NACFE

NORTH AMERICAN COUNCIL FOR FREIGHT EFFICIENCY

GUIDANCE REPORT

Hydrogen Trucks: LONG HAUL'S FUTURE?

ABSTRACT This report focuses on using hydrogen-based powertrains for heavy-duty Class 8 long-haul freight routes pulling van trailers. These powertrains include a range of fuel cell battery electric types and internal combustion engines (ICE) based on the diesel cycle. While there are certainly many other load types that are hauled long distances by Class 8 trucks, such as bulk carriers, fuel tankers, flat beds, etc., NACFE's focus is on van freight. The information in this report may also be of value to those other uses.

"Most countries have committed to decarbonize and experts acknowledge and agree that hydrogen is necessary for decarbonizing the grid, so it is inevitable that low carbon hydrogen will be available."

— Alan Mace, Product Applications Manager, Ballard Power Systems

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Bronze: Allison Transmission, BASF We create chemistry, trucklabs Engineering the Road Ahead, Stoughton, The Aluminum Association, Hendrickson

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ABOUT US

ABOUT NACFE

The North American Council for Freight Efficiency (NACFE) works to drive the development and adoption of efficiency enhancing, environmentally beneficial, and cost-effective technologies, services, and operational practices in the movement of goods across North America. NACFE provides independent, unbiased research, including Confidence Reports on available technologies and Guidance Reports on emerging ones, which highlight the benefits and consequences of each, and deliver decision-making tools for fleets, manufacturers, and others. NACFE partners with RMI on a variety of projects including the Run on Less demonstration series, electric trucks, emissions reductions, and low-carbon supply chains. Visit NACFE.org or follow us on Twitter @NACFE_Freight.

ABOUT RMI

RMI is an independent nonprofit founded in 1982 that transforms global energy systems through market-driven solutions to align with a 1.5°C future and secure a clean, prosperous, zero-carbon future for all. We work in the world's most critical geographies and engage businesses, policymakers, communities, and NGOs to identify and scale energy system interventions that will cut greenhouse gas emissions at least 50 percent by 2030. RMI has offices in Basalt and Boulder, Colorado; New York City; Oakland, California; Washington, D.C.; and Beijing. More information on RMI can be found at www.rmi.org or follow them on Twitter @RockyMtnInst.

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NACFE could use the assistance of fleets, manufacturers and other trucking industry stakeholders in improving freight efficiency. Become a part of this exciting opportunity.

Learn more at www.nacfe.org or contact Mike Roeth at mike.roeth@nacfe.org

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This report focuses on using hydrogen-based powertrains for heavy-duty Class 8 long-haul freight routes pulling van trailers. These powertrains include a range of fuel cell battery electric types and internal combustion engines (ICE) based on the diesel cycle. While there are certainly many other load types that are hauled long distances by Class 8 trucks, such as bulk carriers, fuel tankers, flat beds, etc., NACFE's focus is on van freight. The information in this report may also be of value to those other uses.

In December 2019, the North American Council for Freight Efficiency (NACFE) compared a range of alternative fuel heavy-duty truck technologies including hydrogen in the report *Viable Class 7/8 Electric, Hybrid and Alternative Fuel Tractors*. In December 2020 NACFE issued the in-depth hydrogen report, *Making Sense of Heavy-Duty Hydrogen Fuel Cell Tractors*. These two reports are a solid foundation upon which this new hydrogen report is built.

Hydrogen is entering the marketplace as an energy source for zero-emission long-haul trucking. Two paths are emerging, fuel cell electric and new hydrogen internal combustion engines. Hydrogen is not optimum for all duty cycles. Hydrogen fuel cell tractors are, however, the only viable zero-emission solution currently proposed as a one-for-one replacement for diesel in the future of long-haul heavy-duty trucks.

ACKNOWLEDGMENTS

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What NACFE Got Right And Wrong

NACFE's 2020 *Making Sense of Heavy-Duty Hydrogen Fuel Cell Tractors* report had five major findings.

- Hydrogen fuel cell trucks are just starting to see real-world use and their adoption is being driven by regional or national considerations that are much bigger than what exists for trucking fleets.
- Battery electric trucks should be the baseline for hydrogen fuel cell electric vehicle (HFCEV) comparisons, rather than any internal combustion engine alternative.
- As for all alternatives, fleets should optimize the specifications of HFCEVs for the job they should perform while expecting that the trade cycles will lengthen.
- The future acceleration of HFCEVs is likely not about the vehicles or the fueling but more about the creation and distribution of the hydrogen itself.
- Finally, the potential for autonomous fuel cell trucks to operate 24 hours a day adds significant opportunity for making sense of capital and operational investment in hydrogen.

Those findings continue to be applicable in the rapidly evolving zero-emission commercial vehicle world.

NACFE also attempted to categorize the multiple paths to making hydrogen by generally accepted colors. What NACFE did not foresee was the extensive marketing effort to change the hydrogen color narrative from "how hydrogen is produced" to "how much carbon intensity" each method has.

NACFE forecasted trends in state and federal regulations that could hasten hydrogen adoption. The period 2021 to 2022 has seen significant acceleration of state and federal efforts.

The initial NACFE report correctly outlined that a hydrogen economy cannot be built solely on the shoulders of long-haul trucking, as there simply is not enough there to get the scale needed for cost reduction.

NACFE suggested that standardization will be critical to get volume cost reductions on designs of tanks, fuel systems, fuel cells, batteries, cables and connectors, etc. Individual OEMs will need to consider standardizing on generic system components with their competitors in order to increase demand and reduce unit costs.

There is not one design for a fuel cell powertrain; rather there is a complete spectrum based on choices for sizing both the fuel cell and battery electric system on board a vehicle to meet performance objectives.

NACFE did not forecast in the first report the development and deployment of hydrogen burning diesel-based engines.

What's Changed?

The pace of innovation, investment, regulation and awareness of hydrogen as a heavy-duty truck fuel has increased since the December 2020 NACFE report. In parallel, the topic of zero-emission trucks (ZETs) in general has seen significant focus.

The 2021 to 2022 period has seen the oil industry significantly step-up publicizing and marketing their efforts to lower emissions. Companies like Shell and BP are actively promoting moves to hydrogen as the molecular fuel to replace gasoline, diesel and other fuels in a variety of industries and have publicly announced sustainability goals. The sea change in the oil industry to pursuing zero-emission markets is significant, reinforcing a path toward hydrogen as a fuel in trucks hauling freight. See Figure ES1.

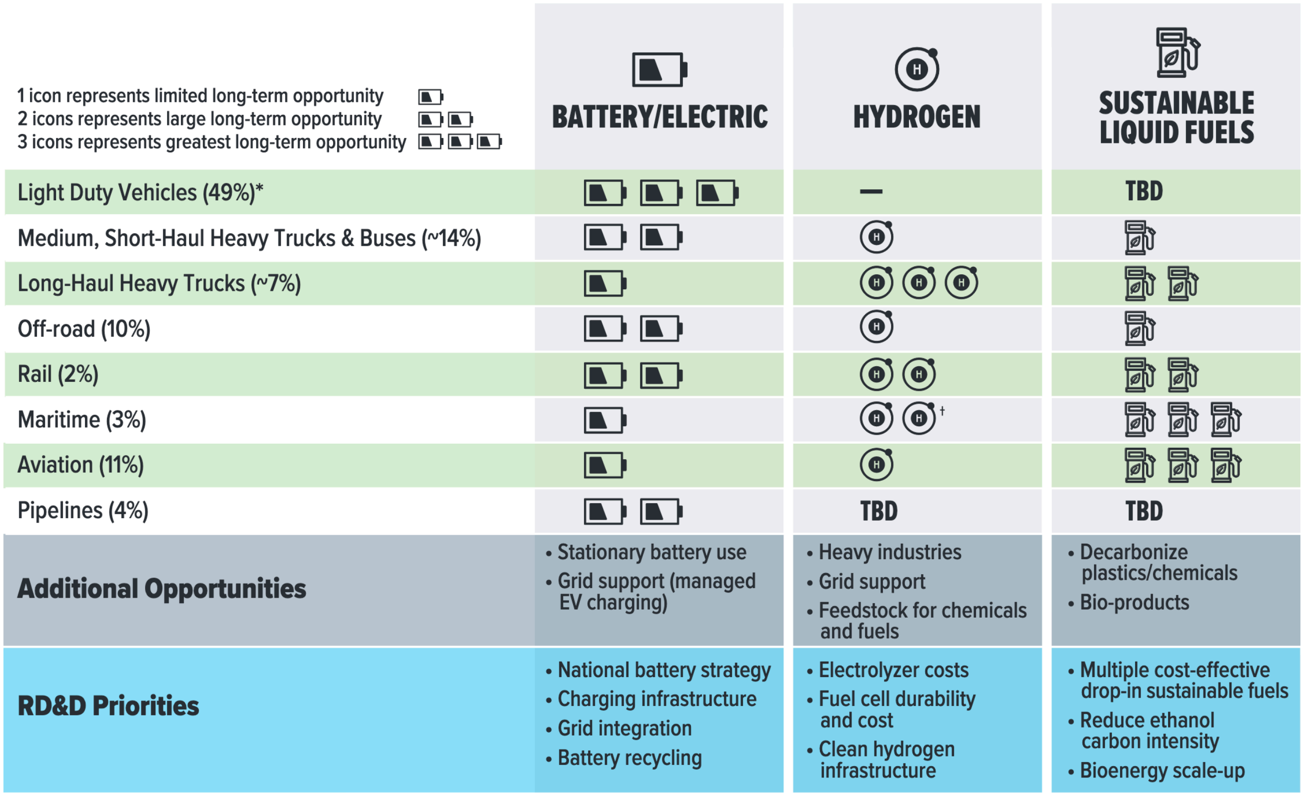
Efforts like COP27, the Infrastructure Investment Jobs Act, the U.S. National Blueprint For Transportation Decarbonization, the Department of Energy's Clean Hydrogen Strategy and Roadmap, the EPA Clean Truck Plan, The Multi-State Zero Emission Medium- and

"Hydrogen technology is coming faster than we expected. We will be testing a truck this year."

— Rob Reich, Executive Vice President, Chief Administrative Officer, Schneider

FIGURE ES1

US DEPARTMENT OF ENERGY BLUEPRINT ENERGY SOLUTIONS FOR DIFFERENT TRAVEL MODES



* All emissions shares are for 2019

† Includes hydrogen for ammonia and methanol

Heavy-Duty Vehicle Memorandum of Understanding, the Advanced Clean Truck Act, The Advanced Clean Fleets Rule, the Heavy-duty Low NOx Omnibus Rule, the Warehouse Indirect Source Rule, and the SEC Reporting Rule are also impacting the development of hydrogen as a fuel for medium- and heavy-duty trucks.

Additionally, awareness of the need for environmental justice has risen dramatically in the period since NACFE's first hydrogen report was issued.

Technology And Infrastructure Changes

There have been developments in technology and infrastructure since the original release of *Making Sense of Heavy-Duty Hydrogen Fuel Cell Tractors*. The most significant is the development of hydrogen internal combustion engines, essentially adaptations of traditional diesel engines replacing diesel or natural gas combustion with hydrogen combustion.

A hydrogen internal combustion engine alternative presents a near-zero emissions vehicle that has the capability of going longer distances with shorter refueling times and weighing less than a battery electric vehicle specified to do the same job. The hydrogen ICE also preserves the conventional powertrain and will likely have a significantly lower initial cost than an equivalent fuel cell equipped vehicle.

However, the overall efficiency of the hydrogen ICE vehicle in terms of miles per kg of H_2 will likely be less than the HFCEV alternative. It should generally have better efficiency on an energy-equivalent basis compared to natural gas-powered engines. Of course, the hydrogen ICE alternative must overcome the challenges of fuel creation, cost, transportation and storage that any other hydrogen alternative has as is outlined in other parts of the full report. In addition, the challenges of servicing and maintaining hydrogen ICE vehicles also will be more involved than traditional diesels. See Figure ES2.

Significant funding is being allocated to hydrogen freight projects since the 2020 NACFE report. In 2022, the DOE announced $8 billion in funding for a hydrogen hub program with $7 billion earmarked to fund six to 10 regional clean hydrogen hubs.

Green hydrogen production infrastructure projects

FIGURE ES2

HYDROGEN TRANSPORTATION METHODS

Liquid Diesel

7,000 gallons

263,480 kWh

Liquid Hydrogen

7,711 kg

260,940 kWh

LH2-sized tank cars have a capacity of 7,711 kg. The pressure within the tank is typically 1.7 bara or lower and the temperature is usually below −252.87 °C. The boil-off rate is around 0.3–0.6% per day.

Gaseous Hydrogen

900 kg

30,456 kWh

Typically, hydrogen is transported in tube trailers in the UK. A typical trailer would be filled to 228 bar and would carry around 300 kg of hydrogen. There are now available on the market, high capacity 300 bar trailers, which could carry 600 kg at 228 bar and 900 kg at 300 bar. There are also 500 bar trailers in development.

1 kg of hydrogen is 0.9 DGE (diesel gallon equivalent)
1 DGE = 37.6 kWh

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are being developed. This includes projects like Hy Stor Energy in Port Bienville, Mississippi, the Houston-centered HyVelocity Hub, the Pacific Northwest Hydrogen Association, the Midwest Alliance for Clean Hydrogen, the Northeast Region Hydrogen hub coalition, the Alliance for Renewable Clean Hydrogen Energy Systems, and the Washington dam project. There also are several projects underway in Canada.

When it comes to hydrogen fuel cell trucks, there has been little deployment away from major ports and it has been limited to relatively short demonstrations, where fueling is provided by mobile equipment.

The port drayage applications have perhaps seen the majority of operational hours. Port demonstrations at the Los Angeles and Long Beach facilities have received significant media coverage with vehicles from several companies. Less known are trials at the Port of Oakland and Port of Houston.

However, Nikola is demonstrating two fuel cell hydrogen trucks in Los Angeles with Anheuser-Busch and Biagi Bros, Toyota partnered with Kenworth on a series of 10 hydrogen grant trucks for the California Zero and Near Zero Emissions Freight Forwarding, Westport Fuel Systems has unveiled a hydrogen ICE demonstrator truck and Cummins announced the development of a 15-liter hydrogen ICE engine.

Paving the way for hydrogen use in freight has been fuel cell forklifts. Terminal tractors is another application

"The H2 ICE engine is a zero-carbon low-risk evolution for diesel truck operators. It is less of a leap than fuel cells."

— Jim Nebergall, General Manager of Hydrogen Engines, Cummins

where hydrogen can be used as a power source. Terminal tractors tend to stay close to their home facilities so range and re-fueling are not an issue. A warehouse equipped for hydrogen forklifts might readily expand to having hydrogen terminal tractors and then evolve into hydrogen ICE and eventually long-haul hydrogen fuel cell tractors.

The State of Hydrogen Today

According to the DOE, today there are more than 50,000 hydrogen fueled forklifts, more than 80 hydrogen buses, and approximately 13,000 hydrogen cars. With the exception of forklifts, the vehicle deployments are in their infancy compared to market sizes. Also of note is that 55% of current production hydrogen usage is in refining oil and 35% is in producing ammonia and methanol. The hydrogen production infrastructure is primarily located, logically, near major coastal oil refining centers.

Converting the transportation industry to diesel alternatives has a steep hill to climb to supplant petroleum's dominance. The market dominance by petroleum companies hints at why hydrogen is attractive to the oil industry as a path forward to continue market prevalence as energy suppliers through products like gray, blue and green hydrogen.

The aggressive zero-emission vehicle goals being implemented at state and federal levels also will potentially reinforce that petroleum-based and natural gas-based hydrogen must be a part of the solution moving forward, due to the extensive economic impact and inertia of these industries, combined with the rapid need for hydrogen at scale. See Figure ES3.

There is a significant volume of information and misinformation on projected costs of hydrogen. Much of it focuses on predicting the cost of production, not the price. These two differ: cost is what the plant expends to actually make the fuel, price is what they charge for

METHODOLOGY

This report was written from interviews with subject matter experts at fleets, OEMs, research groups and industry organizations. Available public information has been referenced to support findings and conclusions.

FIGURE ES3

HYDROGEN PRODUCTION LOCATIONS IN THE US

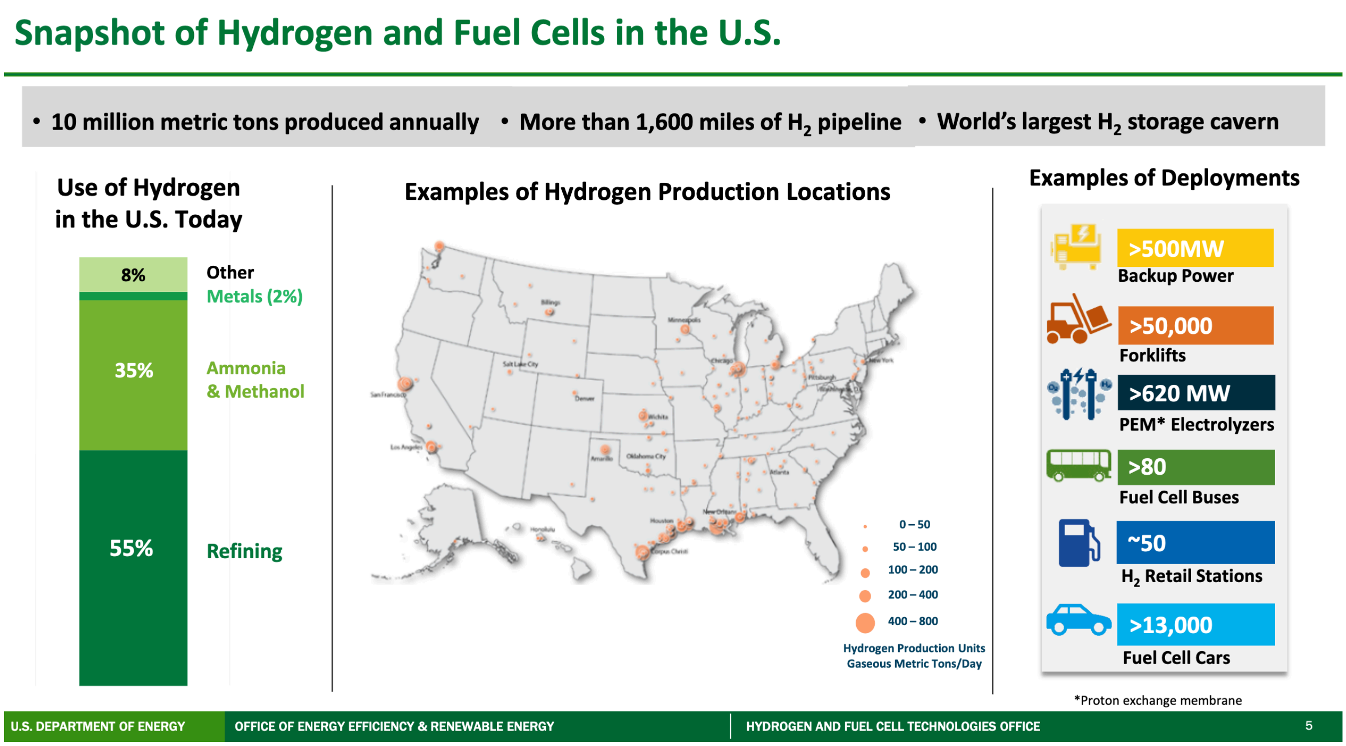
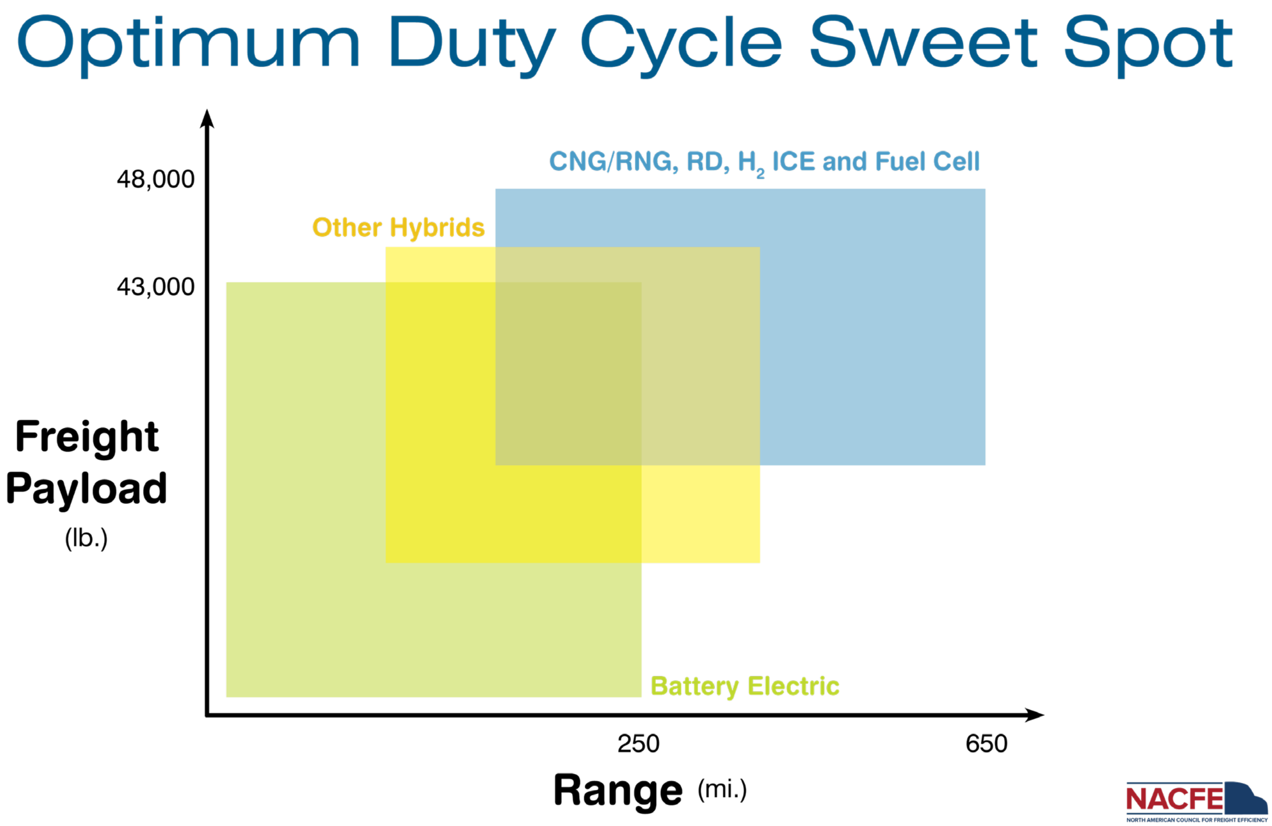


FIGURE ES4

HYDROGEN WILL BE A FACTOR IN FUTURE LONG-DISTANCE FREIGHT HAULING



it. The expected cost to the producer inside the fence of the production facility is not necessarily representative of the retail price of the fuel at the gate of the plant, nor does it factor in transportation, storage, compression or dispensing of the hydrogen at the pump for the vehicle.

The DOE's hydrogen program has targets for driving down the cost of hydrogen. Reducing costs on hydrogen fuel tanks for heavy-duty hydrogen trucks will be challenging in the real world.

Findings

Hydrogen may be the harbinger of a new green industrial revolution, or just the progression from one fossil fuel-based energy carrier to another with greater emphasis on reducing emissions. Either way, hydrogen will be a factor in future long-distance freight hauling in combination with battery electric vehicles for shorter range operations. See Figure ES4. NACFE's first hydrogen report remains relevant and accurate. The changes since that report reinforce the following findings:

1. Hydrogen powered freight is required for a zero-emission freight future.
2. There is a significant amount of funding going toward establishing the basis for a hydrogen economy that includes long-haul freight transportation.
3. The cost of hydrogen production, transportation, storage and dispensing will not be cost competitive with diesel without significant assistance from tax credits and other subsidy mechanisms.
4. Managing the actual retail cost of hydrogen is perhaps more important than continuing discussion of reducing the production cost at the hydrogen plant.
5. Hydrogen is closely tied to electricity. You can't have hydrogen without significant amounts of electricity.
6. Hydrogen is a significant factor in federal, state and local planning and regulations for the zero-emission freight future.
7. Purpose-built hydrogen trucks optimized for specific duty cycles may not be valued well in the secondary market, leading to first owners keeping the vehicle until it is salvaged.
8. Hydrogen costs decrease as the scale of the

hydrogen plants increase. Large production requires multiple industries to increase demand for hydrogen. Trucking alone is insufficient to reach demand scale needed to justify large hydrogen plants.

9. Hydrogen used for creating alternative fuels like renewable diesel will reduce net emissions but at the cost of delaying adoption of zero-emission alternatives.
10. All the answers do not need to be known on day one of hydrogen. Production supply and market demand will evolve in lock step over time. Innovators will find market opportunities where there is an oversupply of hydrogen, creating new market demand.
11. Hydrogen and electricity supply are inherently resilient as there are multiple methods of producing them, leading to competitive forces mitigating price and supply volatility.

Conclusions

Hydrogen is a complex topic. Hydrogen for use in freight transportation is just in its infancy. Trying to summarize the topic in a few closing statements is akin to describing a child's potential impact on the world. NACFE presents four significant conclusions.

- Hydrogen and battery electric are not an "either/or" but an "and" for the zero-emission freight future. Battery electric vehicles will inherently be the most economical and efficient choice for shorter distance zero-emission duty cycles, and hydrogen will be the only viable economic choice for long-haul zero-emission duty cycles. Ultimately fleets in the market will make decisions on which technology succeeds for which duty cycles.
- Hydrogen fuel cell tractors are the only zero-emission solution for many duty cycles for heavy-duty tractors. Significant cost reduction across all cost elements is needed for these tractors to be cost effective. Supply chain companies from shippers, to carriers, to fuel suppliers and others along with government assistance, must share in higher costs for the benefits of zero emissions.
- Alternative fuels like RNG, renewable diesel, and hydrogen used in internal combustion engines will be required to support the transition in the next two decades to help make progress toward zero-emission goals, while in parallel ramping up the hydrogen and battery electric infrastructure and manufacturing base.
- Industry agreement is needed on whether hydrogen long-haul fuel cell tractors, and the transport of the hydrogen fuel itself, will be based on gaseous or liquid hydrogen. This is a core factor that can impact multiple infrastructure and manufacturing systems, and significantly impact market penetration and volume estimates for cost reduction potential.

"As we move to the zero-emissions freight future, in the long run, there are only two choices of power – battery electric and hydrogen fuel cell."

— Rick Mihelic, Director of Emerging Technologies, NACFE

1 INTRODUCTION

Hydrogen is entering the marketplace as an energy source for zero-emission long-haul trucking. Two paths are emerging, fuel cell electric and new hydrogen internal combustion engines. Hydrogen is not optimum for all duty cycles. Hydrogen is, however, the only viable zero-emission solution currently proposed as one-for-one replacements for diesel in the future of long-haul heavy-duty trucks.

Hydrogen is not competing with battery electric technology, as each is optimum for different duty cycles. Other alternative fuel types such as renewable natural gas, renewable diesel and propane have roles as North America transitions from fossil fuel diesel as they are improvements over the traditional diesel, but the trend from federal, state and local governments in the 2035 to 2050 timeframe is for only new zero-emission vehicles to be sold.

Many vested interests are promoting the benefits of hydrogen fuel for burning in new internal combustion engines based on diesel cycles, and for use in fuel cells powering hybrid electric powertrains. Major players in molecular fuel production, storage and delivery are actively advertising the potential of hydrogen to enable zero-emission freight transportation for trucks, trains, ships and even airplanes. Billions of dollars in grants, incentives and tax breaks are being invested in hydrogen by various government agencies at federal, state and local levels. Venture capitalists and investors are forecasting significant future profits from hydrogen. Nations are positioning themselves as hydrogen energy exporters to regions that are net energy importers. All the positive messaging and investment seem destined for triumph, assuming that vast pools of money and positive messaging will guarantee hydrogen's success.

Technologies though are never sure things. Hydrogen has been in the limelight before, many times, earning the prediction that "hydrogen is the fuel of the future, and always will be." Various inventors developed hydrogen combustion prototypes in the mid-1800s. The 1920s and 1930s saw the innovation of transoceanic travel by hydrogen filled dirigibles. The 1940s and 1950s saw the feasibility of releasing massive amounts of energy through hydrogen fusion demonstrated through the Manhattan project. Space programs in the 1960s continuing into today successfully have deployed fuel cell systems into space vehicles. GM prototyped the GM Electrovan fuel cell vehicle in 1966. The 1970s and 1980s oil supply challenges encouraged a range of prototype hydrogen combustion and fuel cell vehicles from researchers and mainstream manufacturers. The 1990s saw another wave of prototype hydrogen-based cars. The period 2000 through 2010 saw hydrogen fuel cell buses enter production. The 2010s saw small numbers of production fuel cell cars enter the market from Hyundai, Toyota, Honda and Mercedes. Investment has been growing in research and prototypes of hydrogen powered heavy-duty trucks, ships, trains and planes with growing media coverage as the world searches for viable transition strategies from traditional fossil fuels to zero-emission solutions.

Hydrogen is all around us. It's in the water we drink (H_2O). Hydrogen is in the fuels we burn including gasoline (C_8H_{18}), diesel ($C_{12}H_{23}$), natural gas (CH_4), propane (C_3H_8), and others. It's used extensively in a variety of industrial processes making everything from fertilizers to cement. Hydrogen has an affinity to readily bond to other atoms and molecules. Hydrogen generally has to be separated from these other materials such as water or natural gas using industrial processes. Natural hydrogen, sometimes labeled white hydrogen, does actually occur in nature but is not available in commercial quantities at this time [5][2].

Separating hydrogen from other materials takes significant amounts of energy. And that is where the story gets much more complicated for use in heavy-duty trucks. Hydrogen is a much bigger question than whether it is the right fuel for the truck. How it is produced, stored and delivered to the truck has significant energy, emission, regional economic, social justice and cost ramifications.

In December 2019, NACFE compared a range of alternative fuel heavy-duty truck technologies including hydrogen in the report *Viable Class 7/8 Electric, Hybrid and Alternative Fuel Tractors* [1]. In December 2020 NACFE issued the in-depth hydrogen report, *Making Sense of Heavy-Duty Hydrogen Fuel Cell Tractors* [2]. These reports have been read in more than 100 countries by researchers, manufacturers, and by government and private organizations. These two reports are a solid foundation on which this new hydrogen report is built.

The 2020s have seen an awakening by the freight industry to the urgency for the world to find viable replacements for traditional diesel-powered tractors to haul freight. Customers and governments are demanding the trucking industry reduce its carbon footprint. Proactive fleets are investing in future zero- and near-zero emission alternative powertrains to meet their own sustainability goals. The world has been made very aware of the concept of supply chains as a result of major upheavals in deliveries during the COVID pandemic and unexpected geopolitical conflicts. The perspective on emissions has shifted from looking at just the individual vehicles to taking a systemic view of the entire supply chain and its impact on the environment.

The pace of technology investment has increased including in battery electric, fuel cell, and near-zero emission internal combustion powertrains which are beginning to reach production maturities. NACFE has found that the term "production" or "series production" has many interpretations, and in January 2020 issued the report *Defining Production* to clarify the many aspects of getting truck technology to maturity [3].

Hydrogen as energy to move freight trucks took on a new twist in 2022 with the Cummins announcement of development of an internal combustion engine that could be powered by burning hydrogen [4]. That engine builds on a century of diesel powertrain development, but rather than combusting diesel fuel with hydrogen imbedded in the fuel molecules, the fuel agnostic engine combusts gaseous hydrogen directly. The approach largely eliminates vehicle carbon emissions and significantly reduces vehicle nitrogen oxides (NOx) and particulate matter (PM) pollutants. The Cummins hydrogen engine assumes an emerging hydrogen infrastructure will be a part of the zero-emission freight transportation future. Cummins is also significantly invested in developing and producing battery electric and fuel cell electric powertrains, seeing a future where all are in use.

Cummins is not alone in pursuing multiple zero-emission technologies for the future. Major established North American truck OEMs including Daimler's Freightliner, PACCAR's Kenworth and Peterbilt, Traton's Navistar, Volvo and Mack and newcomers to the Class 8 market, Lion, Nikola, Tesla, BYD, Xos, Hyzon, and Hyundai, are either in production or headed to production with battery electric and/or fuel cell electric Class 8 trucks. Many are also offering natural gas-powered trucks. Fuel cell manufacturers such as Ballard, Toyota, Bosch, Cummins and others are putting the technology into production. Cummins and Westport are primary producers for hydrogen internal combustion technology.

Fleets are facing an almost overwhelming array of technology choices, which NACFE labeled in 2019 as the "messy middle," that interim period as North American freight transitions from traditional fossil diesel to a distant zero-emission truck future [1]. In 2023, NACFE released *The Messy Middle: A Time For Action* further clarifying the choices facing trucking [175]. Hydrogen is certainly one of the choices.

Over the course of 2022 NACFE interviewed fleets, technology providers, researchers, hydrogen suppliers and others to get first-hand perspectives on the decision-making process leading to choosing hydrogen. The rapid rate of technology development also gave NACFE the opportunity to add to the body of knowledge on the state of hydrogen technologies since our 2019 and 2020 publications. This report consolidates our new findings.

2 Scope

This report focuses on using hydrogen-based powertrains for heavy-duty Class 8 long-haul freight routes pulling van trailers. These powertrains include a range of fuel cell battery electric types and internal combustion engines (ICE) based on the diesel cycle. While there are certainly many other load types that are hauled long distances by Class 8 trucks, such as bulk carriers, fuel tankers, flat beds, etc., NACFE's focus is on van freight. The information in this report may also be of value to those other uses.

3 NACFE's Mission

NACFE's overriding principle in reporting on technologies is to provide an unbiased perspective. NACFE recognizes that it also has vested interests and an agenda. NACFE's mission is simply to improve the efficiency of North American goods movement. Improving efficiency inherently reduces harmful emissions. Improving efficiency reduces costs. The three interrelated goals of reducing fuel use, reducing emissions and reducing costs are central to NACFE's mission. NACFE pursues trucking industry efficiency gains by improving the quality of the information flow and by highlighting successful adoption of technologies.

4 Report Methodology

This report was written from interviews with subject matter experts at fleets, OEMs, research groups and industry organizations. Available public information has been referenced to support findings and conclusions.

5 What NACFE Got Right and Wrong in the 2020 Report

NACFE's 2020 *Making Sense of Heavy-Duty Hydrogen Fuel Cell Tractors* report had five major findings, repeated here:

- Hydrogen fuel cell trucks are just starting to see real-world use and their adoption is being driven by regional or national considerations that are much bigger than what exists for trucking fleets.
- Battery electric trucks should be the baseline for hydrogen fuel cell electric vehicle (HFCEV) comparisons, rather than any internal combustion engine alternative.

- As for all alternatives, fleets should optimize the specifications of HFCEVs for the job they should perform while expecting that the trade cycles will lengthen.
- The future acceleration of HFCEVs is likely not about the vehicles or the fueling but more about the creation and distribution of the hydrogen itself.
- Finally, the potential for autonomous fuel cell trucks to operate 24 hours a day adds significant opportunity for making sense of capital and operational investment in hydrogen.

Those findings continue to be applicable in the rapidly evolving zero-emission commercial vehicle world.

NACFE also introduced an attempt at categorizing the multiple paths to making hydrogen by generally accepted colors. Volvo has published improved graphics that captures greater details, combined in Figure 1 [13].

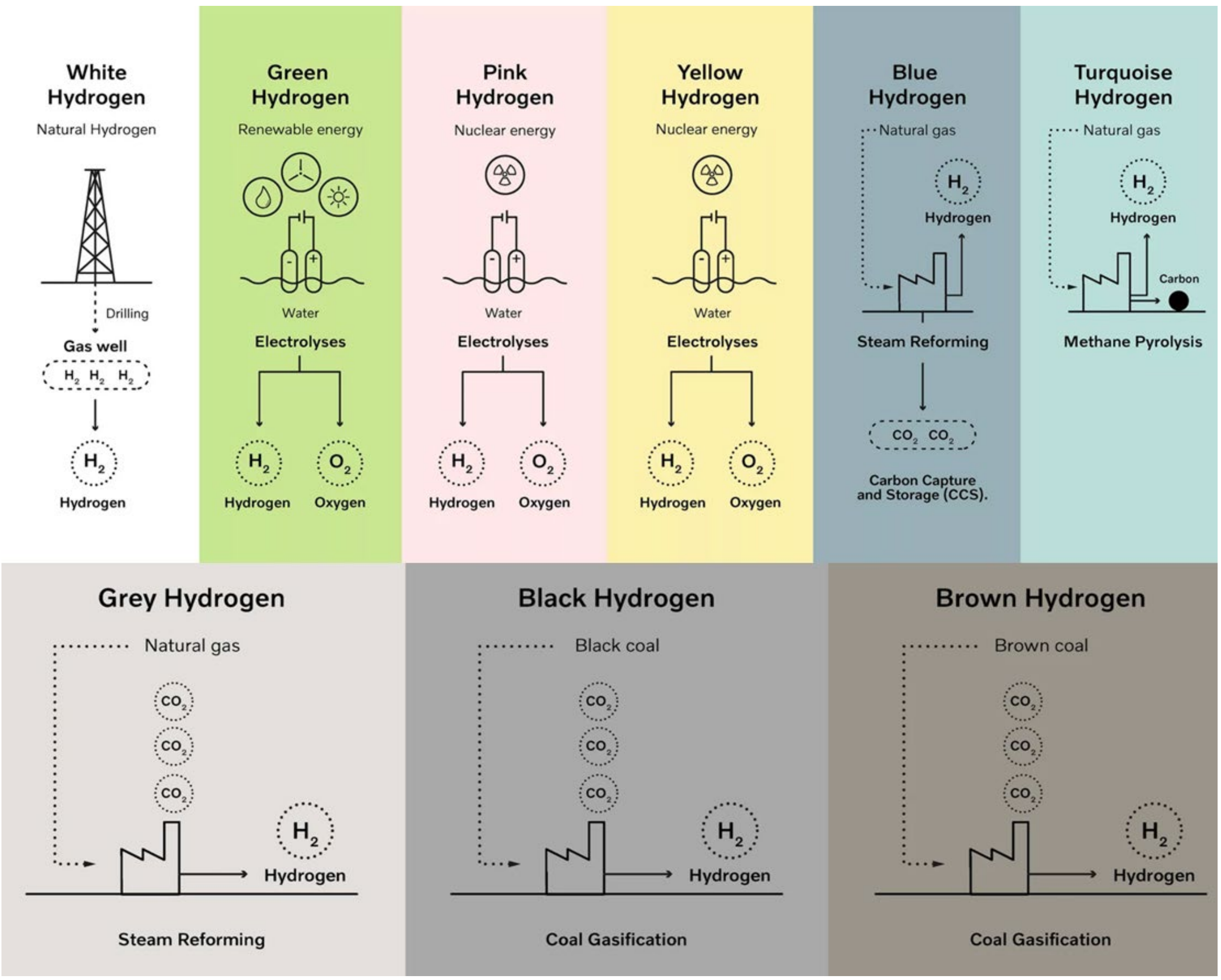


Figure 1. Hydrogen fuel origins (Volvo) [13]

What NACFE did not foresee was the extensive marketing effort to change the hydrogen color narrative from "how hydrogen is produced" to "how much carbon intensity" each method has. This new perspective attempts to redefine perceptions of fossil fuels, paving a path to having any method of hydrogen production be acceptable as long as the carbon intensity is comparable. The change also facilitates discussion of nuclear power as a critical method needed for a national hydrogen economy.

The NACFE report correctly highlighted those multiple methods of energy production that would be used in a hydrogen future, not just wind turbines and solar panels, and that all need to be successful to accelerate carbon emission reductions. NACFE believes the multiple hydrogen production methods are not a horse race but rather a horse team pulling a wagon, and all of us are in the wagon.

NACFE forecasted trends in state and federal regulations that could hasten hydrogen adoption. The period 2021 to 2022 has seen significant acceleration of state and federal efforts, described in detail in this current report. World events have also impacted the pace of development. NACFE's original report outlined efforts by nations such as Canada to become net energy exporters to countries such as Germany that are net energy importers. The current report highlights major steps forward on those paths.

The initial NACFE report correctly outlined that a hydrogen economy cannot be built solely on the shoulders of long-haul trucking, as there simply is not enough there to get the scale needed for cost reduction. It is critical that developments in hydrogen in major industries like steel and cement production occur in parallel with the evolving demand for the use of hydrogen in transportation.

NACFE suggested that standardization will be critical to get volume cost reductions on designs of tanks, fuel systems, fuel cells, batteries, cables and connectors, etc. Individual OEMs will need to consider standardizing on generic system components with their competitors in order to increase demand and reduce unit costs. That suggestion is still critical to the success of hydrogen for freight hauling.

There is not one design for a fuel cell powertrain; rather there is a complete spectrum based on choices for sizing both the fuel cell and battery electric system on board a vehicle to meet performance objectives. NACFE explained this in detail in the original report. Prototypes built since then vary considerably.

Regarding autonomous trucking's potential advantages for employing hydrogen fuel cell tractors in 24/7 operations, the progress to date in North America has focused on automating diesel trucks. Combining too many new technologies into a single freight solution can increase the risk of failure, so the automation efforts seem focused at present on automating mature diesel powertrains. A European consortium led by Hydrogen Vehicle Systems, announced in December 2022 a UK funded project to build two hydrogen-powered heavy-duty autonomous trucks to begin track testing in 2024 [165][166]. The prototype of the fuel cell truck with a human-based cab is shown in Figure 2 [167]. A second prototype replacing the human cab with a fairing is planned. One manufacturer, Gaussin, has developed an HFCEV automated guided vehicle (AGV) for use in container handling at ports [164]. See Figure 3. NACFE expects that at some point North American hydrogen and battery-based automated heavy-duty trucks will be readily adaptable with production automation technologies.

Figure 2. Prototype autonomous hydrogen truck (HVS) [167]

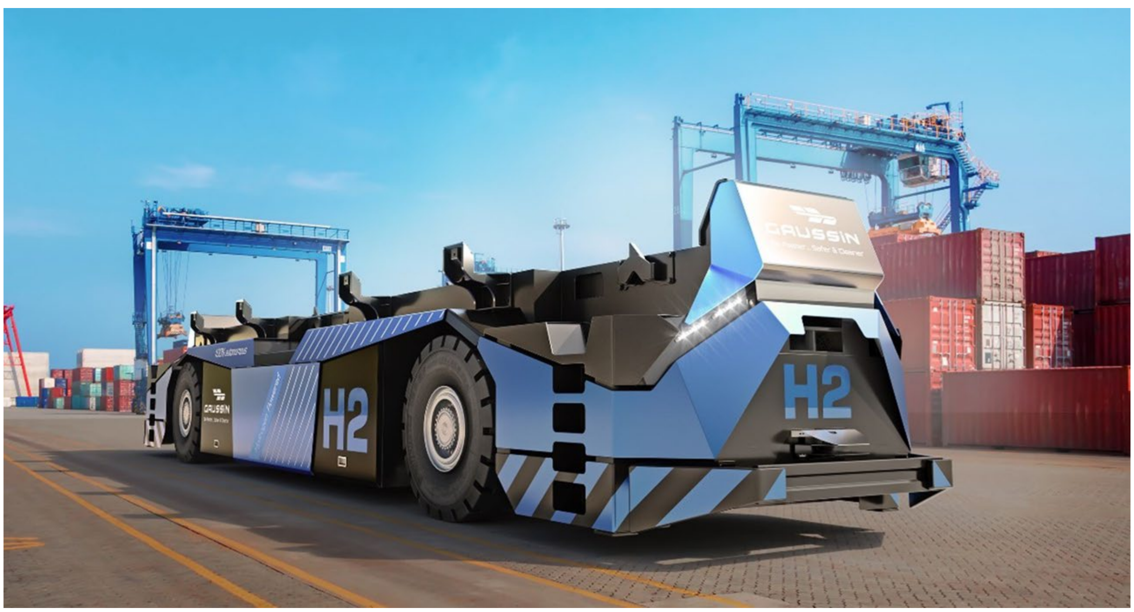


Figure 3. Fuel cell powered AGV (Gaussin) [164]

NACFE did not forecast in the first report the development and deployment of hydrogen burning diesel-based engines. Cummins, Westport and others have since built prototypes and are working on production plans. The hydrogen ICE will be an additional option for fleets but development is similarly challenged by a current lack of hydrogen fueling infrastructure.

6 What's Changed Since NACFE's December 2020 Report?

The pace of innovation, investment, regulation and awareness of hydrogen as a heavy-duty truck fuel has increased since the December 2020 NACFE report. In parallel, the topic of zero-emission trucks (ZETs) in general has seen significant focus. The major new factors accelerating adoption of hydrogen as a heavy-duty long-haul freight solution are discussed in this section.

6.1 Molecular Fuel Industry

The 2021 to 2022 period has seen the oil industry significantly step-up publicizing and marketing their efforts to lower emissions. Fossil fuel industry giants are actively promoting moves to hydrogen as the molecular fuel to replace gasoline, diesel and other fuels in a variety of industries. The molecular fuel industry appears to be adapting to market projections that are radically shifting away from traditional fossil fuels, while reinforcing the fact that molecular-based fuels will have a significant place in the zero-emission future. There are also some company efforts at diversifying energy portfolios to include solar, wind and other sources.

Shell's Sustainability Report for 2021 stated that the company has a target off becoming a "net-zero emissions energy business by 2050." The report says, "Becoming a net-zero emissions energy business means that we are reducing emissions from our operations and from the fuels and other energy products, such as electricity, that we sell to our customers. It also means capturing and storing any remaining emissions using technology, protecting natural carbon sinks and providing high quality nature-based solutions to our customers to offset unavoidable emissions [18]." In October of 2021, Shell announced interim goals of Scope 1 and 2, saying they had an "absolute emissions reduction target of 50% by 2030, compared with 2016 levels on a net basis."

BP similarly pledged that it is "Aiming to be net zero across operations, production and sales by 2050 or sooner [19]." Chevron's resilience report from October 2021 states, "Chevron adopted a 2050 net-zero aspiration for equity upstream Scope 1 and 2 emissions. The TCFD-aligned report describes how Chevron is incorporating Scope 3 emissions into its greenhouse gas (GHG) emission targets by establishing a Portfolio Carbon Intensity (PCI) target inclusive of Scope 1 and 2 as well as Scope 3 emissions from the use of its products [20]." Exxon in 2022 announced Scope 1 and 2 2030 GHG emissions reduction plans [21]

Pilot Flying J announced a joint effort with EVgo and GM to install 2,000 fast chargers in cities and suburbs at up to 500 Pilot and Flying J travel centers [22]. While these may be focused on automobiles, the commitment reflects a growing fueling industry awareness of the need to supply alternatives to traditional fossil fuels. Travel Centers of America announced they were working with Nikola to rollout hydrogen fueling for heavy-duty trucks with some locations opening in California in 2023 [23][24][25].

There are newer fuel supplier entrants such as Plugpower that plan to transport and supply hydrogen to heavy-duty truck fueling sites using Nikola-built HFCEV trucks [26].

The sea change in the oil industry to pursuing zero-emission markets is significant, reinforcing a path toward hydrogen as a fuel in trucks hauling freight.

6.2 COP27 US MDHD Truck Agreement

The US endorsed the Global Memorandum of Understanding (Global MOU) on Zero-Emission Medium- and Heavy-Duty Vehicles at the COP 27 (UN Climate Conference of the Parties) event in November 2022 held in Sharm el-Sheikh, Egypt. The MOU is a non-binding commitment to establishing a path to 100% new zero-emission medium- and heavy-duty vehicle (MHDV) sales by 2040 and at least 30% new zero-emission medium- and heavy-duty vehicle sales by 2030 [15][16][17]. Canada also has signed this MOU. The November 2022 US commitment clarifies the Biden administration's stated focus on transitioning freight transportation to ZETs [27].

6.3 Infrastructure Investment Jobs Act (IIJA)

The Infrastructure Investment and Jobs Act (IIJA) was signed in November 2021 providing $7.5 billion in incentives to deploy and operate a nationwide network of charging stations, and $65 billion to rebuild the electric power grid for future demand [31][32]. The IIJA also has $50 billion in funding to improve the resilience of the infrastructure to protect against droughts, heat, floods and wildfires, in addition to a major investment in weatherization.

6.4 The Inflation Reduction Act (IRA)

The Inflation Reduction Act (IRA) was signed in August 2022, and it provides incentives to significantly reduce the cost of hydrogen production, reduce the cost of manufacturing vehicles and infrastructure, and it provides a $40k credit to purchase a ZET [33][34]. The bill includes $8 billion in funding for the DOE to facilitate clean hydrogen production, $7 billion of which is focused on creating six to 10 hydrogen hubs.

6.5 The U.S. National Blueprint for Transportation Decarbonization

On January 10, 2023, the Biden administration released the U.S. National Blueprint for Transportation Decarbonization [28][29]. The roadmap outlines the "whole-of-government" consensus of the U.S. Department of Transportation (DOT), Department of Energy (DOE), Environmental Protection Agency (EPA) and the Department of Housing and Urban Development (HUD). The goal is to "eliminate nearly all greenhouse gas (GHG) emissions from the sector by 2050 and implement a holistic strategy to achieve a future mobility system that is clean, safe, secure, accessible, affordable, and equitable, and provides sustainable transportation options for people and goods." The joint plan originates from the MOU signed on September 15, 2022 [30]. A summary of vehicle improvement strategies and technology solutions for different travel modes needed to reach a net-zero economy in 2050 are shown in Figure 4.

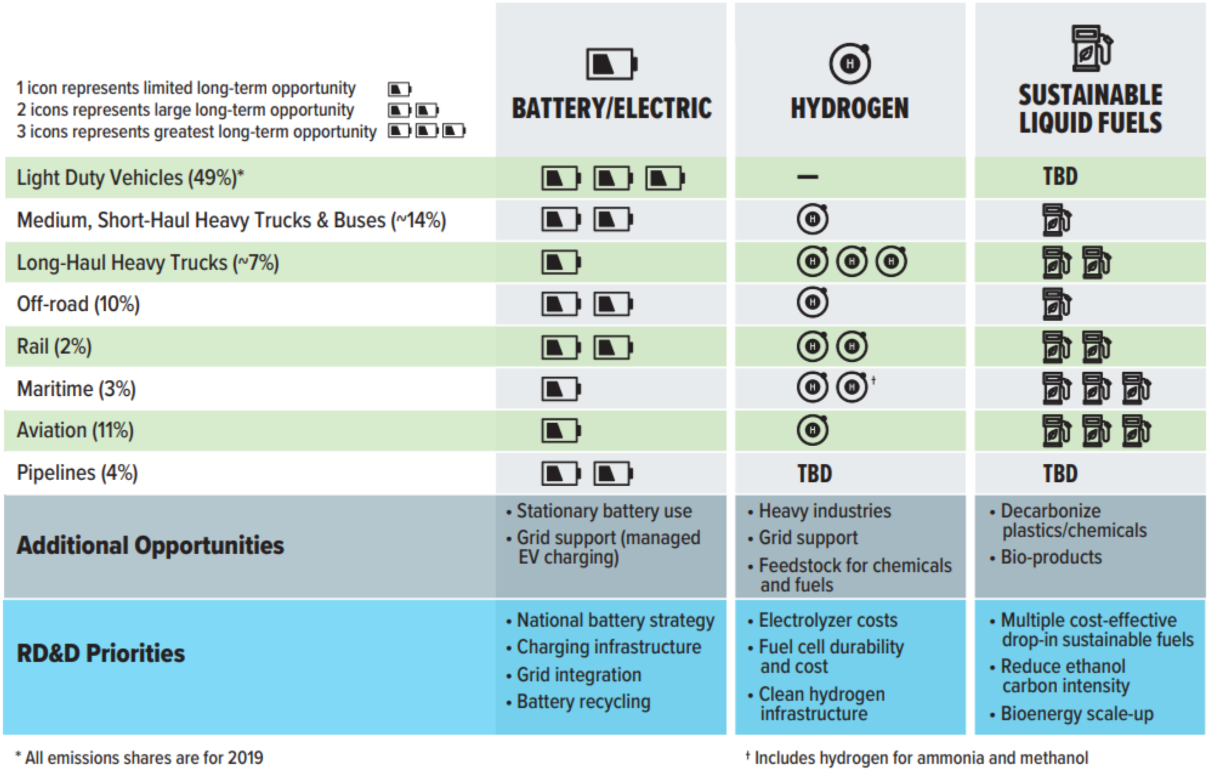


Figure 4. Blueprint energy solutions for different travel modes (DOE) [29]

The strategy clearly shows both battery electric vehicles (BEVs) and HFCEV heavy-duty long-haul trucks will be necessary, but the bulk of the long-haul opportunity will be hydrogen based. The interim goal for medium- and heavy-duty trucks is to "aim to have 30% of new vehicle sales be zero-emission by 2030 and 100% by 2040."

6.6 DOE National Clean Hydrogen Strategy and Roadmap

In September 2022, the DOE published a draft National Clean Hydrogen Strategy and Roadmap [74]. The plan states that, "Fuel cells are particularly viable for applications such as heavy-duty trucks that require fast fill times comparable to diesel today, or long driving ranges above 500 miles."

The DOE is funding significant research as outlined below [74]:

- DOE launched the Million Mile Fuel Cell Truck Consortium (M2FCT) in 2020 to enable the fuel cell durability, cost, and performance required for the long-haul heavy-duty truck market.
- DOE also selected hydrogen and fuel cell truck projects under the Super Truck program to demonstrate medium- and heavy-duty hydrogen fuel cell trucks under real-world operating conditions within the next five years [102]. Other projects supporting this strategy include developing the required infrastructure, fueling components, hydrogen storage and dispensing technologies, and a project that will demonstrate 15 parcel delivery trucks operating in disadvantaged communities.

- Transit agencies with large bus fleets or coach buses with long driving ranges also can benefit by using hydrogen and fuel cells. DOE has been working with the Federal Transit Administration to evaluate fuel cell buses and continues to collect real-world deployment data to guide future advances.
- By focusing the strategy on fleets, freight, and corridors where clusters of dedicated infrastructure can be developed, the US will reduce the risk of stranded assets and ensure the utilization of the developing hydrogen fueling infrastructure.

6.7 EPA Clean Truck Plan

Diesel emissions reduction have been the focus of ever-increasing federal regulatory requirements since the mid-1990s. The EPA enacted the Phase 1 Heavy-Duty Greenhouse Gas (GHG) rules in 2011 effective with model year 2014 and beyond trucks [37]. EPA enacted Phase 2 HD GHG rules in 2016 which applied to model year 2018 and beyond new trucks [38]. In December 2022, the EPA announced the Clean Truck Plan governing heavy-duty emissions that includes NOx requirements for model years 2027 and beyond [39]. The latest rules advocate the "swift adoption of zero-emission vehicle technologies" while recognizing that a transition period from fossil diesel is a necessary reality.

The EPA Clean Trucks plan first outlined in August 2021 has three major elements [40][41].

- Setting stronger NOx standards for heavy-duty trucks beginning in model year 2027 and tightening the Phase 2 GHG emissions for model year 2027 and beyond.
- Setting stronger multi-pollutant emissions standards for medium-duty commercial vehicles for model year 2027 and later. These revised standards will be proposed in combination with new standards for light-duty vehicles for model year 2027 and beyond.
- Setting Phase 3 GHG standards for heavy-duty vehicles beginning as soon as model year 2030 that are significantly stronger than the model year 2027 GHG standards.

The finalized NOx rule calls for "[reducing] NOx emissions from heavy-duty vehicles over a wide range of operating conditions, with significant emissions reductions at low speeds, idling, and in stop-and-go traffic." The rule includes longer useful life periods to ensure engines will meet emission standards for more of their operational lives and to prompt engine manufacturers to design and build more durable engines and emission controls [42].

In *Commercial Carrier Journal*, Jason Cannon summarized the new NOx rule for heavy-duty commercial vehicles which calls for tightening tailpipe NOx limits to a level 80%-plus below the current standard and reducing the particulate matter limit by 50% by the 2027 model year. "The agency also will require that OEMs extend warranties to 450,000 miles from 100,000 and useful life limits to 650,000 miles from 435,000 miles [42]." Cannon states, "The new standards require heavy-duty commercial vehicles to limit NOx emissions to 0.035 grams per horsepower-hour during normal operation, 0.050 grams at low load, and 10.0 grams at idle, and will also increase the useful life of governed vehicles by 1.5 to 2.5 times and yield emissions warranties that are 2.8 to 4.5 times longer — provisions that guarantee that as vehicles age, they will continue to meet EPA's more stringent emissions standards for a longer period of time."

The proposed new multi-pollutant particulate emission rules were issued for comment January 6, 2023 [57]. Cannon said, "EPA's proposal will specifically take comment on strengthening the primary annual

PM 2.5 standard from the current level of 12 micrograms per cubic meter to a level between 9 and 10 micrograms per cubic meter [56]."

The federal regulations in concert with the state and regional ones likely will increase the capital and operating cost of diesel engine vehicles in the future, impacting total cost of ownership (TCO) comparisons between diesels and ZETs.

6.8 MOU-17 STATES AND DC

The Multi-State Zero Emission Medium- and Heavy-Duty Vehicle Memorandum of Understanding was signed by 15 states and the District of Columbia on July 10, 2020, and was discussed in NACFE's original hydrogen truck report. Since the NACFE report was published, in December 2021 Virginia, and in March 2022 Nevada signed the MOU bringing the total to 17 and the District of Columbia [35]. Additionally, six of these states have implemented Advanced Clean Truck rules. CALSTART estimates that, "States that have signed the MOU represent 37% of national [medium- and heavy-duty] truck registrations and 33% of national [medium- and heavy-duty] deployed truck sales [36]."

6.9 ADVANCED CLEAN TRUCK (ACT) RULE

The Advanced Clean Truck (ACT) rule was created in California in 2020, but as of January 2023 has been adopted also in Oregon, Washington, New York, New Jersey and Massachusetts [35]. According to CALSTART, "States that have enacted the ACT regulation represent 25% of national [medium- and heavy-duty] truck registrations and 22% of national [medium- and heavy-duty] deployed truck sales.

The primary targets are that by 2035 in states adopting ACT:

- 55% of Class 2b to 3 new truck sales are zero emissions;
- 75% of Class 4 to 8 new straight truck sales are zero emissions;
- 40% of new truck tractor sales are zero emissions;
- Large fleet reporting requirement.

Transport Topics summarized the ACT Rule as, "Requiring a growing percentage of all medium- and heavy-duty trucks sold to be zero emission starting in 2025. Manufacturers must increase their zero-emission truck sales in those states to 30% to 50% by 2030, and 40% to 75% by 2035 [37]." The International Council on Clean Transportation (ICCT) summarized the rule. "The ACT rule requires the sale of zero-emission or near zero-emission [heavy-duty trucks] starting with the manufacturer-designated model year 2024. Sales requirements are defined separately for three vehicle groups: Class 2b to 3 trucks and vans, Class 4 to 8 rigid trucks, and Class 7 to 8 tractor trucks. The regulation is structured as a credit and deficit accounting system. A manufacturer accrues deficits based on the total volume of on-road [heavy-duty truck] sales within California in a given model year. These deficits must be offset with credits generated by the sale of [ZETs] or near zero-emission vehicles [38]." The phase-in for California is graphed in Figure 5 [38]. The other ACT Rule states have similar phase-ins. The ACT rule represents clear targets and timelines for ZET adoption.

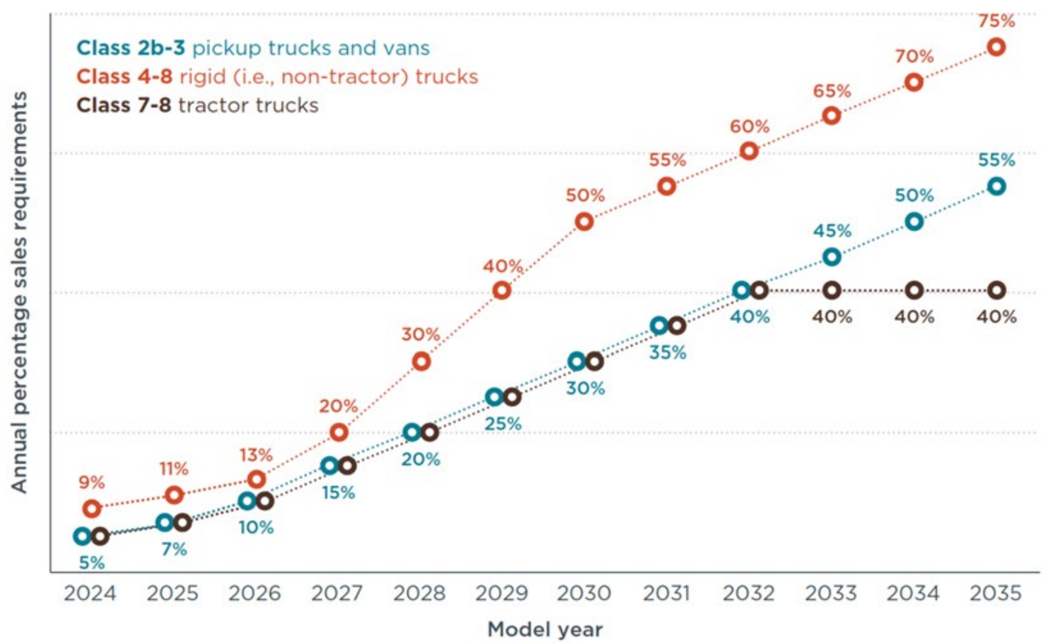


Figure 5. California ACT Rule targets (ICCT) [38]

6.10 Advanced Clean Fleets Rule

The ACT Rule applies to the manufacturers of the vehicles by regulating the market mix of new vehicles sold in a region. This can impact a fleet's choice of new vehicles to buy for specific regions where the rules may vary between regions. Existing older vehicles are not governed by ACT. States such as California have the authority to regulate existing vehicles. California is developing an Advanced Clean Fleets (ACF) rule. The ACF is "a medium- and heavy-duty zero-emission fleet regulation with the goal of achieving a zero-emission truck and bus California fleet by 2045 everywhere feasible and significantly earlier for certain market segments such as last mile delivery and drayage applications. The initial focus would be on high-priority fleets with vehicles that are suitable for early electrification, their subhaulers, and entities that hire them. The goal of this effort is to accelerate the number of medium- and heavy-duty zero-emission vehicle purchases to achieve a full transition to zero-emission vehicles in California as soon as possible [44]." Southern California Edison projected that the ACF rule has an expected implementation in 2023 with a phase-in of zero-emission trucks and buses (over 8,500 lbs. GVWR) to 2045. Drayage trucks are required to be zero emission by 2035 [45]."

6.11 Heavy-Duty Low NOx Omnibus Rule

The federal rules on heavy-duty truck NOx emissions reductions are not necessarily the final story on NOx regulation. State regulations governing NOx and PM also may be tightened under the California Air Resources Board (CARB) Heavy-Duty Low NOx Omnibus Rule. This rule is being considered by other states such as Oregon. The Omnibus rule lowers NOx and PM2.5 standards for new truck engines, extends the useful life and warranty periods, and has other elements such as additional testing requirements. Daimler summarized the Omnibus Rule elements and timing in Figure 6 [46].

CARB Omnibus Overview

2024
- Lower tail pipe NOx and PM
- New low load cycle (LLC)
- Lower Idle standard
- New in use testing on any "commercially available" fuel

2027
- Longer warranty (HD: 450k/7 year)
- Longer useful life (HD: 600k/11 year)
- Lower tail pipe NOx
- Lower low load cycle
- Lower idle standard

2031
- Longer warranty (HD: 600k/10 year)
- Longer useful life (HD: 800k/12 year)

	Today	MY24	MY27	MY31
Nox: FTP, RMC	0.2 g/hp-hr	0.05[1] g/hp-hr	0.02[1] g/hp-hr	
PM: FTP, RMC	0.01 g/hp-hr	0.005 g/hp-hr	0.005 g/hp-hr	
LLC Nox	N/A	0.05 g/hp-hr	0.02 g/hp-hr	
Idling	30 g/h	10 g/h	5 g/h	
HDIUT	NTE Procedure CF: 1.5	3-bin MAW CF: 2.0		3-bin MAW CF: 1.5 [2]
	Customer route	All routes	All routes + Cold start	
Useful Life	HHD: 435k mi / 10 years		HD: 600k mi / 11 years	HD: 800k mi / 12 years
Warranty	HHD: 100k mi/ 5 years	HHD: 350k mi/ 5 years	HD: 450k mi/ 7 years	HD: 600k mi/ 10 years
DF	50% UL: Option for 35% UL	FUL: 9800 h or 50% UL + 600h DAAAC	FUL: DAAAC for 1900 h + in-use data	

This affects new commercial vehicles registered for use in California and CARB Opt in states

[1] At 435k miles, additional allowance at proposed extended FUL
[2] CF change to 1.5 in 2030

Figure 6. CARB Omnibus Rule overview (Daimler) [46]

The Oregon Department of Environmental Quality (DEQ) summarized Omnibus Rule changes from the warranty requirements as shown in Figure 7. [47]

Model Year	Warranty (miles)			
	LHDD	MHDD	HHDD	HDO
June 2018 Step 1 Warranty 2022-2026	110,000 5 years	150,000 5 years	350,000 5 years	50,000* 5 years
2027-2030	150,000 7 years/ 7,000 hours	220,000 7 years/ 11,000 hours	450,000 7 years/ 22,000 hours	110,000 7 years/ 6,000 hours
2031 and Subsequent	210,000 10 years/ 10,000 hours	280,000 10 years/ 14,000 hours	600,000 10 years/ 30,000 hours	160,000 10 years/ 8,000 hours

* Not included under Step 1 Warranty, but current periods are shown here for completeness.

LHDD = Light Heavy-Duty Diesel 14,001-19,500 lb. GVWR
MHDD = Medium Heavy-Duty Diesel 19,501-33,000 lb. GVWR
HHDD = Heavy Heavy-Duty Diesel >33,000 lb. GVWR
HDO = Heavy-Duty Otto-Cycle > 10,000 lb. GVWR

Figure 7. Current and proposed warranty requirements (DEQ) [47]

The extensions to warranty and product life expectancy applies to diesel vehicles. These extensions likely will result in higher prices for diesel trucks, which may influence fleets' decisions on future vehicle technology choices. BEVs are considered to have zero emissions so are not subject to these requirements.

6.12 Warehouse Indirect Source Rule (ISR)

Facilities that have heavy-duty truck operations also may have emissions regulated with respect to the operations of the vehicles while on their property. A new rule for warehouses operating in the greater Los Angeles area requires warehouse operators to track and offset emissions of Class 2b to 8 vehicles that visit their warehouses. The South Coast Air Quality Management District (SCAQWMD) Rule 2305 Warehouse Indirect Source Rule (ISR) — Warehouse Actions and Investments to Reduce Emissions (WAIRE) Program phases in as shown in Figure 8 [48]. The rule states, "The purpose of this rule is to reduce local and regional emissions of nitrogen oxides and particulate matter, and to facilitate local and regional emission reductions associated with warehouses and the mobile sources attracted to warehouses in order to assist in meeting state and federal air quality standards for ozone and fine particulate matter [48]." A summary of ISR rule by DLA Piper group states, "Warehouse operators must earn a specific number of points (called WAIRE Points) to offset the number of truck trips to and from warehouses under their control. Warehouse operators incur their WAIRE Points obligations on a weighted basis, with, until 2026, larger obligations for larger warehouse facilities, and for warehouses hosting larger vehicles (e.g., tractors or tractor-trailers). WAIRE Points are earned through emissions-reducing activities or payment of mitigation fees. Both owners and operators of such warehouses must also comply with significant new information gathering and reporting obligations under the Rule. [49]."

Phase	Warehouse Size (square feet)	Initial Reporting Date (Annual WAIRE Report)	Initial Compliance Period
1	≥ 250,000	January 31, 2023	January 1, 2022 to December 31, 2022
2	≥ 150,000-<250,000	January 31, 2024	January 1, 2023 to December 31, 2023
3	≥ 100,000-<150,000	January 31, 2025	January 1, 2024 to December 31, 2024

Figure 8. ISR Rule phase in (SCAQMD)

This ISR could modify a fleet's choice of vehicles that visit specific facilities at the request or demand of the warehouse operators. This rule is considered a novel approach moving beyond regulating the fleet operators to now include operating warehouses of shippers and receivers.

6.13 Electric Thermal Refrigerated Units

Thermal refrigeration units (TRU) for ZETs also are becoming relevant to the choice of energy. California is developing regulations requiring the use of electric thermal refrigerated units (eTRU) on trailers. New regulations were released in March 2022 affecting TRU use on straight trucks [50]. Those rules state, "Beginning December 31, 2023, TRU owners shall turnover at least 15% of their truck TRU fleet (defined as truck TRUs operating in California) to [zero-emission technology each year (for seven years). All truck TRUs operating in California shall be [zero emission] by December 31, 2029." CARB is planning "to start the development of a second rulemaking to transition non-truck TRUs to [zero-emission] technology in

2022. This second rulemaking is anticipated for Board consideration in 2025." Non-truck includes semi-trailer TRUs.

Zero-emission technologies outlined by CARB include battery-electric TRUs, cold plate TRUs, and indirect cryogenic TRUs [50]. TRU manufacturers and trailer manufacturers already are working on zero-emission trailer development.

The Technology & Maintenance Council (TMC) drafted a Future Truck Position Paper 2022-2 titled *Trailer Energy Harvesting: Regenerative Braking Systems for Trailer Applications* [51]. The document includes the table provided by Great Dane on eTRU energy demands shown in Figure 9.

TABLE 1: eTRU ENERGY REQUIREMENTS FOR TRAILER APPLICATIONS			
OPERATION	TRIP LENGTH	kWH REQUIRED	
	Hours	Pull Down	Total
Long Haul (-20°F) 53'	10	52	70.02
Long Haul (0°F) 53'	10	22	65.62
Food Service (2 - 38°F / ambient temperature)	10	46	76.12
Dairy (35°F)	10	27	58.35
Grocery (35°F)	10	16	46.46
Produce (35°F)	10	16	52.86
			Source: Great Dane, LLC

Figure 9. eTRU energy demands for trailer applications (Great Dane/TMC) [51]

The EPA has released a TRU Emissions Calculator that can be used to estimate the potential emissions reduction from operating transport refrigeration units on grid power, compared to traditional diesel power [72]. Additionally, in April 2020 TMC issued recommended practice RP185 on electrical infrastructure for TRUs.

eTRU equipped trailers may be pulled by many types of tractors — battery electric, hydrogen fuel cell, hydrogen ICE, CNG, etc. Getting energy to the trailer TRU on road trips will factor into tractor operations. With traditional diesel-powered units, the truck and tractor can be fueled at the same diesel fuel pump. However, the physical distances between the tractor and trailer tanks means the driver has to make two stops at the fuel island, inching up for the trailer tank after fueling the tractor.

As of January 2023, the development of hydrogen internal combustion engines and hydrogen fuel cells for tractors does not seem to have progressed to hydrogen for trailer TRUs. The future of TRUs appears to be battery electric on trailers with possible plug-in shore power at warehouses. Tractors in transit needing to refuel their TRU- equipped trailers where the tractor uses one type of energy and the trailer a different type presents operational questions needing answers as the industry transitions to zero-emission systems.

6.14 SEC Reporting Rule

In March 2022, The Securities and Exchange Commission (SEC) announced a proposed rule titled, Enhancement and Standardization of Climate-Related Disclosures for Investors [52]. A fact sheet describes the primary new reporting requirements with respect to climate-related information including:

- Climate-related risks and their actual or likely material impacts on the registrant's business, strategy, and outlook;
- The registrant's governance of climate-related risks and relevant risk management processes;
- The registrant's GHG emissions, which, for accelerated and large accelerated filers and with respect to certain emissions, would be subject to assurance;
- Certain climate-related financial statement metrics and related disclosures in a note to its audited financial statements; and
- Information about climate-related targets and goals, and transition plan, if any.

The rules are proposed to phase-in over several years beginning with elements in 2024. [52]

Progress reporting on reducing climate risk and GHG emissions may influence heavy-duty tractor technology investment choices.

6.15 Federal Reserve

The Federal Reserve "promotes the stability of the financial system and seeks to minimize and contain systemic risks through active monitoring and engagement in the U.S. and abroad [68]." In January 2023, the Federal Reserve requested that the six largest US banks compile reports investigating "how their businesses would be impacted by climate change outcomes and the transition to a lower-carbon economy [69]." They said, "banks will analyze the impact of scenarios for both physical and transition risks related to climate change on specific assets in their portfolios. To support the exercise's goals of deepening understanding of climate risk-management practices and building capacity to identify, measure, monitor, and manage climate-related financial risks, the Board will gather qualitative and quantitative information over the course of the pilot, including details on governance and risk management practices, measurement methodologies, risk metrics, data challenges, and lessons learned [70]." The Federal Reserve is recognizing that there may be potential financial and physical risks from both climate change itself, and moves to mitigate climate change. These factors may weigh eventually on financing research, development and capital investment in new powertrain technologies.

6.16 Canadian Regulations

Canada signed the COP26 MOU setting targets of 30% of new sales of zero-emission medium- and heavy-duty trucks by 2030 and 100% by 2040 [53]. The MOU was proposed by CALSTART. Carolyn Kim, national transportation director at Pembina Institute, said, "For commercial vehicles such as trucks and buses, it has been a challenge to electrify these fleets because they are still part of emerging technology and energy systems. There is also a lack of infrastructure in Canada to support them. But moving forward, the federal government will need to take up leadership and create a national zero-emission vehicles strategy for medium- and heavy-duty vehicles [53]."

Canada issued new ZET regulations as reported in *TruckNews* in March 2022 with a target that "zero-emission vehicles will need to account for 35% of Canada's medium- and heavy-duty truck sales as early as 2030, under a series of sales targets and incentives unveiled in a new federal emissions reduction plan [54][55]." *TruckNews* said the rules come with financial assistance, with "around $547.5 million in purchase incentives for medium- and heavy-duty zero-emission vehicles, along with eligibility dates, [which] are to be unveiled in the coming federal budget. Another $199.6 million will be invested to retrofit large trucks already on the road. And $33.8 million will be available for projects that demonstrate hydrogen-electric trucks, to address barriers such as technical standards that apply to long-haul trucks."

US and Canadian trucks frequently cross the border. Fueling availability for ZETs will need to be a consideration for cross-border operations.

6.17 Environmental Justice

Awareness of the need for environmental justice has risen dramatically in the period since NACFE's first hydrogen report was issued. The EPA describes environmental justice as the need "to provide all people the same degree of protection from environmental and health hazards and equal access to decision-making to maintain a healthy environment in which to live, learn, and work [71]." The Diesel Emissions Reduction Act (DERA) was created in 2005 to fund grants and loans for promoting diesel-emission reductions with funding up to $200 million per year through 2011, and $100 million per year through 2016, and then again reauthorized this funding from 2020 through 2024 [71].

Emissions from trucks tend to disproportionately impact less advantaged communities and regions. Achieving environmental justice has become a critical factor in funding new freight technologies to mitigate these factors. DERA is one of several mechanisms for funding investment in hydrogen trucks.

The DOE uses the phrase "clean and equitable energy transition" to describe its goal. In allocating funding for hydrogen projects, the DOE requires creation of a community benefit plan (CBP). That plan prioritizes funding that "incorporates requirements for community and labor engagement, quality jobs and workforce deployment, diversity, equity, inclusion and accessibility, and the Energy and Environmental Justice and Justice40 Initiative [100]." The Justice40 initiative is the title given in Sec. 233 of Executive Order #14008 that Federal investments have "a goal that 40% of overall benefits flow to disadvantaged communities (DACs) [101]." Note that the goal is 40% of the benefits of the investment, not necessarily 40% of the investment.

The US government provides a website to help locate DACs. The Climate and Economic Justice Screening Tool is shown in Figure 10 [102]. Communities that are disadvantaged are highlighted in gray on the map and live in tracts that experience burdens. Details of 36 burden indicators can be found on the DOE website Justice40 Initiative [103].

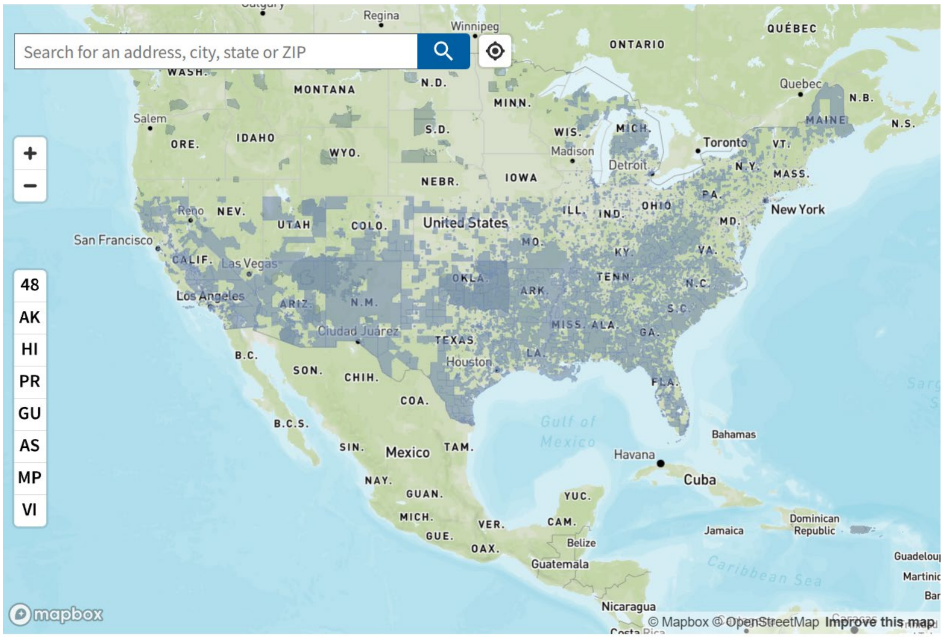


Figure 10. Climate and Economic Screening Tool (U.S. Government) [102]

The DOE also has a Disadvantaged Communities tool as shown in Figure 11 [103]. There are differences in the two maps, and DOE recommended using the DOE map in responding to DOE funding requests.

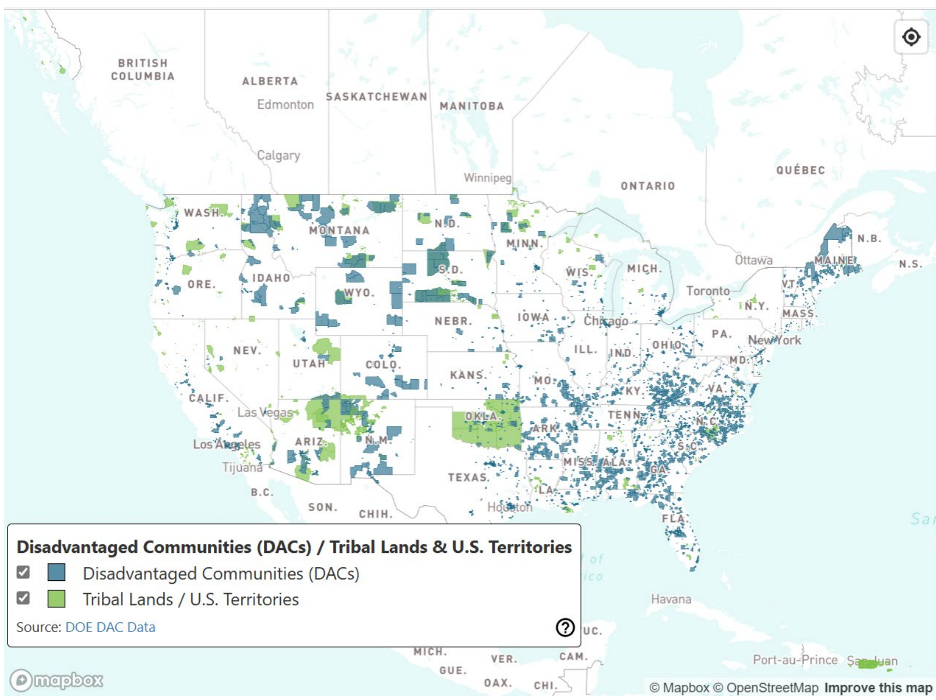


Figure 11. Disadvantaged Communities (DAC) [103]

Hydrogen is clearly linked to economic development, employment and social justice at both regional and national levels in addition to environmental objectives, consistent with conclusions in NACFE's *Making Sense of Heavy-Duty Hydrogen Fuel Cell Tractors* report.

6.18 Liquid H_2 vs Gaseous

The December 2020 NACFE hydrogen report focused on gaseous hydrogen being the on-board fuel for the proposed fuel cell long-haul heavy-duty trucks. The consensus opinion then, and now, is that hydrogen would be transported to fueling stations as a liquid due to the overwhelming advantage in energy density of the liquid versus gas [60]. The liquid would then be converted to 750 bar (10,000 psi) hydrogen gas for use by trucks. Progress was being made toward fueling standards for 750 bar gaseous hydrogen. This immense pressure is needed to package the energy densely enough that the tractor chassis can be a reasonable length for commercial operations. Multiple high-pressure tanks are required on a gaseous hydrogen fueled tractor as illustrated in the example from Kenworth in Figure 12.

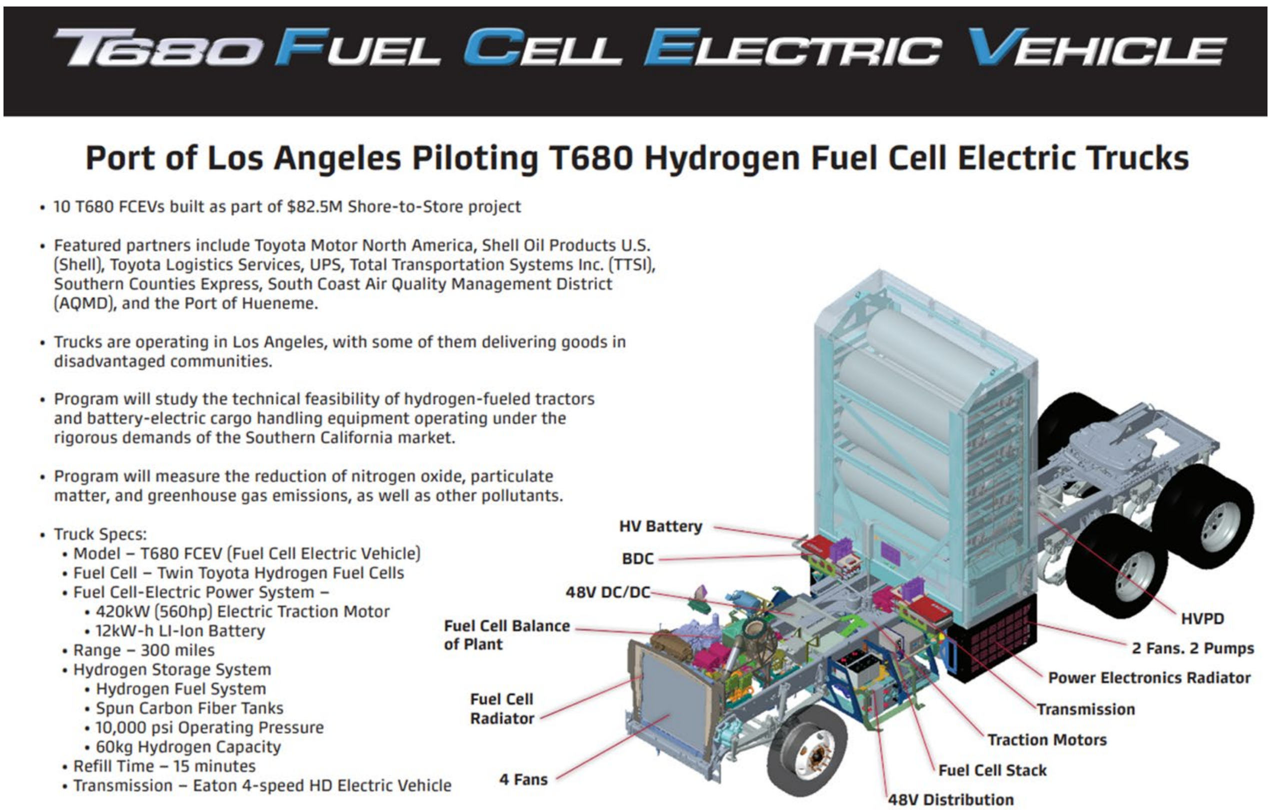


Figure 12. Example fuel cell tank arrangement (Kenworth) [176]

Ginger Gardiner writing for *Composites World* published the graph in Figure 13 which captures the physical properties of the multiple paths to storing hydrogen on a truck [143]. The densest energy storage is achieved with liquid hydrogen (LH_2) in the gray area at the left of the graph where temperatures are below 33 Kelvin (-400 °F) but can be at very low pressure because it is a liquid. Getting equivalent energy densities from gaseous hydrogen requires significant levels of compression shown by the pressure lines, such as the 700-bar line. Higher pressures allow for higher storage temperatures reducing the requirements for the thermal containment systems of the on-board tanks. The yellow shaded area shows gaseous hydrogen at 350 bar and 700 bar can be stored about -40°C (-40°F), but cannot reach the same energy densities of liquid. The green region in the graph is for "cryo-compressed" hydrogen, which is much colder temperatures but still gaseous.

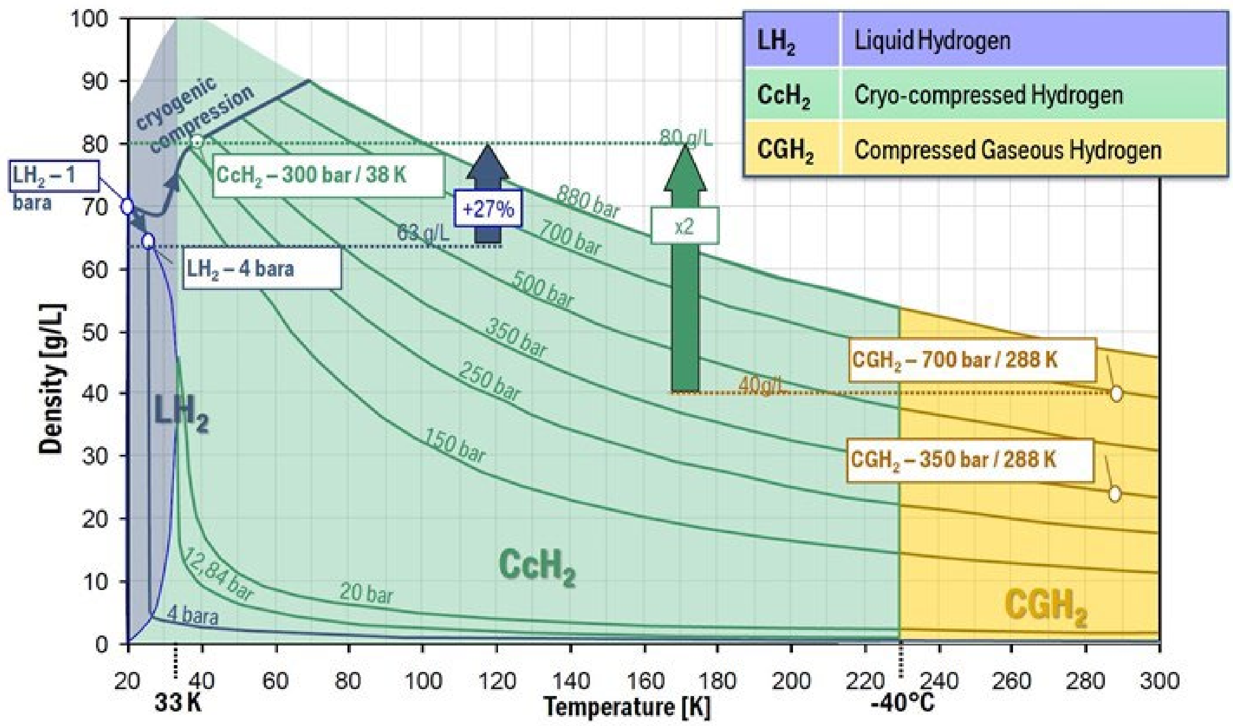


Figure 13. Hydrogen physical properties (BMW) [143]

The significant difference between a gallon of diesel (a unit of volume) and a gallon of hydrogen is that the diesel can exist as a liquid in normal conditions and can be stored in truck fuel tanks with simple unpressurized fueling. Hydrogen must be cooled and compressed to put the same amount of energy into a gallon of volume. All that cooling and compression requires energy, mostly in the form of electricity running coolers and pumps.

There is no easy solution for storing hydrogen. Either the tanks are complex thermos bottle types with venting systems keeping the hydrogen cold enough that it can stay a liquid, or they are extensively reinforced tanks operating at high pressures up to 700 bar (10,000 psi). Gone are the simple single-wall welded aluminum cylindrical fuel tanks from the diesel trucks as shown in Figure 14 [147]. Gardiner provides the BMW graphic in Figure 15 illustrating the three hydrogen fueling options [143]. Each is significantly more complex than the traditional liquid diesel fuel tank, incorporating the need for handling extremely cold temperatures, extremely high pressures, or both.

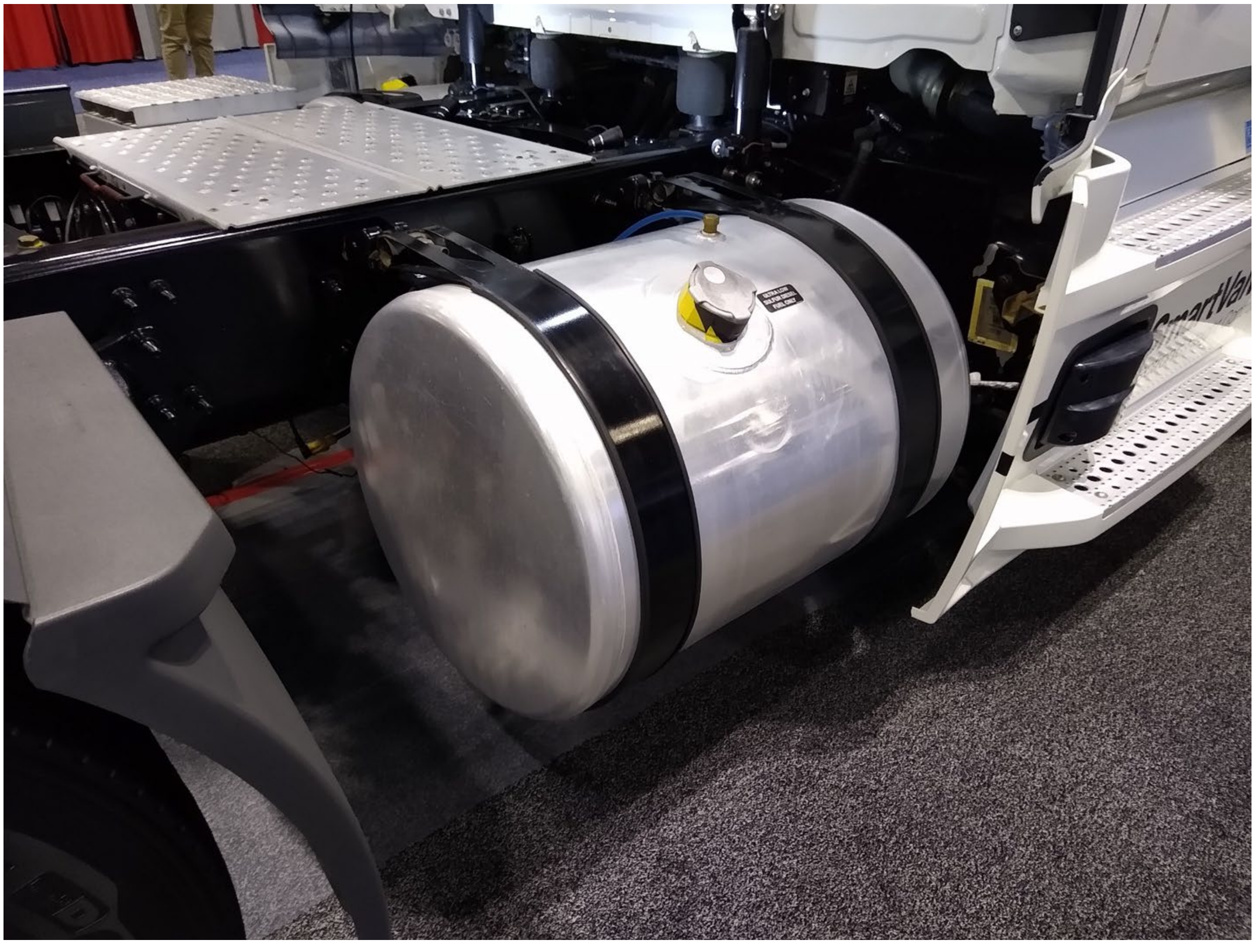


Figure 14. Example diesel truck tank (NACFE) [146]

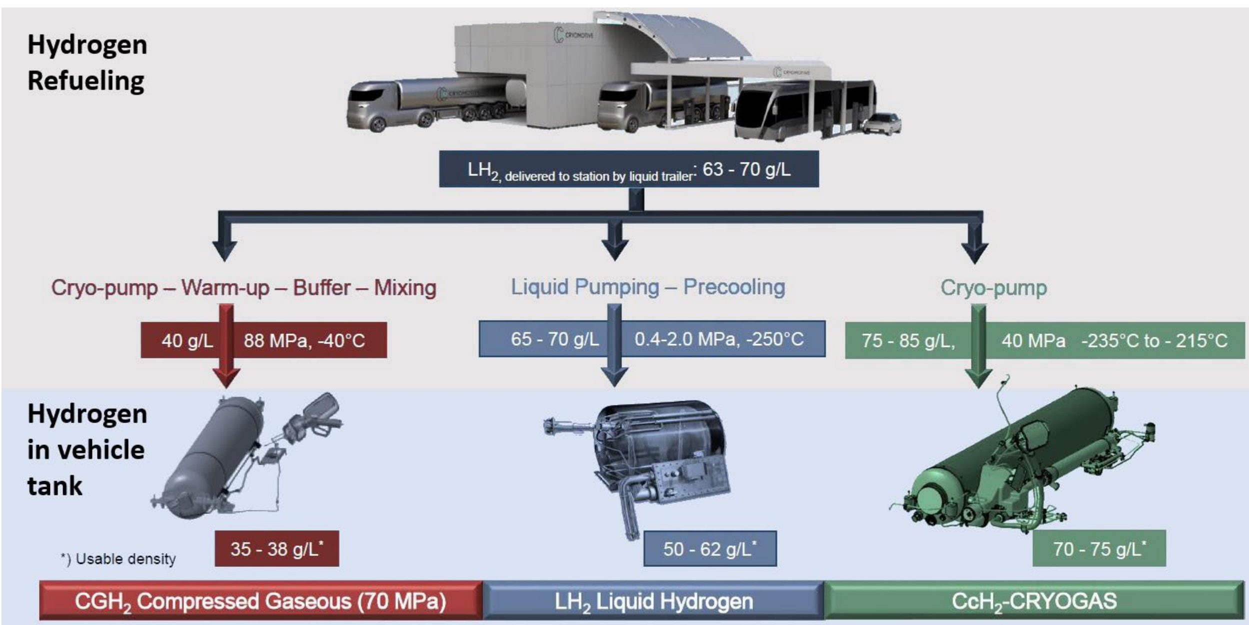


Figure 15. Hydrogen fueling choices (BMW) [143]

The differences between diesel and hydrogen can be viewed in terms of tankers as shown in Figure 16. The graphic compares the energy carrying capacity of a standard diesel tanker with a liquid hydrogen tanker and a gaseous hydrogen tube tanker. The graphic illustrates that liquids are more efficient at bulk hauling energy versus gaseous product.

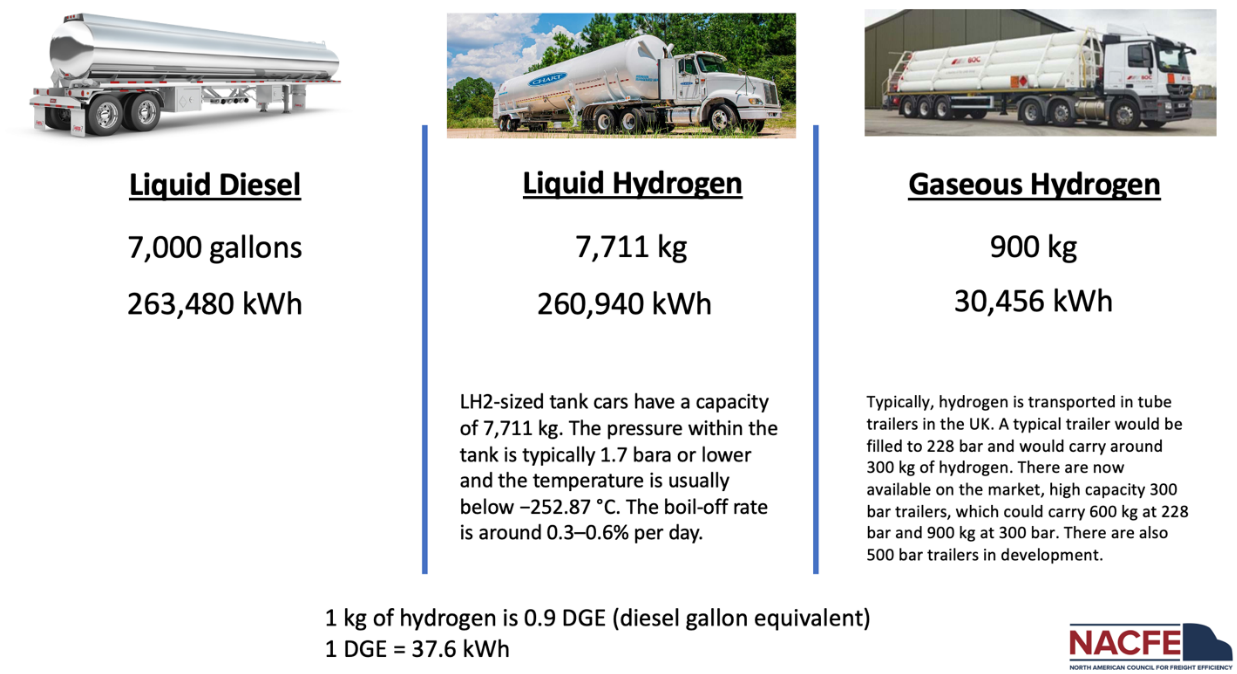


Figure 16. Fuel transport comparison (NACFE) [157][158][159]

In 2022, Daimler Truck North America proposed using liquid hydrogen on trucks rather than gaseous hydrogen, because packaging liquid fuel tanks for long-haul trucks allows for shorter wheelbases without compromising payload versus a comparable diesel under the DOE SuperTruck 3 program [62]. The demonstration is for "two Class 8 fuel cell trucks with 600-mile range, 25,000-hour durability, equivalent payload capacity and range to diesel [59]."

After a development milestone fueling test in Germany, company officials stated, "Daimler Truck prefers liquid hydrogen in the development of hydrogen-based drives. In this aggregate state the energy carrier has a significantly higher energy density in relation to volume compared to gaseous hydrogen. As a result, more hydrogen can be carried, which significantly increases the range and enables comparable performance of the vehicle with that of a conventional diesel truck [61][62]." The company demonstrated a 4x2 tractor configuration shown in Figure 17 with saddle-mounted tanks.

Figure 17. Daimler 1,000 km capable liquid hydrogen FCEV (Daimler Truck) [62]

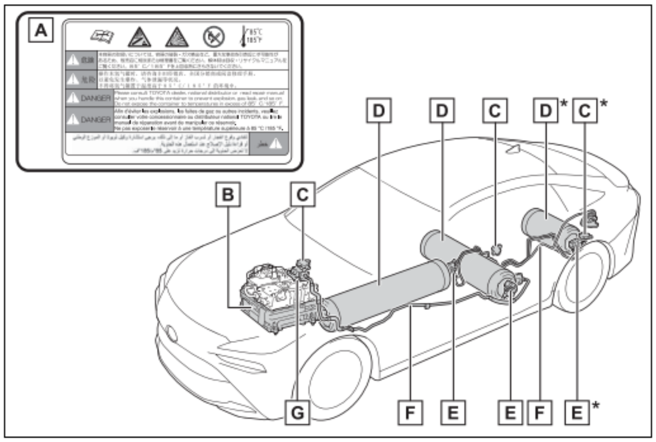
Gaseous hydrogen storage for 1,000 km (600 mile) ranges are expected to require vehicles with longer wheelbases to allow packaging the storage tanks. An example of a gaseous hydrogen prototype is shown in Figure 18.

Figure 18. Nikola 800 km (500-mile) hydrogen FCEV (Anheuser-Busch) [63]

The Toyota Mirai hydrogen HFCEV car uses small 4.7 kg gaseous hydrogen fuel tanks at 350 bar (5,000 psi). The tanks are capable of 700 bar (10,150 psi) pressures holding 5.7 kg of gaseous hydrogen. Most fueling stations in California are delivering 350 bar hydrogen. The Mirai tanks are shown in Figure 19 [65].

■ **Hydrogen-related components**

The fuel cell vehicle has hydrogen tanks (10150 psi [70 MPa, 714 kgf/cm^2, 700 bar]), fuel cell stack, and hydrogen pipelines as hydrogen-related components. Pay attention to all warning labels attached to the vehicle.



The illustration is an example for explanation and may differ from the actual item.

A Warning label

B Fuel cell stack (fuel cell and hydrogen pump)

C Hydrogen detectors

D Hydrogen tanks

E Hydrogen tank valves

F Hydrogen pipelines

G Hydrogen supply unit

*: If equipped

Figure 19. Mirai FCEV components (Toyota) [65]

Hydrogen has additional requirements for compression, storage and distribution (CSD) versus traditional diesel. The DOE states, "Gaseous hydrogen is liquefied by cooling it to below −253°C (−423°F). Once hydrogen is liquefied it can be stored at the liquefaction plant in large insulated tanks. It takes energy to liquefy hydrogen — using today's technology, liquefaction consumes more than 30% of the energy content of the hydrogen and is expensive. In addition, some amount of stored hydrogen will be lost through evaporation, or 'boil off' of liquefied hydrogen, especially when using small tanks with large surface-to-volume ratios. Currently, for longer distances, hydrogen is transported as a liquid in super-insulated, cryogenic tanker trucks. After liquefaction, the liquid hydrogen is dispensed to delivery trucks and transported to distribution sites where it is vaporized to a high-pressure gaseous product for dispensing. Over long distances, trucking liquid hydrogen is more economical than trucking gaseous hydrogen because a liquid tanker truck can hold a much larger mass of hydrogen than a gaseous tube trailer can. Challenges with liquid transportation include the potential for boil-off during delivery [89]."

Pressurizing gaseous hydrogen to 750 bar (10,000 psi) also requires significant energy. In 2014, The DOE National Renewable Energy Laboratory (NREL) estimated an energy consumption of "2 kWh to 4 kWh/kg of hydrogen for compression for 350-bar refueling [90]." The report cites demonstrated values of 2.7 kWh/kg to more than 8.3 kWh/kg for compression above 430 bar. Assuming 3 kWh/kg means an 80-kg

700-bar tank would require 240 kWh of energy just to compress the hydrogen to fill the vehicle's tanks. Consider this as energy overhead spent to package fuel onboard the truck, not tied to making the wheels move.

The energy involved with liquification at the hydrogen plant, energy needed to move the liquid hydrogen by liquid tanker truck to the fuel station, energy losses in transporting the liquid hydrogen due to boil off, and energy required to compress gaseous hydrogen at the pump for use in the vehicle means significant energy costs are associated with getting hydrogen to the vehicle.

An evolving challenge for hydrogen infrastructure planners is whether to design for dispensing gaseous or liquid hydrogen at the vehicle, and what standards will be tied to each form of hydrogen. Automotive hydrogen fueling stations will not be able to support heavy-duty trucks due to the significantly different volumes of fuel needing to be dispensed per vehicle. Heavy-duty HFCEV trucks will need 50 to 80 kg of fuel, whereas cars like the Mirai use approximately 4 kg per fill [66][67]. Hydrogen internal combustion engine trucks may require even larger fuel capacities than fuel cell ones for similar ranges due to their lower energy conversion efficiencies.

7 Technology and Infrastructure Changes Since First NACFE Report

There have been developments in technology and infrastructure since the original release of *Making Sense of Heavy-Duty Hydrogen Fuel Cell Tractors* [2]. The most significant is the development of hydrogen internal combustion engines, essentially adaptations of traditional diesel engines replacing diesel or natural gas combustion with hydrogen combustion.

7.1 H_2 ICE Engines

A hydrogen internal combustion engine alternative presents a near-zero emissions vehicle that has the capability of going longer distances with shorter refuel times and weighing less than a battery electric vehicle specified to do the same job. The hydrogen ICE also preserves the conventional powertrain and will likely have a significantly lower initial cost than an equivalent fuel cell equipped vehicle. However, the overall efficiency of the hydrogen ICE vehicle in terms of miles per kg of H_2 will likely be less than the HFCEV alternative. It should generally have better efficiency on an energy-equivalent basis compared to natural gas-powered engines.

Of course, the hydrogen ICE alternative must overcome the challenges of fuel creation, cost, transportation and storage that any other hydrogen alternative has as outlined in other parts of this report. In addition, the challenges of servicing and maintaining hydrogen ICE vehicles also will be more involved than traditional diesels.

Once hydrogen has been stored on the vehicle in either gaseous or liquid form, there are several ways of using that stored energy to move the vehicle down the road. Three approaches to using hydrogen to move a truck are first the fuel cell, which has received a great deal of press over the past few years. Second, a more conventional internal combustion engine can use hydrogen in a similar way to the way natural gas or methane is used. The hydrogen ICE is a spark ignited versus a compression ignition engine like the conventional diesel application. Third, hydrogen fuel can be combined with natural gas or other spark-ignited fuel in a dual fuel or blended arrangement. This third approach creates several redundancies in vehicle hardware design and may be more complex to build and maintain in the heavy-duty transportation space.

7.1.1 Hydrogen ICE Basics

For use in ICE applications, hydrogen has some distinct advantages as a fuel.

- Since the primary combustion product is water vapor, emissions can be minimized. The hydrogen internal combustion engine has virtually no output of greenhouse gas CO_2, PM or hydrocarbons. However, NOx, is still a byproduct of the combustion process. This is described in the next section on disadvantages.
- Hydrogen internal combustion engines have a very broad range of fuel-air mixtures where combustion can be initiated. This allows the engine manufacturers a great deal of flexibility to tune the air-fuel ratios and other combustion parameters to meet targets for power output and emissions performance.
- The energy to initiate combustion in a hydrogen internal combustion engine is relatively low compared to gasoline or natural gas, so the combustion ignition system has fewer demands on it.
- Hydrogen as a fuel allows the use of slightly higher compression ratios in the engine compared to other spark ignited fuels, thus allowing somewhat greater thermal efficiency to be achieved.

However, hydrogen also has some disadvantages when used in an ICE configuration.

- Hydrogen combustion in an ICE can be prone to pre-ignition problems where combustion is started at the wrong time resulting in knock or backfire.
- NOx output of the combustion process can still be a problem due to high combustion temperatures and the presence of nitrogen in the intake air. Although there are ways to minimize NOx output, NOx aftertreatment will almost certainly be required for hydrogen internal combustion engines similar to traditional diesels. Large amounts of exhaust gas recirculation (EGR) also almost certainly will be required to manage the combustion process.
- Depending on the hydrogen induction system, engine power output can be limited for a given displacement engine. With either a throttle body or port injection system the peak power output almost certainly will be lower than either natural gas or diesel for the same displacement engine. Hydrogen gas takes up more space in the combustion chamber compared to natural gas or any liquid fuel. Therefore, less air (i.e., oxygen) can be introduced in the cylinder volume, thus limiting maximum power output. Direct injection of the hydrogen gas after the intake valves are closed allows the power output to match or slightly exceed that of a natural gas engine for the same displacement.
- Hydrogen combustion works best from a NOx-emissions standpoint with a very high fuel-air ratio (Phi). Natural gas works best where there is just enough oxygen to match the amount of gas that has been introduced. Hydrogen, on the other hand, works best when there is about twice as much oxygen in the combustion chamber as needed for the combustion process. The chart in Figure 20 highlights this. A Phi of 1 represents the stoichiometric fuel-air ratio for the

fuel. Note that NOx emissions go to nearly zero at about 0.5 Phi which represents twice the amount of air compared to the fuel quantity.

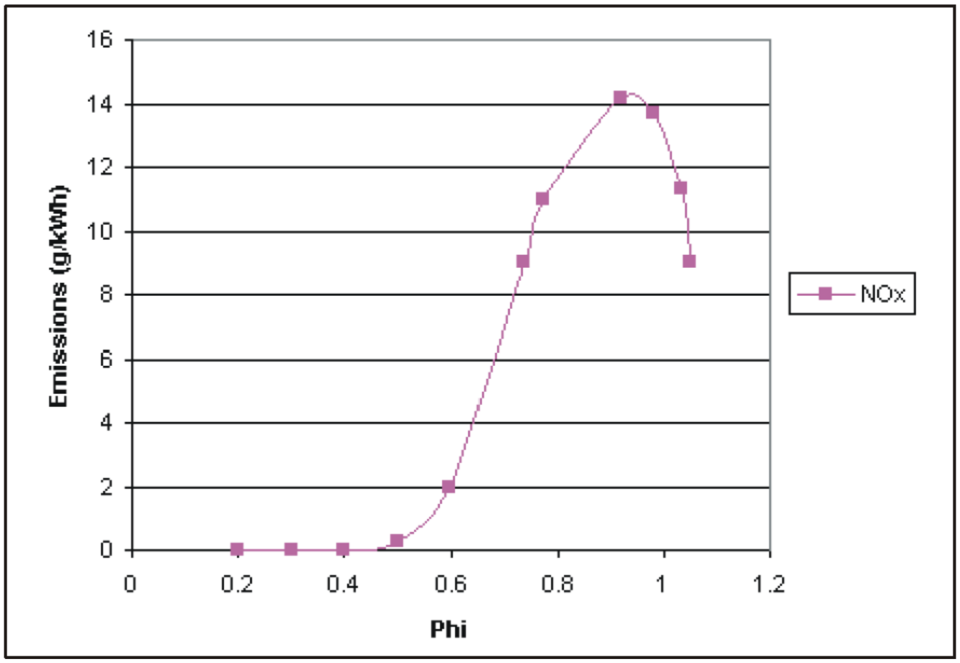


Figure 20. Emissions for hydrogen engine (DOE) [168]

- NOx production can be further managed by recirculating exhaust gas back into the power cylinder. Exhaust gas has a lower oxygen content, so it has the effect of slowing down the combustion process and therefore the peak temperatures that are reached during the power stroke. The lower the peak temperatures achieved, generally the lower the NOx output is. Of course, engine designers must balance all these effects as the engine is under development.
- The need for such a significant amount of excess air (much more than even diesel applications) means the matching of the turbomachinery and EGR systems will be a challenge for engine designers.

Cummins has written that hydrogen internal combustion engines tend to have the best fuel efficiency when they are heavily loaded [170][171]. Conversely, the hydrogen fuel cell tends to have the best efficiency at lighter load conditions. Generally, it would appear that the hydrogen ICE overall efficiency is likely to be lower than that of the hydrogen fuel cell due to differences in the physics of converting energy [169]. It is possible that the efficiency numbers in real-world operational hydrogen ICE and fuel cells may be close enough that matching the chosen technology to the vehicle's duty cycle as well as the initial cost of the vehicle will be a critical part of determining the best product for a particular application.

Two additional challenges NACFE identified relative to hydrogen internal combustion engines:

- In order for the ICE manufacturer to reach reasonable power-to-displacement numbers with a hydrogen ICE vehicle, direct injection of hydrogen gas will be required, as opposed to liquid, into the power cylinder after the intake valves are closed. This technology is not widely used in any production high-volume engine applications. Traditional direct fuel injection systems have been designed to work with liquid fuels that are injected at fairly high pressures that provide good atomization and distribution of the liquid as it passes into the combustion chamber. Injecting a gaseous fuel is quite a different story and NACFE believes the technology for doing so is still relatively new and unproven. If engine manufacturers have to revert to port injection, then both the power density of the engine package and the efficiency will be lower than with the direct injection alternative. This will make the hydrogen ICE a less attractive alternative in the marketplace.

- The other concern with hydrogen ICE is the potential for hydrogen embrittlement of metals in the engine [172][173][174]. Hydrogen is such a small molecule that it can infiltrate some metals and cause engine parts to become much more brittle and susceptible to fracture. Steel, iron and some other metals are particularly susceptible to hydrogen embrittlement. Although this is a problem that must be solved with any hydrogen delivery system, the ICE alternative has many more parts that could be subjected to embrittlement than a fuel cell system. Of course, engine manufacturers are aware of this phenomenon and will be actively working to minimize any effects, but it remains a concern due to the newness of the technology. Hydrogen embrittlement in engines has occurred in the past with traditional diesel fuel injection systems due to processing issues, and process changes were successfully implemented to avoid failures.

7.2 Reliability Growth of Major Components

In 2020, the DOE's Hydrogen and Fuel Cell Technologies Office (HFTO) hydrogen program launched the Million Mile Fuel Cell Truck Consortium (M2FCT), a DOE-funded consortium formed by five primary national labs to overcome durability and efficiency challenges in polymer electrolyte membrane fuel cells (PEMFCs) for heavy-duty applications with an initial focus on long-haul trucks [154][155][156].

M2FCT began setting a 2025 heavy-duty truck fuel cell lifetime durability goal of 25,000 hours, estimated to be a million miles of operation. The ultimate goal is 30,000 hours as shown in Figure 21 [154].

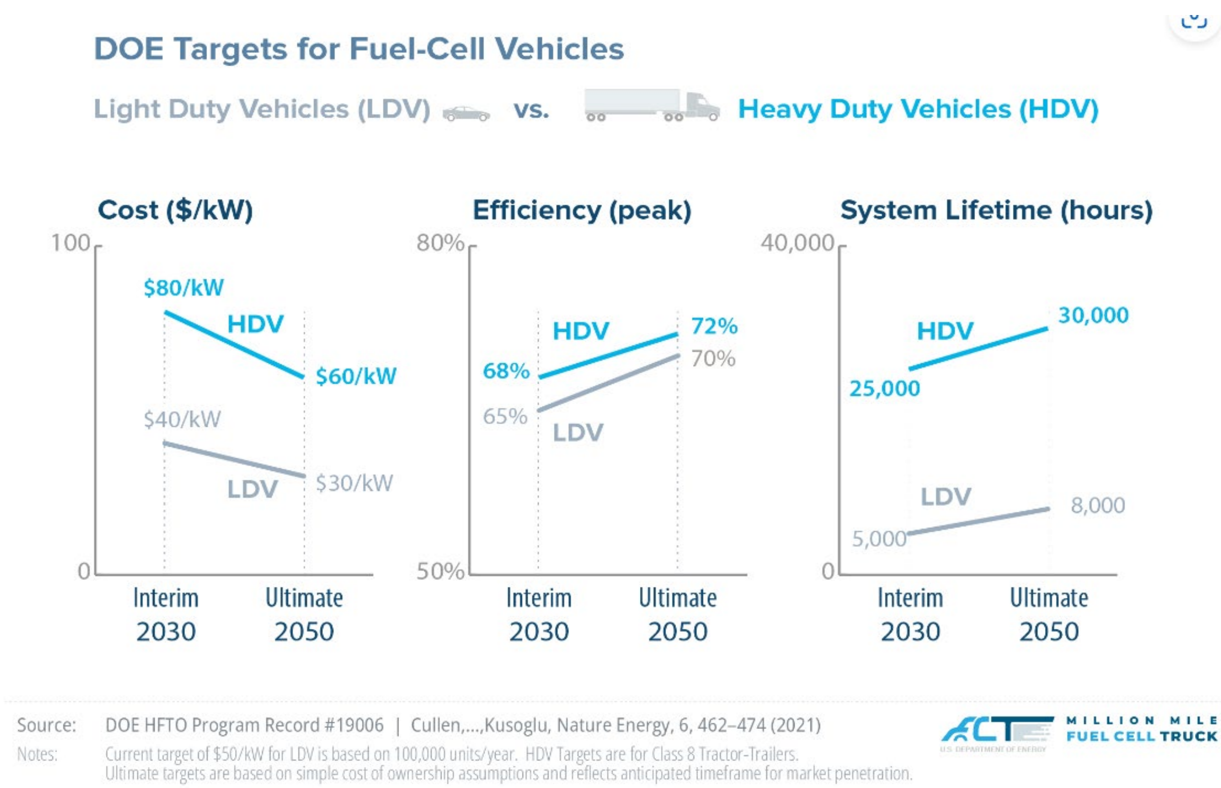


Figure 21. DOE Targets for Fuel-Cell Trucks (DOE) [154][155]

The hours are intended to reflect one million miles of heavy-duty truck operations. As there are very limited numbers of production heavy-duty HFCEVs in real-world operations, much of this work is somewhat theoretical or prototype based. However, fuel cell technologies have been maturing for decades in multiple environments and uses. The technology needed to make a long-lived heavy-duty truck fuel cell likely is known, the challenge is making it affordable.

As an example of costly materials, currently platinum is a critical fuel cell material required to attain a 25,000-hour operational life for heavy-duty trucks. Less expensive substitutes may be possible for use in automotive fuel cells, but platinum is required for the long-lived heavy-duty truck cells. The entire system supporting the fuel cell will introduce new materials and processes to the long-haul trucking environment. There will be a learning curve as the technology transfers from the lab and prototypes into real-world operations, as has been repeatedly experienced with other new technology introductions over the last century.

7.3 Hydrogen Projects Tied to Trucking

Significant funding is being allocated to hydrogen freight projects since the NACFE 2020 report. A sampling of these is discussed in this section.

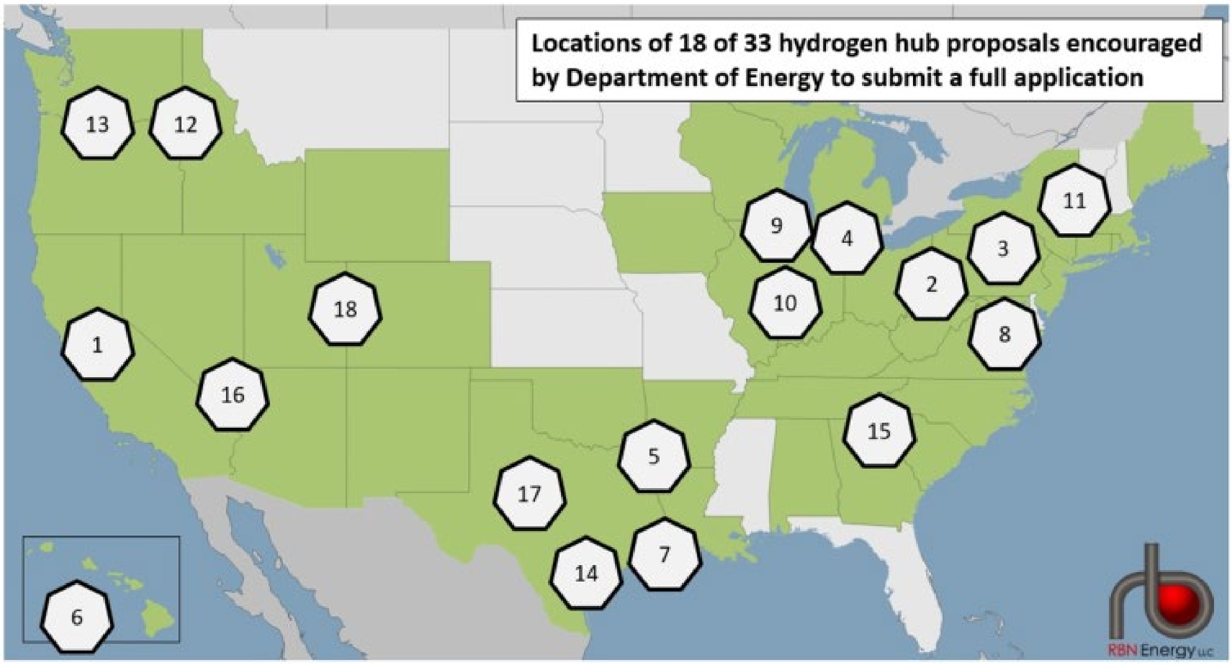
7.3.1 Hydrogen Hubs

In 2022, the DOE announced $8 billion in funding for a hydrogen hub program as part of the IIJA [31][32]. Of that amount, $7 billion is earmarked to fund establishing "six to 10 regional clean hydrogen hubs across America." A clean hydrogen hub is a regional network of clean hydrogen producers, clean hydrogen users, and the associated infrastructure [75]. The DOE also released a draft of the National Clean Hydrogen Strategy and Roadmap [74].

The objectives of the funding opportunity include community social justice goals:

- Support meaningful community and labor engagement;
- Invest in America's workforce;
- Advance diversity, equity, inclusion, and accessibility; and
- Contribute to the President's goal that 40% of the overall benefits of certain federal investments flow to disadvantaged communities.

The DOE received 79 hydrogen hub concept paper submissions as of December 2022 constituting some $60 billion in funding requests [76]. The DOE encouraged 33 of these to submit full applications in the spring of 2023 [73]. While the complete list has not been published, applicants are permitted to release public statements. Jason Lindquist, an analyst for RBN Energy LLC, assembled a list of 18 of the 33 from scouring public records, outlined in Figure 22. Funding awards are expected to be announced in 2023. It is possible that regional groups may combine proposals to improve their chances of receiving DOE awards.



Project	States Involved	Project	States Involved
1. Alliance for Reliable Clean Hydrogen Energy Systems	CA	10. Midwestern Hydrogen Coalition	IL, IN, KY, MI, MN, OH, WI
2. Appalachian Regional Clean Hydrogen Hub	WV, KY, OH	11. Northeast Region Hydrogen Hub	NY, CT, NJ, MA, RI, ME
3. Decarbonization Network of Appalachia	PA	12. Obsidian Pacific Northwest Hydrogen Hub	OR, WA, ID
4. Great Lakes Clean Hydrogen	OH, MI, PA, IN	13. Pacific Northwest Hydrogen Hub	OR, WA
5. HALO Hydrogen Hub	OK, AR, LA	14. Port of Corpus Christi	TX
6. Hawaii Pacific Hydrogen Hub	HI	15. Southeast Hydrogen Hub	KY, TN, AL, GA, SC, NC
7. HyVelocity Hub	TX, LA	16. Southwest Clean Hydrogen Innovation Network	AZ, NV
8. Mid-Atlantic Hydrogen Hub	DC, MD, VA	17. Trans Permian H2Hub	TX, LA
9. Midwest Alliance for Clean Hydrogen	IL, MI	18. Western Interstate Hydrogen Hub	CO, NM, UT, WY

Figure 22. Subset of hydrogen hub applicants (Lindquist) [73]

The DOE-funded hydrogen hubs are a small down payment on a national hydrogen infrastructure. Fully replacing the diesel heavy-duty long-haul transportation infrastructure with hydrogen is potentially trillions of dollars in investment over decades. That investment must cover electrolyzer production, hydrogen production facilities, storage facilities, and a distribution network including trucks, pipelines and other methods. There are costs for developing carbon capture and sequestration capacity and increasing the production and distribution of electricity production to enable green hydrogen production.

7.3.2 Hy Stor

The Hy Stor Energy in Port Bienville, Mississippi, is an example of a green hydrogen production infrastructure. This project is "expected to produce an estimated 350 tons/day (320,000 kg/day) of renewable hydrogen and store more than 71,000 tons (69 million kg) of hydrogen in underground salt caverns [77]." Combining green hydrogen production with storage is intended to ensure 24/7 reliability for energy supply, including seasonal factors. Hydrogen is to be produced through a combination of solar and wind energy powering electrolyzers [78]. The Gulf Coast location also is amenable to establishing a hydrogen export capability.

7.3.3 Houston HyVelocity Hub

The Houston-centered HyVelocity Hub is an example of a multi-state, multi-organization effort to secure DOE hydrogen hub funding to establish a hydrogen ecosystem per the Houston Clean Energy Roadmap [79][80]. The region is already a hydrogen producer and user due to the extensive petroleum refining industry where hydrogen is used in the refining of oil products like diesel and gasoline. This region has more than 900 miles of existing hydrogen pipelines as shown in Figure 23 representing half of all existing US hydrogen pipelines. The region also has available potential underground storage caverns [80]. The region also is well suited for establishing a hydrogen export capability.

Figure 23. Existing hydrogen system in Gulf Coast area (Center for Houston's Future) [80]

The Texas Triangle, the interstate highway network connecting Houston, Dallas/Fort Worth and San Antonio, represents an opportunity for hydrogen. Major cities in the south-central US are separated generally by distances between 250 to 550 miles, with round trips of 500 to 1,100 miles as illustrated in Figure 24.

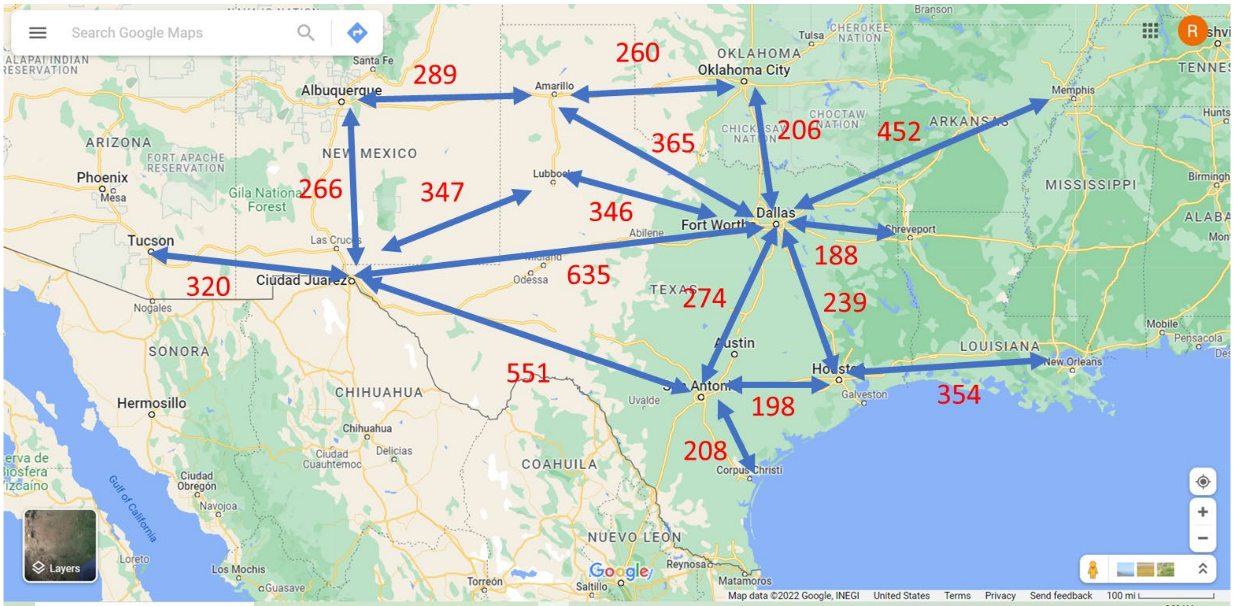


Figure 24. Miles between major urban centers in south central U.S. (NACFE) [81]

These long-haul ranges are challenging for battery electric trucks that are currently primarily focused on 150 to 250-mile ranges between charges. A challenge today is that the early hydrogen fuel cell prototypes are being designed for 300- to 500-mile ranges between fills, which also may be challenging on some routes. Daily hours of service rules permit 11 hours of driving time, typically averaging between 55 mph and 65 mph, representing daily one-driver, one-fill truck ranges need to be on the order of 600 to 700 miles with some reserve. Fuel storage on the vehicle becomes more challenging at these ranges leading to chassis lengths longer and heavier than their diesel equivalents. These challenges exist for the hydrogen ICE vehicles as well because the hydrogen does not package as densely or as cost effectively as liquid diesel.

7.3.4 Pacific Northwest Hydrogen Association Hub

A Washington-Oregon collaboration for DOE hydrogen hub funding is the Pacific Northwest Hydrogen Association (PNWH$_2$). The extensive hydro, wind and solar power in the Northwest region represents a significant resource for creating green hydrogen through electrolysis [82]. A goal of the DOE hydrogen hub effort is to promote diversity in energy associated with creating hydrogen. Where the Houston hub is capable of building off an existing fossil fuel hydrogen infrastructure with carbon capture and sequestration technology, the PNWH$_2$ hub is building from an existing renewable energy foundation to produce what one group terms evergreen hydrogen [83]. According to the Washington State Department of Commerce, "The PNWH$_2$ Hub serves a diverse stakeholder group in the Pacific Northwest that will leverage several of the region's primary strengths: abundant renewable energy resources, utility companies that today produce 81,000 MWh of clean energy (including hydroelectric), 947,000 labor union members, 172 transit providers, 64 public colleges and university zones [82]."

7.3.5 Midwest Alliance for Clean Hydrogen Hub

A Midwest group pursuing DOE hydrogen hub funding is the Midwest Alliance for Clean Hydrogen (MachH$_2$) [84]. This coalition includes representation from seven Midwest states — Illinois, Indiana, Kentucky, Michigan, Minnesota, Ohio and Wisconsin. This diverse region's electric grid has a significant, nuclear power component and a growing renewable power sector, representing yet another foundation to producing hydrogen. According to MachH$_2$, "Hydrogen projects already proposed by alliance members will support an estimated 4,500 construction jobs and 400 permanent positions once complete. Total construction spending is estimated at nearly $4 billion, including $1.7 billion in wages and $65 million to $70 million in state income taxes. The 400 permanent positions will generate an estimated $60 million in wages annually — or roughly $900 million over the 15-year operating life of the projects — and an additional $35 million to $40 million in state income taxes. More projects may be added as the hub continues to develop, leading to further economic benefits for the region [84]."

7.3.6 Northeast Region Hydrogen Hub

The Northeast Region Hydrogen hub coalition includes representatives from Connecticut, Maine, Maryland, Massachusetts, New Jersey, New York, and Rhode Island. This region includes diverse energy sources, major urban centers and significant rural regions. Urban centers in this region are separated by distances ranging between 50 and 200 miles as shown in Figure 25. These ranges are suited to a mix of heavy-duty truck types including battery electric, hydrogen fuel cell, hydrogen ICE and other vehicles.

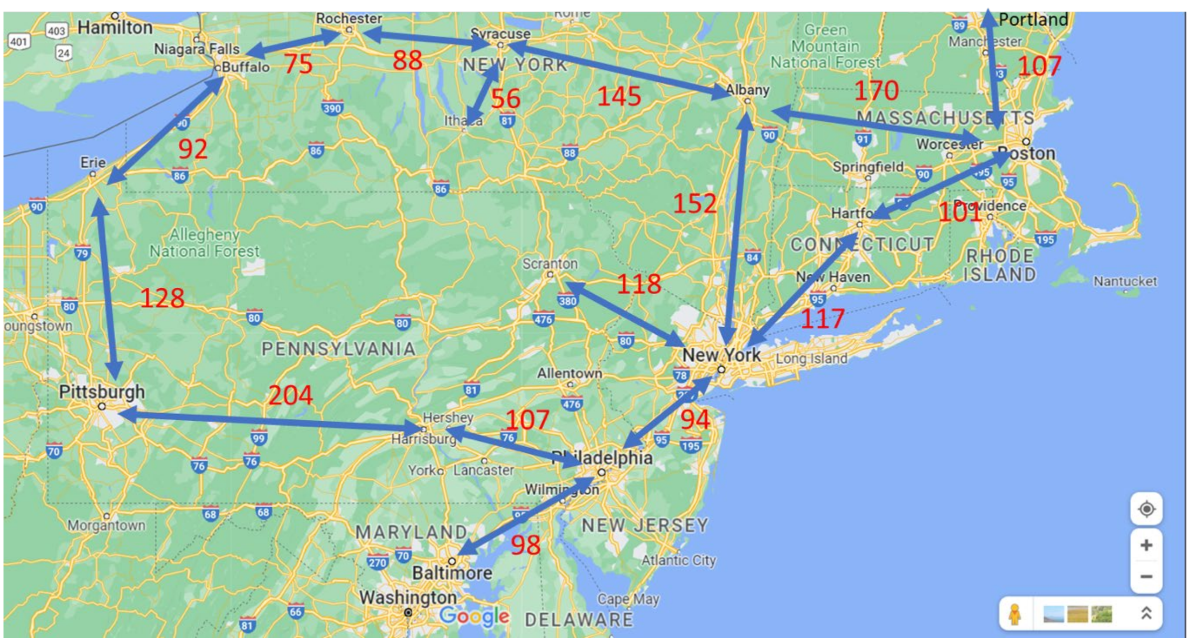


Figure 25. Miles between urban centers in northeast region (NACFE) [81]

The northeast regions suitability to multiple powertrain technologies means competition between them, with more factors than range to be considered. Note that Pennsylvania is not part of this coalition, rather they submitted their own hydrogen hub proposal, The Decarbonizing Network of Appalachia [73][85].

7.3.7 Alliance for Renewable Clean Hydrogen Energy Systems

California is unquestionably in the US lead in deploying hydrogen infrastructure and demonstrating hydrogen fuel cell trucks, cars and buses. The Alliance for Renewable Clean Hydrogen Energy Systems

(ARCHES) is a public-private partnership pursuing DOE hydrogen hub funding [85][87]. Prior projects at the Ports of Los Angeles and Long Beach, along with new projects at the Port of Oakland have focused on establishing the viability of heavy-duty hydrogen fuel cell trucks in port drayage operations with Kenworth, Toyota, and others. Companies such as Anheuser-Busch and Biagi Bros are demonstrating hydrogen fuel cell vehicles with Nikola in beverage delivery service. There are active programs building hydrogen production and storage infrastructure. California also has a focus on social justice aspects of a hydrogen economy. A governor's press release states, "Success on this project means that hydrogen will accelerate electrification across multiple sectors while opening opportunities to bring zero-emission solutions to multiple, hard-to- electrify sectors, including heavy industry. It means the ARCHES system will increase confidence, enabling exponential growth in private capital — the capital ultimately needed to scale the market and drive costs down for everyone. And it means clean air, especially for those who have suffered the most, along with the creation of green jobs and economic growth across the state [88]."

7.4 ALBERTA PROJECTS

NACFE's *Making Sense of Heavy-Duty Hydrogen Fuel Cell Tractors* report discussed plans to create a hydrogen freight corridor in Alberta, Canada, capitalizing on Alberta's extensive natural gas supply infrastructure. According to an expert interviewed by NACFE, the Calgary-Edmonton freight corridor reportedly sees 5,000 trucks per day and there are some 110,000 trucks in Alberta. Since that initial NACFE report, the government of Alberta published a hydrogen roadmap in November 2021 [94]. They outlined the primary objectives as follows:

1. **Build new market demand**. Establishing hydrogen demand is required to build out supply and commercialization pathways.
2. **Enable Carbon Capture, Utilization and Storage (CCUS).** For Alberta to deploy clean hydrogen into the economy, CCUS infrastructure must be widely available.
3. **De-risk investment**. Long-term investment certainty and funding are required as hydrogen is an emerging opportunity with challenging economics.
4. **Activate technology and innovation**. Demonstration projects, research, and innovation are needed to prove and scale emerging clean hydrogen technologies. Training and development with Alberta's world-class universities and technical schools are important to support a labor force capable of working within the hydrogen economy.
5. **Ensure regulatory efficiency, codes, and standards to drive safety**. As the clean hydrogen economy is emerging, a regulatory regime including codes and standards must be inclusive of hydrogen and enshrine a safety-first mindset across the value chain.
6. **Lead the way and build alliances**. Public-private partnerships and government-to-government relationships, including with Indigenous partners, are essential to advance the hydrogen economy, send coordinated signals to investors, and build public education and acceptance.
7. **Pursue hydrogen exports**. The international community is looking to lock in hydrogen supply agreements now. Alberta must move aggressively to establish market access and close intra-Alberta and hydrogen export gaps in supply chain logistics.

A key element of the plan is building Canada's first hydrogen hub in the Edmonton region. In May 2021, Suncor and ATCO announced plans to build a world-class hydrogen plant that includes capability to capture and store 90% of CO_2 produced in making the hydrogen [95][96]. The plant is described by the government of Alberta as follows: "Project details include a joint venture between Suncor and ATCO to build a hydrogen production facility, capable of producing 300,000 tonnes of hydrogen annually. It will be located near ATCO's Heartland Energy Centre near Fort Saskatchewan. The project is expected to face an investment decision in 2024 and could be operational as early as 2028. According to Suncor, approximately 65% of the hydrogen would be used by Suncor in refining processes and cogeneration of steam and electricity, reducing emissions by up to 60% at its Edmonton refinery. Another 20% would be added to the provincial natural gas grid to reduce emissions from uses such as home and business heating. The rest will be sold to various users."

In June 2021, Air Products also announced plans to build a hydrogen production and liquification plant in Edmonton [97][98]. The graphic in Figure 26 outlines the proposed hydrogen system.

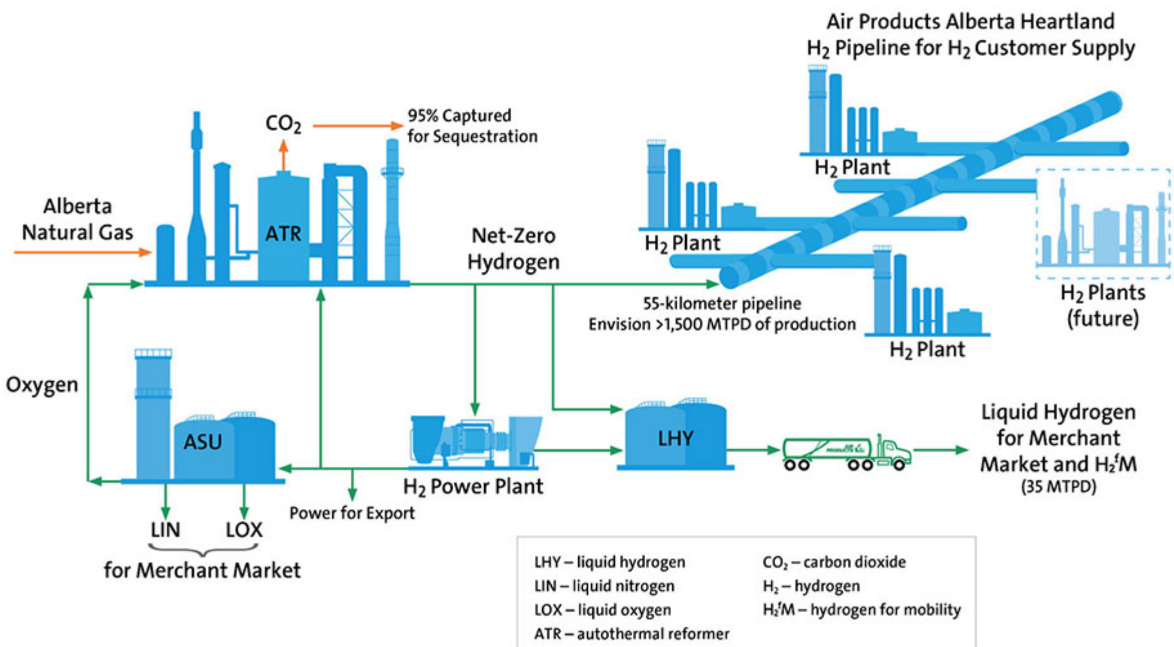


Figure 26. Edmonton Air Products hydrogen production plan (Air Products) [98]

Imperial, a user of Air Products hydrogen, plans "to produce renewable diesel at Strathcona that substantially reduces GHG emissions relative to conventional production. The hydrogen and biofeedstock will be combined with a proprietary catalyst to produce premium low-carbon diesel fuel [99]."

A freight-focused effort reported by NACFE in its first hydrogen report is the Alberta Zero-Emissions Truck Electrification Collaboration (AZETEC) project [94]. "The AZETEC project includes the design, manufacture, and deployment of two prototype heavy-duty extended-range hydrogen fuel cell electric trucks that will move freight between Edmonton and Calgary and includes a demonstration fueling station. The C$15-million project is led by the Alberta Motor Transport Association and has received more than $7.3 million from Emissions Reduction Alberta. Following the trial period, the next phase of the project envisions a fleet of several dozen hydrogen-powered trucks and a network of fueling stations." Funding for the fueling station was authorized in June 2021 [104]. The two prototype Freightliner hydrogen fuel cell trucks operating with gross vehicle weight ratings (GVWR) of 64-tonne (141,000 lbs.) and operating as B-train doubles were expected to attain up to 700 km (434 miles) between fueling stops. The B-train doubles are 53' van trailers. The latest expectation is that the two trucks will be operational in the second or third quarter of 2023, originally planned to be on the road in July of 2021 [105][106]. Additional fuel cell trucks may be used in the transport of hydrogen in Alberta. The two fleets investigating the fuel cell vehicles are Bison and Trimac.

The specifications for these Canadian trucks are significantly different than those being demonstrated in the US. According to Jude Grove, chair of the Alberta Motor Transport Association (AMTA), "The US builds trucks to lower weights, to shorter distances, and does not design them, at least in a preliminary phase, for Canadian climates." He says, "So, we've really turned that process on its head, designing a truck that was built to be able to pull Canadian weight, travel distances that are larger than standard long-haul vehicles and are built for Canadian climates [106]." Tare weights of hydrogen vehicles are expected to still be greater than the diesels they replace, though not as much as equivalent battery electric vehicles would be for the same ranges. One expert contacted by NACFE estimated that the fuel tank weights are approximately 25 kg (55 lbs.) of materials per 1 kg (2.2 lbs.) of hydrogen at 350 bar (~5,000 psi) pressures.

Tank sizes have complicated the designs of the prototypes. The original AZETEC range goal was a 600 km (~380 miles) round trip from Calgary to Edmonton. Experts contacted by NACFE indicated the current designs now have settled on a 300 km (217 mi) range with 70 kg (154 lb.) of 350-bar gaseous hydrogen with plans to refuel midway to achieve the 600 km (~380 miles) round trip. The 350-bar fueling also allows the fueling station to service potential fuel cell buses planned in the region.

The station in Edmonton is reportedly planned to be 200 kg (400 lbs.) per day — a pilot installation — but initial use will be from trailer tanks. As of September 2022, the City of Edmonton's Fleet and Facility Services Branch Manager Eddie Robar said, "The City of Edmonton and Strathcona County will use the first hydrogen vehicle fueling station in Alberta, which is a collaboration between Suncor and the Alberta Motor Transport Association. The City of Edmonton's new hydrogen fuel cell electric bus will be fueled daily at Suncor's Edmonton liquefied petroleum gas (LPG) loading facility using a leased mobile hydrogen storage trailer from HTEC, with the hydrogen fuel being generated by Suncor. The same is true for Strathcona County's new hydrogen fuel cell electric bus [114]." There are reportedly only six hydrogen stations in Canada outside of Alberta as of late 2022, four in British Columbia, one in Toronto and one in Quebec as shown in Figure 27 [115].

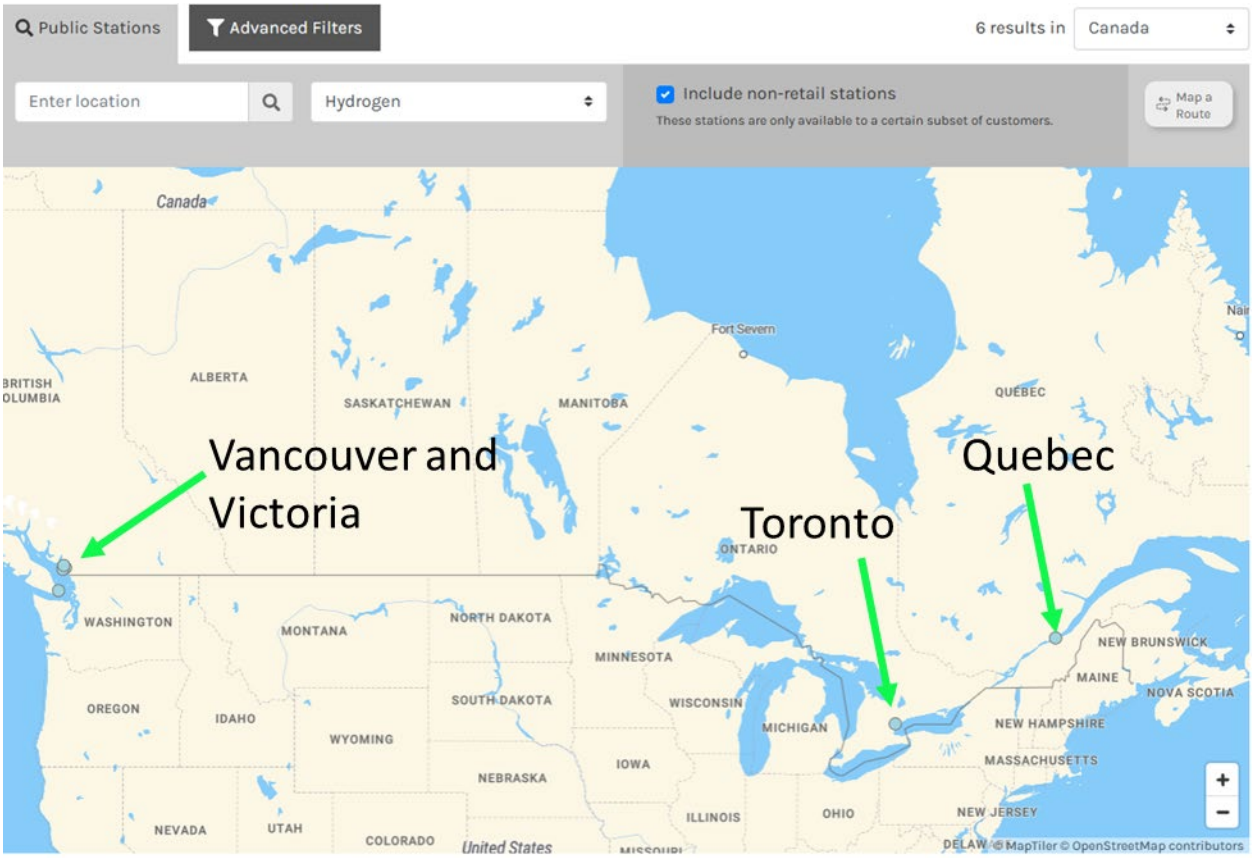


Figure 27. Hydrogen fuel stations Canada (NRC) [115]

Hydrogen also is being demonstrated in freight trains through the Canadian Pacific Railway, Edmonton buses, and some 230 fuel cell forklifts are operating at a Walmart facility in Alberta [94].

Hydrogen is a regional solution for Alberta due to the province's extensive engagement with fossil fuels. Critical to success will be to actualize, at scale, carbon capture, utilization and storage (CCUS) technologies. According to the Albert Hydrogen Roadmap, Alberta currently hosts two large-scale CCUS projects that reduce industrial emissions, described below [94].

- In 2015, the Quest project began operations to the northwest of Edmonton, capturing over five Mt of CO_2 by the end of 2020. The CO_2 emissions are captured from hydrogen production at three steam-methane-reforming (SMR) units at the Scotford Upgrader complex, which is owned by the Athabasca Oil Sands Project consortium and is operated by Shell Canada. Hydrogen is required to upgrade oil sands and heavy oil into synthetic crude oil, increasing its overall quality and efficiency to transport by pipeline. The captured CO_2 is transported 65 kilometers to the north by pipeline and injected by three wells into a two-kilometer deep underground geologic reservoir for permanent storage.
- In 2020, the Alberta Carbon Trunk Line (ACTL) commenced operations as one of the world's largest CCUS systems with CO_2 gathering and transportation infrastructure, and the capacity to transport up to 14.6 Mt of CO_2 per year. The ACTL currently transports approximately 1.6 Mt of captured CO_2 per year by a 240-kilometre pipeline from the North West Redwater Partnership Sturgeon Refinery and the Nutrien Redwater Fertilizer Facility to mature oilfields in Central

Alberta for enhanced oil recovery (EOR) and permanent storage. Multiple partners are involved with the ACTL, including Wolf Midstream which owns and operates the pipeline and Enhance Energy, which owns and operates the geologic storage reservoir. Based on its current capacity, the ACTL could support an additional 12 Mt of CO_2 per year.

Carbon capture is not constrained to the production of hydrogen. NACFE also discussed with an Alberta company that diesel trucks with on-board carbon capture capability were being investigated for use in delivering materials to cement plants. The duty cycle for this is very specific to this operation. Diesel truck emissions are captured on the trucks as they travel from and then to the cement plant where they can deliver both raw materials and the CO_2 to the plant which uses both in the creation of cement. Remora is one of the technology developers for this capability [107][108]. An example diesel truck outfitted with Remora carbon capture is shown in Figure 28.

Figure 28. On-board carbon capture (Remora) [109]

The Alberta hydrogen roadmap recognizes that several technology areas need to mature. "Closing technological gaps and reaching higher technology readiness levels for some production and deployment applications will allow for a smoother transition to a future where clean hydrogen becomes widespread and integrated as both an energy carrier and commodity. Areas for additional research and accompanying technology, innovation, and demonstration support may include:

- Methane-based technologies such as methane pyrolysis and chemical looping which show significant promise but are not yet at a high technology-readiness level.
- Underground coal gasification with CCUS and biomass conversion, which both show promise as clean hydrogen production methods for Alberta.
- Research and analysis to better understand hydrogen impacts on high-pressure steel pipes as well as other system-wide impacts (for example, compression requirements, welding, and maintenance) to ensure operational safety as hydrogen is transported across the province to an expanding base of end users.
- Research to determine ideal carbon sequestration locations and available pore space for permanent CO_2 storage in the province. Clean hydrogen production will require accompanying incremental carbon sequestration.
- Research for hydrogen storage options with natural gas, including salt caverns. Given its small molecular size, hydrogen may be prone to migration from storage compared to

natural gas. As such, it will be critical to better understand the ability of salt cavern storage to contain hydrogen [94].

In NACFE's interviews with Canadian fleets, a further area needing to mature is with fuel cell and infrastructure cold weather and snow operations that see arctic conditions. Testing in the AZETEC project is expected to validate capabilities in the temperature range "from -30°C (-22°F) to +30°C (86°F), the ability of the infrastructure to provide SAE J2719 purity hydrogen, re-fueling within 20 to 45 minutes, while enabling safe and reliable operation and management of the hydrogen fueling station for daily fueling [111]." Temperatures in Calgary and Edmonton have seen records as low as -43°C (-45°F) and over 21 days of snowfall [112][113].

NACFE's interviews also found that low-cost hydrogen requires large production. Scaling hydrogen requires increasing demand across a range of industries, not just transportation, as transportation does not represent enough demand. Putting that in perspective, if trucks need 140 kg of hydrogen a day to traverse the Calgary-Edmonton round trip, and there are 5,000 trucks on that corridor, that translates to a demand of perhaps only 700,000 kg (1,543,235 lbs.) per day. The planned Suncor plant is expected to produce 300,000 tonnes of hydrogen per year, which translates to approximately 821,000 kg (1,810,015 lbs.) per day for a 365-day year. Even if all the trucks on the corridor operated seven days a week, the single plant will exceed demand. So other new users and new demand are required to use these large hydrogen plant outputs such as trains, buses, industries like cement, etc. If part of the new hydrogen capacity is slated to go to producing renewable diesel, that means fewer hydrogen trucks would be used. Modeling demand growth across multiple industries is challenging, but required to rationalize use and support getting to low-cost hydrogen.

Alberta is committed to hydrogen as a molecular fuel industry critical to advancing the nation's economy as it transitions to cleaner energy, but officials are also committed to natural gas as the primary raw material for hydrogen. The success of these efforts will depend greatly on CCUS technologies and markets proving out at scale.

7.5 Canada and Germany Hydrogen Exports/Imports

Beyond Alberta's efforts, Canada sees significant opportunity to become a major hydrogen exporter to the world as predicted in NACFE's *Making Sense of Heavy-Duty Hydrogen Fuel Cell Tractors* report. According to CBC in March 2021, Canada "signed agreements to use hydro power on the east coast to produce hydrogen for export to Germany and other markets [109]." In August 2022, a joint declaration of intent also was signed forming a "hydrogen alliance" establishing a "transatlantic Canada-Germany supply corridor" by 2025 for starting hydrogen exports [110]. "Under the agreement, Canada will export wind-generated hydrogen to Germany as that country looks to move away from Russian imports. While the Ukrainian war has made for an immediate crisis, Germany also has been shopping for long-term sustainable solutions," the German Chancellor stated. "Hydrogen will play a major role in Germany's future energy supply, especially in industries that are hard to decarbonize, such as shipping and aviation."

7.6 WASHINGTON DAM PROJECT

A new project in eastern Washington state has the potential for providing hydrogen infrastructure for trucking. Dams on rivers differ from dams on lakes in that operators are expected to maintain river flows rather than accumulate water in reservoirs. This presents energy producers with some challenges since river flows are not necessarily synchronized with regional power demands over the course of a day, week or month. Balancing electricity production with electricity demand is what permits the grid to function. Currently, river dam energy when demand is low is wasted by turning off generation or shedding unneeded electricity. A new approach being implemented at the Wells Dam is to salvage unneeded river energy by creating hydrogen. The hydrogen can then be marketed regionally.

Cummins is providing a 5 MW electrolyzer for the Douglas County Public Utility District (PUD) [116]. The pilot facility, according to NACFE interviews, is sized to create 2,000 kg of hydrogen per day, to be stored in 36 above ground tanks. The hydrogen would then be trucked by two tube-trucks per day to various industrial sites and fueling stations. The tube trucks would carry gaseous hydrogen at 500 bar (7,500 psi). There is no liquid hydrogen planned at the pilot facility. Interviewees felt liquification would have significantly increased the size of the plant needed for the pilot. The hydrogen will be trucked to locations such as Centralia, WA, about 260 miles from the hydrogen plant as shown in the map in Figure 29. Groundbreaking occurred in March of 2021 [117]. A Washington State University concept study detailed that an electrolyzer takes 55.5 kWh of electricity to produce 1 kg of hydrogen [119]. The research suggests potential new hydrogen markets in the farm industry powering farm equipment.

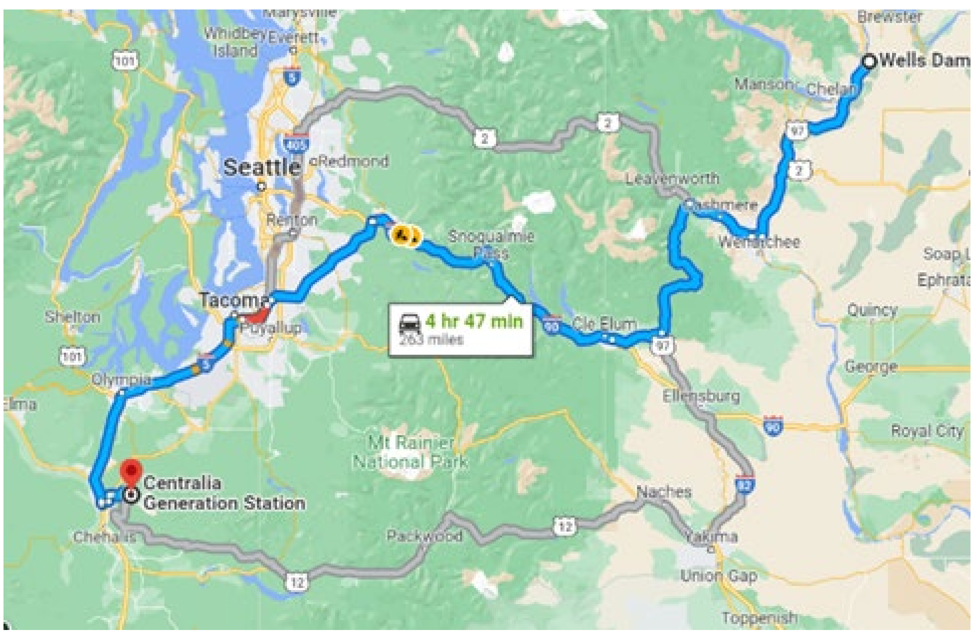


Figure 29. Potential hydrogen freight corridor (Google Maps) [118]

Energy storage is one of the evolving promises of hydrogen. Hydrogen molecular fuel has the potential of being created in June and used in January, taking advantage of energy sources when demand is low to create hydrogen, and then storing it until such time that demand is high. Or to put that another way, create hydrogen when its cheap to do so, and sell it when it the market will pay higher prices. There are flip sides to all technologies — benefits and impediments. It is difficult to predict how these will impact the retail price of the hydrogen fuel.

The Wells Dam hydrogen project epitomizes the "build it and they will come" nature of new technology adoption. The demand market for hydrogen in the region will need to grow to support the production of the hydrogen plant at Wells Dam. This requires hydrogen trucks to be available commercially, whether as fuel cell or internal combustion engines. It requires other industrial users — potentially even agricultural use of hydrogen for farm equipment — to increase demand for hydrogen in place of other energy types. These market shifts are out of the control of the PUD operating the hydrogen plant, however, producing the hydrogen is clearly the starting point for those other market demand areas to be incentivized to grow.

7.7 Hydrogen Trucks in the Field

Deployment of hydrogen fuel cell trucks away from major ports has been limited to relatively short demonstrations, where fueling is provided by mobile equipment. The port drayage applications have perhaps seen the majority of operational hours. Port demonstrations at the Los Angeles and Long Beach facilities have received significant media coverage with vehicles from several companies. Less known are trials at the Port of Oakland and Port of Houston.

7.7.1 Hyundai Port of Oakland

At the Port of Oakland, Hyundai is planning to use their hydrogen fuel cell tractors to move imported autos from the port to dealerships in the region. Hyundai is to "deploy 30 Class 8 6x4 XCIENT fuel cell heavy-duty tractors at the Port of Oakland, California, in 2023. The deployment is part of Hyundai's involvement in the NorCal ZERO project. ZERO stands for Zero-Emission Regional Truck operations with Fuel Cell Electric Trucks. [120]" A recent press article states, "Hyundai will deliver 30 XCIENTs — the largest commercial deployment of Class 8 hydrogen fuel cell electric trucks in the US — to the Port of Oakland in the second quarter of 2023. Five more will follow in the third and fourth quarters in the Los Angeles area, subsidized by a $3.5 million U.S. Environmental Protection Agency grant [124]."

The XCIENT is touted by Hyundai as the world's first production fuel cell truck. The company initiated a fleet in Switzerland in 2020 that is expected to grow to 1,600 vehicles by 2025 [121]. An example of 20 fleet vehicles assembled in October 2022 are shown in Figure 30. A view of the entire XCIENT truck is shown in Figure 31.

Figure 30. XCIENT hydrogen trucks in Switzerland (Hyundai) [123]

Figure 31. XCIENT fuel cell planned for Port of Oakland (Hyundai) [125]

Fluctuating green energy prices have been an issue in the Swiss deployment, but the vehicles have reportedly accumulated in excess of 5 million kilometers (3.1 million miles) [122]. Regarding the energy markets, Hyundai said, "The unpredictable disruption in the energy market affects the availability and costs of electricity from sustainable energy sources. This includes the production costs of green hydrogen in the short and medium term. Nevertheless, all the players in the Swiss hydrogen ecosystem are fully committed to their goals to further expand and develop solutions to adapt the overall system to the new situation [121][122]." The European and world energy markets have been dramatically impacted by the war in the Ukraine and its effects on the flow of energy from exporting countries.

The Oakland deployment is facilitated by grant funding. The expectation is that the fleet operator, Glovis America, is to see a comparable cost of ownership to similarly spec'd diesels over a six-year period [125]. One estimate is that more than $29 million has been secured in grants for the Oakland demonstration. The support system for Hyundai's Oakland truck deployment is NorCal Kenworth. Regarding hydrogen fuel costs, Jeffrey Harrington of Air Liquide said, “Today [in 2021] hydrogen is about 2X the price of diesel without government subsidies or incentives [125][126].” He expects that volume increases in trucks and miles along with more infrastructure will bring pricing down and they expect parity with diesel “within a few short years.” However, Harrington goes on to state that “even the Department of Energy has projected a 4X reduction in the price of hydrogen as a part of their new Earthshot program by the end of the decade [126].”

7.7.2 Hyzon Port of Houston

The Port of Houston is the first to demonstrate the Hyzon fuel cell truck in Texas; an example is shown with its mobile fueling truck in Figure 32. The Houston demonstration builds off a 30-day test of a Hyzon fuel cell equipped Freightliner Cascadia at the ports of Los Angeles and Long Beach by Total Transportation Systems Inc. (TTSI) [124].

Figure 32. Hyzon mobile fueling trailer and hydrogen tractor (Wyke) [128]

The Houston demonstration was temporary in nature, with little infrastructure for freight truck fueling in place. Laura Parkan, Air Liquide's vice president of hydrogen energy for the Americas, is quoted in the *Houston Chronicle*, saying, “Houston is already the largest producer of hydrogen in the country, used largely for refining and petrochemical processes. But the region, and much of the country outside of California, lacks the infrastructure to make it feasible for use in freight trucks or cargo ships. Even the hydrogen used for the Port of Houston pilot project was shipped from an Air Liquide facility in North Las Vegas, Nevada, even though an Air Liquide facility produces hydrogen just up the road in La Porte. The Nevada facility is one of a handful of sites in the country that can liquify hydrogen, packaging it at a pressure of 7,500 pounds per square inch. There are only three hydrogen fueling stations for heavy trucks, and all of them are in the greater Los Angeles area [128]."

Speaking about the GCWR of the trucks, Richard Heath, CEO and president of Baytown logistics firm Talke USA, said, "The hydrogen fuel cells are larger than traditional engines too, but not by that much." His diesel-powered trucks typically carry 93,000 lbs., but the Hyzon truck will carry 82,000 lbs., and rather than using the 40' containers that usually travel this route, they'll switch to 20' [containers] [128].

The Hyzon trucks hold approximately 50 kg giving it a range of 300 to 350 miles. To put things in perspective, the fuel efficiency metric would be 6 to 7 mi/kg. Comparable diesels have fuel economies ranging from 6 to 10 MPG. A kg of hydrogen is roughly equivalent in energy content to a gallon of diesel.

7.7.3 Nikola Los Angeles Beverage Delivery

Nikola is demonstrating two fuel cell hydrogen trucks in Los Angeles with Anheuser-Busch and Biagi Bros. The vehicles actually drove from their Nikola Phoenix factory with loaded trailers to Ontario, California, a distance of 340 miles with significant grades [130]. One of the trucks is shown in Figure 33. The units are being demonstrated in the region. Biagi has placed an order for 15 production Nikola Tre fuel cell trucks for delivery in the fourth quarter of 2022 [131].

Figure 33. Nikola fuel cell tractor (Biagi Bros) [64][130]

Costs for the vehicles are currently heavily subsidized. "Purchasers of the Nikola Tre FCEV in 2023 may be able to qualify for California's state-based incentive valued at $240,000 per truck; $270,000 per truck for drayage fleets; or up to $288,000 per truck for fleets with (i) 10 trucks or less, (ii) performing drayage operations, and (iii) located within a disadvantaged community area. Eligible non-drayage fleets may secure up to 30 HVIP vouchers and drayage fleets may secure up to 50 vouchers. In addition to the funding provided by HVIP, according to NGT News, purchasers of Nikola's Tre FCEVs will also qualify for an additional $40,000 clean commercial vehicle tax credit in 2023 from the federal government due to the passage of the Inflation Reduction Act [131]."

7.7.4 Toyota/Kenworth Demonstration

Toyota partnered with Kenworth on a series of 10 hydrogen grant trucks for the California Zero and Near Zero Emissions Freight Forwarding (ZANZEFF) program [132][133]. The trucks are shown in a convoy in Figure 34. The partnership capitalized on Toyota's Mirai fuel cell car technology adapting it for use in heavy-duty trucks doing drayage duty cycles. Two Mirai fuel cells were used in each truck. The trucks were delivered to fleets in 2021 and operated through late 2022 in the ports of Los Angeles/Long Beach for fleets such as TTSI. Toyota expects to be producing heavy-duty truck fuel cells in the 2023 timeframe at their Kentucky manufacturing plant [134].

Figure 34. Toyota/Kenworth Fuel cell trucks (Toyota) [133]

These 10 trucks were prototypes. According to SAE's Kami Buchholz, the trucks were equipped with a "four-speed automatic transmission — part of the eDrivetrain module that also includes two electric motors to provide up to 450 kW of peak power and 2400 Nm (1,770 lb.-ft.) of peak torque. The 60 kg (132 lbs.) of onboard hydrogen provides approximately 1,800 kWh of usable energy. That represents more than three times the 565-kWh battery capacity of the Volvo VNR Electric Class 8 truck. The advanced prototype's 200-kWh lithium-ion battery pack is located below the cab. It provides supplemental power when needed and regenerative braking assistance [134]."

According to Toyota, the production versions of the fuel cell trucks are projected to have a 300-mile (483 km) range when operating at maximum allowed GCWR of 82,000 lbs. (37,194 kg). That gives an energy efficiency of "about 5 miles (8 km) per kg of hydrogen when at maximum vehicle load." Note that Toyota is not entering the tractor OEM marketplace, but rather is acting as a Tier 1 supplier of fuel cell powertrains to other OEMs.

It is noteworthy that fleets such as TTSI have been investing in hydrogen trucks for some years. In 2011, for example, according to *Transport Topics*, TTSI placed an order for 100 hydrogen fuel cell trucks from Vision Industries [135]. Vision Industries converted vehicles to run on hydrogen and filed for Chapter 11 bankruptcy in 2014 [136].

7.7.5 Westport Hydrogen ICE Demonstrator

Westport Fuel Systems unveiled a hydrogen ICE demonstrator truck in May 2022 [137]. Westport is a Tier 1 supplier of powertrain systems to OEMs. Westport described that the demonstrator, shown in Figure 35, adapts the liquid natural gas high pressure direct injection (HPDI) engine to run on hydrogen, achieving over a 98% reduction in CO_2 emissions versus a comparable diesel.

Figure 35. Westport prototype hydrogen ICE truck 2022 (Westport) [6]

According to Westport, the hydrogen HPDI engine has these specifications:

- Power and torque: 20% higher power and torque than the base diesel engine;
- Efficiency: 5% to 10% better thermal efficiency than the base diesel engine;
- Turbocharged 13-liter, in-line six-cylinder engine;
- Fuel: Hydrogen, with pilot ignition; and

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- Four-cycle, compression ignition, direct injection.

Westport explains, "The HPDI fuel system technology uses compression ignition combustion with the overwhelming majority of the energy derived from the combustion of, typically, a gaseous fuel. Combustion is initiated via late cycle direct injection of a small quantity of a pilot fuel, followed by direct injection of the primary gaseous fuel; both fuels are injected via a proprietary dual concentric needle injector design. By Diesel-Cycle thermodynamics, the HPDI fuel system retains the thermal efficiency, power, torque, and engine braking of the base diesel internal combustion engine [137]."

Testing conducted with European manufacturer Scania show preliminary performance with a peak brake thermal efficiency of 51.5 % complemented by 48.7% at road load conditions, all with engine-out NOx similar to the base diesel engine, which is compatible with Euro VII and EPA27 [138]."

The demonstration has been challenged with finding hydrogen refueling infrastructure as it tours the US. The vehicle is a technology demonstrator, actual production vehicles are expected to have greater range with more onboard fuel and other option content choices. These trucks do not have an electric powertrain system or battery packs, so are expected to be fairly similar in weight to comparable diesels.

7.7.6 Cummins ICE Engine Demonstrator

In May 2022, Cummins announced the development of a 15-liter hydrogen ICE engine [139]. The engine had been in testing since mid-2021 in a medium-duty version. According to Cummins, "Cummins intends to produce hydrogen internal combustion engines in both the 15-liter and 6.7-liter displacements, believing that these engines enable the industry to take action and reduce GHG emissions yet this decade, ultimately accelerating carbon reduction." The production engine is labeled a "fuel agnostic X series engine," however, that does not mean fleets can change fuel types at will on the road [144]. The Cummins graphic in Figure 36 illustrates that each fuel has its own unique fuel delivery system, while allowing significant harmonization of the lower engine block and systems. On-board fuel storage and delivery systems also will be unique to each fuel type.

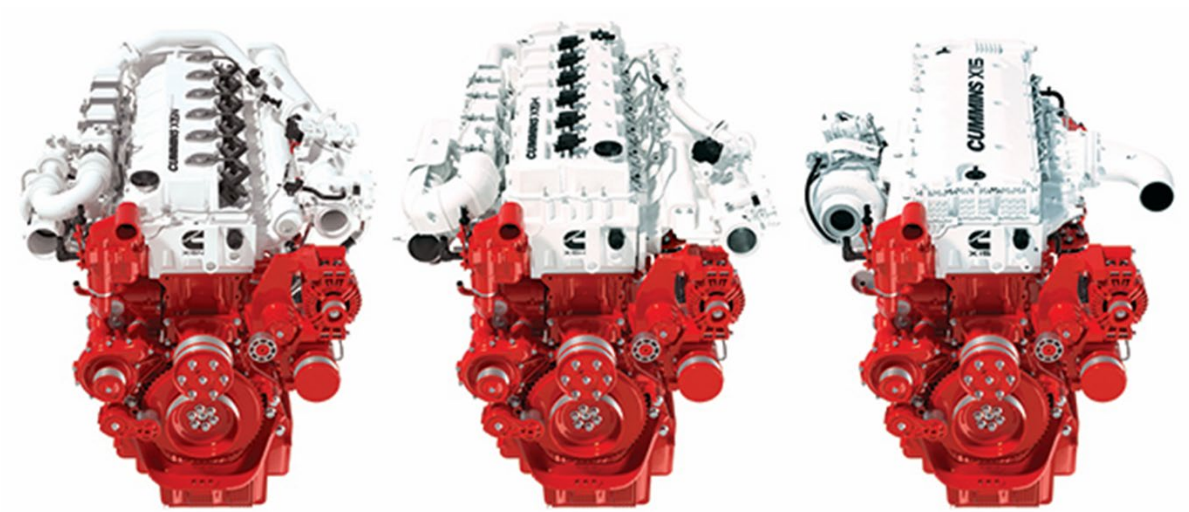

Figure 36. Fuel-Agnostic engine (Cummins) [144]

The key financial aspect going for the hydrogen ICE is a lower initial capital cost versus other alternatives like fuel cells and battery electric trucks. The efficiency of combusting hydrogen versus using it in a fuel cell, however, will always be significantly less. Therefore, hydrogen internal combustion engines will need more hydrogen per mile than comparable fuel cells, likely making operating costs higher. The simplicity of dropping in a hydrogen ICE in a diesel platform is also attractive, as one Cummins executive states, "These engines look like engines, they sound like engines, and fit where engines normally fit."

Hydrogen fueling infrastructure is still an issue whether hydrogen ICE or fuel cell. The choice of fuel type, liquid or gaseous for dispensing, and at what pressures, remains a potential challenge since this has not been standardized between the various competing hydrogen technologies. "Cummins specifies that the carbon-fiber fuel tanks of an H_2 truck will store the fuel at 700 bar (10,000 psi). Cummins notes that this is not an industry standard; systems can range from 350 bar (5,000 psi) to 700 bar. However, the company claims that 700-bar pressure enables greater onboard fuel storage and range. This storage pressure does increase the number of windings required for each fuel tank, which increases weight and cost of the system versus natural gas, but these tanks can be used for either a hydrogen ICE or FCEV [140]." Cummins expects the engine to be used in heavy-duty trucks where duty cycle ranges exceed 250 miles (400 km).

NOx emissions remain an issue for internal combustion engines, even those burning hydrogen. Cummins believes these issues can be handled through prudent engineering and adapting proven technologies from diesel systems.

Cummins expects they "Could bring a PFI (port fuel injection) H_2 system to market as early as 2023 and would be able to launch a DFI (direct fuel injection) system by 2025. FEV claims a 5% increase in efficiency from its PFI system to a DFI system [140]."

7.7.7 Forklifts

Paving the way for hydrogen use in freight has been fuel cell forklifts. The fuel cell forklift market took off in 2009 as a result of the American Recovery and Reinvestment Act (ARRA). The 2022 draft National Clean Hydrogen Strategy and Roadmap estimates that there are "more than 50,000 fuel cell forklifts at commercial warehouses around the nation and over 115 fueling stations [74]." A 2018 DOE report stated, "U.S. Department of Energy's Hydrogen and Fuel Cell Technologies Office funded approximately $40 million through ARRA for fuel cell forklifts and backup power units [141]." They estimated that "cumulative material handling equipment (MHE) deployments (units shipped and on-order) though year-end 2017 total 21,838 units and equate to more than 140,000 kW of fuel cell systems. The MHE deployments include 713 MHE fuel cell units cost shared by industry and DOE funds which led to 21,125 MHE fuel cell units with no DOE funding."

A partial list of companies that are using fuel cell forklifts are shown in Figure 37.

Ace Hardware	Golden State Foods	Stihl
Amazon	IKEA	Sysco Foods
BMW Manufacturing Co.	Kimberly-Clark/GENCO	Testa Produce
Canadian Tire	Kroger Co.	Unified Grocers
Central Grocers	Lowes	United Natural Foods, Inc. (UNFI)
Coca-Cola	Martin-Brower	U.S. Foodservice
CVS	Mercedes	Walmart
EARP Distribution	Nestle Waters	Wegmans
East Penn Manufacturing	Nissan North America	Whole Foods Market
FedEx Freight	Proctor and Gamble	WinCo Foods, LLC

Figure 37. Partial list of companies using fuel cell forklifts (DOE) [141]

The volume of hydrogen required for forklifts is significantly less than what heavy-duty trucks require, however, getting the facility and personnel experienced with hydrogen fuel cells is a steppingstone toward having on-site heavy-duty truck hydrogen fueling and operations. Additionally, fuel cell manufacturers such as Plug, Ballard and others are gaining valuable production experience.

7.7.8 Fuel Cell Terminal Tractors

In between forklifts and long-haul trucks are terminal tractors. Hydrogen is a proposed option for terminal tractors. Capacity is a company developing a hydrogen fuel cell terminal tractor as shown in Figure 38. Capacity expects to offer battery electric, fuel cell and other alternative fuel terminal tractors to fill fleet specific needs.

Figure 38. Capacity fuel cell terminal truck (Capacity) [12]

Another prototype fuel cell terminal truck was shown at the ACT EXPO 2022 from Gaussin, shown in Figure 39 [162][163].

Figure 39. Gaussin hydrogen fuel cell spotter (NACFE) [162]

Terminal tractors tend to stay close to their home facilities so range and re-fueling is not an issue. A warehouse equipped for hydrogen forklifts might readily expand to having hydrogen terminal tractors, and then evolve into hydrogen ICE and eventually long-haul hydrogen fuel cell tractors. That technology path, simplistically, may be appealing to fleets worried about stranding fueling infrastructure assets due to rapid obsolescence. Walmart is one company that is evaluating hydrogen as one path for a complete freight eco-system from forklifts to long-haul trucks as described in their press release from June 2022 [145].

"To make a meaningful impact, we're taking a meaningful approach by evaluating various attributes of three different fuel types — renewable natural gas, hydrogen and electric. We're piloting solutions not only for our over-the-road trucks but for refrigerated trailers and [terminal] trucks too. Here is how we are layering solutions to determine the best recipe for building a Walmart that is regenerative in action [145]."

Note there are significant differences between fueling requirements for these different types of vehicles. A forklift might need 4 to 10 kg of hydrogen fuel per tank, a terminal tractor might need 10 to 20 kg, and a long-haul tractor might need 60 to 100 kg. As noted previously, storage and delivery are significant costs tied to the volume of fuel needed.

7.8 International Conflicts and Hydrogen Resiliency

The international energy market is unpredictable. Physical and economic conflicts — ranging from tariffs and embargoes to outright war — are always possible. The invasion of the Ukraine in February 2022 rocked the energy markets and intensified finding alternatives to fossil fuels. Supply and demand were significantly put out of synchronization causing extreme energy price volatility. All energy markets are interconnected, so when Europe was experiencing natural gas shortages, suppliers of natural gas in other regions boosted production to help meet demand, even moderating local supplies to sell to higher bidders, ultimately impacting fuel prices in all regions.

A graphic representation of the extreme geopolitical volatility is captured by Roland Berger from World Bank data from 1970 to 2022 in the graph shown in Figure 40 [151].

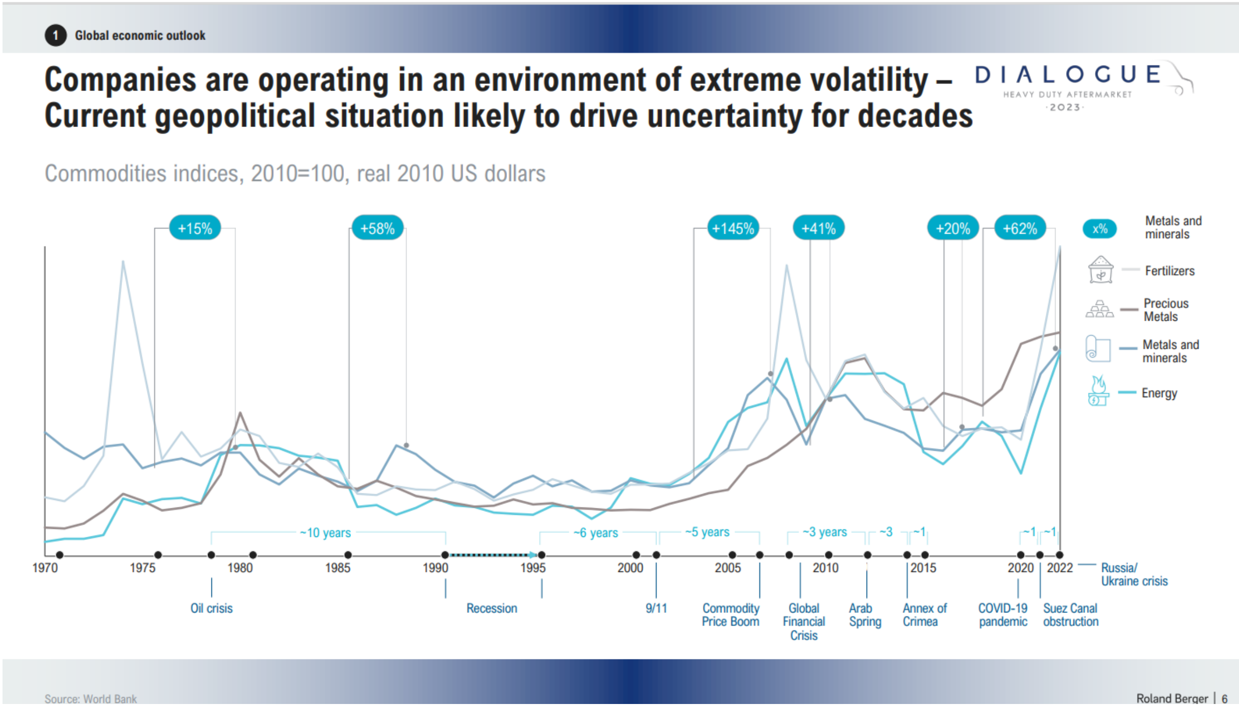

Figure 40. Extreme geopolitical volatility (World Bank) [151]

Conflicts significantly reinforce weaknesses in supply chains. Systems with single-point failure modes quickly are highlighted, such as a single Nord Stream supply line of natural gas to Europe, or in the US disruption in the Colonial gasoline pipeline. Alternative sources for fossil fuels can respond but often that takes significant time to ramp up to fill the void in supply. When these weaknesses are brought to the attention of corporations and governments, new emphasis can be placed on risk mitigation strategies.

Vertical integration is one of the risk mitigation strategies companies and countries are taking. Whether computer chips, platinum or lithium or energy production, "bringing it all in-house" is occurring in an attempt to exercise greater control of the supply chain. At the national level, it's called "on-shoring."

Both electricity production and hydrogen production offer some inherent market stabilization opportunities. There are multiple ways to generate electricity and hydrogen which build in resiliency to the energy supply marketplace. Monopolized distribution is still a potential issue with both, but production is feasible through multiple means unlike traditional gasoline and diesel which are largely handcuffed to oil's infrastructure. NACFE's interviews with fleets and manufacturers has highlighted an expectation that hydrogen's ability to be produced through multiple methods will lead to competition in pricing as market shortages become market opportunities for hydrogen suppliers.

8 The State of Hydrogen Today

Dr. Sunita Satyapal, director, hydrogen and fuel cell technologies office and DOE hydrogen program coordinator, summarized the current deployment of hydrogen infrastructure and vehicles as of the June 2022 DOE Hydrogen Programs Annual Merit Review as shown in Figure 41 [147].

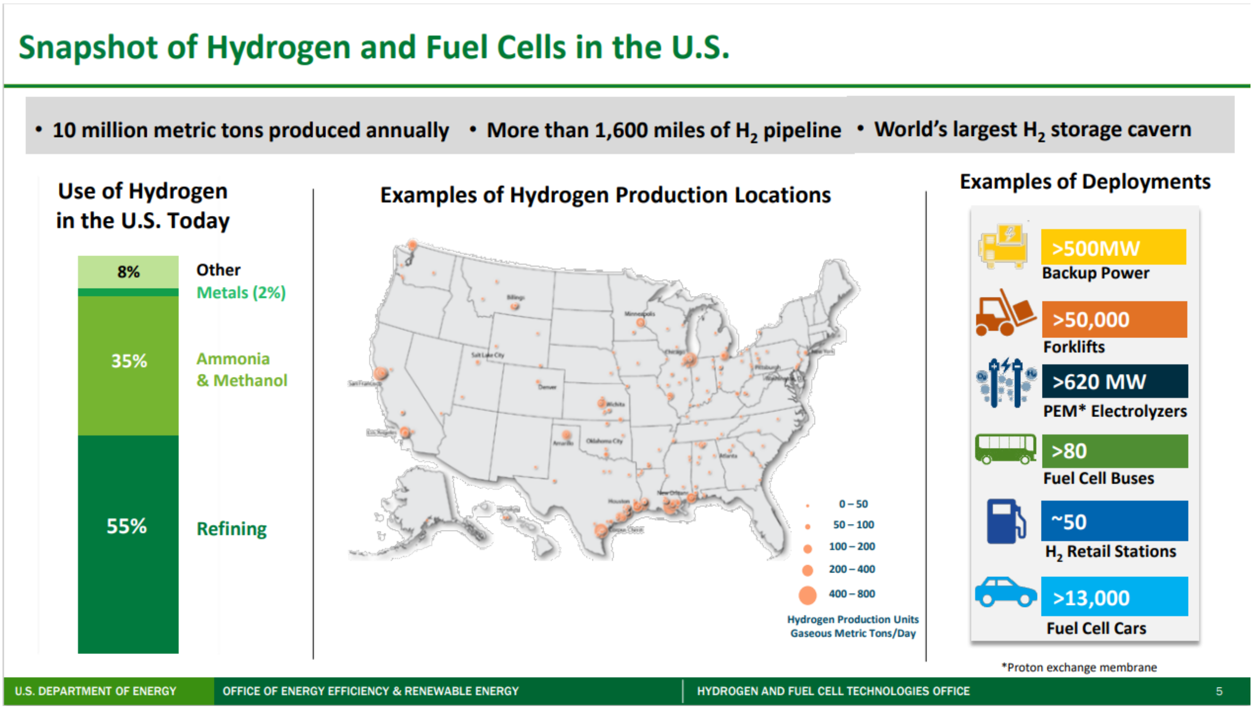

Figure 41. Current state of hydrogen (DOE) [147]

Satyapal showed deployments of hydrogen fueled forklifts exceeding 50,000 units, greater than 80 hydrogen buses, and approximately 13,000 hydrogen cars. With the exception of forklifts, the vehicle deployments are in their infancy compared to market sizes. Of note also is that 55% of current production hydrogen usage is in refining oil and 35% is in producing ammonia and methanol. The hydrogen production infrastructure is primarily located, logically, near major coastal oil refining centers.

Hydrogen production via electrolyzers, under construction as of June 2022, is shown in Figure 42 [147]. Again, note that this emerging green hydrogen production is located near hydrogen demand centers such as oil refineries.

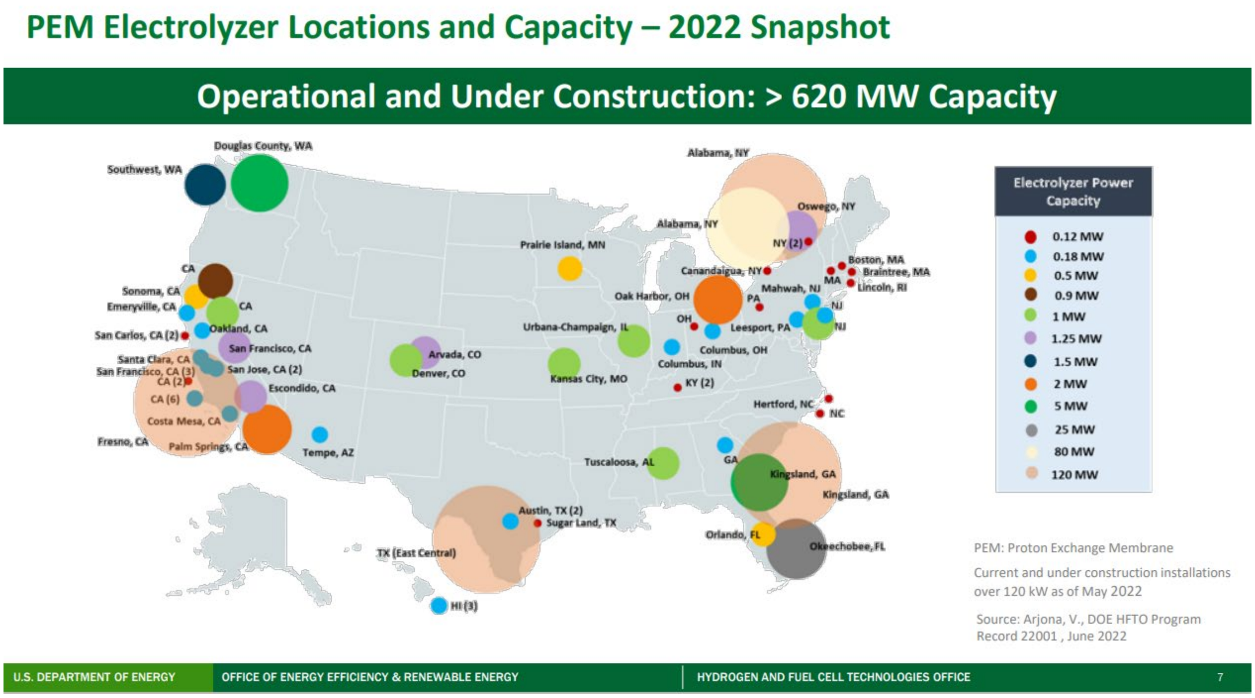

Figure 42. Electrolyzer hydrogen production being built as of June 2022 (DOE) [147]

Lawrence Livermore National Laboratory (LLNL) provides a Sankey diagram of US energy use shown in Figure 43. DOE's June 2022 estimate of electrolyzer capacity under construction or already operational was 620 MW – translating to perhaps 5,431,200,00 kWh over the course of a year. LLNL's Sankey shows that US transportation in 2021 used 26.9 Quads, where 1 Quad is "293 billion kilowatt-hours or, for fuels of average heating values, the energy of 183 million barrels of petroleum, 38.5 million tons of coal, or 980 billion cubic feet of natural gas [149]." The energy demand for transportation then is 7,881,700,000,000 kWh. The electrolyzers under construction or in operation as of June 2022 represent perhaps 0.07% of the transportation's market demand. This is a drop in the bucket, but everything has to start somewhere.

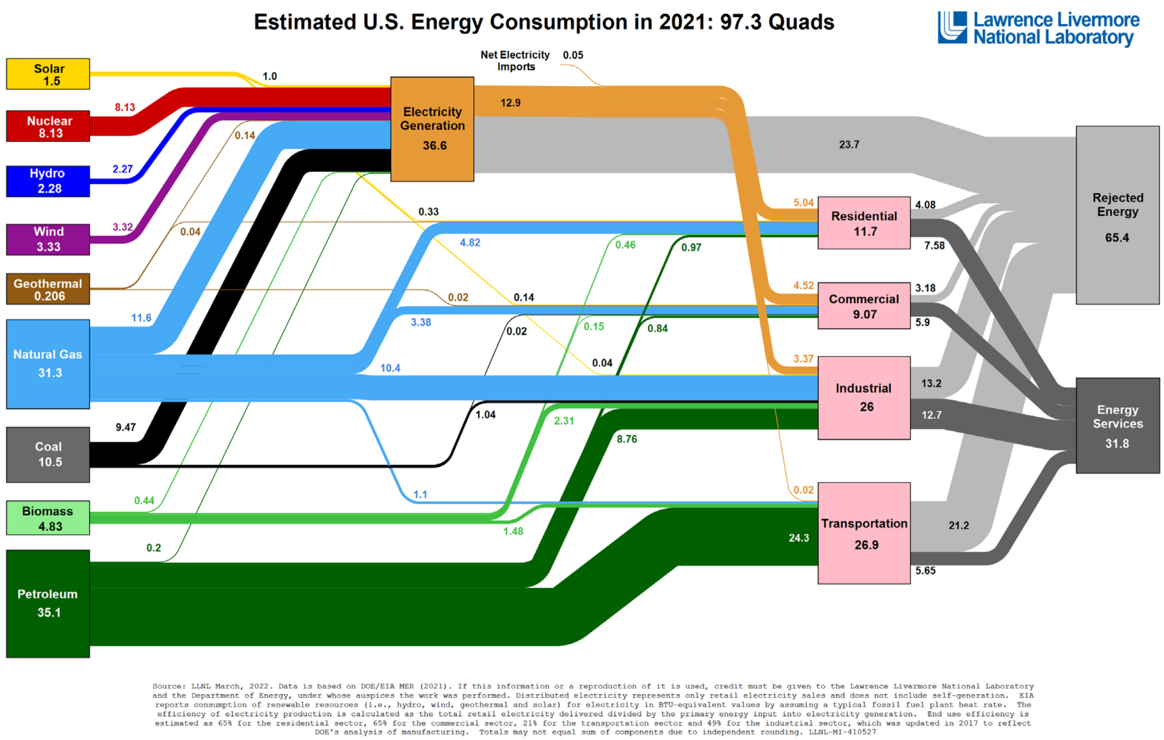

Figure 43. U.S. energy use in 2021 (LLNL) [148]

The Sankey diagram shows the majority, 90%, of this energy used in transportation originates from petroleum, complemented by very small amounts of biomass, natural gas and electric sources. The Sankey diagram also highlights that much of that transportation energy demand, 78%, is spent as waste heat due to the inefficiencies inherent in the predominant ICE technology engines.

Converting the transportation industry to diesel alternatives has a steep hill to climb to supplant petroleum's dominance. The market dominance by petroleum companies hints at why hydrogen is attractive to the oil industry as a path forward to continue market prevalence as energy suppliers through products like gray, blue and green hydrogen. The aggressive zero-emission vehicle goals implementing at state and federal levels also will potentially reinforce that petroleum-based and natural gas-based hydrogen must be a part of the solution moving forward, due to the extensive economic impact and inertia of these industries, combined with the rapid need for hydrogen at scale.

Confirmation of petroleum's focus on remaining relevant in the zero-emission transportation world can be found in BP's Energy Outlook 2023 report, which stated a core belief that "oil demand declines over the outlook, driven by falling use in road transport as the efficiency of the vehicle fleet improves and the electrification of road vehicles accelerates. Even so, oil continues to play a major role in the global energy system for the next 15-20 years [152]."

Regarding hydrogen, BP further states the core belief that "Low-carbon hydrogen plays a critical role in decarbonizing the energy system, especially in hard to-abate processes and activities in industry and transport. Low-carbon hydrogen is dominated by green and blue hydrogen, with green hydrogen growing in importance over time [152]."

Regarding carbon capture technology, BP believes that, "Carbon capture, use and storage plays a central role in enabling rapid decarbonization trajectories: capturing industrial process emissions, acting as a source of carbon dioxide removal, and abating emissions from the use of fossil fuels."

While committed to continuing fossil fuels, BP recognizes that the energy market is shifting, that "the share of fossil fuels as a primary energy source will fall from 80% in 2019 to between 55% and 20% by 2050, while renewables' share will grow from 10% to between 35% and 65% over the same time period [152]." That statement reinforces that fossil fuels still will be a significant part of post-2050 energy use, but made possible through hoped for viable carbon capture and use technologies.

The massive inefficiencies in burning fuel will be replaced with more efficient energy conversion methods such as battery electric vehicles, particularly in the automotive marketplace. That will concurrently reduce demand on petroleum energy use for transportation while doubling or tripling the efficiency of use of the energy by the electric vehicles and the associated energy delivery infrastructure. However, that growing demand for electricity in transportation, in 2021 estimated at only 0.07% in the Sankey diagram, requires significant national growth in electricity production. NACFE has stated that converting to zero-emission freight is akin to something on the scale of the 1950s to 1960s national highway construction. This remains consistent with NACFE's 2020 *Making Sense of Heavy-Duty Hydrogen Fuel Cell Tractors* report. All forms of energy are also on the table to facilitate the transition.

8.1 Hydrogen Cost Realities

There is a significant volume of information and misinformation on projected costs of hydrogen. Much of it focuses on predicting the cost of production, not the price. These two differ: cost is what the plant expends to actually make the fuel, price is what they charge for it. The expected cost to the producer inside the fence of the production facility is not necessarily representative of the retail price of the fuel at the gate of the plant, nor does it factor in transportation, storage, compression or dispensing of the hydrogen at the pump for the vehicle.

As we all have experienced, fuel prices are not necessarily "what they should be" but rather what the marketplace allows. Fuel prices at the pump incorporate obvious things like capital cost recovery, research and development, maintenance, transportation, storage, waste, etc. Fuel prices also fluctuate based on supply and demand, and there is this nagging "profit" factor that consumers have little control over. One day, everything is at a given price, then some country invades another, or there is a hurricane, or the threat of an interest rate hike, an economic crash, or any number of real-world events and the next day the price is a significantly higher, even though fundamentally the fuel at the station has not changed. Accurately predicting actual at-the-pump fuel prices is challenging. Even the experts can be significantly wrong as seen in fuel price estimations over the dynamic last 15 years.

In 2020, the DOE Office of Fossil Energy published hydrogen production costs, what their research indicated was the actual production cost, as shown in Figure 44 [91].

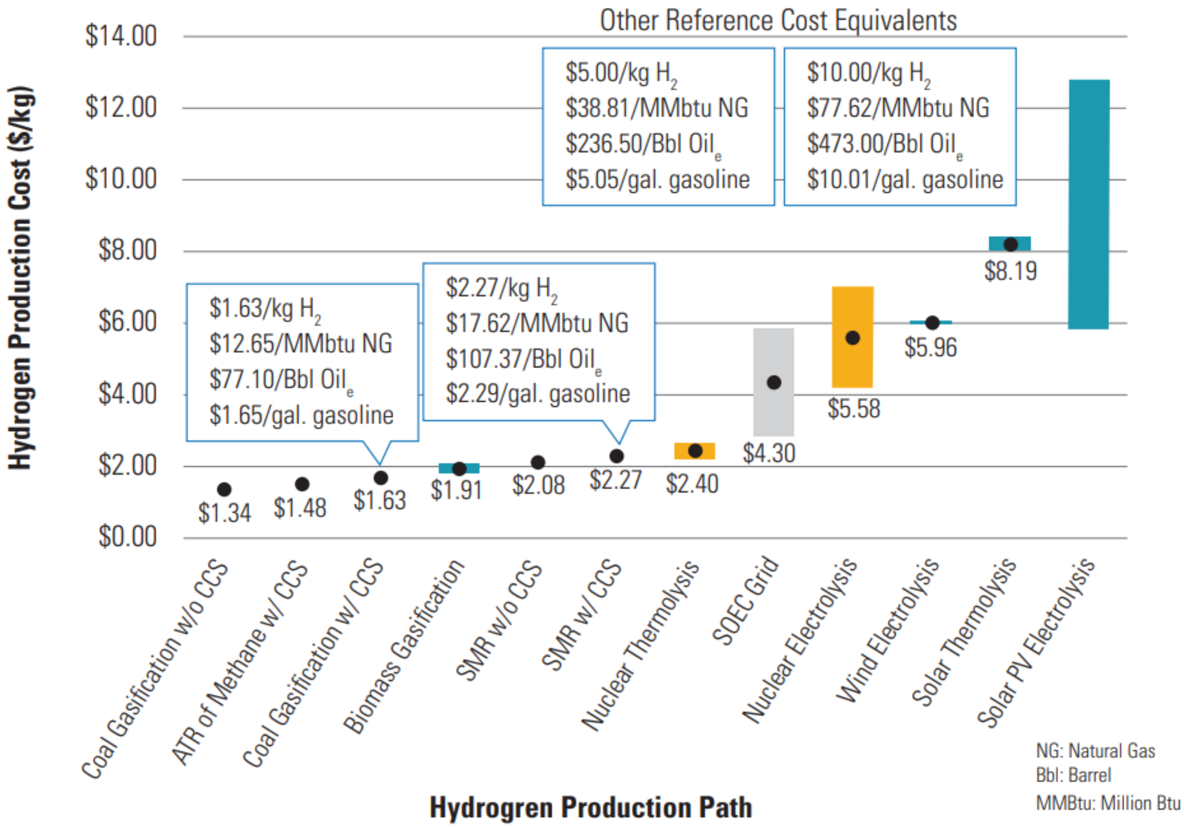

Figure 44. Hydrogen production cost (DOE) [91]

A second DOE report published in October 2020 documents "the levelized unit cost of hydrogen delivery and dispensing at fueling stations in 2020. For liquid tanker-based stations, delivery costs are calculated to be approximately $11/kg at 450 kg/day and projected to be roughly $8/kg at 1,000 kg/day for stations operating in California. For tube-trailer gaseous stations, delivery costs are projected to be $9.50/kg and $8/kg at 450 kg/day and 1,000 kg/day for stations operating in California, respectively (2016$). The cost range has been derived using the Hydrogen Delivery Scenario Analysis Model (HDSAM) under specific assumptions consistent with operation data from today's stations operating in California [92]."

The actual hydrogen fuel prices in California for 2019 were described by the Hydrogen Fuel Cell Partnership. "The average price of hydrogen for a light-duty fuel cell electric vehicle (passenger car) in California is $16.51 per kilogram, according to the 2019 Joint Agency Report. As more retail stations open and have higher utilization, the price per kilogram of hydrogen is projected to drop to ranges more competitive with the prices of gasoline. For example, in late 2019, the True Zero Oakland hydrogen station opened with three times the capacity of previous stations. It offers hydrogen at $13.11 per kilogram (tax included) due, in part, to the larger volume and other factors [93]."

These numbers highlight that hydrogen production cost and actual pump retail price differ significantly. The proposal that hydrogen fuel retail prices can come down significantly is questionable since the major component of pricing today is not production, but rather transport and delivery by truck.

The DOE's Satyapal estimated in June 2022 the threshold cost of retail hydrogen as shown in Figure 45 [147]. The estimates "includes cost of production, delivery, storage, compression/processing/dispensing, as required, to the point of use for each application." However, the costs do not include profit margins for any of that. Again, cost and price may differ significantly.

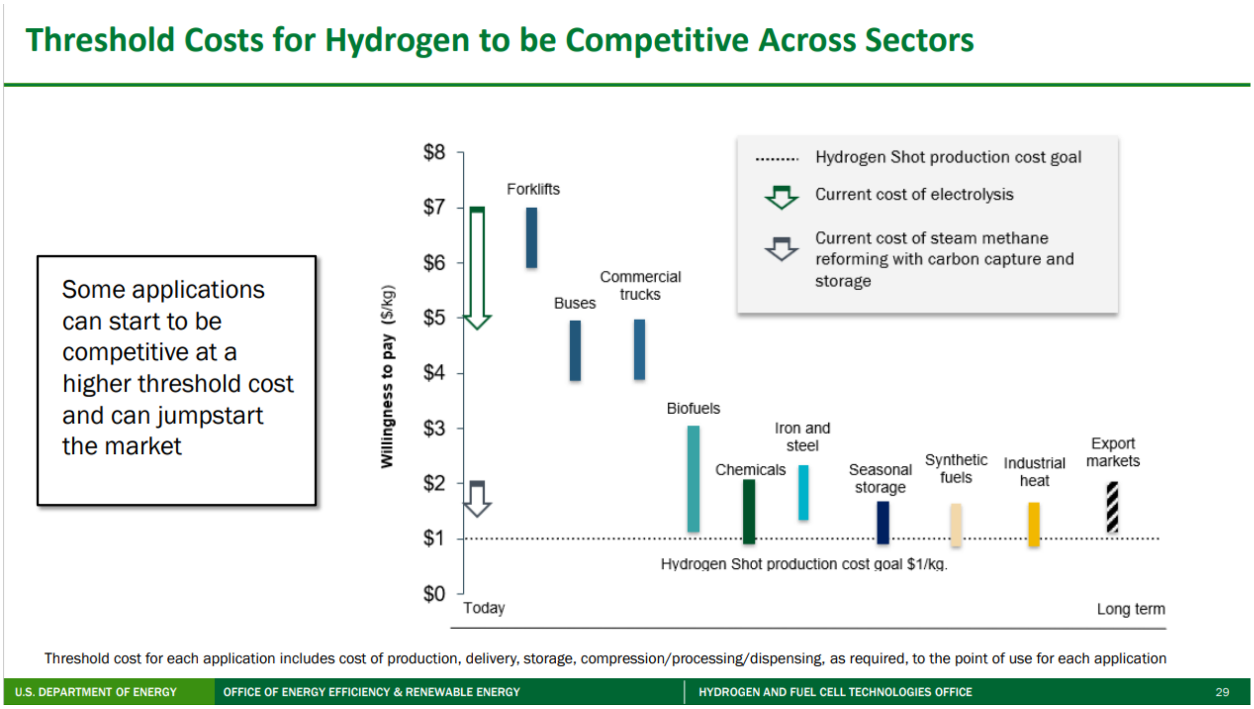

Figure 45. Retail threshold cost for hydrogen by application (DOE) [147]

The production cost of SMR-based hydrogen is shown as 3x to 4x less than electrolyzer-based hydrogen production.

The DOE's hydrogen program targets for driving down the cost of hydrogen are [147]:

- $1/kg clean H_2 production
- $2/kg H_2 delivery
- $9/kg H_2 storage
- $150/kW stationary electrolyzer capital
- 73% stationary electrolyzer energy conversion efficiency
- 80,000 hour stationary electrolyzer durability
- $80/kW heavy-duty truck fuel cell capital cost
- 25,000 hour heavy-duty truck fuel cell durability

The clean hydrogen cost of $1/kg was estimated as an 80% reduction at the release of the DOE Hydrogen Earthshot program in June 2021 [150]. The target timeframe for the goal is 2031.

8.2 Hydrogen Tank Costs

Storing compressed hydrogen requires tanks capable of high pressures and low temperatures. In 2015, DOE estimated the total costs of compressed storage systems shown in Figure 46 [160][161]. The costs are linked to manufacturing volumes.

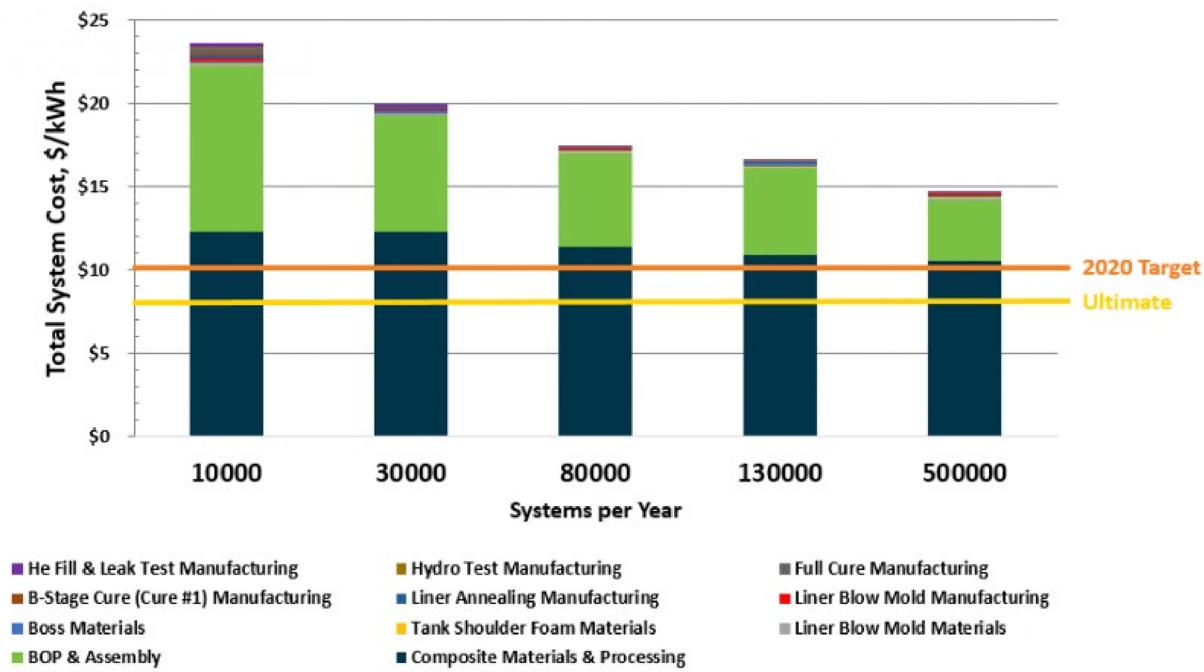

Figure 46. 700-bar compressed H_2 storage system cost breakout (DOE)[160]

The challenge with estimating manufacturing volumes is understanding the OEM marketplace. Each vehicle manufacturer has a commercial need to differentiate their product from other OEMs. This leads to proprietary systems being combined with non-proprietary systems. Diesel fuel tanks have largely been proprietary systems. The OEMs also have provided multiple sizes of tanks as option choices for fleets that select tank capacities based on their specific duty cycles. There are also significant legal liability factors for OEMs reinforcing making fuel systems proprietary.

A very good production year for heavy-duty trucks may be 350,000 total units. This sales volume is then divided up among the various OEMs, and for each OEM, divided up among different models and options. Specific configurations of fuel tanks may never have production volumes of more than a few hundred to as many as 50,000 units. Getting to significant volume price breaks requires the trucking industry to agree to standardize on specific designs, which means product differentiation for storage systems would be minimal.

The numbers game applies to all aspects of vehicles, not just the fuel storage systems, and it is equally relevant to alternatives such as battery electric, CNG/RNG, hydrogen ICE and others. The truck market is not very large in comparison to automotive where millions of similar vehicles are produced by manufacturers like Ford, GM, BMW, etc.

One method of increasing volume is to share specific tanks across multiple platforms like buses, cars, medium-duty trucks, trains, planes, etc. However, this leads to inevitable packaging and performance compromises trying to have a one-size-fits-all approach. For example, a car might need a 5 kg tank where a long-haul heavy-duty truck needs 50 to 80 kg of hydrogen. Chassis designs differ significantly as well, making packaging difficult to standardize and integrate into the custom exterior designs of the vehicles. Also, to avoid monopolies, a standard design would need to be universally available from multiple tank vendors, ensuring competitive pricing.

Reducing costs on hydrogen fuel tanks for heavy-duty hydrogen trucks will be challenging in the real world.

8.3 Truck Energy Conversion Efficiency

The Traton corporation that now manufactures Navistar, Scania and MAN brand heavy-duty trucks, estimates the net energy conversion efficiency of a hydrogen fuel cell from well-to-truck to be 25% versus battery electric trucks achieving a 75% system efficiency as shown in Figure 47 [142].

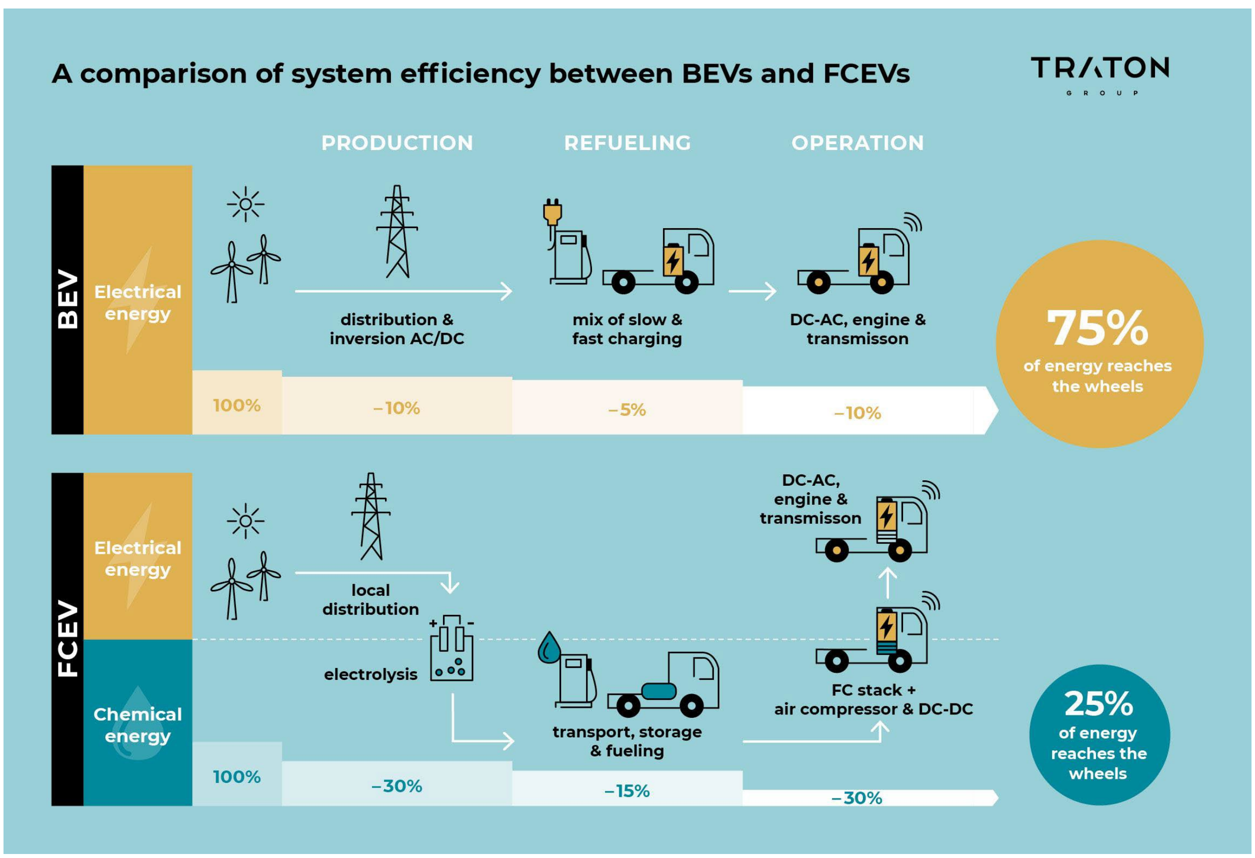

Figure 47. Energy use comparison (Traton) [142]

This significant difference in efficiencies was discussed in detail in NACFE's 2020 *Making Sense of Heavy-Duty Hydrogen Fuel Cell Tractors* report. The NACFE report stressed that hydrogen is much more complex than just fuel in the truck. The Traton graphic fails to clarify that the two trucks differ in both range and allowable freight weight capacity, and both differ significantly in those factors versus diesels.

These are "apples-to-oranges" comparisons that while technically correct are incomplete. There are no average routes, no average trucks, no average loads, no average drivers, no average energy sources, etc. Each vehicle has unique and varying daily operational demands.

For example, comparing a fuel cell tractor, battery electric tractor and a diesel tractor on truly equivalent specifications would require the vehicles to have identical tare weights and identical vehicle ranges. It is well documented that adding both fuel cells and battery electric powertrains to replace a diesel result in higher vehicle tare weights. These higher weights reduce maximum payload capacities, even when including the U.S. DOT 2,000 lbs. allowance. What is often also not mentioned is that a diesel may have a 100 gallon or greater fuel capacity allowing recent models to exceed 1,000 miles per fill-up. Compare this range capacity to battery electric specifications that are between 150 and 250 miles per charge, and fuel cell vehicles that are expected to have 300- to 500-mile one-fill ranges.

Truly "equivalent" truck specifications are uncommon when comparing these three powertrains. This can lead to erroneously focusing on single-trip vehicle comparisons where real-world fleets instead need to see one driver shift, one 24-hour, one week, one month and one year comparisons. Those comparisons may show that two or more trucks are needed to replace one diesel to accomplish the same required freight transfers.

Traton is correct in that hydrogen-based vehicles will require much greater net energy to go the same distance as battery electric trucks, at least 3x more energy due to handling, storing, and delivering hydrogen as a molecular fuel — and much of that required energy is actually electricity. Simplistically, hypothetically, if it takes one wind turbine to provide power for a particular fleet of battery electric trucks, it could take three wind turbines to provide the same amount of hydrogen energy for fuel cell trucks to accomplish the same duty cycle due to liquification, compression, losses and other factors tied to processing hydrogen, whether or not the hydrogen starts from SMR or electrolyzers. Electricity and hydrogen are invariably linked together.

8.4 FCEV Price Estimates

Price projections for vehicles that are not yet in production are full of assumptions and should be used with caution. Manufacturer list prices are further complicated by additional factors such that they may not reflect the actual out-the-door cost to the purchaser. The ICCT compiled available estimates and created the retail price projections shown in Figure 48 for battery electric, fuel cell and diesels in a variety of commercial vehicle classes through 2035 [153]. In general, HFCEVs are more expensive than BEVs and both are currently more expensive than the diesels they are intended to replace.

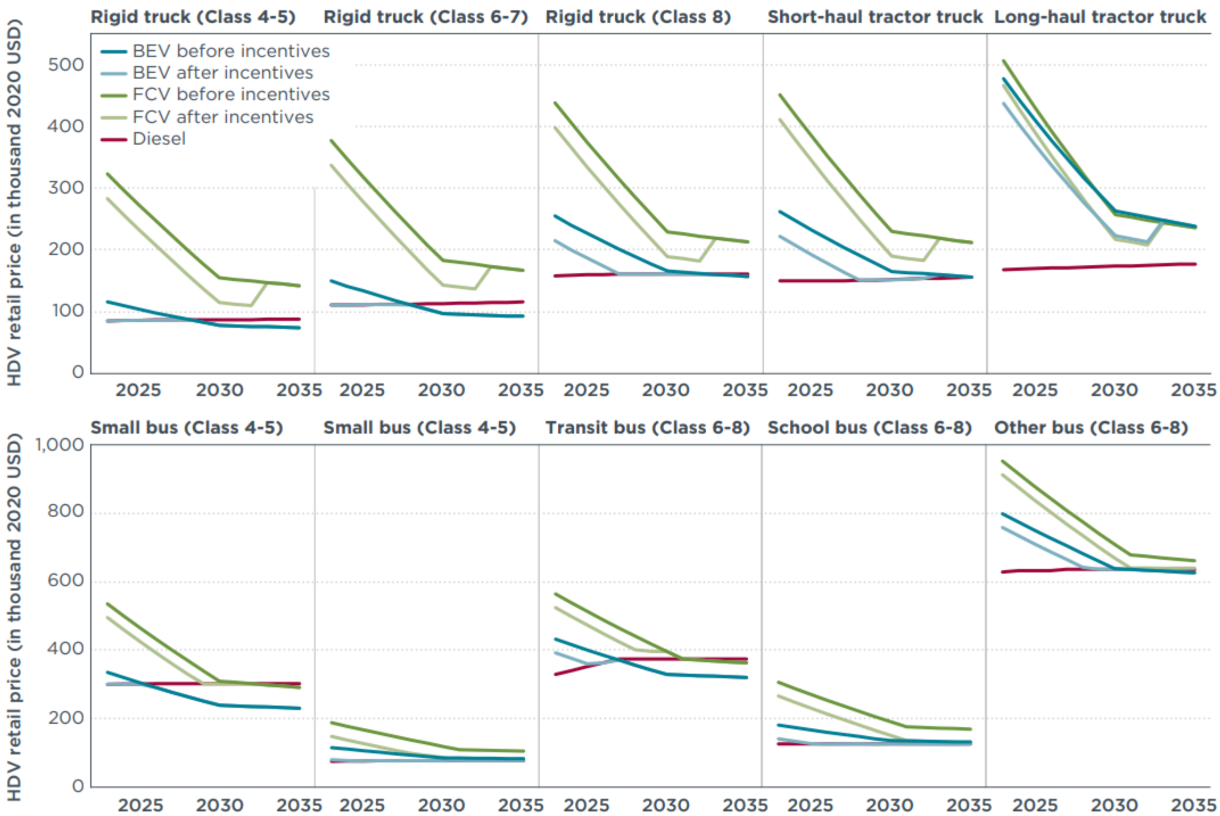

Figure 48. Comparison retail prices before and after IRA incentives (ICCT) [153]

The goal of government incentives and tax credits is to encourage the purchase of zero-emission technologies, so helping achieve out-the-door pricing comparable to diesels is necessary. If short-haul heavy-duty BEVs are currently 2x to 3x more costly than diesels, HFCEVs are perhaps 6x to 9x more costly in terms of list pricing, but grants and incentives significantly reduce these differences.

One of the factors that may impact out-the-door costs for purchases is how their diesel trade-ins are valued. This is a significant unknown in markets that are discouraging purchasing diesels either through regulations or market mechanisms. Used truck values for unwanted technologies may be minimal, requiring the vehicles to be sold into other regional markets where they can be marketed successfully. In other cases, obtaining grants and incentives may actually require scrapping the diesel trade-in, in which case the used diesel vehicle is valued for only for its raw material salvage value.

A second challenge faces used ZET truck valuation and whether or not those used ZETs also will receive grants and incentives to bring down the vehicle purchase cost to what second buyers can afford.

Guaranteed residual value sales models may be necessary during both the transition from diesels to ZETs, and once ZETs start entering the used truck market.

9 FINDINGS

Hydrogen may be the harbinger of a new green industrial revolution, or just the progression from one fossil fuel-based energy carrier to another with greater emphasis on reducing emissions. Either way, hydrogen will be a factor in future long-distance freight hauling in combination with battery electric vehicles for shorter range operations. NACFE's first hydrogen report remains relevant and accurate. The changes since that report reinforce the following findings:

1. Hydrogen powered freight is required for a zero-emission freight future. There really are no viable alternatives to hydrogen for hauling freight 600+ miles per day with zero emissions. While it is technically viable for a battery electric truck to go 800+ miles in a day with enroute charging and carrying equivalent freight weight to a diesel, the situations where this is feasible are limited.
2. There is a significant amount of funding going toward establishing the basis for a hydrogen economy that includes long-haul freight transportation. The amounts of funding committed so far measure in the billions of dollars but are just a small down payment on what is needed for a national network of hydrogen production and distribution systems for freight use, and a manufacturing capacity to produce hundreds of thousands of fuel cell trucks each year. This is just the beginning of the transition from diesel.
3. The cost of hydrogen production, transportation storage and dispensing will not be cost competitive with diesel without significant assistance from tax credits and other subsidy mechanisms.
4. Managing the actual retail cost of hydrogen is perhaps more important than continuing discussion of reducing the production cost at the hydrogen plant. A free-market approach that heavily subsidizes the production of hydrogen while doing nothing to control the retail price will lead to disproportionate profits for producers and no real support for market adoption of hydrogen vehicles.
5. Hydrogen is closely tied to electricity. You can't have hydrogen without significant amounts of electricity. Liquification, compression, storage and distribution of hydrogen, irrespective of hydrogen's source, require electrically driven systems and use significant amounts of electrical energy. Green hydrogen from electrolyzers will require additional electricity. The national grid needs to be built to produce and distribute this new hydrogen economy energy demand.
6. Hydrogen is a significant factor in federal, state and local planning and regulations for the zero-emission freight future. Multiple agencies are funding and requiring the transition to hydrogen. Corporations are similarly advancing the need for hydrogen directly or indirectly through their sustainability efforts.
7. Purpose-built hydrogen trucks optimized for specific duty cycles may not be valued well in the second market, leading to first owners to keep the vehicle until it is salvaged.
8. Hydrogen costs decrease as the scale of the hydrogen plants increase. Large production requires multiple industries to increase demand for hydrogen. Trucking alone is insufficient to reach demand scale needed to justify large hydrogen plants.
9. Hydrogen used for creating alternative fuels like renewable diesel will reduce net emissions but at the cost of delaying adoption of zero-emission alternatives.
10. All the answers do not need to be known on day one of hydrogen. Production supply and

market demand will evolve in lock step over time. Innovators will find market opportunities where there is an oversupply of hydrogen, creating new market demand. Where market demand exceeds supply, energy producers will increase capacity. These will not be instantaneous, but supply and demand are integrally tied.

11. Hydrogen and electricity supply are inherently resilient as there are multiple methods of producing them, leading to competitive forces mitigating price and supply volatility.

10 CONCLUSIONS

Hydrogen is a complex topic. Hydrogen for use in freight transportation is just in its infancy. Trying to summarize the topic in a few closing statements is akin to describing a child's potential impact on the world. NACFE presents four significant conclusions.

- Hydrogen and battery electric are not an "either/or" but an "and" for the zero-emission freight future. Battery electric vehicles will inherently be the most economical and efficient choice for shorter distance zero-emission duty cycles, and hydrogen will be the only viable economic choice for long-haul zero-emission duty cycles. Ultimately fleets in the market will make decisions on which technology succeeds for which duty cycles.
- Hydrogen fuel cell tractors are the only zero-emission solution for many duty cycles for heavy-duty tractors. Significant cost reduction across all cost elements is needed for these tractors to be cost effective. Supply chain companies from shippers, to carriers, to fuel suppliers and others along with government assistance, must share in higher costs for the benefits of zero emissions.
- Alternative fuels like RNG, renewable diesel, and hydrogen used in internal combustion engines will be required to support the transition in the next two decades to help make progress toward zero-emission goals, while in parallel ramping up the hydrogen and battery electric infrastructure and manufacturing base.
- Industry agreement is needed on whether hydrogen long-haul fuel cell tractors, and the transport of the hydrogen fuel itself, will be based on gaseous or liquid hydrogen. This is a core factor that can impact multiple infrastructure and manufacturing systems, and significantly impact market penetration and volume estimates for cost reduction potential.

11 REFERENCES

All website links were last accessed in January 2023.

1. Mihelic, Rick. Kevin Otto, Jessie Lund, Mike Roeth. 2019. Guidance Report: *Viable Class 7/8 Electric, Hybrid and Alternative Fuel Tractors*. North American Council for Freight Efficiency (NACFE). https://nacfe.org/research/electric-trucks/#viable-heavy-duty-electric-tractors.

2. Mihelic, Rick. Kevin Otto, Jessie Lund, Jennifer Wheeler, Mike Roeth. December 2020. *Making Sense of Heavy-Duty Hydrogen Fuel Cell Tractors*. North American Council for Freight Efficiency (NACFE). https://nacfe.org/research/electric-trucks/making-sense-of-heavy-duty-hydrogen-fuel-cell-tractors/.

3. Mihelic, Rick. Mike Roeth. January 2020. *Defining Production*. North American Council for Freight Efficiency (NACFE). https://nacfe.org/research/thought-leadership/#defining-production.

4. Cummins. February 14, 2022. Cummins' New Low-Carbon Fuel-Agnostic Engine Platform Strategy. Cummins press release. https://www.cummins.com/news/2022/02/14/cummins-new-low-carbon-fuel-agnostic-engine-platform-strategy.

5. Ball, Phillip. Krystian Czado. March 1, 2022. Natural hydrogen: the new frontier. Geoscientist. https://geoscientist.online/sections/unearthed/natural-hydrogen-the-new-frontier/.

6. Ker, Charlie. September 17, 2022. Westport prototype H_2 ICE truck. E-mail to Rick Mihelic.

7. Hyundai. May 10, 2022. Hyundai Motor Details Plans to Expand into U.S. Market with Hydrogen-powered XCIENT Fuel Cells at ACT Expo. Hyundai press release. https://www.hyundai.com/worldwide/en/company/newsroom/hyundai-motor-details-plans-to-expand-into-u.s.-market-with-hydrogen-powered-xcient-fuel-cells-at-act-expo-0000016825.

8. Fuel Cell Works. December 26, 2021. The Port of Oakland Gets a Federal Grant of $5.2 Million for Its Clean Energy Efforts, Including Fuel Cell Site. https://fuelcellsworks.com/news/the-port-of-oakland-gets-a-federal-grant-of-5-2-million-for-its-clean-energy-efforts-including-a-fuel-cell-site/

9. Hyzon website. https://www.hyzonmotors.com/vehicles/hyzon-class-8.

10. Nikola website. https://nikolamotor.com/tre-fcev.

11. Nikola website. https://nikolamotor.com/two-fcev.

12. Capacity Trucks website. August 26, 2021. Capacity Trucks Introduces First North American Hydrogen Fuel Cell Electric Truck Built from the Ground Up. Capacity press release. https://capacitytrucks.com/capacity-trucks-introduces-first-north-american-hydrogen-fuel-cell-electric-hybrid-truck-built-from-the-ground-up/.

13. Sustainable Truck & Van. June 27, 2022. FCEV truck with liquid hydrogen? Mercedes-Benz starts testing it. Sustainable Truck & Van. https://www.sustainabletruckvan.com/mb-truck-liquid-hydrogen-tests/.

14. Volvo Group website. What are hydrogen fuel cells? https://www.volvogroup.com/en/future-of-transportation/innovation/electromobility/hydrogen-fuel-cells.html.

15. CALSTART. November 29, 2022. The Biden Administration Signs Ambitious Global Agreement to Accelerate Zero-Emission Transport. CALSTART press release. https://calstart.org/biden-administration-signs-ambitious-global-agreement/.

16. Global Commercial Vehicle Drive To Zero website. December 20, 2021. Global Memorandum of Understanding on Zero-Emission Medium- and Heavy-Duty Vehicle. Global Commercial Vehicle Drive To Zero. https://globaldrivetozero.org/mou-nations/.

17. Campbell, Colin. November 29, 2022. Biden backs shift to zero-emissions truck sales at COP27. Transport Dive. https://www.transportdive.com/news/US-backs-shift-zero-emission-truck-sales-COP27/637441/.

18. Shell website. Shell Sustainability Report 2021. https://reports.shell.com/sustainability-report/2021/achieving-net-zero-emissions.html.

19. BP website. Net Zero by 2050. https://www.bp.com/en/global/corporate/news-and-insights/reimagining-energy/net-zero-by-2050.html.

20. Chevron website. October 2011. Chevron sets net zero aspiration and new GHG intensity target. Chevron press release. https://www.chevron.com/newsroom/2021/Q4/chevron-sets-net-zero-aspiration-and-new-GHG-intensity-target.

21. Exxon website. 2023 Advancing Climate Solutions Progress Report. https://corporate.exxonmobil.com/climate-solutions/advancing-climate-solutions-progress-report.

22. Pilot Flying J website. GM and Pilot Company to Build Out Coast-to-Coast EV Fast Charging Network. Pilot Flying J press release. https://pilotflyingj.com/press-release/19335.

23. *The Wall Street Journal*. Travel Centers of America to Add Hydrogen Fueling Sites for Big Rigs. WSJ. https://www.wsj.com/articles/travelcenters-of-america-to-add-hydrogen-fueling-sites-for-big-rigs-11619125565.

24. Adler, Alan. April 22, 2021. TravelCenters of America and Nikola plan California hydrogen stations. FreightWaves. https://www.freightwaves.com/news/travelcenters-of-america-and-nikola-plan-california-hydrogen-stations.

25. Nikola. April 22, 2021. Nikola Energy and TravelCenters of America to Deploy Hydrogen Fueling Infrastructure. Nikola press release. https://nikolamotor.com/press_releases/nikola-energy-and-travelcenters-of-america-to-deploy-hydrogen-fueling-infrastructure-117.

26. Plugpower website. December 15, 2022. Plug and Nikola announce collaboration to push hydrogen economy forward. Plugpower press release. https://www.ir.plugpower.com/press-releases/news-details/2022/Plug-and-Nikola-Announce-Collaboration-toPush-Hydrogen-Economy-Forward/default.aspx.

27. The White House. November 11, 2022. FACT SHEET: President Biden Announces New Initiatives at COP27 to Strengthen U.S. Leadership in Tackling Climate Change. Whitehouse press release. https://www.whitehouse.gov/briefing-room/statements-releases/2022/11/11/fact-sheet-president-biden-announces-new-initiatives-at-cop27-to-strengthen-u-s-leadership-in-tackling-climate-change/.

28. U.S. Department of Energy. January 10, 2023. Biden-Harris Administration Releases First-Ever Blueprint to Decarbonize America's Transportation Sector. U.S. DOE press release. https://www.energy.gov/articles/biden-harris-administration-releases-first-ever-blueprint-decarbonize-americas.

29. U.S. Department of Energy. January 2023. The U.S. Blueprint for Transportation Decarbonization. DOE/EE-2674. U.S. Department of Energy. https://www.energy.gov/sites/default/files/2023-01/EERE-Decarbonization-Transportation-Report-508.pdf.

30. U.S. Department of Energy. September 15, 2022. Memorandum of Understanding. U.S. Department of Energy. https://www.energy.gov/sites/default/files/2022-09/mou-doe-dot-epa-hud-final_09-15-2022.pdf.

31. The White House. August 14, 2022. By The Numbers: The Inflation Reduction Act. https://www.whitehouse.gov/briefing-room/statements-releases/2022/08/15/by-the-numbers-the-inflation-reduction-act/.

32. Bipartisan Policy Center. August 2022. Inflation Reduction Act (IRA) Summary: Energy and Climate Provisions. https://bipartisanpolicy.org/blog/inflation-reduction-act-summary-energy-climate-provisions/.

33. The White House. President Biden's Bipartisan Infrastructure Law. https://www.whitehouse.gov/bipartisan-infrastructure-law/.

34. Lobosco, Katie. Tami Luhby. July 28, 2021, updated November 15, 2021. Here's what's in the bipartisan infrastructure package. CNN. https://www.cnn.com/2021/07/28/politics/infrastructure-bill-explained/index.html.

35. Nevada state government. March 29, 2022. Multi-State Zero-emission Medium- and Heavy-Duty Vehicle Initiative - Memorandum of Understanding. Nevada state government. https://gov.nv.gov/uploadedFiles/govnewnvgov/Content/News/Press/2022/MHDV_ZEV_MOU_20220329_signed.pdf.

36. CALSTART. June 2022. Zeroing in on Zero-Emission Trucks. CALSTART. https://calstart.org/wp-content/uploads/2022/07/ZIO-ZETs-June-2022-Market-Update.pdf.

37. Bliss, Laura. January 6, 2022. "Six States Adopt Clean Truck Rule." *Transport Topics*. https://www.ttnews.com/articles/six-states-adopt-clean-truck-rule.

38. Buysse, Claire. Ben Sharpe. July 20, 2020. California's Advanced Clean Trucks Regulation: Sales Requirements for Zero-Emission Heavy-Duty Trucks. International Council on Clean Transportation (ICCT). https://theicct.org/publication/californias-advanced-clean-trucksregulation-sales-requirements-for-zero-emission-heavy-duty-trucks/.

37. U.S. EPA. September 2011. Final Rule for Phase 1 Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles. U.S. Environmental Protection Agency. https://www.epa.gov/regulations-emissions-vehicles-and-engines/final-rule-phase-1-greenhouse-gas-emissions-standards.

38. U.S. EPA. October 2016. Final Rule for Phase 2 Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles. U.S. Environmental Protection Agency. https://www.epa.gov/regulations-emissions-vehicles-and-engines/final-rule-phase-2-greenhouse-gas-emissions-standards.

39. U.S. EPA. December 20, 2022. Final EPA Standards for Heavy-Duty Vehicles to Slash Dangerous Pollution and Take Key Step Toward Accelerating Zero-Emissions Future. U.S. Environmental Protection Agency. https://www.epa.gov/newsreleases/final-epa-standards-heavy-duty-vehicles-slash-dangerous-pollution-and-take-key-step.

40. U.S. EPA. August 5, 2021. Clean Trucks Plan. U.S. Environmental Protection Agency website. https://www.epa.gov/regulations-emissions-vehicles-and-engines/clean-trucks-plan.

41. U.S. EPA. August 2021. EPA Announces the "Clean Trucks Plan." U.S. Environmental Protection Agency EPA-420-F-21-057. https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1012ON0.pdf.

42. Proposed Rule and Related Materials for Control of Air Pollution from New Motor Vehicles: Heavy-Duty Engine and Vehicle Standards. March 28, 2022. U.S. Environmental Protection Agency (EPA). https://www.epa.gov/regulations-emissions-vehicles-and-engines/proposed-rule-and-related-materials-control-air-1

43. Cannon, Jason. December 20, 2022. Trucking groups slam 'challenging' new EPA rule that slashes truck emissions limits. *Commercial Carrier Journal* (*CCJ*). https://www.ccjdigital.com/regulations/article/15304695/epa-sets-tougher-heavy-truck-emissions-regulations

44. Advanced Clean Fleets. California Air Resources Board (CARB). https://ww2.arb.ca.gov/our-work/programs/advanced-clean-fleets

45. Zero-Emission Regulations. January 2022. Southern California Edison. https://image.email.sce.com/lib/fe9612727166057577/m/5/de84b6cb-8e7b-476f-8a6de442fed29720.pdf?et_cid=ISR+Email_01_2022+-+Level+1&et_rid=584259084

46. Daimler Regulatory Update. March 16, 2021. Daimler Trucks North America presentation to the National Automobile Dealers Association (NADA) ATD Virtual Roundtable. Provided to Mike Roeth by David J. Bell, Director Legislative Affairs National Automobile Dealers Association.

47. Clean Trucks Rule 2021. Jun 24, 2021. Oregon Department of Environmental Quality (DEQ) Public Stakeholder Meeting. https://www.oregon.gov/deq/Regulations/rulemaking/RuleDocuments/ctr2021m1pres.pdf.

48. SCAQMD. May 2021. Rule 2305. Warehouse Indirect Source rule – Warehouse Actions and Investments to Reduce Emissions (WAIRE) Program. South Coast Air Quality Management District (SCAQMD). http://www.aqmd.gov/docs/default-source/rule-book/reg-xxiii/r2305.pdf

49. Sobhani, Casey. George Gigounas, Paul Hemmersbaugh, Andrew Brady, Paul Wierenga, Caroline Lee, Isabella Neal. June 30, 2021. Understanding California's South Coast AQMD Warehouse Indirect Source Rule – key points for warehouse owners, operators and tenants. DLA Piper.

https://www.dlapiper.com/en-us/insights/publications/2021/06/understanding-californias-south-coast-aqmd-warehouse-indirect-source-rule.

50. CARB. March 17, 2022. 2022 Amendments to the Airborne Toxic Control Measure for In-Use Diesel-Fueled Transport Refrigeration Units (TRU) and TRU Generator Sets, and Facilities Where TRUs Operate. California Air Resources Board (CARB). https://ww2.arb.ca.gov/sites/default/files/2022-03/TRU%20ATCM%202022%20Amendments%20Fact%20Sheet_0.pdf.

51. TMC. January 2022. Trailer Energy Harvesting: Regenerative Braking Systems for Trailer Applications. American Trucking Association (ATA) Technology and Maintenance Council (TMC). Future Truck Position Paper 2022-2. https://tmc.trucking.org/.

52. SEC. March 2022. Enhancement and Standardization of Climate-Related Disclosures. Securities and Exchange Commission (SEC). https://www.sec.gov/files/33-11042-fact-sheet.pdf.

53. Yakub, Mehanaz. November 8, 2021. On Transport Day at COP26, 15 nations commit to accelerating the shift toward zero-emission medium- and heavy-duty vehicles, targeting 30 per cent new ZEV sales by 2030 and 100 per cent new ZEV sales by 2040. Electric Autonomy. https://electricautonomy.ca/2021/11/09/cop26-zero-emission-truck-bus-canada/.

54. Smith, John. March 30, 2022. Canada commits to zero-emission truck sales targets and incentives. TruckNews. https://www.trucknews.com/equipment/canada-commits-to-zero-emission-truck-sales-targets-and-incentives/1003158200/.

55. "2030 Emissions Reduction Plan." Environment and Climate Change Canada. ISBN: 978-0-660-42686-0. https://www.canada.ca/content/dam/eccc/documents/pdf/climate-change/erp/Canada-2030-Emissions-Reduction-Plan-eng.pdf.

56. Cannon, Jason. January 6, 2023. EPA eyeing more strict particulate matter regulation. *Overdrive*. https://www.overdriveonline.com/regulations/article/15305192/epa-eyes-more-strict-particulate-matter-regulation

57. U.S. EPA. January 6, 2023. EPA Proposes to Strengthen Air Quality Standards to Protect the Public from Harmful Effects of Soot. U.S. Environmental Protection Agency (EPA) press release. https://www.epa.gov/newsreleases/epa-proposes-strengthen-air-quality-standards-protect-public-harmful-effects-soot.

58. DTNA. November 11, 2021. Daimler Trucks North America Receives SuperTruck 3 Award. Daimler Trucks North America (DTNA) press release. https://northamerica.daimlertruck.com/PressDetail/daimler-trucks-north-america-receives-supertruck-2021-11-01.

59. U.S. DOE. November 1, 2021. DOE Announces Nearly $200 Million to Reduce Emissions From Cars and Trucks. U.S. Department of Energy (DOE) press release. https://www.energy.gov/articles/doe-announces-nearly-200-million-reduce-emissions-cars-and-trucks.

60. DOE website. Liquid Hydrogen Delivery. U.S. Department of Energy. https://www.energy.gov/eere/fuelcells/liquid-hydrogen-delivery.

61. HDT staff. June 27, 2022. Daimler Truck Tests Fuel-Cell Truck with Liquid Hydrogen. Heavy-Duty Trucking (HDT). https://www.truckinginfo.com/10175707/daimler-truck-tests-fuel-cell-truck-with-liquid-hydrogen.

62. Daimler Truck. June 27, 2022. Development milestone: Daimler Truck tests fuel-cell truck with liquid hydrogen. Daimler Truck press release. https://media.daimlertruck.com/marsMediaSite/en/instance/ko/Development-milestone-Daimler-Truck-tests-fuel-cell-truck-with-liquid-hydrogen.xhtml?oid=51975637.

63. Ohnsman, Alan. February 11, 2021. Busch. Forbes. https://www.forbes.com/sites/alanohnsman/2022/02/11/nikola-kicks-off-hydrogen-truck-tests-with-pre-super-bowl-beer-runs-for-anheuser-busch/?sh=5d08f2b55f87.

64. Biagi Bros. March 14, 2022. Cheers to Zero Emissions – A Partnership With Nikola Motors & Annheuser Busch. Biagi Bros. https://www.biagibros.com/blog/biagi-greener-environment/nikola-annheuser/.

65. Toyota. 2022 Mirai Owner's Manual. https://www.toyota.com/owners/resources/warranty-owners-manuals.mirai.2022

66. Ballard. June 11, 2020. Exploring Hydrogen Fuel Cells for Freight Transport [Interview]. https://blog.ballard.com/fuel-cells-for-freight.

67. Ballard. June 2020. Fuel Cell Electric Trucks. Ballard. https://info.ballard.com/fuel-cell-electric-trucks

68. Federal Reserve website. https://www.federalreserve.gov/aboutthefed.htm.

69. Schneider, Howard. Ann Saphir. January 17, 2023. Fed wants climate risk analysis from 6 largest U.S. banks by July 31. Reuters. https://www.reuters.com/business/sustainable-business/fed-wants-climate-risk-analysis-6-largest-us-banks-by-july-31-2023-01-17/

70.Federal Reserve website. Federal Reserve Board provides additional details on how its pilot climate scenario analysis exercise will be conducted and the information on risk management practices that will be gathered over the course of the exercise. Federal Reserve press release. https://www.federalreserve.gov/newsevents/pressreleases/other20230117a.htm.

71. EPA website. Learn About Impacts of Diesel Exhaust and the Diesel Emissions Reduction Act (DERA). U.S. Environmental Protection Agency (EPA). https://www.epa.gov/dera/learn-about-impacts-diesel-exhaust-and-diesel-emissions-reduction-act-dera.

72. EPA website. Refrigerated Trailers and Transport Refrigeration Units (TRUs). U.S. Environmental Protection Agency. https://www.epa.gov/verified-diesel-tech/refrigerated-trailers-and-transport-refrigeration-units-trus.

73. Lindquist, Jason. January 16, 2023. The Contenders - What We Know Of The Secret List Of Survivors Of DOE's Hydrogen Hub Cutdown. RBN Energy LC. https://rbnenergy.com/the-contenders-what-we-know-of-the-secret-list-of-survivors-of-does-hydrogen-hub-cutdown.

74. DOE website. September 2022. DOE National Clean Hydrogen Strategy and Roadmap (Draft). U.S. Department of Energy (DOE). https://www.hydrogen.energy.gov/clean-hydrogen-strategy-roadmap.html.

75. DOE website. Regional Clean Hydrogen Hubs. Department of Energy (DOE). https://www.energy.gov/oced/regional-clean-hydrogen-hubs.

76. DOE website. Regional Clean Hydrogen Hubs Notifications. Department of Energy (DOE). https://www.energy.gov/oced/regional-clean-hydrogen-hubs-notifications.

77. Hy Stor Energy. June 29, 2022. Hy Stor Energy Strategic Partnership with Key Gulf Coast Port Becomes First to Deliver Renewable Hydrogen Access for Manufacturing, Industrial Applications, Port Operations and Long Duration Energy Storage. Hy Stor Energy press release. https://www.businesswire.com/news/home/20220629005311/en/Hy-Stor-Energy-Strategic-Partnership-with-Key-Gulf-Coast-Port-Becomes-First-to-Deliver-Renewable-Hydrogen-Access-for-Manufacturing-Industrial-Applications-Port-Operations-and-Long-Duration-Energy-Storage.

78. Hy Stor Energy website. https://hystorenergy.com/.

79. HyVelocity Hub website. HyVelocity Hub: Rapidly Scaling Clean Hydrogen Supply and Demand. https://www.hyvelocityhub.us/.

80. Center for Houston's Future website. Introducing HyVelocity Hub: A Commitment to Advance Clean, Affordable, At-Scale Hydrogen in Texas and Louisiana. https://www.centerforhoustonsfuture.org/h2houstonhub.

81. Mihelic, Rick. November 15, 2022. Hydrogen as a Transportation Solution. Maine MHDV industry stakeholder group meeting presentation. Available from author or Benjamin Lake.

82. Washington State Department of Commerce. November 7, 2022. Pacific Northwest Hydrogen Association submits concept paper, advances bid for US Dept. Energy Hydrogen Hubs opportunity. Washington State Department of Commerce press release. https://www.commerce.wa.gov/news/pacific-northwest-hydrogen-association-submits-concept-paper-advances-bid-for-us-dept-energy-hydrogen-hubs-opportunity/.

83. Washington Green Hydrogen Alliance website. Washington Evergreen Hydrogen: Energy in a State of Nature. https://www.wagreenhydrogen.com/.

84. MachH2. November 3, 2022. Midwest Alliance for Clean Hydrogen (MACHH2) Announces Bid to Create Regional Hydrogen Hub to Combat Climate Change. Midwest Alliance for Clean Hydrogen (MACHH2) press release. https://dpi.uillinois.edu/news/midwest-alliance-fir-clean-hydrogen-machh2-announces-bid-to-create-regional-hydrogen-hub-to-combat-climate-change/.

85. Casey, Tina. August 28, 2022. Monster Clean Hydrogen Hub Rising In Northeast US. Clean Technica. https://cleantechnica.com/2022/08/28/monster-clean-hydrogen-hub-rising-in-northeast-us/.

86. Alliance for Renewable Clean Hydrogen Energy Systems website. https://archesh2.org/.

87. California government website. Hydrogen. https://business.ca.gov/industries/hydrogen/.

88. California government website. October 6, 2022. California Launches Statewide Alliance to Establish Federally Co-Funded Hydrogen Hub. California Governor press release. https://business.ca.gov/california-launches-statewide-alliance-to-establish-federally-co-founded-hydrogen-hub/.

89. DOE website. Liquid Hydrogen Delivery. U.S. Department of Energy (DOE). https://www.energy.gov/eere/fuelcells/liquid-hydrogen-delivery.

90. Parks. G. R. Boyd, J. Cornish, R. Remick. May 2014. Hydrogen Station Compression, Storage, and Dispensing Technical Status and Costs. U.S. National Renewable Energy Laboratory (NREL). Technical Report NREL/BK-6A10-58564. https://www.nrel.gov/docs/fy14osti/58564.pdf.

91. DOE Office of Fossil Energy. July 2020. Hydrogen Strategy – Enabling A Low-Carbon Economy. U.S. Department of Energy. https://www.energy.gov/fecm/downloads/hydrogen-strategy-enabling-low-carbon-economy.

92. Koleva, Mariya. Neha Rustagi. October 2, 2020. Hydrogen Delivery and Dispensing Cost. U.S. Department of Energy (DOE). https://www.hydrogen.energy.gov/pdfs/20007-hydrogen-delivery-dispensing-cost.pdf.

93. Hydrogen Fuel Cell Partnership website. Cost to Refill. Hydrogen Fuel Cell Partnership. https://h2fcp.org/content/cost-refill.

94. Government of Alberta. November 2021. Alberta Hydrogen Roadmap. Government of Alberta. https://www.alberta.ca/hydrogen-roadmap.aspx.

95. Government of Alberta website. Suncor ATCO Hydrogen Project. https://majorprojects.alberta.ca/details/Suncor-ATCO-Hydrogen-Project/4438.

96. The Canadian Press. May 11, 2021. Oilsands producer Suncor and utility Atco to pursue 'world-class' hydrogen project. The Canadian Press. https://www.cbc.ca/news/canada/calgary/suncor-atco-hydrogen-project-alberta-1.6021796.

97. Government of Alberta website. Air Products Hydrogen Production and Liquefaction Facility. https://majorprojects.alberta.ca/details/Air-Products-Hydrogen-Production-and-Liquefaction-Facility/4461

98. Air Products. June 9, 2021. Air Products Announces Multi-Billion Dollar Net-Zero Hydrogen Energy Complex in Edmonton, Alberta, Canada. Air Products press release. https://www.prnewswire.com/news-releases/air-products-announces-multi-billion-dollar-net-zero-hydrogen-energy-complex-in-edmonton-alberta-canada-301308810.html.

99. Air Products website. September 6, 2022. Imperial Advances Renewable Diesel Plans, Awards Hydrogen Contract to Air Products. Air Products press release. https://www.airproducts.com/news-center/2022/09/0906-imperial-advances-renewable-diesel-plans-awards-hydrogen-contract-to-air-products.

100. Walrond, Christina, et al. January 24, 2023. DOE OCED Industrial Demonstration Program Notice of Intent Webinar. U.S. Department of Energy. https://www.energy.gov/oced/industrial-demonstrations-program-notice-intent-informational-webinar.

101. White House. January 27, 2021. Environmental Justice. White House Executive Order 14008. https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/27/executive-order-on-tackling-the-climate-crisis-at-home-and-abroad/

102. U.S. Government website. The Climate and Economic Justice Screening Tool. U.S. Government. https://toolkit.climate.gov/tool/climate-and-economic-justice-screening-tool and https://screeningtool.geoplatform.gov/en/#3/33.47/-97.5.

103. DOE website. Justice40 Initiative. https://www.energy.gov/diversity/justice40-initiative.

104. Banks, Kerry. June 15, 2021. Groundbreaking Edmonton-Calgary heavy-duty hydrogen truck pilot ready to roll. Electric Autonomy. https://electricautonomy.ca/2021/06/15/alberta-hydrogen-truck-pilot/.

105. Menzies, James. September 25, 2020. Alberta's hydrogen fuel cell truck project pushing on through Covid-related delays. *TruckNews*. https://www.trucknews.com/equipment/albertas-hydrogen-fuel-cell-truck-project-pushing-on-through-covid-related-delays/1003144980/.

106. Forrest, Ben. July 29, 2022. Hydrogen technology is key to innovating the commercial transportation sector. *Edmonton Journal*. https://edmontonjournal.com/technology/innovation-and-tech-in-alberta/sponsored-innovation-and-tech-in-alberta/hydrogen-technology-is-key-to-innovating-the-commercial-transportation-sector.

107. Remora website. https://remoracarbon.com/.

108. Dills, Todd. July 12, 2022. A run at mobile CO2 capture, straight from the stacks -- and growing markets for the gas. *Overdrive*. https://www.overdriveonline.com/equipment/article/15294060/a-run-at-mobile-co2-capture-and-growing-markets-for-the-gas.

109. The Canadian Press. March 16, 2021. Canada, Germany sign green energy deal in bid to power fledgling hydrogen sector. CBC News. https://www.cbc.ca/news/politics/canada-germany-energy-transition-1.5951584

110. Moore, Mike. August 23, 2022. 'Hydrogen alliance' formed as Canada, Germany sign agreement on exports. CBC News. https://www.cbc.ca/news/canada/newfoundland-labrador/canada-germany-hydrogen-partnership-nl-1.6559787.

111. NRCan Website. Alberta Zero-Emissions Truck Electrification Collaboration (AZETEC) Fueling Station. National. Government of Canada. https://www.nrcan.gc.ca/science-and-data/funding-partnerships/funding-opportunities/current-investments/alberta-zero-emissions-truck-electrification-collaboration-azetec-fueling-station/23620.

112. Current Results website. Calgary - Lowest Temperature for Each Year. https://www.currentresults.com/Yearly-Weather/Canada/AB/Calgary/extreme-annual-calgary-low-temperature.php.

113. Time and Date website. Climate & Weather Averages in Calgary, Alberta, Canada. https://www.timeanddate.com/weather/canada/calgary/climate.

114. Nordlund, Scott. September 26, 2022. Edmonton Transit launches hydrogen-electric bus pilot. Drive Tesla Canada. https://driveteslacanada.ca/news/edmonton-transit-launches-hydrogen-electric-bus-pilot/.

115. NRCan website. Electric Charging and Alternative Fueling Stations Locator. Canadian Government. https://www.nrcan.gc.ca/energy-efficiency/transportation-alternative-fuels/electric-charging-alternative-fuelling-stationslocator-map/20487#/find/nearest.

116. Renewables Now. September 7, 2020. Cummins to supply 5-MW electrolyzer for green hydrogen project. https://renewablesnow.com/news/cummins-to-supply-5-mw-electrolyzer-for-green-hydrogen-project-712708/.

117. Douglas County PUD. March 8, 2021. Renewable Hydrogen Production Facility Groundbreak. Douglas County PUD. https://douglaspud.org/renewable-hydrogen-production-facility-groundbreaking-d30/.

118. Google Maps website. https://www.google.com/maps.

119. Phillips, Charles. Jacob Leachman. August 4, 2021. The hydrogen fueled farm of the future. Washington State University. https://hydrogen.wsu.edu/2021/08/04/the-hydrogen-fueled-farm-of-the-future/.

120. Walton, Rod. May 10, 2022. Hyundai Motor Co. bringing Hydrogen Fuel-Cell Heavy-duty Trucks into U.S. commercial vehicle market. Energy Tech. https://www.energytech.com/emobility/article/21241392/hyundai-motors-bringing-hydrogen-fuelcell-heavy-duty-tractors-into-us-commercial-vehicle-market.

121. Randall, Chris. October 21, 2022. Is Hyundai pulling out of hydrogen project in Switzerland? Electrive.com. https://www.electrive.com/2022/10/21/hyundai-pulls-out-of-hydrogen-project-in-switzerland/.

122. Hyundai website. October 21, 2022. Statement concerning Hyundai Hydrogen Mobility business case in Switzerland. Hyundai press release. https://hyundai-hm.com/en/2022/10/21/statement-concerning-hyundai-hydrogen-mobility-business-case-in-switzerland/.

123. Hyundai website. October 15, 2022. On the road together: 20 hydrogen electric trucks drive the 5 millionth kilometer together. Hyundai press release. https://hyundai-hm.com/en/2022/10/15/on-the-road-together-20-hydrogen-electric-trucks-drive-the-5-millionth-kilometer-together-2/.

124. Adler, Alan. November 29, 2022. Hyundai's Xcient positioned for instant US fuel cell truck leadership. FreightWaves. https://www.freightwaves.com/news/hyundais-xcient-positioned-for-instant-us-fuel-cell-truck-leadership.

125. CTE website. July 26, 2021. CTE Wins Grant to Complete Largest Commercial Deployment of Class 8 Fuel Cell Electric Trucks in North America. CTE. https://cte.tv/norcal-zero-announcement/.

126. Road to Zero Emissions. YouTube/Hyundai. https://www.youtube.com/watch?v=kCtR0XoJYFg&t=429s.

127. Gordon, Amy. December 14, 2022. Texas' first hydrogen-powered truck hits the streets of Houston. Local Today. https://localtoday.news/tx/texas-first-hydrogen-powered-truck-hits-the-streets-of-houston-121843.html.

128. Webb, Shelby. Dec. 14, 2022. Houston Chronicle. First hydrogen-powered truck in Texas hits Houston roads. https://www.houstonchronicle.com/business/energy/article/First-hydrogen-powered-truck-in-Texas-hits-17651790.php

129. Hyzon. December 14, 2022. First Hydrogen Powered Truck in Texas. Hyzon Motors press release. https://www.hyzonmotors.com/in-the-news/first-hydrogen-powered-truck-in-texas.

130. Biagi Bros. March 14, 2022. Cheers to Zero Emissions – A Partnership With Nikola Motors & Annheuser Busch. Biagi Green blog. https://www.biagibros.com/blog/biagi-greener-environment/nikola-annheuser/.

131. Fine, Ariana. January 25, 2023. Nikola Plans Delivery of 15 Hydrogen Fuel-Cell Electric Vehicles to Biagi. NGT News. https://ngtnews.com/nikola-delivers-15-hydrogen-fuel-cell-electric-vehicles-to-biagi.

132. Toyota website. Decemberr 10, 2020. First Heavy-Duty Fuel Cell Electric Trucks Set for Delivery to Pilot Program Customers at Ports of L.A. and Long Beach. Toyota press release. https://pressroom.toyota.com/first-heavy-duty-fuel-cell-electric-trucks-set-for-delivery-to-pilot-program-customers-at-ports-of-l-a-and-long-beach/.

133. Toyota website. November 15, 2022. Trucking World Endorses Toyota's Hydrogen-Powered Fuel Cells as a Step Toward a Cleaner Planet. Toyota press release. https://pressroom.toyota.com/trucking-world-endorses-toyotas-hydrogen-powered-fuel-cells-as-a-step-toward-a-cleaner-planet/.

134. Buckholz, Kami. September 6, 2022. Truckin' on hydrogen. SAE International. https://www.sae.org/news/2022/09/toyota-hydrogen-fuel-cell-powertrain.

135. *TTNews*. August 1, 2011. TTSI to Purchase 100 Zero-Emission Class 8 Trucks. *TTNews*. https://www.ttnews.com/articles/ttsi-purchase-100-zero-emission-class-8-trucks.

136. Yahoo Finance website. September 25, 2014. Vision Industries Files for Voluntary Chapter 11 Bankruptcy Protection. Yahoo Finance. https://finance.yahoo.com/news/vision-industries-files-voluntary-chapter-210000055.html.

137. Westport Fuel Systems website. May 3, 2022. Westport Fuel Systems Unveils Hydrogen HPDI Fuel System for Internal Combustion Engines for Heavy-Duty Truck Applications. Westport Fuel Systems press release. https://investors.wfsinc.com/news/news-details/2022/Westport-Fuel-Systems-Unveils-Hydrogen-HPDI-Fuel-System-for-Internal-Combustion-Engines-for-Heavy-Duty-Truck-Applications/default.aspx.

138. Westport Fuel Systems website. October 26, 2022. Westport and Scania Announce Impressive Test Results of H_2 HPDI™ Fuel System for Heavy-Duty Transport. Westport Fuel Systems press release. https://investors.wfsinc.com/news/news-details/2022/Westport-and-Scania-Announce-Impressive-Test-Results-of-H-HPDI-Fuel-System-for-Heavy-Duty-Transport/default.aspx.

139. Cummins website. May 9, 2022. Cummins Inc. Debuts 15-Liter Hydrogen Engine at ACT EXPO. Cummins press release. https://www.cummins.com/news/releases/2022/05/09/cummins-inc-debuts-15-liter-hydrogen-engine-act-expo.

140. Wolfe, Matt. May 3, 2022. Hitting the gas on hydrogen tech for commercial trucks. SAE International. https://www.sae.org/news/2022/05/hydrogen-technology-commercial-trucks.

141. Devlin, Pete. Greg Moreland. May 30, 2018. Industry Deployed Fuel Cell Powered Lift Trucks. DOE Hydrogen and Fuel Cells Program Record. https://www.hydrogen.energy.gov/pdfs/18002_industry_deployed_fc_powered_lift_trucks.pdf.

142. Gründler, Matthias. Andreas Kammel. April 13, 2021. Why the future of trucks is electric. Traton website. https://traton.com/en/newsroom/current-topics/furture-transport-electric-truck.html.

143. Gardiner, Ginger. January 26, 2023. Cryo-compressed hydrogen, the best solution for storage and refueling stations? *CompositesWorld*. https://www.compositesworld.com/articles/cryo-compressed-hydrogen-the-best-solution-for-storage-and-refueling-stations.

144. Cummins website. September 21, 2022. Cummins New Fuel Agnostic X Series Platform Brings Low-to-Zero Carbon Fuel Capability to IAA. Cummins press release. https://www.cummins.com/news/releases/2022/09/21/cummins-new-fuel-agnostic-x-series-platform-brings-low-zero-carbon-fuel.

145. Cortes, Fernando. June 8, 2022. Zero Sum: How Walmart Transportation is Working to Reduce Emissions Now and in the Future. Walmart press release. https://corporate.walmart.com/newsroom/2022/06/08/zero-sum-how-walmart-transportation-is-working-to-reduce-emissions-now-and-in-the-future.

146. Mihelic, Rick. March 8, 2022. Photo at ATA TMC Spring 2022 Orlando event. NACFE.

147. Satyapal, Sunita. June 6, 2022. 2022 Hydrogen Program Update. AMR Plenary Session. U.S. Department of Energy (DOE) Hydrogen Annual Merit Review. https://www.hydrogen.energy.gov/pdfs/review22/plenary4_satyapal_2022_o.pdf.

148. Estimated U.S. Energy Consumption in 2021. U.S. Department of Energy (DOE) Lawrence Livermore National Laboratory (LLNL), https://flowcharts.llnl.gov/sites/flowcharts/files/2022-04/Energy_2021_United-States_0.png. And https://flowcharts.llnl.gov/.

149. Britannica website. https://www.britannica.com/science/quad.

150. Hydrogen Shot website. U.S. Department of Energy. https://www.energy.gov/eere/fuelcells/hydrogen-shot.

151. Schelfi, Giovanni. January 16, 2023. Global economic environment and its impact on the CVOH industry. Roland Berger. Slides provided by Mike Roeth.

152. BP. The Energy Outlook 2023 Edition. BP. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2023.pdf.

153. Slowik, Peter. Stephanie Searle, Hussein Basma, Josh Miller, Yuanrong Zhou, Felipe Rodríguez, Claire Buysse, Sara Kelly, Ray Minjares, Logan Pierce, Robbie Orvis, Sara Baldwin. January 2023.

Analyzing the Impact of the Inflation Reduction Act on Electric Vehicle Uptake in the United States. International Council on Clean Transportation and Energy Innovation Policy & Technology LLC. https://energyinnovation.org/publication/analyzing-the-impact-of-the-inflation-reduction-act-on-electric-vehicle-uptake-in-the-united-states/.

154. Borup, Rod. Adam Weber. June 2022. M2FCT: Million Mile Fuel Cell Truck Consortium. DOE hydrogen programs annual merit review. https://www.hydrogen.energy.gov/pdfs/review22/fc339_weber_borup_2022_o.pdf.

155. Million Mile Fuel Cell Truck (M2FCT) website. https://millionmilefuelcelltruck.org/.

156. Julin, Kiran. April 8, 2021. Hydrogen Offers Promising Future for Long-Haul Trucking Industry. Berkeley Lab. https://newscenter.lbl.gov/2021/04/08/hydrogen-offers-promising-future-for-long-haul-trucking-industry/.

157. Brown, Andy. June 2019. Hydrogen Transport. The Chemical Engineer. https://www.thechemicalengineer.com/features/hydrogen-transport/.

158. AFDC website. Fuel Properties Comparison. U.S. Department of Energy (DOE) Alternative Fuels Data Center (AFDC). https://afdc.energy.gov/fuels/properties.

159. Heil website. https://heiltrailer.com/.

160. DOE website. Physical Hydrogen Storage. U.S. Department of Energy (DOE). https://www.energy.gov/eere/fuelcells/physical-hydrogen-storage.

161. Ordaz, Grace. Cassidy Hoouchins. Thanh Hua. 2015. Onboard Type IV Compressed Hydrogen Storage System - Cost and Performance Status 2015. U.S. Department of Energy (DOE). https://www.hydrogen.energy.gov/pdfs/15013_onboard_storage_performance_cost.pdf.

162. Mihelic, Rick. May 2022. Photographs from ACT EXPO 2022. Long Beach, CA. NACFE.

163. Gaussin website. https://www.gaussin.com/apm.

164. Gaussin. March 16, 2022. GAUSSIN presents world's first hydrogen-powered fuel cell Automated Guided Vehicles (AGV H2) for ports application. Guassin press release. https://www.gaussin.com/news/gaussin-presents-worlds-first-hydrogen-powered-fuel-cell-automated-guided-vehicles-agv-h2-for-ports-application.

165. Anderson, Brad. December 7, 2022. HVS Gets UK Government Funding For Hydrogen Truck With Autonomous Tech. Carscoops. https://www.carscoops.com/2022/12/hvs-gets-uk-government-funding-for-hydrogen-truck-with-autonomous-tech/.

166. Anderson, Brad. February 4, 2023. World's First Self-Driving Hydrogen Truck To Begin Testing In 2024 After $8M Funding. World's First Self-Driving Hydrogen Truck To Begin Testing In 2024 After $8M Funding | Carscoops.

167. HVS. October 10, 2022. HVS Unveils Game-changing All-New Zero-emission Hydrogen-Electric Commercial Vehicle in Lead up to Production of Hydrogen HGV. Hydrogen Vehicle Systems press release. https://www.hvs.co.uk/_files/ugd/567e91_60f8cb8d61124ca9844253a1c24007bb.pdf.

168. College of the Desert. March 7, 2014. Hydrogen Fuel Cell Engines and Related Technologies Course Manual. U.S. Department of Energy (DOE). https://www1.eere.energy.gov/hydrogenandfuelcells/tech_validation/pdfs/fcm03r0.pdf and https://www.energy.gov/eere/fuelcells/articles/hydrogen-fuel-cell-engines-and-related-technologies-course-manual.

169. Y. Haseli, Y. March 2018. Maximum conversion efficiency of hydrogen fuel cells. ScienceDirect. https://www.dynamictidalpower.eu/resources/Documenten/Maximum_conversion_efficiency_of_hydroge.pdf.

170. Nebergall, Jim. January 27, 2022. Hydrogen Internal Combustion Engines and Hydrogen Fuel Cells. Cummins. https://www.cummins.com/news/2022/01/27/hydrogen-internal-combustion-engines-and-hydrogen-fuel-cells.

171. Nebergall, Jim. January 26, 2022. How Do Hydrogen Engines Work? Cummins. https://www.cummins.com/news/2022/01/26/how-do-hydrogen-engines-work?

172. Murakami, Yukitaka. 2019. Hydrogen Embrittlement. Metal Fatigue. Academic Press. ISBN 978-0-12-813876-2. https://doi.org/10.1016/C2016-0-05272-5.

173. Popov, Branko. Jong-Won Lee, Milos Djukic. 2018. Hydrogen Permeation and Hydrogen-Induced Cracking. Handbook of Environmental Degradation of Materials (Third Edition), Chapter 7. Elsevier Inc. https://doi.org/10.1016/C2016-0-02081-8.

174. San Marchi, Chris. Kevin Simmons. May 1, 2020. H-Mat Overview: Metals. U.S. Department of Energy. https://www.hydrogen.energy.gov/pdfs/review20/in001_san_marchi_2020_o.pdf.

175. Seger, Jeff. Rick Mihelic, Mike Roeth. February 2023. The Messy Middle: A Time for Action. North American Council for Freight Efficiency (NACFE). https://nacfe.org/research/thought-leadership/the-messy-middle/.

176. Kenworth website. Zero Emissions. https://www.kenworth.com/media/voffdzok/ata-fuel-cell-flyer-08-25-2021-v2.pdf.