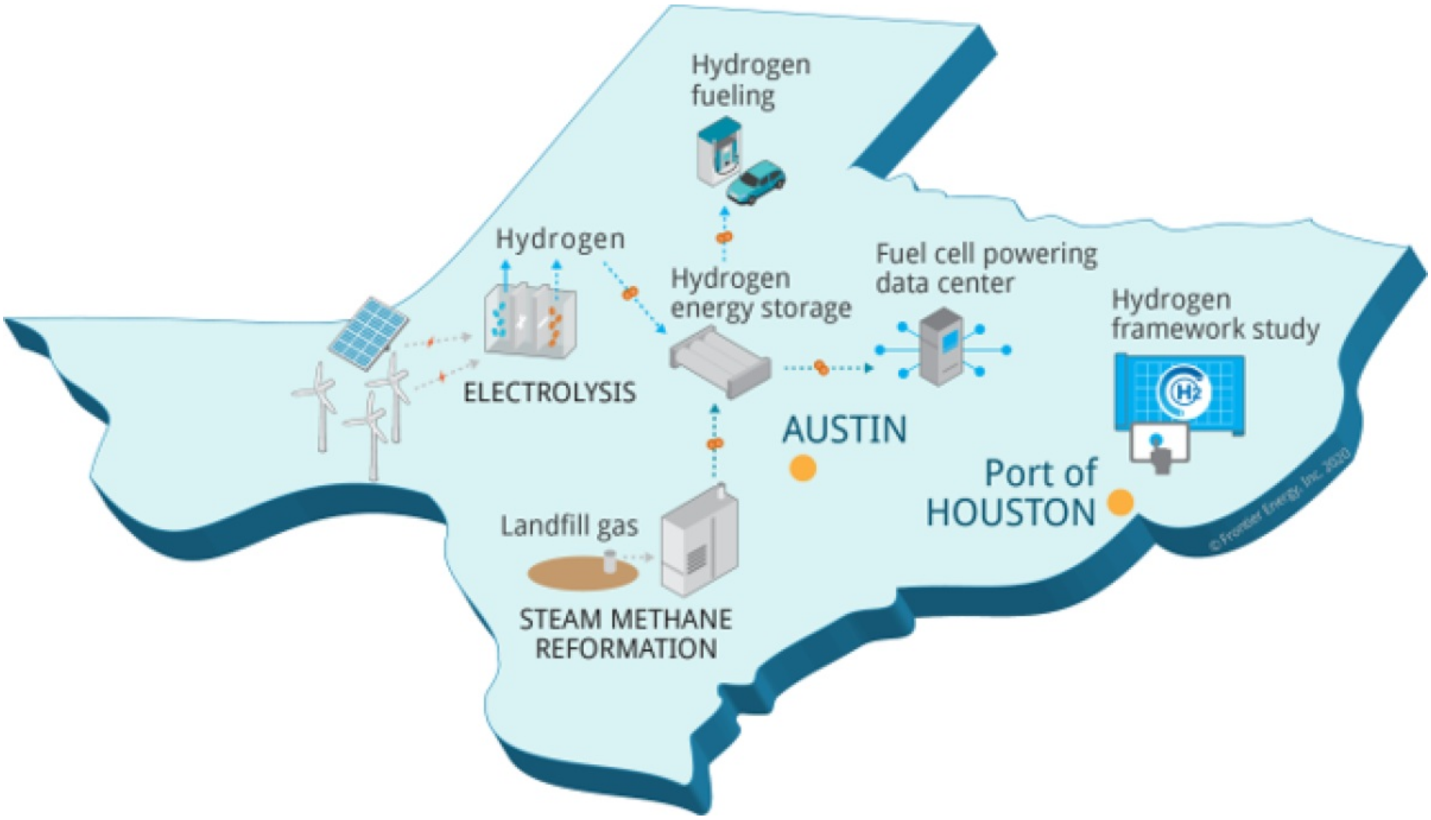
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Texas Air Pollution Considerations

Texas Air Pollution Considerations

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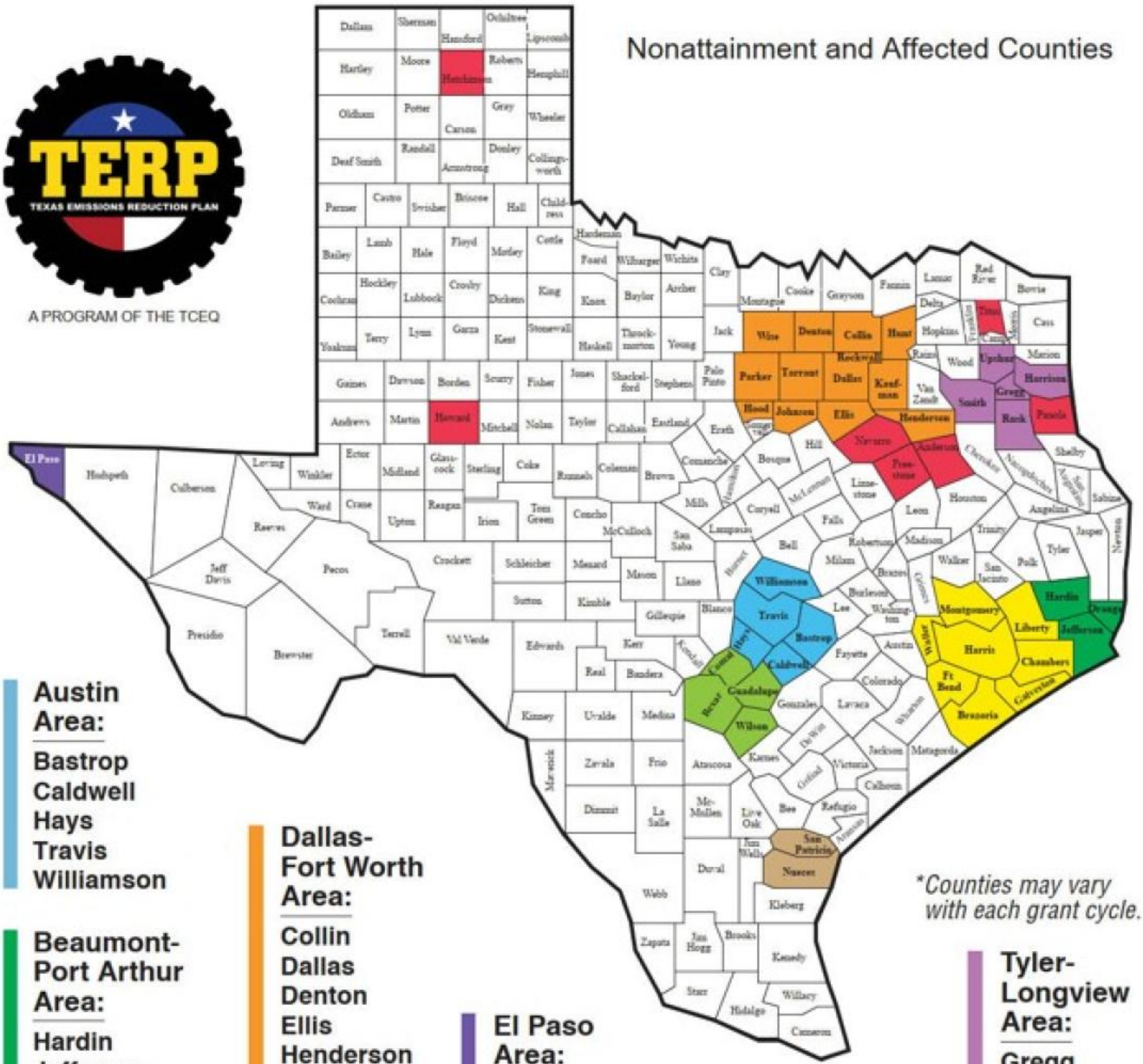
TERP
TEXAS EMISSIONS REDUCTION PLAN
A PROGRAM OF THE TCEQ

Nonattainment and Affected Counties



Counties may vary with each grant cycle.

Austin Area:
Bastrop
Caldwell
Hays
Travis
Williamson

Beaumont-Port Arthur Area:
Hardin
Jefferson
Orange

Corpus Christi Area:
Nueces
San Patricio

Dallas-Fort Worth Area:
Collin
Dallas
Denton
Ellis
Henderson
Hood
Hunt
Johnson
Kaufman
Parker
Rockwall
Tarrant
Wise

El Paso Area:
El Paso

Houston-Galveston-Brazoria Area:
Brazoria
Chambers
Fort Bend
Galveston
Harris
Liberty
Montgomery
Waller

San Antonio Area:
Bexar
Comal
Guadalupe
Wilson

Tyler-Longview Area:
Gregg
Harrison
Rusk
Smith
Upshur

Other:
Anderson
Freestone
Howard
Hutchinson
Navarro
Panola
Titus

TEXAS COMMISSION ON ENVIRONMENTAL QUALITY

January 2023

This map was generated by the TCEQ's Air Grants Division solely for informational purposes and does not represent property boundaries. If you have questions concerning this map, contact the division at 800-919-TERP.

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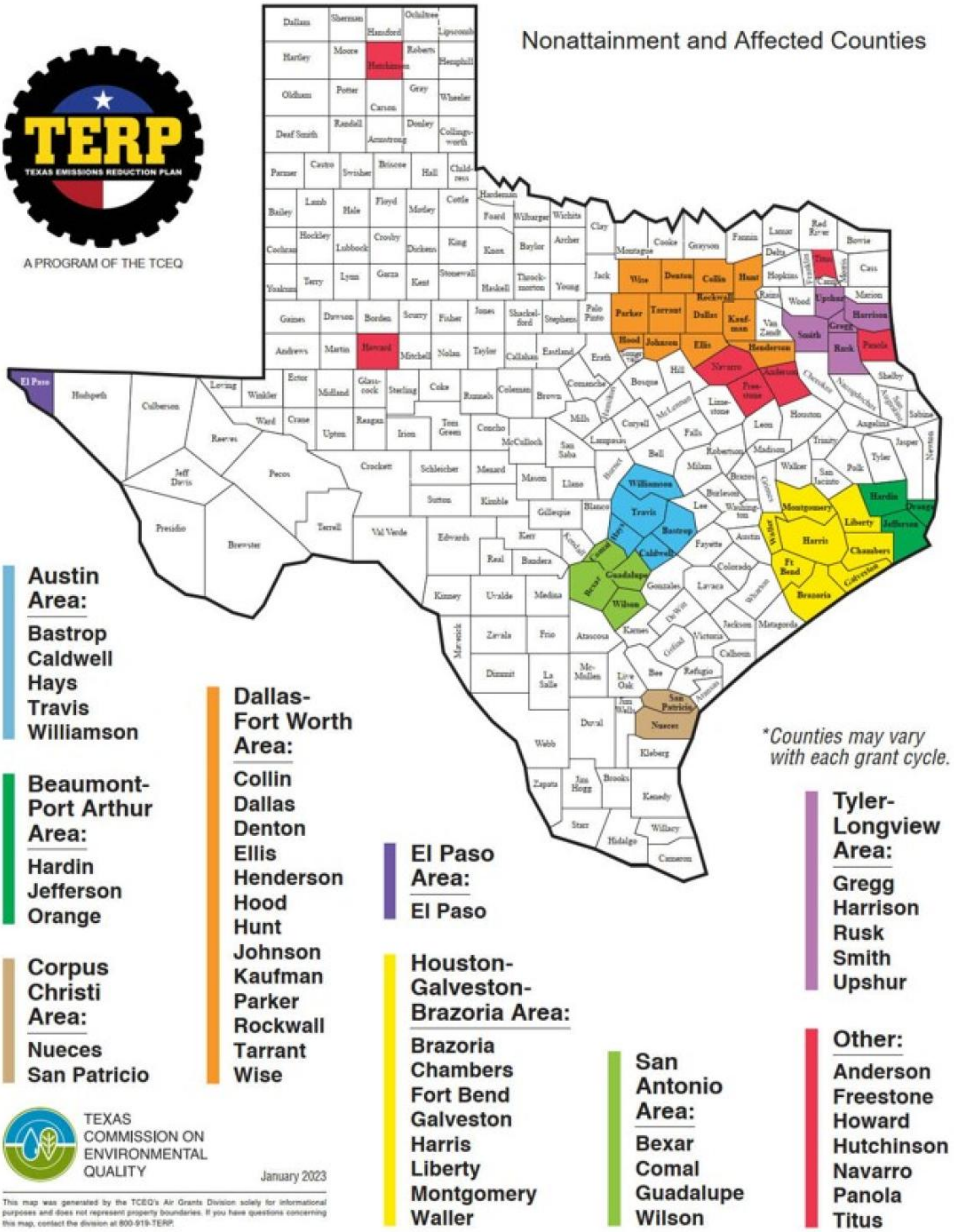

Hydrogen Air Pollution Benefits

US EPA has designated several geographic areas within Texas as having air pollution that is sufficiently concerning that it must be measured and tracked (see map). The types and levels of air pollution vary in severity; however, the metropolitan areas of Dallas-Fort Worth and Houston-Galveston are particularly of concern. The pollutants associated with diesel trucks are particulate matter (PM) and nitrogen oxides (NOx, which contributes to ozone). Counties affected by air pollution are eligible for TCEQ grants to clean up truck fleets.

The exhaust from hydrogen fueled trucks is primarily water vapor. In fact, hydrogen powered fuel-cell electric trucks emit only water vapor from the tailpipe, and hydrogen powered combustion engines primarily emit water vapor and some NOx.

Hydrogen powered trucks are being designed to replace diesel trucks on a 1:1 basis.

Demonstration Projects

[Demonstration Projects]

Hydrogen Truck Demonstrations Will De-Risk Early Market Technology Adoption

Hydrogen as a truck fuel is a new commercial choice and truck manufacturers are in a race to market. The hydrogen truck market initiated in 2019 (compared with the diesel truck which initiated in 1908) and the first commercial trucks are just beginning to be delivered now, in 2024, all in California. It is critical to understand if hydrogen fueled trucks can meet commercial truck fleet performance and operational demands, both practically and economically.

Hydrogen fueling logistics are as important as truck performance and need to be understood. Hydrogen is dispensed into the truck as either a high-pressure gas or a cryogenic liquid; both are significantly more challenging to handle than diesel. Early hydrogen vehicle markets have exposed that fueling infrastructure technologies lag vehicle technology; therefore, smaller scale truck deployments can identify the true cost of doing business in a low-risk manner and subsequently inform challenges, solutions and investment necessary for commercial scale.

Hydrogen truck demonstration projects are active in other markets but have yet to be launched in Texas. Hydrogen powered truck demonstration projects will be supported by power train and truck OEMs, who have active R&D focused on hydrogen fuel cell, hydrogen combustion engine, hybridization (diesel-electric) and novel power generation technologies. As important as demonstrating hydrogen power trains, is demonstrating that the fuel supply chain is also up to task. In this section we will go over the components of these demonstration projects and provide case studies as reference.

Port of Los Angeles

Port of Los Angeles

Image

Image

Shore to Store Hydrogen Fuel Cell-Electric Truck Demonstration Project

In 2019, the fuel-cell electric truck industry was born with the launch of the "Shore-to-Store" project at the Ports of Los Angeles and Hueneme. Shore-to-Store successfully demonstrated the viability of hydrogen fuel cell trucks in real-world, full GVWR, port drayage operation. This first-of-its-kind project had a budget of $84 million ($42 million CARB Grant and $42 million cost share).

The project involved ten prototype, Class 8 zero-emission fuel cell-electric truck tractors (built by Kenworth and equipped with Toyota fuel cells), supported by three hydrogen fueling stations developed by Equilon Enterprises (dba Shell Hydrogen), which book-ended the drayage route. These trucks were put into commercial service by Southern Counties Express, Total Transportation Services, Toyota Logistics Services and UPS.

Partnership was critical for project success. The core participants included the Ports of Los Angeles and Hueneme, Kenworth, Toyota, Shell Hydrogen, Southern Counties Express, Total Transportation Services, Toyota Logistics Services, UPS, the California Air Resources Board, the South Coast Air Quality Management District, and the National Renewable Energy Laboratory. The project manager was provided by the Port of Los Angeles.

The project concluded on April 1, 2023, and is expected to have reduced greenhouse gas emissions by 500 tons annually and save 1.2 million gallons of diesel fuel over the five-year demonstration period.

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Port of Oakland

Port of Oakland

Image

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NorCAL ZERO Project Fuel Cell-Electric Truck Demonstration Project

On May 2, 2024, the "NorCAL ZERO" project officially launched. This $53 million project will demonstrate 30 Class 8, Hyundai XCIENT fuel cell truck tractors, which will be centrally fueled at First Element Fuel's 18,000 kg hydrogen fueling station and will provide Port of Oakland drayage service to the San Francisco Bay area and Central Valley of California. The XCIENT tractors have a GVWR of 82,000 lbs. and stores 69 kg hydrogen fuel on-board, providing a fully-loaded range of 450 miles.

The project is sponsored and managed by the Center for Transportation and the Environment (CTE) and has a multitude of additional partners which include the Port of Oakland, fleet operator, Glovis America, hydrogen fuel provider, Air Liquide, hydrogen fueling site host, East Bay Municipal Utility District and with data analysis assistance from the UC Berkeley Transportation Sustainability Research Center.

The project is funded in part with $11.98 million from CARB's California Climate Investments Program, $9.89 million from the CEC's Clean Transportation Program, $3.64 million from Alameda CTC's Clean Freight Program, $3.36 million from BAAQMD, and $24 million from project technology partners.

Sample Budget

Sample Budget

Image

Project Line Item	Suggested Budget
Two Mobile Hydrogen Fueling Station, 1000 kg H2 capacity*	$5,200,000
10-Fuel Cell-Electric Truck Tractors	$6,000,000
Fuel Cell Truck Operations (12- months)	$3,000,000
Data Collection & Analysis	Approximately 10% of demonstration project cost
Project Management	Approximately 10% of demonstration project cost
Contingency (e.g., construction cost overrun, hydrogen fuel price volatility, station OpEx overrun)	This can be highly variable depending on project specifics

*Can support up to 10 trucks with fills of 80 kg/truck/day

Sample Texas-based Hydrogen Powered Truck Demonstration Project

Hypothetically, a 12-month project that demonstrates a fleet of ten hydrogen-powered trucks might include the following elements and costs.

- Ten hydrogen fuel cell-electric Class 8 truck tractors
- Two mobile hydrogen fueling stations

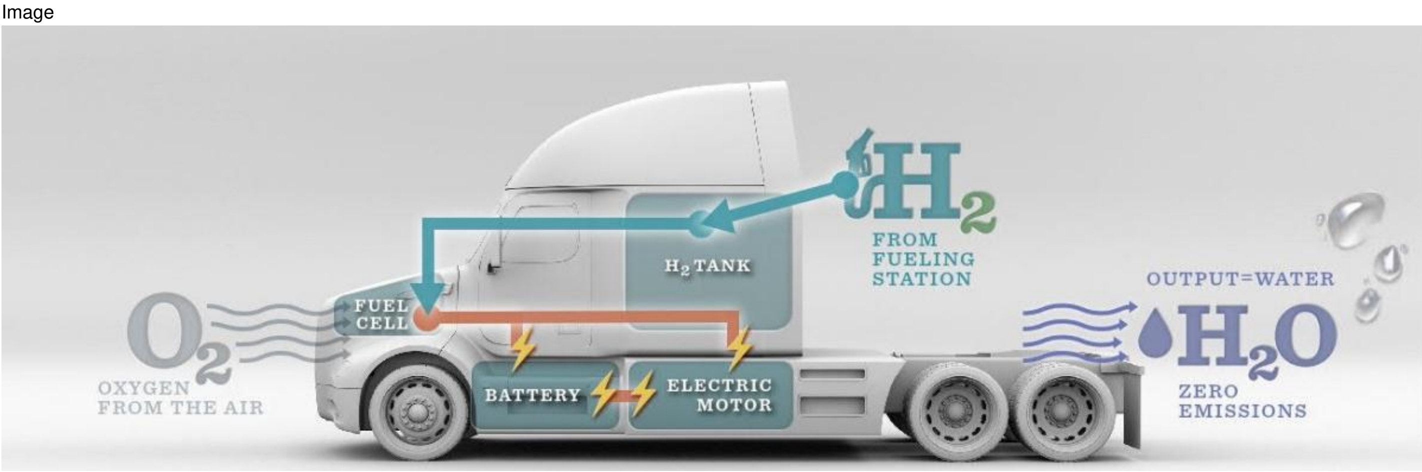
Additional costs include the truck fleet operational budget which are incurred by the fleet. In the demonstration project, these would include hydrogen fuel, vehicle maintenance, vehicle operations, infrastructure maintenance, insurance, etc.

Typically, these projects are partially funded using grants and there are little to no upfront cost to the fleet.-

Hydrogen Fuel Cell Trucks

Hydrogen Fuel Cell Trucks

Image



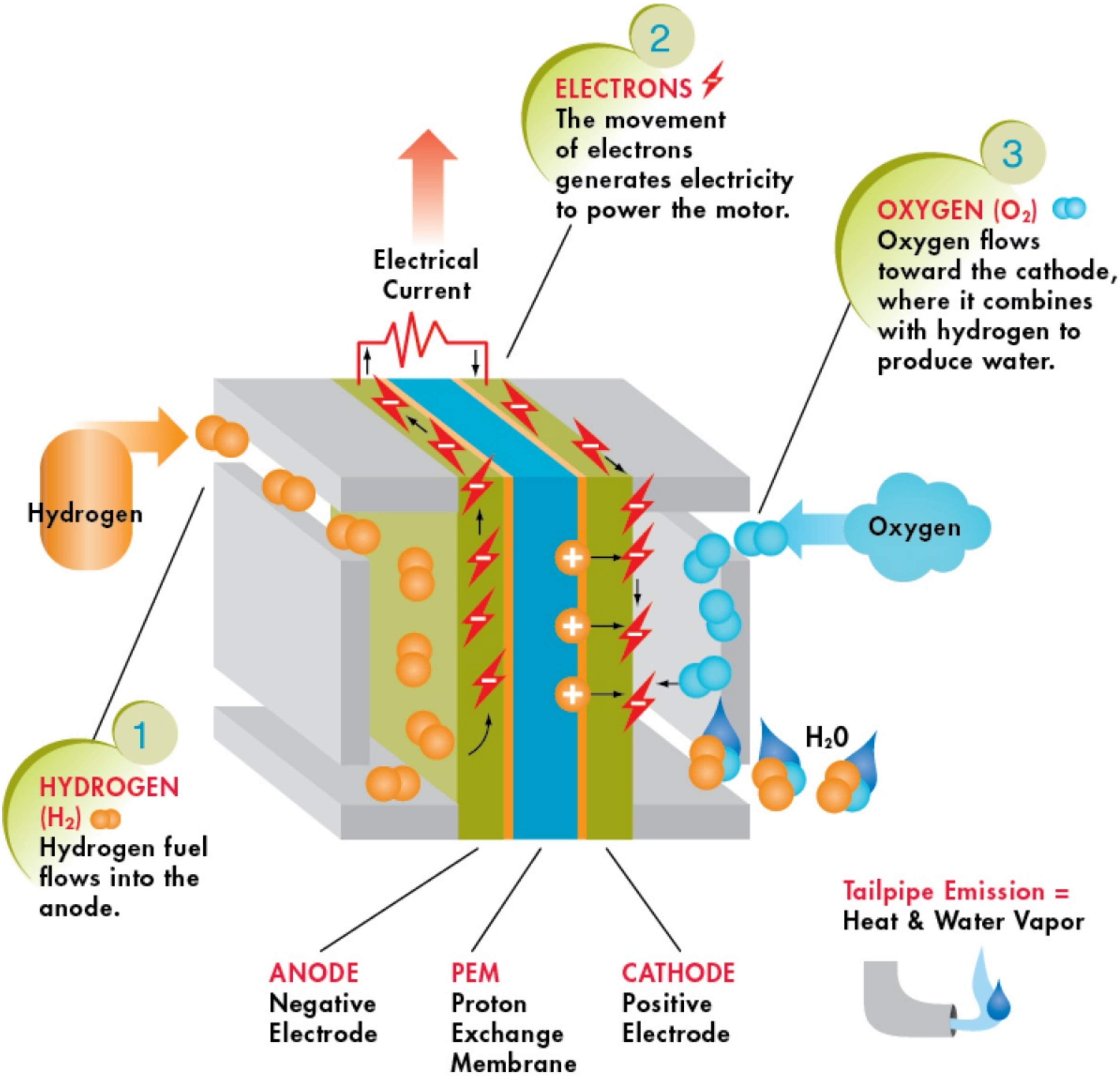
A hydrogen fuel cell truck, also known as a hydrogen fuel cell electric vehicle (FCEV), uses hydrogen gas as the fuel to generate electricity in the fuel cell, which in-turn powers an electric drive motor that propels the vehicle. This offers a clean and efficient alternative to gas and diesel-powered trucks while retaining a diesel-like fueling experience, meaning a full fill in 15 to 20 minutes.

In commercial transportation applications, Class 8 included, electric drive motors offer significant power and torque benefits for handling heavy loads and navigating varying terrain. Electric drive motors, designed with high torque capability, provide necessary pulling power, delivering instantaneous torque from the start. This is advantageous in hauling heavy loads. In addition, electric drive systems can recover energy through regenerative braking, where the vehicle's kinetic energy can be captured as electrical energy during deceleration and braking. This energy is captured and stored in a battery, increasing overall efficiency, and extending the vehicle's range.

How Fuel Cells Work

How Fuel Cells Work

Image



The fuel cell is a electric power generation device. The type of fuel cell used in trucks are a proton exchange membrane (PEM) design, which passively generate electricity through the chemical reaction of hydrogen and oxygen with the assistance of a platinum catalyst. Like batteries, fuel cells contain an anode and a cathode, but the difference is these are separated by the PEM.

The platinum catalyst disassociates the hydrogen atom into its component electron and proton, at the anode. The proton can pass through the PEM, however the electron cannot and therefore runs through the vehicle's electrical circuit. This is the source of electricity that powers the vehicle.

At the cathode, the platinum catalyst disassociates the oxygen molecule, making it receptive to combining with the hydrogen protons as they pass through the PEM and electrons at the end of the circuit, forming H2O (water). The majority of energy in this reaction is captured as electrical energy and the amount of heat generated is significantly less than in the case of hydrogen combustion.

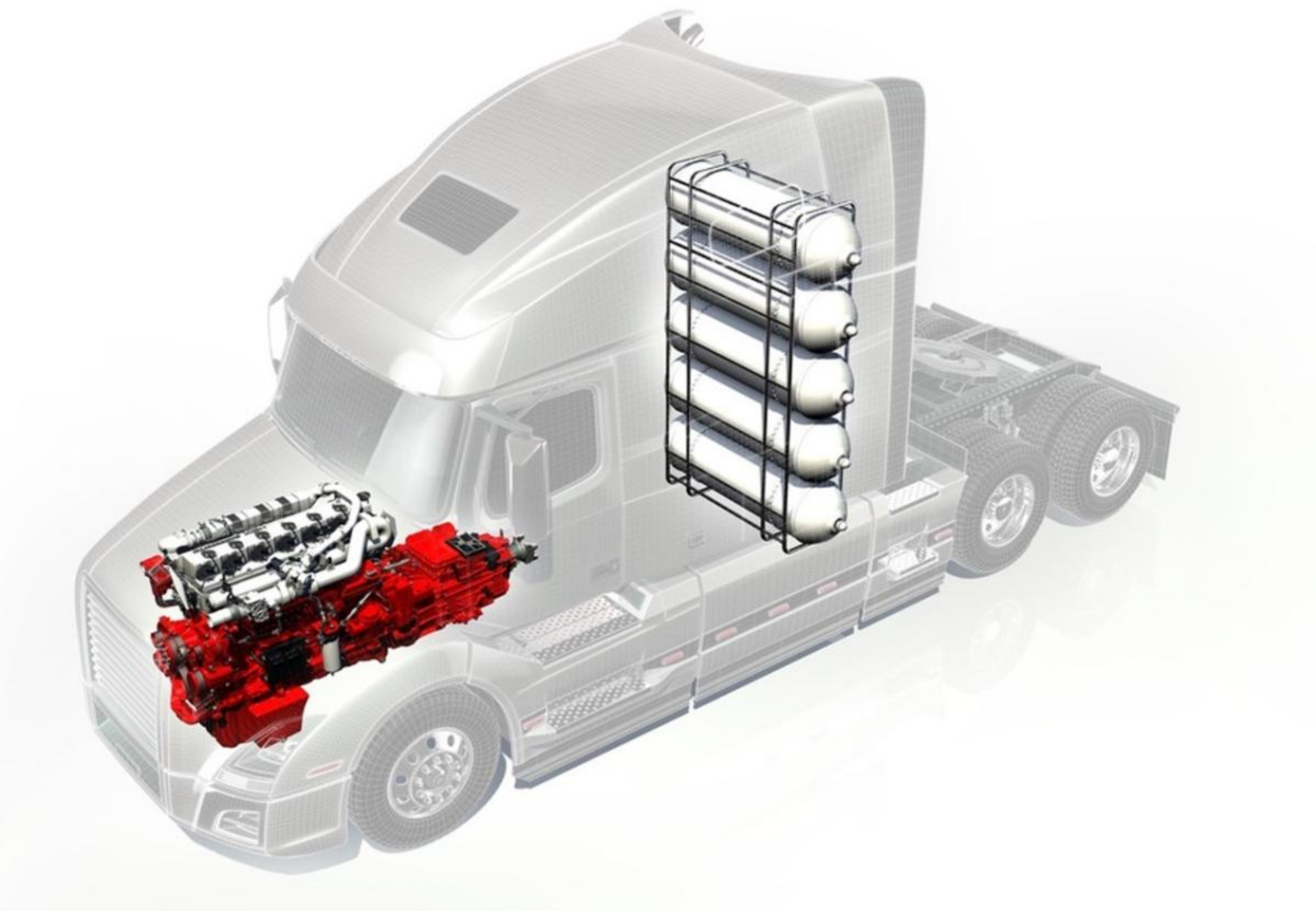
Hydrogen Fueled Internal Combustion Truck

Hydrogen Fueled Internal Combustion Truck

Hydrogen internal combustion engine (ICE) technology offers a potential low-cost, clean, alternative fuel. A major benefit is it potentially can be introduced at cost comparable to diesel trucks and use hydrogen at a cost that approaches diesel fuel. To reduce manufacturing costs, hydrogen engines are designed to use shared common diesel engine components below the head gasket (engine block, crank shaft, manifolds, etc.), and fuel specific components above the head gasket (cylinder head, fuel injectors, valve train, etc.). Hydrogen ICEs offer advantages such as high-power output, low emissions, robustness, low upfront costs and has higher tolerance to impurities in hydrogen fuel. This technology is particularly suitable for larger, higher-horsepower applications. The cost of hydrogen ICEs is forecasted to initially be lower than fuel cell technologies. However, as the technologies progress, this gap will narrow.

Several methods of combustion are in development including spark- and compression-ignition (with diesel pilot ignition) technologies. As these are combustion engines, they have some air pollution impact, however manufacturers are committed to minimizing these.

Image



Hydrogen Combustion

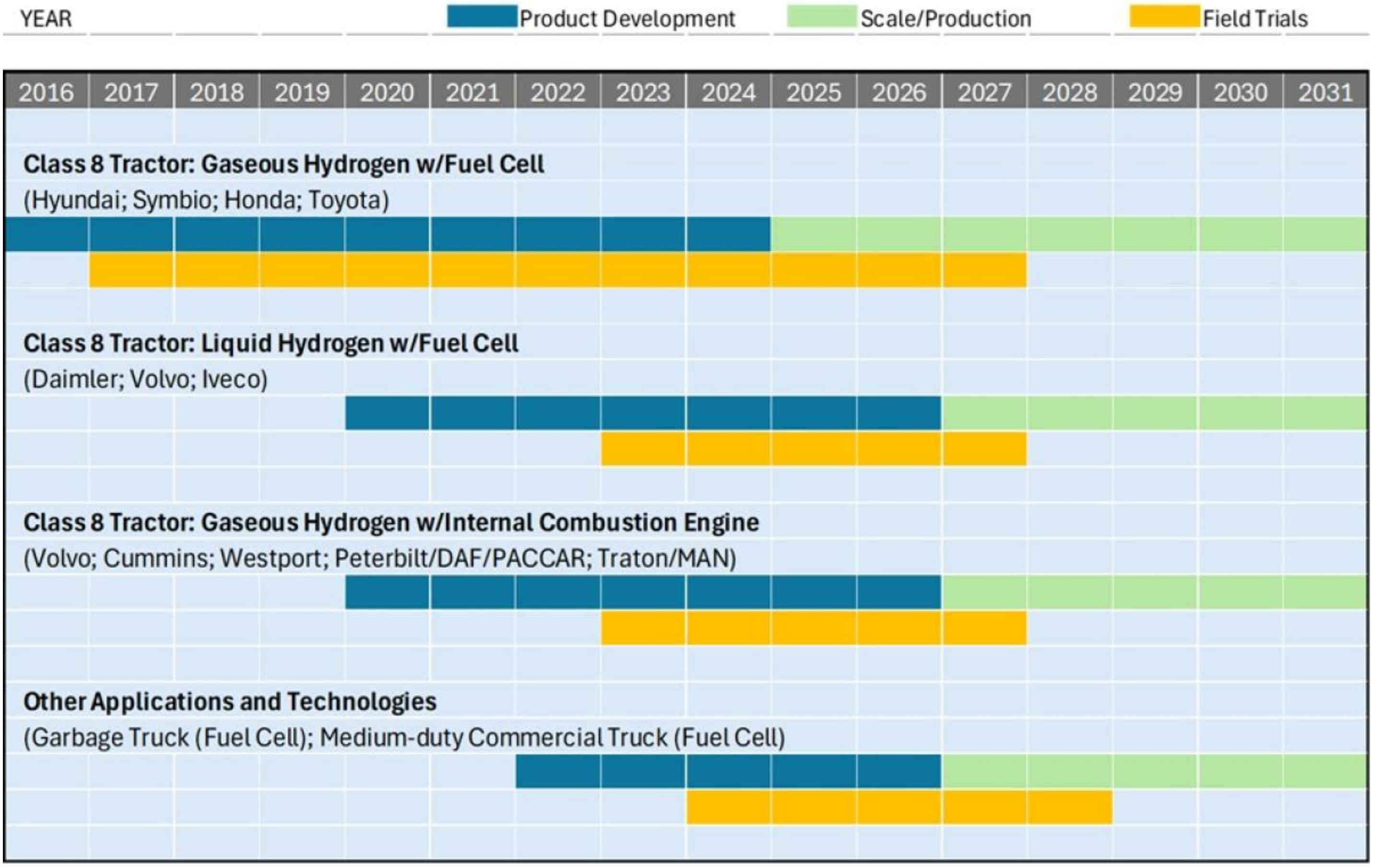
One kilogram of hydrogen has approximately the same energy content as a gallon of diesel fuel. Hydrogen combustion in the presence of oxygen releases a significant amount of heat and water vapor. Since hydrogen does not contain carbon, there are no CO_2 emissions, however the combustion process reacts with nitrogen in the air to form some NO_x, which must be managed.

Hydrogen has an auto-ignition temperature of 1,085°F vs. gasoline's 450°F vs. diesel's 410°F, therefore hydrogen engines can achieve significantly higher compression ratios than gasoline or diesel, which translates to higher power output per engine stroke.

Commercialization Timelines

Commercialization Timelines

Image



Onboard Storage

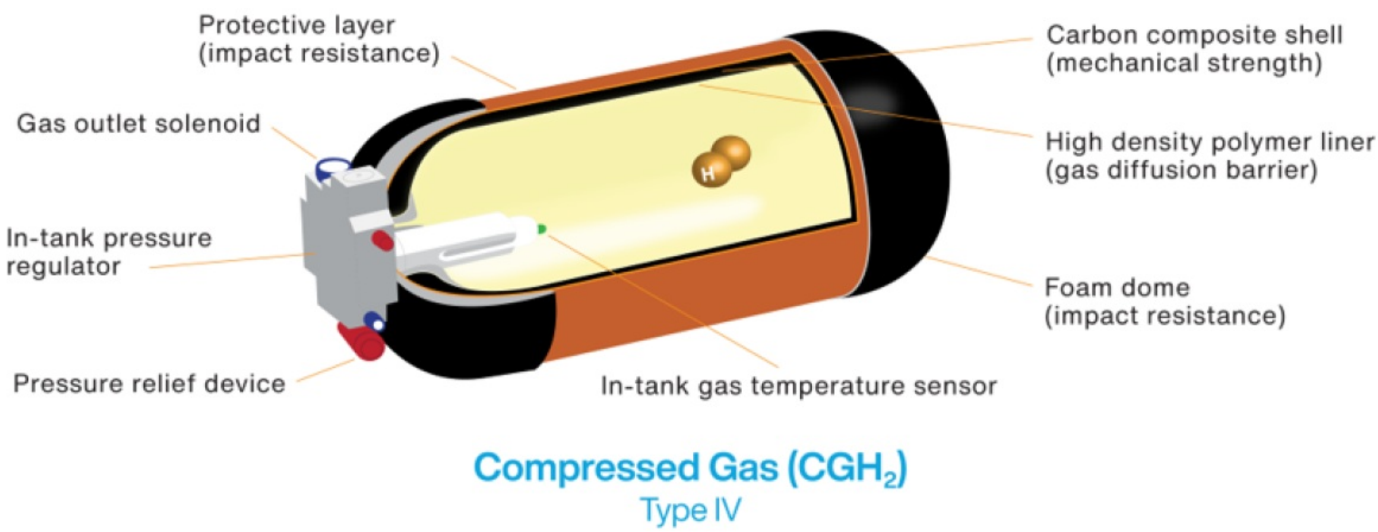
Onboard Storage

Storage Options (Compressed Gas vs. Cryogenic Liquid)

As a trucking fuel, the challenge for hydrogen is how to store enough hydrogen onto the truck to achieve needed operational range and carrying capacity without taking away valuable gross vehicle weight. In its natural state, hydrogen is a lighter-than-air gas that must be either highly compressed into gas cylinders or transferred as a cryogenic liquid into dewar-type liquid tanks. All hydrogen storage systems require more space and weight than conventional diesel fuel storage. Currently all commercially available fuel cell tractors are equipped with gaseous hydrogen storage; however significant investment is going into cryogenic liquid hydrogen dispensing and its onboard truck storage.

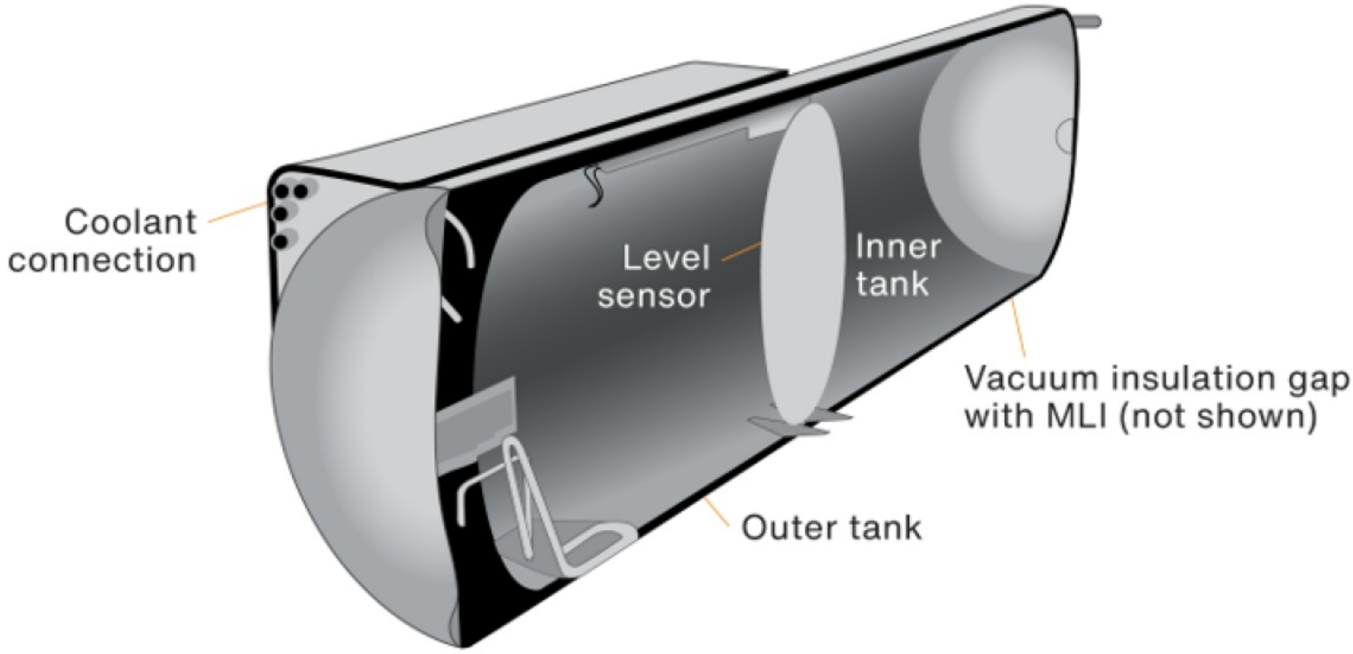
Storage of hydrogen gas requires high-pressure (35 MPa or 70 MPa) composite wrapped tanks to achieve sufficient fuel density. Gaseous hydrogen has the advantage that once pressurized there are fewer mechanical parts on the vehicle. However, gaseous storage also comes with limitations in energy density and storage volume compared to cryogenic storage. Most heavy-duty hydrogen trucks today are designed to accommodate 40-80 kg of gaseous hydrogen storage in an array of four to six gas cylinders; this translates to approximately 300-600 miles.

Image



Hydrogen in liquid form offers the possibility of faster fueling and storage of more mass in a smaller volume as compared withcompressed gas, however with a boiling temperature of -423°F (-253°C), liquid hydrogen requires special handling. In ambient conditions, a phenomenon called boil-off occurs, where liquid hydrogen vaporizes and is potentially lost to the atmosphere. Currently two methods of mitigating liquid hydrogen boil-off are cryo-compression and subcooled liquid hydrogen storage systems.

Image



Subcooled Liquid (sLH_2)
Type I inner/MLI + vacuum/metal outer

Subcooled liquid hydrogen (sLH2) systems are the newest innovation in this space. These systems slightly increase the pressure of liquid hydrogen (by 1.6 MPa), raising the boiling temperature (albeit more modestly than cryo-compression), stabilizing the cryogenic hydrogen. At this lower pressure the storage tank can be vacuum insulated, double-walled stainless steel construction, without a need for additional carbon fiber reinforcement. The developers of this technology indicate that the lower pressure greatly simplifies the hydrogen refueling process, lowering the total system cost. This is the method demonstrated in 2024 by Daimler Truck and Hyzon (see inset).

Hydrogen physical properties and their impacts on its use as a fuel

- Hydrogen is a gas at room temperature and pressure.
- Hydrogen is the lightest and smallest molecule.
- Hydrogen as a transportation fuel must be stored in a way that increases its energy density, meaning packing more hydrogen fuel into a given space to enable long distance travel. This can be done in two ways, as a highly compressed gas or as a cryogenic liquid.
- Hydrogen transitions from gas to liquid at the cryogenic temperature of -423°F (-253°C) which is called cryogenic liquid hydrogen. Liquid hydrogen does “boil off,” therefore it is best used in high utilization applications.
- Vehicles with gaseous hydrogen fuel on-board: hydrogen is pressurized to either 5,000 psi or 10,000 psi (35 MPa or 70 MPa). The higher pressure allows the use of smaller fuel tanks. Currently, this is the dominant storage technology.
- Hydrogen gas is dispensed expanding the very high pressure gas through the fueling nozzle into a lower pressure holding tank on the vehicle. When hydrogen gas expands, it heats up.
- Vehicles with cryogenic liquid hydrogen on-board: Hydrogen in liquid state has much higher energy density than in its gaseous form and therefore can be stored in smaller volume contains and achieve increased vehicle range. Currently this storage technology is in development.
- Due to the gaseous/liquid forms of dispensing, hydrogen is dispensed by weight (kg) rather than volume.
- One kilogram of hydrogen has the energy equivalent of a gallon of diesel fuel.

Daimler Truck Liquid Hydrogen Tractor

Daimler Truck Liquid Hydrogen Tractor

Image

In 2023, two manufacturers independently demonstrated real-world operation of liquid hydrogen powered Class 8 fuel cell tractor-trailers (Daimler Truck and Hyzon Motors). The Daimler demonstration truck had a GVWR of 80,000 lbs. and 80 kg cryogenic liquid hydrogen onboard storage and traveled 600 miles, under real-life conditions without requiring refueling.

Hyzon, in partnership with Chart Industries, demonstrated over 540 miles of cargo delivery to eight Texas locations.

Daimler Truck has announced a preference for liquid hydrogen on-board storage due to the higher energy density, smaller storage volume, and longer vehicle range it affords.

Hydrogen Fueling Infrastructure

Hydrogen Fueling Infrastructure

Hydrogen's property as a low-density gas makes it particularly tricky as a diesel replacement. For hydrogen to be useful as a truck fuel, it must either be compressed or liquified (see the section on hydrogen's chemical and physical properties), making refueling complex. Hydrogen fueling station major components include high-pressure compressors, hydrogen storge pressure vessels, hydrogen gas chillers and high-pressure gas dispensers. In all cases, this technology is actively developing and the method(s) for hydrogen storage and dispensing to trucks continues to evolve. The following are considerations for hydrogen storage, delivery and dispensing from the fueling station to the vehicle, including tradeoffs as the technologies mature.

Hydrogen Storage & Delivery at the Station:

Today, hydrogen is delivered to the station by truck. Commercial stations are trending to above ground cryogenic liquid hydrogen storage because liquid hydrogen can be delivered to the station in larger, tank truck quantities and therefore at lower cost, where cryogenic liquid hydrogen in quantities up to 1,600 kg is delivered in a single load, which could support twenty hydrogen fills of 80 kg.

In the early market (e.g., demonstration phase), where there is lesser hydrogen demand, gaseous storage and delivery offers economical option. Such stations take deliveries of pre-compressed hydrogen (up to 900 kg/day). This higher delivered pressure reduces some components at the station and therefore cost. Manufacturers are also developing pre-fabricated gaseous hydrogen fueling stations that can expedite infrastructure buildout (see the discussion on pre-fabricated hydrogen fueling stations).

In the future, when hydrogen demand is high, pipelines have potential to deliver gaseous hydrogen inexpensively and therefore lower cost. In the United States, there is one pipeline delivered hydrogen station in Torrance, Ca, that serves the light-duty automotive market.

Storage and Dispensing

Storage and Dispensing

Hydrogen's property as a low-density gas makes it particularly tricky as a diesel replacement. For hydrogen to be useful as a truck fuel, it must either be compressed or liquified (see the call-out box on hydrogen's properties), making refueling complex. Hydrogen fueling station major components include high-pressure compressors, hydrogen storge pressure vessels, hydrogen gas chillers and high-pressure gas dispensers. In all cases, this technology is actively developing and the method(s) for hydrogen storage and dispensing to trucks continues to evolve. The following are considerations for hydrogen storage, delivery and dispensing from the fueling station to the vehicle, including tradeoffs as the technologies mature.

Gaseous Dispensing

Gaseous Dispensing

Gaseous stations dispense pressurized gaseous hydrogen into trucks at pressures of either 350 bar (5,000 psi) or 700 bar (10,000 psi), depending on the truck's required onboard storage pressure (see figure). The benefit of the lower, 350 bar, pressure is it is easier to achieve, and the stations can be more resilient. The benefit of the higher, 700 bar, pressure is more hydrogen can be packed onto the truck and facilitating longer range and heavier cargo loads. Truck manufacturers determine the required hydrogen storage pressure.

When hydrogen is dispensed as a high-pressure gas, it is done at one of two pressures, denoted by H35 and H70 which stand for 35MPa and 70 MPa, respectively (please see the table for the pressure equivalent units of each). Note that the H35 and H70 designations only refer to the pressure of fueling and not the grade of fuel. Vehicles that fuel at 70MPa pack hydrogen gas at higher density and therefore have longer range. In terms of interoperability, H70 vehicles can fuel using a H35 dispenser as this is lower pressure, however the reverse case is not true. H35 vehicles cannot use a H70 dispenser.

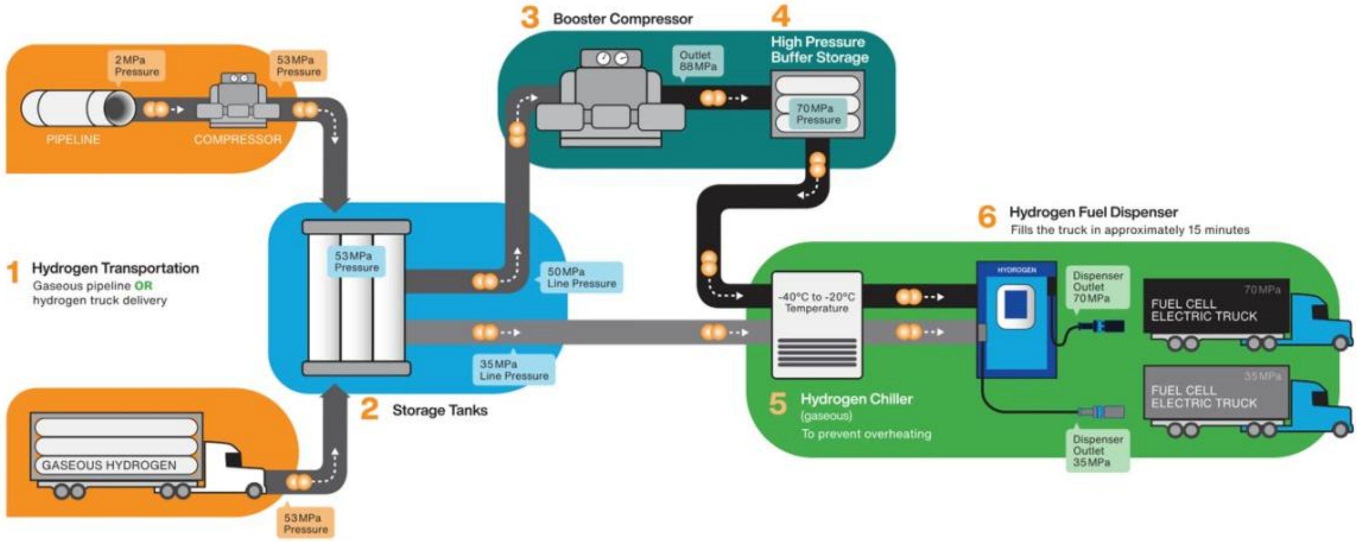
H35 Trucks

These trucks store hydrogen in gas cylinders at 35 MPa. This lower pressure is easier to accommodate, and hydrogen stations, which have storage at 50 MPa push the fuel directly into the vehicles, without the need for a booster compressor (see figure).

H70 Trucks

Trucks that have 70 MPa on-board storage require that the station dispense hydrogen at very high-pressure, which is dispensed out of a high-pressure buffer storage system (see figure). The method of accomplishing this very high-pressure is dependent on whether the hydrogen is stored as a gas or a cryogenic liquid (see figures).

Image



Hydrogen fueling stations that store hydrogen as a gas and dispense hydrogen as a high-pressure gas.

1. Hydrogen gas is delivered to the station in one of two methods, via pipeline (continuous delivery) or tube truck (in amounts on the order of 500 kg/delivery). If delivered by pipeline, the hydrogen must be compressed above the 500 bar pressure of the storage tanks (2). Gaseous hydrogen delivered by truck is at a pressure (520 bar) higher than the storage tanks (2) and therefore is bled into the gaseous hydrogen storage tanks (2).

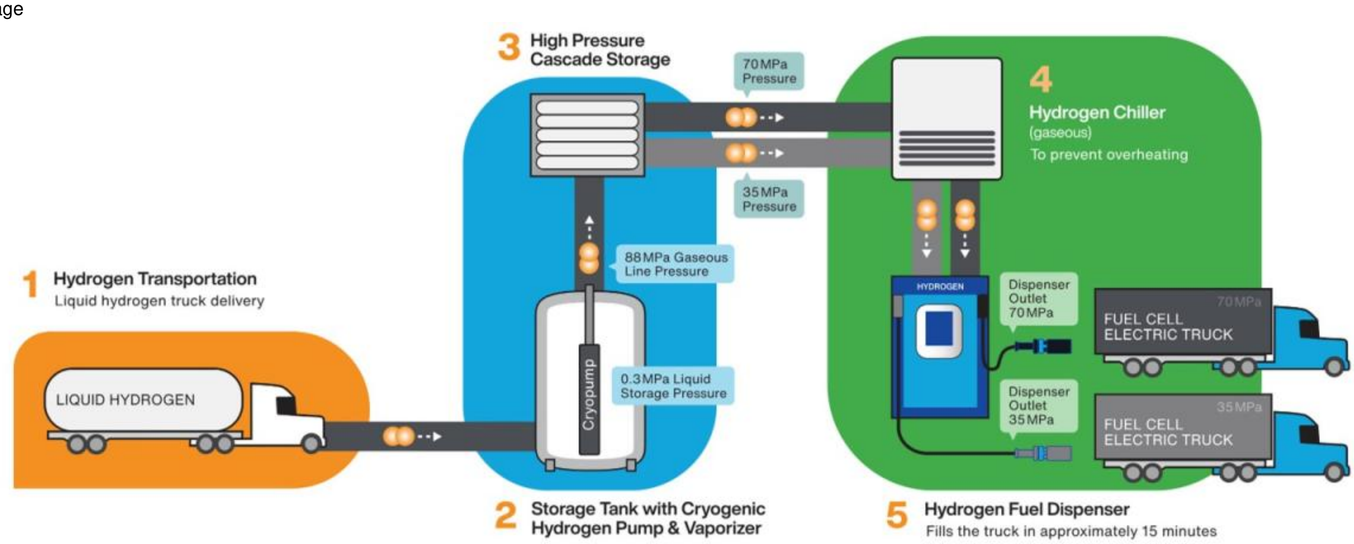
2. Hydrogen gas is held in storage tanks at a pressure of 500 bar, with total storage capacity up to 800 kg.

3. and 4. The booster compressor and high-pressure buffer storage are necessary to fill vehicles that adhere to the SAE J2601, 700 bar storage pressure. If the vehicle's filling pressure is 350 bar, then the booster compressor and high-pressure buffer storage are not necessary, as the station storage pressure exceeds this.

5. The chiller pre-cools hydrogen to -40°C, just before filling the vehicle. Hydrogen gas, unlike all other gases, heats up upon rapid expansion, therefore this pre-cooling step offsets the increase in temperature, as hydrogen expands into the vehicle tanks.

6. Hydrogen is dispensed to the truck at pressures of 350 bar or 700 bar, depending on the manufacturer. The dispensing nozzle is a sophisticated device that contains a communication link to the vehicle diagnostics, which the station uses to monitor the vehicle as hydrogen is dispensed.

Image



Hydrogen fueling stations that store hydrogen as a cryogenic liquid and dispense hydrogen as a high-pressure gas

1. Hydrogen is delivered as a cryogenic liquid (below -253 C) to the station via a liquid hydrogen tanker truck in amounts of 1,000+ kg/ delivery.

2. Cryogenic liquid hydrogen is contained in an insulated storage tank at ambient pressure, with total storage capacity of 1,600+ kg. When hydrogen is needed, a cryogenic liquid pump pressurizes the liquid hydrogen to 875 bar and vaporizes it as a high-pressure gas into buffer storage (3).

3. High-pressure buffer storage is the intermediate step necessary to fill vehicles that adhere to the SAE J2601, 700 bar storage pressure. Vehicles at the lower, 350 bar can also be accommodated by this buffer storage.

4. The chiller pre-cools hydrogen to -40 C, just before filling the vehicle, however the gas may already be cold due to the cryogenic nature of storage (2). Hydrogen gas, unlike all other gases, heats up upon rapid expansion, therefore this pre-cooling step offsets the increase in temperature, as hydrogen expands into the vehicle tanks.

5. Hydrogen is dispensed to the truck at pressures of 350 bar or 700 bar, depending on the manufacturer. The dispensing nozzle is a sophisticated device that contains a communication link to the vehicle diagnostics, which the station uses to monitor the vehicle as hydrogen is dispensed.

Image

Note about gaseous hydrogen dispensing pressures

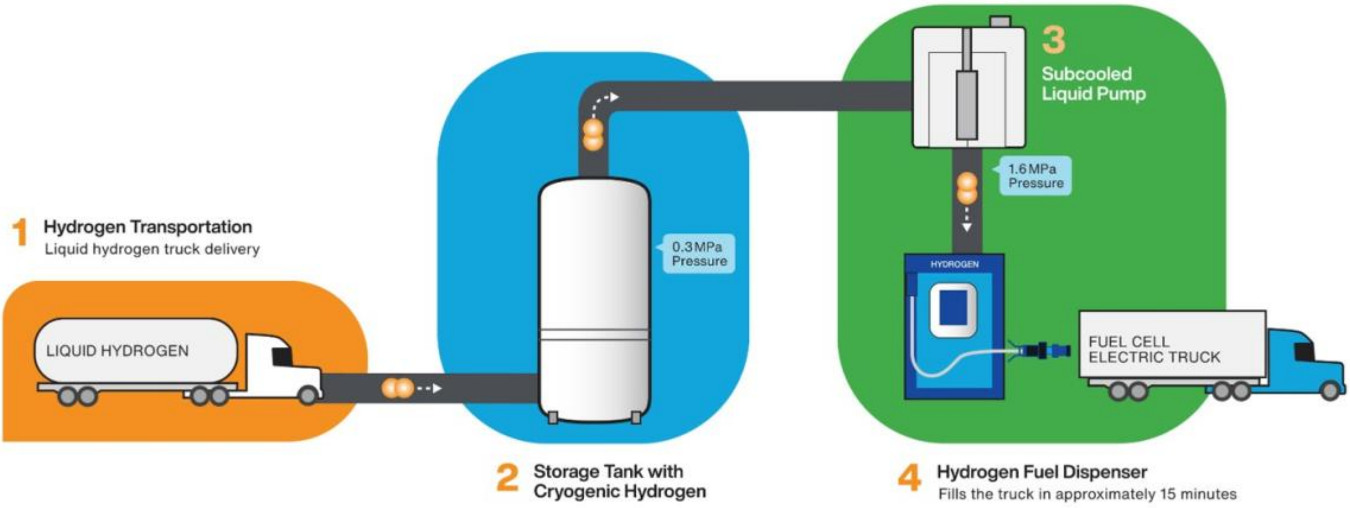
When hydrogen is dispensed as a high-pressure gas, it is done at one of two pressures, denoted by H35 and H70 which stand for 35MPa and 70 MPa, respectively (please see the table for the pressure equivalent units of each). Note that the H35 and H70 designations only refer to the pressure of fueling and not the grade of fuel. Vehicles that fuel at 70MPa pack hydrogen gas at higher density and therefore have longer range. In terms of interoperability, H70 vehicles can fuel using a H35 dispenser as this is lower pressure, however the reverse case is not true. H35 vehicles cannot use a H70 dispenser.

Hydrogen Dispenser Button	**Pressure Equivalents** (in Megapascal, bar and psi)
	• 35 MPa • 350 bar • ~5,000 psi
	• 70 MPa • 700 bar • ~10,000 psi

Liquid Dispensing

Liquid Dispensing

Image



Hydrogen liquid is denser than hydrogen gas. Fueling stations that can dispense hydrogen as a liquid hydrogen promises faster refueling times and reduced fueling station costs. Within this space, subcooled liquid hydrogen (sLH2) is showing promise. This method uses a modest increase in storage pressure (1.6 MPa) to increase the hydrogen boiling temperature, resulting in a more stabilize liquid. Hydrogen storage vessels do not need carbon fiber reinforcement, and compressors and chillers are eliminated. With fewer components, the station design is simplified resulting in reduced cost.

Prefabricated Stations

[Prefabricated Stations]

Image

At this demonstration stage of the heavy-duty hydrogen market, prefabricated hydrogen fuelers offer a potentially cost-effective refueling option due to the high capital investment and development time for a permanent heavy-duty refueling station. Prefabricated hydrogen refuelers are preferred for modest-sized truck fleets (up to 10 trucks) due to their ease and speed of implementation. These devices are complete storage and dispensing devices either containerized or mounted on a truck-trailer chassis and are plug-and-play. Hydrogen can be stored either as a liquid or a pressurized gas. Liquid is currently preferred due to the larger storage capacity of 1000 – 2500kg.

While permitting of these units can be faster than a permanent station as site requirements are minimal (consisting of a concrete pad for placement and an electrical connection to the grid for power) and the 2023 update to national fire code contains specifications for these types of installations, Texas fire code is based on a 2015 version and therefore those benefits do not translate.

These fueling devices operate similarly to their permanent counterparts with some modifications to simplify their design (refer to the “hydrogen station design” section). The liquid storage/ gaseous dispensing systems are virtually identical their permanent-station counter-part, where a cryopump, installed inside the liquid hydrogen storage container, pressurizes the liquid hydrogen to the needed pressure and when vaporized, the gaseous hydrogen is at the correct dispensing pressure.

The gaseous storage/ gaseous dispensing unit are designed specific to the truck fleet that they will be serving. If the requirement is 70MPa fueling, then the unit requires hydrogen storage compatible with 90MPa storage, which does away with the need for a separate compressor. It does require a chiller, so the hydrogen is dispensed at the appropriate temperature.

A Tale of Two Stations

A Tale of Two Stations

Shell Hydrogen Heavy-Duty Truck Fueling Station

Three permanent Shell Hydrogen truck stations were commissioned in 2021 to support the Port of Los Angeles, Shore to Store, FCET demonstrations. They are the first of their kind, globally. These stations have 1600 kg gaseous hydrogen stored at 50 MPa. The station is equipped to dispense hydrogen fuel at two pressures, 35MPa and 70MPa. These stations utilizes light-duty hydrogen dispensers as it predates the establishment of HD fueling protocols. To facilitate the 40 – 80 kg truck fills, the station is designed to fuel trucks with dual hydrogen gas receptacles. The station fills a single truck using two nozzles. The flow rate is on average, 2kg/min with a maximum rate of 3.6 kg/min.

First Element Fuel HD Truck and LD Automotive H2 Fueling Station

This permanent, First Element Fuel, hydrogen truck fueling station was commissioned in 2024. The station has 18,000 kg of liquid hydrogen storage. It is equipped with a private truck lane that has two fueling positions that fill at 70 MPa pressure and 35 MPa pressure. The dispensers use high flow nozzles that fill at (xx kg/min). The station has a 10 min/truck fill time and can fill 200 trucks/day .

Also on site is a segregated, publicly available, light-duty fueling island that has five fueling positions, four are 70 MPa and one is 35 MPa.

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Hydrogen Safety Considerations

Hydrogen Safety Considerations

Hydrogen Characteristics

Hydrogen is a carbon-free, non-toxic fuel that is colorless, odorless, and tasteless. Hydrogen is flammable and burns with an invisible/ near invisible flame that radiates less heat than a typical hydrocarbon flame. When hydrogen burns, it produces heat and water vapor.

Hydrogen is 14 times lighter than air and when released, diffuses rapidly, elevating at approximately 65 feet per second. Due to this very low density, hydrogen stored on vehicles as a gas, is at very high pressure, 5,000 psi or 10,000 psi, which can be more than double the storage pressure of natural gas. Hydrogen can be stored as a liquid; however, it is cryogenic, -423°F (- 253°C).

Hydrogen Safety

Codes and standards for vehicles and hydrogen dispensing into automobiles are mature and are currently being adapted for heavy-duty truck applications because heavy-duty specific codes and standards are actively in development. The application of appropriate codes and standards make hydrogen fuel as safe as gasoline or other commonly used fuels, such as compressed natural gas (CNG).

Retail and fleet hydrogen stations are designed to be operated safely by new hydrogen users with minimal training. However, a general understanding of the physical properties of hydrogen can be beneficial. To date, widespread commercial and government fleet CNG stations have provided valuable experience as equipment for hydrogen fueling becomes more readily available. CNG stations have a safe operating record and, similarly, hydrogen stations have not exhibited safety concerns when applying appropriate codes and standards during the development process.

The National Fire Protection Association has adopted NFPA2, Hydrogen Technologies Code, which provides fundamental safeguards for the generation, installation, storage, piping, use, and handling of hydrogen in compressed gas (GH2) form or cryogenic liquid (LH2) form.

Resources

National Fire Protection Association, NFPA2, Hydrogen Technologies Code

NFPA 2: Hydrogen Technologies Code

AIChE Center for Hydrogen Safety, H2Tools

Home | Hydrogen Tools (h2tools.org)

GoBiz, Hydrogen Station Permitting Handbook (California specific)

Hydrogen Station Permitting Guidebook (ca.gov)

Hydrogen Fuel Cell Partnership, Hydrogen Refueling Station Buyers Guide

Hydrogen_Station_Buyers_Guide.pdf (h2fcp.org)

The Science of Hydrogen

The Science of Hydrogen

Hydrogen Basics. Chemical and Physical Properties

Hydrogen is valued because of its versatility. It can be used directly as a truck fuel, or it can be used as a building block to make other fuels and products. Understanding the chemical and physical properties of hydrogen provides insights into how it is utilized as a truck fuel and the systems required to store, distribute, and dispense it.

Hydrogen's unique chemical and physical properties make it a double-edged sword—offering both vast potential and distinct challenges. Hydrogen (H_2) is diatomic in nature (two hydrogen atoms bonded to one another). It is the smallest and lightest molecule yet is high in energy. It is the most common element, yet it is typically bound to other elements for form compounds including water (H_2O) and hydrocarbon fuels (methane (CH_4) is the simplest hydrocarbon).

Hydrogen Gas

Hydrogen Gas Temperature, Pressure and Density factors related to hydrogen truck fueling. Pure hydrogen exists as a gas under standard conditions (68°F (20°C) and 1 atmosphere at sea level). Under these conditions, hydrogen is extremely diffuse (low density) and buoyant (lighter than air). Hydrogen boasts an impressive specific energy of 120 megajoules per kilogram (MJ/kg), nearly three times that of diesel (45.5 MJ/kg). However, hydrogen's density is only 0.09 g/L, which translates to a low volumetric energy density of 0.01 MJ/L (diesel is about 38 MJ/L). Therefore, in trucks where space is at a premium, hydrogen gas must be highly compressed and stored in tanks at pressures of 5,000 psi or 10,000 psi (35 MPa or 70 MPa). At 70 MPa, up to 120 kg of hydrogen can be loaded into storage tanks, greatly improving truck range. However, even at these high pressures, gaseous hydrogen still occupies more volume than liquid fuels like diesel.

A further complication arises during hydrogen refueling with its rapid expansion from the dispenser into onboard storage tanks. Hydrogen gas is dispensed from a very high-pressure dispenser, which connects to the truck's fueling valve. Upon opening, the hydrogen expands into a lower-pressure fuel tank. During this process, called adiabatic expansion, hydrogen gas heats up as it expands—unlike most other gases. This heating effect must be countered by pre-chilling the hydrogen to around -40°F (-40°C) before dispensing. This is necessary to prevent excessive heating and to maintain proper fueling speed and equipment safety.

How much space does hydrogen gas occupy? It depends on the storage pressure. See how much hydrogen fits into a one-liter vessel at three different pressures.

Hydrogen Pressure	Volume	Hydrogen Mass	Hydrogen Energy
0.1 MPa (sea level)	1 liter	0.00008 kg	0.01 MJ/L
35 MPa	1 liter	0.023 kg	2.8 MJ/L
70 MPa	1 liter	0.042 kg	5.0 MJ/L

Hydrogen Gas Buoyancy. Buoyancy is the force that makes things float. A simple way to think about this is that less dense materials tend to be more buoyant and float on materials that are denser (think of wood floating on water). Buoyancy also applies to gases, where less dense gases float on top of denser gases. Hydrogen, as the smallest and lightest element, is also the least dense and, therefore, the most buoyant. When hydrogen molecules are introduced into a mixture of other gases, like air (which is primarily nitrogen, oxygen, and carbon dioxide), hydrogen molecules rise very quickly. In fact, hydrogen is 14 times lighter than air and rises at an extremely fast rate of 44 mph (20 m/s). This can be beneficial in outdoor environments, where any leakage dissipates very quickly.

In confined spaces, hydrogen's buoyancy and rapid diffusion can become a safety concern. Unlike in open air, where hydrogen quickly rises and disperses, in enclosed areas, hydrogen may accumulate near the ceiling or in pockets, creating a potential explosion hazard if it reaches a flammable concentration and comes into contact with an ignition source. Due to hydrogen's wide flammability range (4% to 75% in air) and low ignition energy, proper ventilation and hydrogen detection systems are essential to prevent dangerous buildups in confined environments.

Hydrogen Gas Diffusivity. Diffusivity is the rate at which molecules intermingle and spread through another medium, whether it be a gas, liquid, or solid, moving from areas of higher concentration to lower concentration. The small size, mass, and density of hydrogen molecules allow them to rapidly diffuse through other materials (visualize water seeping through sand). Hydrogen molecules are so small that they can even permeate through some metals over time, such as steel. This can lead to hydrogen embrittlement, where hydrogen atoms diffuse into the metal, accumulating at imperfections and causing it to become brittle and prone to cracking under stress. To mitigate this, specialty materials and coatings are required to eliminate pores and imperfections in containers, tubing, valves, and seals, preventing leakage and ensuring structural integrity.

Preventing hydrogen leakage is a critical design challenge due to its small molecular size and high diffusivity. Even the tiniest imperfections in seals or joints can allow hydrogen to escape. Storage systems must be equipped with high-performance seals and non-permeable barriers designed to handle hydrogen at high pressures. Continuous monitoring and regular maintenance are also essential to detect leaks, as hydrogen's wide flammability range makes even minor leaks potentially hazardous.

Liquid Hydrogen

Hydrogen gas can be condensed into its liquid state, but under extreme conditions. With a volumetric energy density of approximately 70 MJ/L, liquid hydrogen is significantly more energy-dense than as a gas (about 0.01 MJ/L at 0.1 MPa). This makes liquid hydrogen particularly advantageous in applications like long-distance trucking, where the storage tanks can be sized similarly to those of diesel fuel (diesel fuel has energy density around 38 MJ/L).

However, liquid hydrogen is cryogenic, with a boiling point of -423°F (-253°C) at 0.1 MPa (1 atmosphere). Insulated, dewar-type tanks are required for its storage. At these low temperatures, even a small amount of heat can cause liquid hydrogen to "boil off," transitioning back into its gas form, which leads to energy losses. Boil-off is unavoidable, making it challenging to maintain hydrogen in its liquid phase for extended periods, especially if the fuel is not being consumed quickly.

Therefore, liquid hydrogen is most effective in high-utilization applications, where fuel is consumed rapidly after being transferred. High utilization is crucial because it minimizes the time that liquid hydrogen remains in storage, reducing the likelihood of boil-off and maximizing the efficiency of the storage system.

Hydrogen-Oxygen Energy Reactions

Hydrogen and oxygen are both highly reactive elements, and when they react, a tremendous amount of energy is released as they combine to form water (H_2O). There are two types of hydrogen/oxygen chemical reactions: combustion or electrochemical.

Hydrogen-Oxygen Electrochemical Reactions. The hydrogen-oxygen electrochemical reaction is a passive reaction initiated by the contact of hydrogen and oxygen gases with a platinum catalyst, where the resulting energy is directly converted into electrical current. This reaction occurs within a Proton Exchange Membrane (PEM) fuel cell. Structurally similar to a battery, a PEM fuel cell has an anode, a cathode, and an ionic channel membrane (the proton exchange membrane) separating the two. A short description of the chemistry involved follows.

Reaction 1 (Catalytic): Oxidation of Hydrogen. At the anode, hydrogen molecules (H_2) are split into protons (H^+) and electrons (e^-) through a catalytic process stimulated by contact with the platinum catalyst. This is known as the oxidation reaction:

$$H_2 \rightarrow 2H^+ + 2e^-$$

The protons (H^+) move through the proton exchange membrane toward the cathode, while the electrons (e^-) travel through an external circuit, generating an electric current, before eventually reaching the cathode.

Reaction 2 (Catalytic): Simultaneous Reduction of Oxygen and Formation of Water: At the cathode, oxygen molecules (O_2) from the air undergo a reduction reaction by gaining electrons (e^-) that traveled through the external electrical circuit. This reduction reaction is catalyzed by a platinum-based catalyst. Simultaneously, the reduced oxygen combines with the electrons (e^-) and the protons (H^+) that pass through the proton exchange membrane, resulting in the formation of water.

$$O_2 + 4e^- + 4H^+ \rightarrow 2H_2O$$

The oxygen reduction and the proton-electron combination occur in tandem, continuously producing of water and generating electricity.

PEM Fuel Cell Efficiency: Efficiency is the difference between the amount of energy put into the system compared to the useful energy coming out of the system. For a PEM fuel cell, this is the chemical energy of the hydrogen fuel input compared to the electrical energy produced. Typically, a PEM fuel cell operates at an electrical efficiency of 40-60% under optimal conditions with some high efficiency designs reaching close to 65%. Some of the hydrogen's energy is lost as heat during the catalytic reactions at both the anode and the cathode. Additionally, resistance in the flow of electrons through the external circuit and the flow of protons through the membrane generates further heat (ohmic resistance). Inefficiency can also arise at the anode and cathode during periods of high demand if hydrogen and oxygen are consumed faster than they can be replenished at the electrode surfaces.

Heat Losses: The heat generated by the PEM fuel cell is relatively low in temperature, typically around 176°F (80°C), which is favorable for certain applications such as in vehicles.

Hydrogen-Oxygen Combustion Reactions. Hydrogen internal combustion engines (ICE) rely on the burning of hydrogen gas, an exothermic reaction between hydrogen and oxygen that produces water vapor and releases energy as heat, which powers the engine. The fundamental reaction for hydrogen combustion can be represented as:

Activation Energy (Ea) $\longrightarrow 2H_2 + O_2 \rightarrow 2H_2O$ + Energy

As with other internal combustion fuels, the combustion reaction requires an activation energy, which can be a spark, to initiate the reaction.

There are a few notable characteristics of hydrogen combustion that differentiate it from either diesel or gasoline combustion.

Flame Temperature: The combustion of hydrogen can produce very high flame temperatures, potentially reaching around 2,500°C (4,532°F). This is due to a combination of factors including hydrogen's high specific energy relative to its mass and its ability to react almost completely with available oxygen.

Combustion Speed: Hydrogen has high diffusivity, leading to fast flame propagation. This can create challenges in engine design, such as pre-ignition and knocking (abnormal combustion). Therefore, engineering is required for the fuel injection system to accommodate these characteristics.

Combustion Products: The primary product of hydrogen-oxygen combustion is water vapor (H_2O). This reaction does not produce carbon dioxide (CO_2) because there is no carbon in the hydrogen fuel. This lack of CO_2 emissions is a major advantage of hydrogen over conventional hydrocarbon fuels (like gasoline and diesel) and a key driver of the shift to hydrogen as a fuel for trucks and other applications.

Combustion Byproducts: A byproduct of hydrogen combustion nitrogen oxides (NOx), formed in a secondary reaction within the engine. This byproduct is common to all combustion reactions and is independent of the fuel being burned. It occurs because Earth's atmosphere is 79% nitrogen (N_2) and 21% oxygen (O_2). Although nitrogen and oxygen are stable under normal conditions, high temperatures (above 1,200°C or 2,200°F) can cause them to react and form NO_x in a process called thermal NO_x formation. This process is governed by three primary reactions

$$N_2 + O \rightarrow NO + N$$

$$N + O_2 \rightarrow NO + O$$

$$N + OH \rightarrow NO + H$$

Similar to gasoline and diesel engines, hydrogen engines rely on air intake, which introduces a large amount of nitrogen. The fuel-oxygen reaction generates significant heat and pressure in the cylinder, raising the temperature. Any excess oxygen will tend to react with the nitrogen, forming NO_x. There are several engineering solutions to limit NO_x formation, including controlling the oxygen level in the combustion chamber and using exhaust gas aftertreatment to remove NO_x. Conventionally fueled engines already use similar NO_x reduction solutions.

Hydrogen Engine Efficiency: Efficiency is the difference between the amount of energy input to a system and the useful energy output. In the case of hydrogen engines, this refers to the chemical energy of the hydrogen fuel compared to the mechanical energy produced. Overall, hydrogen ICE typically achieve 30% - 40% efficiency which is similar to diesel and gasoline engines. Manufacturers are working to improve this efficiency with some reporting results approaching 50% efficiency. Major areas of energy loss include thermal losses, where heat of combustion is lost through exhaust and engine cooling, friction losses from the mechanical friction between moving parts, incomplete combustion where unburned fuel goes into the exhaust and pumping loses, where work to intake air and expel exhaust further reduces efficiency.

Heat Losses: The heat loses of the hydrogen ICE are significant, typically ranging from 900 – 1,700°F (500 - 900°C).

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