



Exploring Hydrogen's Role in Heavy-Duty Trucking

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1. Introduction

Clean hydrogen (H₂) fuel can play a role in decarbonizing the heavy-duty transportation sector. Transportation is the biggest source of anthropogenic CO₂ emissions within the United States, and medium- and heavy-duty vehicles make up 23 percent of transportation emissions. The heavy-duty transportation sector is defined as commercial vehicles with gross vehicle weight ratings¹ more than 26,001 pounds and generally includes drayage trucks, short and regional day cabs, and long-haul Class 8 trucks.² This sector is particularly difficult to decarbonize, as these trucks often require long ranges and carry heavy payloads. This report provides an overview of H₂ truck technology, its current status in the United States, comparisons to diesel and battery electric trucks, challenges to deployment, and policy issues.

2. How It Works

H₂ can be used in heavy-duty transportation through two primary technologies: **fuel cell electric vehicles** (FCEVs) or **H₂ internal combustion engines** (H₂ICEs). This report focuses on FCEVs, as this is the primary use today and envisioned for the future. In both cases, the fueling process looks similar to conventional diesel, with H₂ being directly put into the tank as a liquid or gas.

However, fuel cells operate similarly to batteries, with a smaller onboard battery and fuel cell, which produces electricity as long as H₂ is supplied. The fuel cells include one positive electrode (cathode) and one negative electrode (anode) that surround an electrolyte. The anode receives H₂, and the cathode receives air. H₂ is then separated into protons and electrons; the electrons travel through an external circuit, creating electricity. The protons migrate to the cathode and ignite with oxygen and the electron, emitting water and heat as the only tailpipe emissions (DOE 2024).

H₂ can be stored as either a liquid or a gas, with gaseous storage requiring extremely high-pressure tanks at 350–700 bar to increase density and liquified H₂ requiring refrigeration to **-253°C**. H₂ has the highest energy per mass of any fuel; however, it has a low energy per unit of volume, creating challenges for storage and transportation. Liquifying H₂ increases energy per unit volume, therefore allowing more to be transported and stored and increasing truck range. Nevertheless, most attention is focused on gaseous H₂ due to the cost and complexities of keeping liquified H₂ at such low temperatures, as well as safety concerns, as any temperature above -253°C will cause it to turn to gas and build pressure within the tank that could lead to explosion.

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- 1 Gross vehicle weight rating is the maximum operating weight including vehicle, passenger, fuel, and payload.
 - 2 Drayage trucks are a form of short-haul heavy-duty trucking that transports containers and freight between different shipping modes. Short and regional day cabs are heavy-duty trucks without a sleeper cabin. Long-haul class 8 trucks generally include tractors and tractor-trailers with a sleeper cabin for long-haul routes.

3. The Status of Hydrogen-Fueled Heavy-Duty Vehicles

Although H₂ light-duty FCEVs are already in public use (particularly in California), heavy-duty transportation applications are just reaching commercial deployment. Several companies are investing in H₂ fuel cell trucks, with notable examples being Nikola, Hyzon, Daimler, Volvo, and Hyundai. Most of these companies are in the early demonstration phases; however, Nikola just delivered its first production run in 2023, with 42 trucks, and expects to deliver up to 350 more in 2024. For comparison, **266,752 new heavy-duty trucks** were sold in the United States in 2023; around **1,200 were battery electric**, and most of the remaining were diesel.

H₂ fueling infrastructure is also in its infancy within the United States. There are currently only **56 open retail stations**, with all but one in California and almost all serving light-duty vehicles. Only **six refueling stations** serve heavy- or medium-duty vehicles, with three serving trucks and the remaining serving bus transit fleets. However, this situation is set to improve, with Nikola planning to open 60 heavy-duty fueling stations over the next few years, **nine of them running by the middle of 2024**.

Fuel cell transit buses are comparatively further along than trucks, with California operating 66 such buses. As of 2020, the National Renewable Energy Lab (NREL) considered fuel cell buses to be at a technology readiness level of 7–8, indicating that they are undergoing full-scale validation in a relevant environment (Eudy and Post 2021). Notable examples exist in other areas of the country, such as Ohio's Stark Area Regional Transit authority, which operates 18 H₂ buses and a refueling station.

4. Environmental, Environmental Justice, Cost, and Operational Considerations

This section explores the environmental, environmental justice, cost, and operational considerations of FCEVs and compares them to diesel vehicles, the incumbent choice, and battery electric vehicles (BEVs), the widely embraced low-emission alternative.³

4.1. Environmental

Assessing the environmental impacts of H₂ FCEVs can be challenging, as upstream emissions will have the largest impact on life-cycle emissions. Fuel cell engines directly emit only heat and water; however, upstream emissions from the H₂ production pathway can significantly increase emissions. Currently, 95 percent of H₂ in the US is “gray,” produced from natural gas, which **emits 7–10 kgCO₂/kg H₂**. “Green” H₂, from zero-carbon electricity (such as solar, wind, hydropower, and nuclear), makes up less than 1 percent of US production and does not emit any CO₂ during production. However, the environmental benefit of green H₂ will be lessened if the clean electricity is not “additional,” as clean energy used for H₂ production can come at the opportunity cost of decarbonizing elsewhere. Although the **US Regional Clean Hydrogen Hubs** are aimed at increasing the amount of both “blue” H₂ (produced from natural gas with technology for capturing CO₂ emissions and storing it permanently) and green H₂ produced within the United States, production (and the distribution system to reach demand centers) will take years to come to fruition. Because FCEVs are being deployed now, they will be fueled mostly by gray H₂ until clean H₂ (and refueling infrastructure) is widely available at competitive (or subsidized) prices.

Most studies find that H₂ trucks would reduce life-cycle greenhouse gas (GHG) emissions compared to diesel trucks, but the degree varies by study, vehicle type, and H₂ pathway. One study (O’Connell et al. 2023) conducted a life-cycle assessment in Europe and found that gaseous H₂ produced using natural gas only reduces GHG

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- 3 **Biodiesel diesel, renewable diesel, and e-fuels** are additional alternatives in the heavy-duty trucking sector. They are not included in detail in this report, as we have focused on zero-tailpipe-emission options. However, they can provide an attractive alternative, as they can function as a drop-in fuel, allowing existing internal combustion vehicles to continue to be used. Biodiesel is made from vegetable oils and animal fats via an esterification process. Renewable diesel is similar but uses a hydrogenation process, which makes it chemically equivalent to petroleum diesel. Renewable diesel is the most suitable as a drop-in fuel and can be produced in existing petroleum refineries with small changes. E-fuels are made by synthesizing captured CO₂ and hydrogen, making them CO₂-neutral, as any CO₂ from combustion was already released previously. These options would all lead to relative reductions in CO₂ emissions compared to diesel, but they would still produce CO₂ tailpipe emissions and criteria air pollutants.

emissions by 15 percent compared to conventional diesel. When adding the energy to liquify the H₂, emissions are greater than those of diesel. However, they found that green H₂ could decrease emissions by as much as 84 percent for tractor-trailers, falling short of 100 percent because the study included vehicle production emissions as well. Another life-cycle comparison study by Lee et al. (2018) found similar results, with FCEVs using gaseous H₂ from natural gas reducing GHG emissions by 20–45 percent, depending on vehicle weight and type. However, this study found that with the current electricity generation mix, FCEVs create more SO_x emissions than diesel. These comparisons also play into the debate about H₂ tax credit eligibility (see later in this paper).

The environmental effects of BEVs will also depend on upstream production pathways—the electricity grid. Like FCEVs, BEVs come at the opportunity cost of using renewable electricity elsewhere; however, they are twice as efficient as FCEVs at converting renewable electricity to a mobility service (Ligen et al. 2018). O’Connell et al. (2023) and Lee et al. (2018) found that BEVs lead to greater emissions reductions compared to FCEVs.

Finally, H₂ production, fuel cell, and battery components require more critical minerals compared to diesel engines, increasing demand for lithium, nickel, copper, platinum, iridium and other minerals. Electrolysers require increased nickel and zirconium, and fuel cells require copper and platinum-group metals (IEA 2021). The latter, which are already used for internal combustion vehicles, are of particular concern given the low annual production. However, DOE has set targets for platinum requirements per kW for FCEVs, and the IEA found that in a Sustainable Development Scenario, internal combustion engine demand for platinum-group metals still dominates fuel cells in 2040 (IEA 2021). BEVs require a comparatively larger battery than FCEVs (**8–16 times larger**), increasing the demand for critical minerals. Continued innovation will be necessary to keep critical mineral requirements as low as possible. If these substances are imported, they may add to energy security concerns; if made domestically, their production and refinement can lead to significant environmental pollution.

4.2. Environmental Justice

Environmental justice communities express significant concerns around H₂ production, especially regarding blue H₂. Some perceive H₂ as a strategy for the fossil fuel industry to continue production, fearing that once H₂ infrastructure is established, there will be an economic incentive for producers to still use fossil fuels to make blue H₂. The CO₂ capture and storage technologies needed for blue H₂ engender additional skepticism, as they do not automatically capture criteria air pollutants and necessitates pipeline construction, posing leakage and explosion risks to local environments and communities. **Juan Jhong Chung** from the Michigan Environmental Justice Coalition characterizes these concerns: “Carbon capture technology and hydrogen will increase local air pollution, taint clean drinking water, threaten the safety of communities in the path of new pipelines, and raise energy bills for families nationwide.” Some groups advocate for only green H₂, although water use and non-additionality of clean electricity used for electrolysis are still of concern.

The federal government's emphasis on directing grants for blue H₂ production to fund projects in environmental justice communities that yield community benefits sets up a potential trade-off between economic development and potentially increasing negative externalities. Some environmental justice and disadvantaged communities perceive this emphasis as perpetuating environmental injustices and unfairly burdening communities with the safety and air pollution concerns associated with blue H₂ production, pipelines, and use.

However, some positive support exists for H₂ use in heavy-duty trucking. Many community groups feel that electrification should be the priority for transportation decarbonization but recognize that BEVs may not be suitable for long-haul trucks, with **EarthJustice** stating, "Hydrogen is rarely a solution for vehicle pollution, except possibly in extremely niche transportation sectors we cannot otherwise easily electrify." Given that diesel tailpipe emissions disproportionately affect environmental justice communities, particularly for last-mile delivery centers, H₂ presents an opportunity to mitigate this issue. Nonetheless, organizations caution that H₂ adoption should be restricted to cases where no other decarbonization solution is feasible.

4.3. Cost

Total cost of ownership (TCO) is a common metric to compare fleet costs across fuel types. TCO accounts for the overall cost of the vehicle throughout its life cycle, making capital costs, fuel costs, and maintenance costs particularly important. Several studies have attempted to compare the TCO of FCEVs with alternatives. All studies agree that FCEVs have a much higher TCO than diesel, but studies disagree on whether parity will ever be reached and whether FCEVs or BEVs face higher TCOs. One study by NREL found that for certain scenarios, FCEVs reach cost parity with diesel by 2050 (Hunter et al. 2021). However, Argonne National Laboratory conducted a similar study and found much higher TCOs, with FCEVs never reaching cost parity for Class 8 sleeper and day cabs (Burnham et al. 2021). Ledna et al. (2024) conducted a study that incorporated considerations from IRA tax credit 45W⁴ and DOE H₂⁵ cost projections. They found that heavy-duty FCEVs could reach parity by 2034. Studies disagree on the TCOs for BEVs. Hunter et al. (2021) and Ledna et al. (2024) both estimate that BEVs will be more expensive for heavy-duty applications, with Hunter et al. (2021) finding that BEVs will be more expensive than FCEVs in 2050 and reach cost parity with diesel later. However, Burnham et al. (2021) estimates BEVs will be cheaper than FCEVs even in 2025. These estimates are highly sensitive to H₂ fuel cost assumptions, which have uncertain trajectories. Medium- and heavy-duty BEVs have begun to emerge in the market, which allows us to quantify realized market prices. However, the resulting prices we will expect to see in the FCEV market as it develops are largely still unknown and may not accurately reflect the engineering and economic estimates of projected costs given market conditions (such as market power among manufacturers).

4 45W is the "Commercial Clean Vehicle Credit," which provides tax credits for qualified commercial clean vehicles. This tax credit is discussed in the "Policy Landscape" section.

5 DOE hydrogen cost projections implicitly incorporate incentives similar to 45V, as cost projections will require additional incentives and investments.

4.4. Operational

Operational considerations, such as range, refueling time, payload, and maintenance, are important for fleet owners, as decarbonized solutions often come at a cost premium compared to diesel. Given how new FCEVs are, estimates will continue to evolve as the technology advances. [Nikola](#) claims a range of up to 500 miles and refueling times of 20 minutes. [Hyzon Motors](#) is investing in liquid refueling stations and engines, completing its first commercial trial of a liquid H₂ FCEV in Texas, travelling more than 540 miles without refueling and expecting ranges of 650–800 miles in the future. Some diesel trucks can travel more than 1,000 miles, refueling in 10–20 minutes, but only a little more than **10 percent of all heavy-duty vehicles operate at a range more than 500 miles**. Differences in maintenance requirements cannot be reliably estimated yet, although it is expected that FCEVs will have higher maintenance costs compared to diesel, particularly in early stages of the technology.

Clean Air Task Force (CATF) conducted a study comparing the operational dimensions of FCEV and BEVs and found that H₂ edges out electricity at least in range, load, and refueling time (Walker 2023). However, CATF assumed the H₂ could be delivered to refueling stations. CATF also assumed 20-minute refueling for FCEVs compared to 330-minute charging for BEVs, but these assumptions are rapidly becoming out of date, with advancements in BEV batteries and chargers. Volvo's Class 8 electric truck claims a range of 275 miles and 90-minute charging. The Class 8 Tesla Semi reports ranges closer to 500 miles with charging up to 70 percent in 30 minutes. Although BEVs are making notable progress, FCEVs are still expected to have better range and faster refueling at a comparatively earlier stage of the technology. BEVs are also expected to face more performance degradation in extremely cold conditions and lose payload, as the battery is bigger than in an FCEV. Decreased payload capacity can increase TCO by more than 10 percent for large batteries (Burnham et al. 2021). FCEVs do not require large payload reductions, making them operationally competitive with diesel.

At this time, BEVs appear to be better equipped for regional and local use, with environmental and environmental justice advantages. However, given some operational disadvantages of BEVs, FCEVs may be better suited for niche long-haul applications. For a more in-depth look at BEV medium- and heavy-duty trucks, see [Spiller et al. \(2023\)](#).

5. Key Challenges to H₂ Deployment

5.1. Infrastructure

One of the biggest hindrances to wide-scale deployment of H₂ fuel cells is lack of refueling infrastructure and limited incentives for private investment in it. H₂ refueling stations face a “chicken and egg” problem, with the private sector lacking incentives to invest in infrastructure until the technology is more widely deployed and wide-scale deployment difficult without that infrastructure. Although the government has **released a strategy** for a national network of zero-emission refueling stations, buildout still has a long way to go, with only six heavy-duty stations available.⁶ ICCT found that 250,000 long-haul H₂ trucks would require 22,000 refueling stations (Ragon et al. 2023). Comparatively, **140,000 US diesel refueling stations** already exist to serve the approximately **seven million medium and heavy-duty trucks** on the road.

BEVs will also require a significant investment in charging stations to support truck electrification. Despite a dense preexisting electricity grid nationwide, substantial upgrades will likely be required before being able to accommodate heavy-duty charging. Furthermore, only a handful of public charging stations for heavy-duty trucks exist. However, the landscape is changing. For instance, BP **recently acquired TravelCenters of America**, which has 280 travel centers for heavy-duty trucks along major highways, adding to the more than 8,000 off-highway locations that it already owns. BP plans to build heavy-duty fast chargers for trucks (investing \$1 billion in charging stations by 2030) and could add H₂ refueling infrastructure with the appropriate incentives. As noted, Nikola also plans to build H₂ refueling stations to help reduce range anxiety for buyers of its H₂-fueled trucks.

5.2. Fleet Transition Costs

Transitioning diesel fleets to FCEVs will also come with significant transition costs, including the upfront vehicle purchase costs and refueling costs.

FCEVs are much more expensive than diesel equivalents across manufacturers. In 2018, the average Class 8 diesel truck cost **\$117,430**. Nikola executives reported an average FCEV selling price of \$351,000. However, their average production costs are (at these small volumes) **\$679,000**, resulting in a huge loss per truck. Although the H₂ truck costs will almost certainly fall as supply chain issues are alleviated and volumes pick up, that still presents a large barrier for both producers and consumers, and it is unclear at what point they will achieve cost parity.

6 Optimal implementation of this strategy will also require significant coordination between different levels of government and across states.

Even in places where H₂ infrastructure exists, fuel is still prohibitively expensive, with California truckers facing prices **up to \$36/kg**, much of this caused by an underutilized capacity. The TCO for an FCEV fleet is most sensitive to fuel cost; although these costs are expected to come down, it is still unknown if they will ever be low enough to compete with diesel or electric charging. One kilogram of H₂ has about the same energy content as a gallon of diesel, and the average US diesel fuel price was **\$4.21/gallon in 2023**. Ledna et al. (2024) found that for long-haul trucks, FCEVs would become competitive with diesel on a total cost of driving basis at H₂ costs below \$5/kg.

Ledna et al. (2024) found that long-range BEVs become competitive on a total cost of driving basis with diesel at charging costs below \$0.22/kWh for 1MW charging speeds. For comparison, US DC fast-charging stations averaged **\$0.41–0.50/kWh** as of January 2024. However, heavy-duty vehicles—particularly long-haul vehicles conducting on-route charging—will require the Megawatt Charging System (MCS) to ensure operational viability through reduced refueling times, thus increasing charging power and with it the speed and cost. With MCS, demand charges⁷ can substantially increase the cost of refueling and require a different type of calculation of price, as they are assessed on a kW rather than kWh basis. How much public MCS operators will charge truck drivers is still an open question, as public charging stations for heavy-duty BEVs are scarce and will likely change with greater use. Co-located storage and solar and managed charging software can help keep peak demands down, reducing the cost of refueling at these stations. Thus, the resulting cost of MCS at public locations is still an open question.

Furthermore, fleets must consider any “soft” transition costs. FCEV drivers will require additional safety training, as H₂ is extremely flammable and potentially explosive. This training will require both time and supplementary expenditures. This is also an important consideration for fleets considering BEV adoption, as they must deal with issues such as charging station investments, logistical adjustments, retraining their maintenance teams, and learning how to deal with complex electric tariffs, which will add soft transition costs for fleets.⁸

5.3. Secondary Truck Market

The secondary (used) truck market could also impact the adoption of FCEVs. Once depreciation for taxes has ended (we assume after around 5 years), FCEVs are usually sold on the secondary market, where the resale value offsets a large share of initial costs. Heavy-duty diesel trucks can be driven more than 750,000 miles in their lifetimes, often changing ownership several times. These older trucks generally service local and regional needs rather than using the interstates. This change in use means that both BEVs and FCEVs would need extensive local and regional refueling

7 Commercial electricity users typically face additional “demand charges” based on their maximum demands during a set period (such as a month), to account for the higher electric demands these customers place on the grid. An MCS facility will be subject to these demand charges, as it will require extremely large KW capacity from the grid.

8 See Spiller et al. (2023) for greater discussion of BEV fleet transition costs.

opportunities if the secondary market is to remain robust and make the purchase of new trucks more economic. Ubiquitous availability of electricity within cities and towns favors BEVs over FCEVs. Additionally, BEVs can swap batteries once performance begins to degrade, perhaps giving them a higher relative value on the secondary market. It is possible that FCEVs will also be able to swap fuel cells once they begin to degrade. However, it is too early to know how quickly fuel cells will degrade or the practicality of replacing them.

6. Policy Landscape

Existing policies tackle a variety of the different challenges H₂ fuel cells face, including fuel costs, purchase costs, and infrastructure. Although not an exhaustive list, this section highlights some of the main policies affecting H₂-fueled heavy-duty transportation. It also notes other government nonregulatory programs.

6.1. California Policies

California has arguably the most developed policy landscape supporting FCEVs in the United States, including a mix of standards, subsidies, and disincentives affecting high-carbon fuels.

California's Advanced Clean Truck (ACT) regulation is a requirement that manufacturers who certify Classes 2b–8 chassis or complete vehicles are required to sell an increasing percentage of zero-emission medium and heavy-duty trucks from 2024 to 2035. By 2035, zero-emission trucks sales are required to be 75 percent of Classes 4–8 “box truck” sales and 40 percent of semitrailer sales. FCEVs are defined as a “zero-emission” truck along with BEVs. Ten other states have also adopted California's ACT regulation.

California's Advanced Clean Fleet (ACF) regulation builds off the ACT regulation by requiring drayage, state and local government-owned, and federal and high-priority⁹ fleets to purchase an increasing share of zero-emission trucks beginning in 2024. The regulation also requires drayage, federal, and high-priority fleets to discontinue non-zero-emission truck use at the earlier of 18 years or 800,000 miles. ACF has an additional manufacturing sales requirement, mandating only zero-emission medium and heavy-duty vehicle sales beginning in 2036.

The **Low Carbon Fuel Standard** requires that fuel suppliers reduce the carbon intensity of transportation fuels by setting a decreasing limit and allowing suppliers to trade credits to meet the limit. The program also allows for credits to be generated by parties who own the equipment that dispenses H₂ to vehicles. It provides demand-side support for H₂ as a low-carbon fuel.

The **Hybrid and Zero-Emission Truck and Bus Voucher Incentive Program** offers point-of-sale incentives for the purchase of zero-emission trucks to bring down the TCO for fleet owners. For example, the program offers incentives of \$240,000 for Hyundai, Hyzon, and Nikola's fuel cell electric truck models.

9 High-priority fleets are fleets that have \$50 million or more in gross annual revenues or that own, operate, or have common control/ownership of 50 or more vehicles.

California's **Assembly Bill 8** provided the Energy Commission with up to \$20 million to cofund the development of H₂ fueling stations in California from 2014–2023, distributed through competitive grants annually. Station developers aimed to have 100 stations open by the end of 2023, but 51 projects have been cancelled due to challenging station economics.

6.2. Federal Policies

On a national level, federal policy has focused on subsidizing FCEVs and H₂ through grants for infrastructure and tax credits for H₂ production, carbon sequestration, infrastructure buildout, and clean-vehicle purchases. However, it lacks significant market disincentives for using diesel, as in California. The most stringent disincentive emerges through the GHG emissions standards that are going into effect in 2027.

The **Charging and Fueling Infrastructure** (CFI) grant program provides \$2.5 billion in competitive grants over four years for light- and heavy-duty fueling for electric, H₂, natural gas, and propane, half of which is reserved to be along Alternative Fuel Corridors.

The **Alternative Fuel Infrastructure Tax Credit** provides a tax credit for businesses installing H₂ refueling stations for up to 30 percent of depreciable costs up to \$100,000 if the installation meets prevailing wage and apprenticeship requirements.

The **clean hydrogen production tax credit** (45V) provides incentives for producing clean H₂, up to \$3/kilogram. 45V includes a tiered incentive structure based on the carbon intensity of H₂ production. For more information, see **Bergman (2024)**.

The **45W Commercial Clean Vehicle Credit** provides a maximum credit of \$40,000 for heavy-duty plug-in electric or fuel cell vehicles.

The **45Q Tax Credit for Carbon Sequestration** provides a tax credit of \$85/tonne of sequestered carbon dioxide and \$60/tonne of carbon dioxide utilized and not released in products or processes, both when meeting prevailing wage and apprenticeship requirements. This tax credit affects the cost of H₂ fuel, as carbon sequestration is used to make blue H₂.

The **Greenhouse Gas Emissions Standards for Heavy-Duty Vehicles** sets technology-neutral, performance-based standards for heavy-duty vehicles that go into effect between 2027 and 2032. FCEVs and H₂ICE are possible options to achieve these standards, but manufacturers could also opt for hybrid or advanced internal combustion engine vehicles.

The **Regional Hydrogen Hubs program** provides \$8 billion to the Office of Clean Energy Demonstrations (OCED) to establish and subsidize clean H₂ hubs throughout the country, designed to connect clean H₂ suppliers with users. DOE is currently negotiating with the seven winning applicants. Six out of the seven hubs listed heavy-duty truck transportation as an end use.

The **Clean Hydrogen Hubs Demand-Side Support Mechanism** takes up to \$1 billion from the H₂ Hubs program to provide subsidies to H₂ users affiliated with the seven hubs. Implementation is expected in early 2025.

The **National Zero-Emission Freight Corridor Strategy** was released by the Joint Office of Energy and Transportation and outlines a strategy for the buildout of networks of H₂ refueling stations and battery charging stations. The strategy aims to guide infrastructure investments to promote coordination, initially focusing on “first success regions.”

7. How Can We Overcome Challenges to Deployment?

Although existing policies go a long way to incentivizing H₂ fuel cell deployment, two policy gaps remain if FCEVs are to be seriously pursued: coordination and disincentives for continued diesel use. Coordination matters for both the location of infrastructure buildout and refueling station design, and given the strength of the secondary market for heavy-duty vehicles, national policy may need to also focus on disincentivizing continued use of existing diesel vehicles.

Although any infrastructure buildup will be beneficial, transportation corridors will need to logically connect to allow for national deployment. The National Zero-Emission Freight Corridor Strategy (led by the Department of Energy and Transportation joint effort and discussed earlier) offers guidance but may need to be paired with policies targeting zero-emission freight hubs, including coordinating with regional H₂ hubs, if it is to succeed in advancing FCEV adoption. Coordination is especially difficult given the early stages of both BEV and FCEV technologies, as the government would ideally remain technology neutral to allow the full capabilities of the technologies to be demonstrated. BEVs and FCEVs will likely fill different niches within the heavy-duty sector, as BEVs may be better suited for short-haul and regional routes and FCEVs for long-haul routes or heavy payloads; however, this situation may change over time as technology improves. Given their different advantages, infrastructure rollout would benefit from research and coordination with and directed to the Joint Office of Energy and Transportation.

In addition, refueling stations can be designed to allow maximum interoperability among stations and consumers to ensure that they are accessible to as many drivers as possible. Lessons can be learned from the rollout of light-duty BEV charging stations, where manufacturers originally used different charging connector standards. Ford and General Motors used the Combined Charging Standard (CCS) and Tesla used the North American Charging Standard (NACS), which created separate networks of incompatible connectors. Heavy-duty H₂ stations are vulnerable to similar problems, with different possibilities for nozzle and receptacle designs and continued debate over liquified versus gaseous H₂. The socially optimal outcome would be that all FCEV trucks could use the same refueling stations, without having to travel to manufacturer

stations. A national standard for refueling components could help alleviate concerns over component designs and allow for competition, avoiding situations such as Tesla's dominance in charging stations.

The policy landscape for H₂ also risks “**new source bias**,” which refers to the situation where environmental policies disproportionately target new technologies over old, raising the cost of the new technology and increasing the lifetime of the existing vehicle stock. The Greenhouse Gas Emissions Standards for Heavy-Duty Vehicles, which impose emissions standards on new vehicles beginning in 2027, risk raising the cost of purchasing new vehicles but not old diesel vehicles. As the stringency of the regulation increases, low-emission options could still be too expensive, incentivizing the prolonged use of existing diesel trucks. Given the strength of the secondary truck market, this is especially important, as used diesel vehicles can continue to be sold, decreasing fleet turnover. This could initially have a negative effect on emissions, as the used trucks will have worsening fuel efficiencies over time and increased conventional pollution emissions. To counteract this perverse effect, more disincentives on the national level, such as a national low-carbon fuel standard, scrapping requirements for old diesel vehicles, or a diesel carbon tax, could help limit use of high-carbon fuel options and increase fleet turnover.

In any event, the first serious use of clean H₂-fueled heavy-duty trucks is likely to be within or possibly linking some subset of the seven H₂ hubs supported by DOE along with up to \$1 billion in spending to bolster H₂ demand. Research is needed on the appropriate design for and distribution of user subsidies and on the myriad choices that the hub leadership, producers and pipeline, and refueling companies will need to make to realize clean H₂'s potential as a heavy-duty truck fuel.

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