MAKING SENSE OF HEAVY-DUTY HYDROGEN FUEL CELL TRACTORS

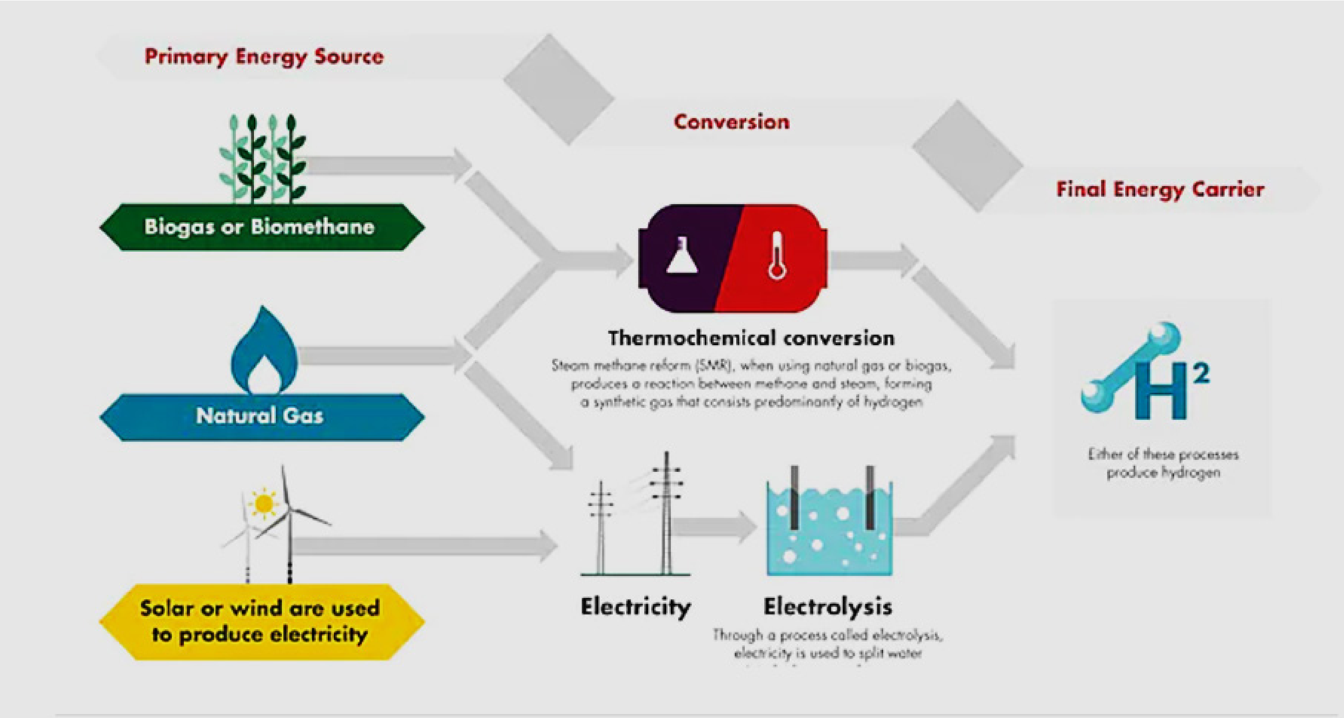
Nearly a day doesn't pass without new announcements about hydrogen and fuel cell electric trucks. Why are these two interrelated topics so popular today? How are they relevant to fleets, drivers, customers, manufacturers, investors, and owners? This NACFE report is intended to help make sense of hydrogen for commercial freight movement.

The fuel cell is the starting point of the discussion. It is a device that does not burn fuel as does an internal combustion engine (ICE), but rather chemically converts the stored energy in the fuel to create electricity while emitting only water as a byproduct.

Hydrogen is the fuel of choice for fuel cells, although there are other alternatives that can operate in fuel cells such as ammonia. Hydrogen is energy dense and abundant but does not occur naturally; it has to be coaxed out of other materials to be useful. There are many ways to produce hydrogen. (See Figure ES 1.)

FIGURE ES 1

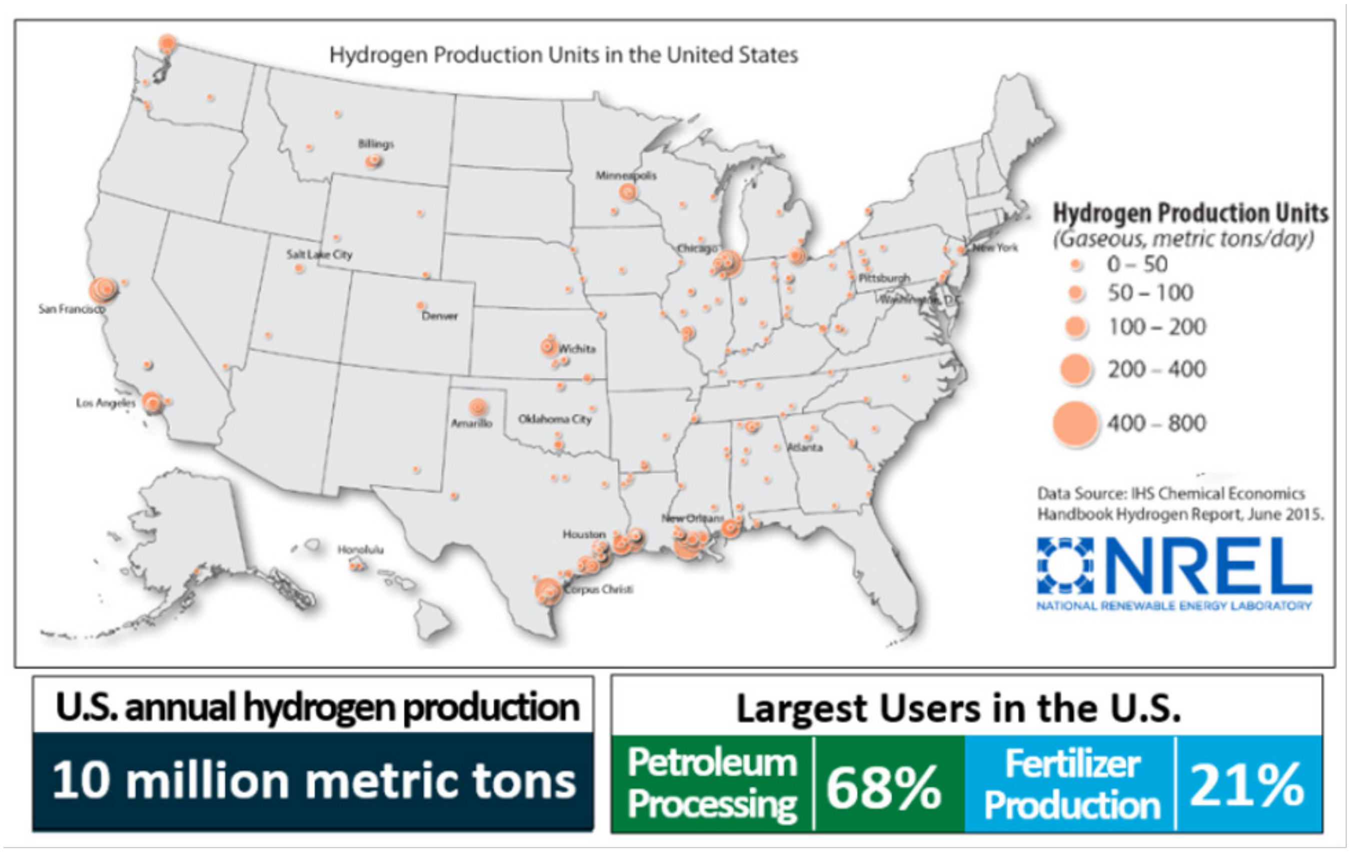
MANY PATHS TO HYDROGEN (SHELL)



Hydrogen is produced in bulk in many locations in North America today for a variety of end uses in industry, and a small fraction is used today for automobiles and buses in specific regions. (See Figure ES 2.)

FIGURE ES 2

US HYDROGEN PRODUCTION CAPACITY (NREL)



"While hydrogen fuel cell technology is very promising, we know that widespread adoption will take time. Many factors will influence this, including emissions regulations, infrastructure, hydrogen availability and total costs of ownership. Buses and trains will likely be some of the first applications to transition to hydrogen, with the Hydrogen Council predicting that heavy-duty trucks will fall further out on the curve with about 2.5 % of hydrogen adoption in 2030."

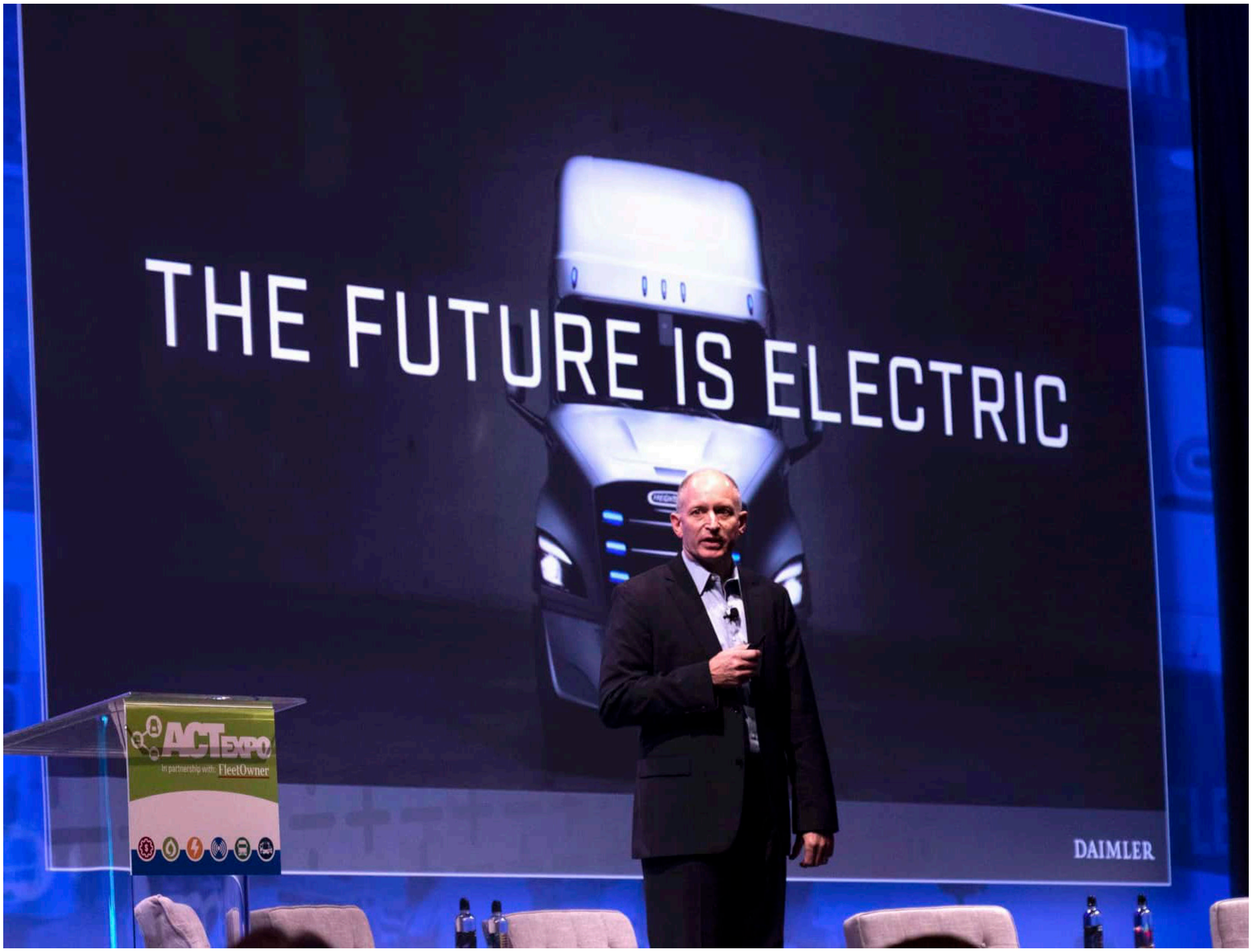
— Amy Davis, President of New Power Business, Cummins

The fuel cell translates the chemical energy stored in the hydrogen molecule into electricity, which then powers the vehicle motors and batteries. Essentially, a hydrogen fuel cell truck is a hybrid electric vehicle, sharing many of the components and operations of a pure battery electric vehicle (BEV).

At the April 2019 ACT EXPO in Long Beach, California, Daimler Trucks North America's president and CEO Roger Nielsen famously stated that "the future is electric." NACFE believes that prescient prediction is an accurate assessment whether talking of pure battery electric vehicles or hybrid fuel cell electric vehicles (HFCEVs), or more likely both in a zero-emissions freight transport future. (See Figure ES 3.)

FIGURE ES 3

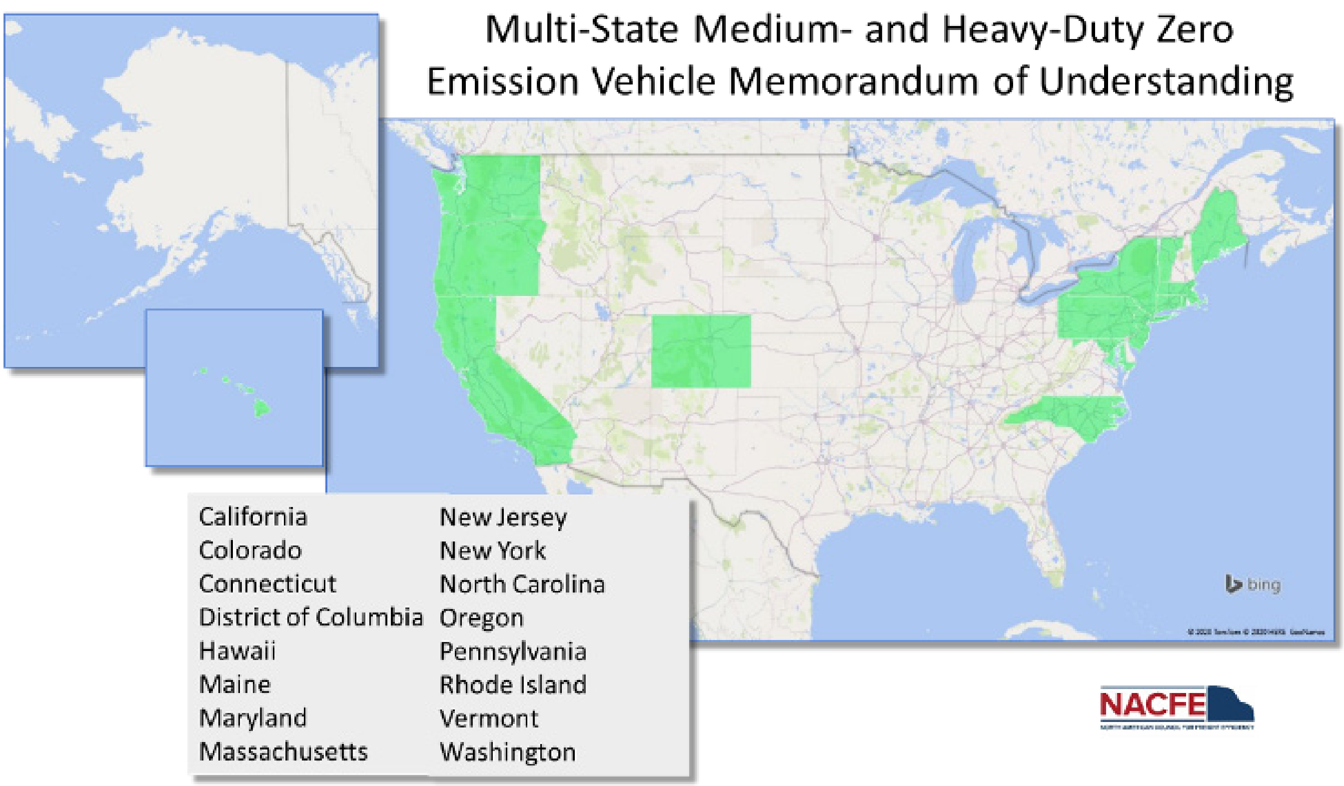
ROGER NIELSEN AT 2019 ACT EXPO (PHOTO BY TAYLOR HANNON)



Why is a zero-emissions future important to trucking? California enacted regulations in 2020 that require a graduated transition to zero-emissions trucks sold in the state starting in 2024 at 5% of the California market, and growing to 40% in 2032, and the governor signed executive order N-79-70 stating that it is a goal that all medium- and heavy-duty trucks be zero emission by 2045 for all operations where feasible and by 2035 for drayage trucks. In July 2020, 15 US states and the District of Columbia signed a memorandum of understanding (MOU) targeting 100% of all new medium-duty and heavy-duty truck sales to be zero-emissions vehicles (ZEVs) by 2050, with an interim target of 30% of new sales by 2030. (See Figure ES 4.) Canada has set a goal of net zero-emissions by 2050, and the national government, provincial governments, and city governments are working with industries to map out how to achieve those goals.

FIGURE ES 4

15 STATE ZEV MOU (NACFE)



In parallel with these high-level goals, federal, state, and local governments are taking steps to encourage adoption of lower-emitting freight solutions. This is being done through a variety of funding mechanisms including funding straight research and development, funding pilot studies, funding infrastructure deployment, and raising awareness. A plethora of industry organizations are further promoting migration to lower emissions solutions. Corporations are actively supporting these efforts by establishing sustainability plans and working toward net zero-emissions for their companies and supply chains.

Responding to all these forces, original equipment manufacturers (OEMs) have accelerated development of zero-emissions product lines, with many committing to production level vehicles in the 2021–2023 timeframe. The industry has even spawned start-up

METHODOLOGIES

NACFE's research for this report included interviewing key people with first-hand knowledge of heavy-duty tractor operations at fleets, manufacturers, and industry groups. The full report includes an extensive list of references to assist readers interested in pursuing more detail. These references were researched with the same diligence and thoughtful processes NACFE uses with its technology Confidence and Guidance Reports. This report builds off the previous three NACFE Guidance Reports: Electric Trucks—Where They Make Sense (published in May 2108), Medium Duty Electric Trucks—Cost of Ownership (published in October 2018), Amping Up: Charging Infrastructure for Electric Trucks (published in March 2019), Viable Class 7/8 Electric, Hybrid, and Alternative fuel Tractors (published December 2019); and High-Potential Regions for Electric Truck Deployments (published November 2020).

truck manufacturers, a new market phenomenon further pushing the industry into this new zero-emissions world and providing record investment in revolutionary new zero-emissions powertrains.

The prospects for zero-emissions trucks are even bringing electric utilities into the trucking industry as potential “vehicle fuelers” and causing traditional gasoline and diesel energy providers like Shell, BP, and others to consider becoming electricity and hydrogen suppliers.

Whether that electric future is battery electric, fuel cell electric, or catenary wire electric, the key need is electricity. The greenest method of producing hydrogen involves using electrolyzers powered by electricity, essentially running a fuel cell in reverse. The current industry is dominated by steam method reformation (SMR), which essentially uses natural gas to produce hydrogen. More than 95% of hydrogen production today is by SMR processes.

Today, the transportation sector uses only a small portion of US electricity—below 1% of total electricity use in the United States as reported by the US Department of Energy Lawrence Livermore National Laboratory. Estimates of an electric future with both battery electric and fuel cell vehicles will need anywhere from 2X to 8X the amount of electric energy produced today. Similarly, little of today’s hydrogen production is used for transportation. The production of both electricity and hydrogen will need to aggressively increase; and in lockstep, the demand for both will need to dramatically increase.

Quickly ramping up both electricity supply and demand, in the matter of a couple decades or less, is challenging. Application of funding can only do so much. Innovations will be required across a range of technologies. Priorities will need to support this effort through regional and national commitments.

Several nations have outlined roadmaps to net zero-emissions by 2050. Hydrogen and electricity play major roles in those roadmaps. They universally recognize that a portfolio solution to energy sourcing is needed, requiring a wide range of energy supply paths. When discussing how to produce hydrogen, these paths are labeled as colors in a spectrum, a metaphor recognizing that each energy path has its own set of challenges and opportunities with respect to being environmentally responsible. However, nearly all the paths could be viable, and likely all the paths may be needed to reach the goals in the targeted timeframes. (See Figure ES 5.)

FIGURE ES 5

HYDROGEN ENERGY COLOR SPECTRUM (NACFE)

Hydrogen Color Spectrum

GREEN
Hydrogen produced by electrolysis of water, using electricity from renewable sources like hydropower, wind, and solar. Zero carbon emissions are produced.

TURQUOISE
Hydrogen produced by the thermal splitting of methane (methane pyrolysis). Instead of CO_2, solid carbon is produced.

PINK/PURPLE/RED
Hydrogen produced by electrolysis using nuclear power.

BLACK/GRAY
Hydrogen extracted from natural gas using steam-methane reforming.

YELLOW
Hydrogen produced by electrolysis using grid electricity.

BLUE
Grey or brown hydrogen with its CO_2 sequestered or repurposed.

WHITE
Hydrogen produced as a byproduct of industrial processes.

BROWN
Hydrogen extracted from fossil fuels, usually coal, using gasification.

Note: There are no official definitions of these colors, but the above represents common industry nomenclature.

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Stating the goal is net zero-emissions by 2050 allows innovators to develop the technologies and facilities to achieve that target, irrespective of the starting point of the energy. NACFE's research identified that many countries that have committed to this goal recognize that getting there quickly will require environmentally responsible use of a portfolio of hydrogen production pathways.

In essence, we are at a hydrogen racetrack, and all the colors of horses are at the gate. Fleets, drivers, regulators, suppliers, manufacturers, and the public are all at the track. There ultimately will be one first-place horse but all the horses cross the finish line at the end of the long race, and ticket holders can win off of combinations of horses, like winning an exacta or trifecta. In fact, a hydrogen future requires all the horses to be in the race. (See Figure ES 6.)

FIGURE ES 6

THE ENERGY TO MAKE HYDROGEN RACE (LONE STAR PARK)

The costs of hydrogen, vehicles, and hydrogen production all must come down significantly to make hydrogen economically competitive with alternatives. The industry advocates and researchers are confident that these costs will be reduced through scale and innovation over time. The challenge is that truck populations change very slowly in comparison to the ambitious scheduled targets identified for decarbonizing transportation.

Trucking cannot carry the entire load for a hydrogen future. It's true that transportation—including commercial truck, automotive, planes, trains, and ships—represents from one-fifth to one-third of most nations' energy demand. However, there are not enough heavy-duty trucks to create sufficient demand to scale up hydrogen production fast enough to accelerate cost reduction. Fleets adopting hydrogen might see high fuel costs for some years if trucks are the only incentive for hydrogen production. Industrial use of hydrogen must increase for end-users like energy power plants, chemical industries, steelmakers, other material producers, and others. All

"There are many variables — dominoes that need to fall — to accurately predict the future for fuel cell vehicles. The technology is promising, and the massive level of investment is encouraging."

— Rick Mihelic, Director Emerging Technologies, North American Council for Freight Efficiency

these end-users need to step up demand to allow the scaling of hydrogen to happen quickly.

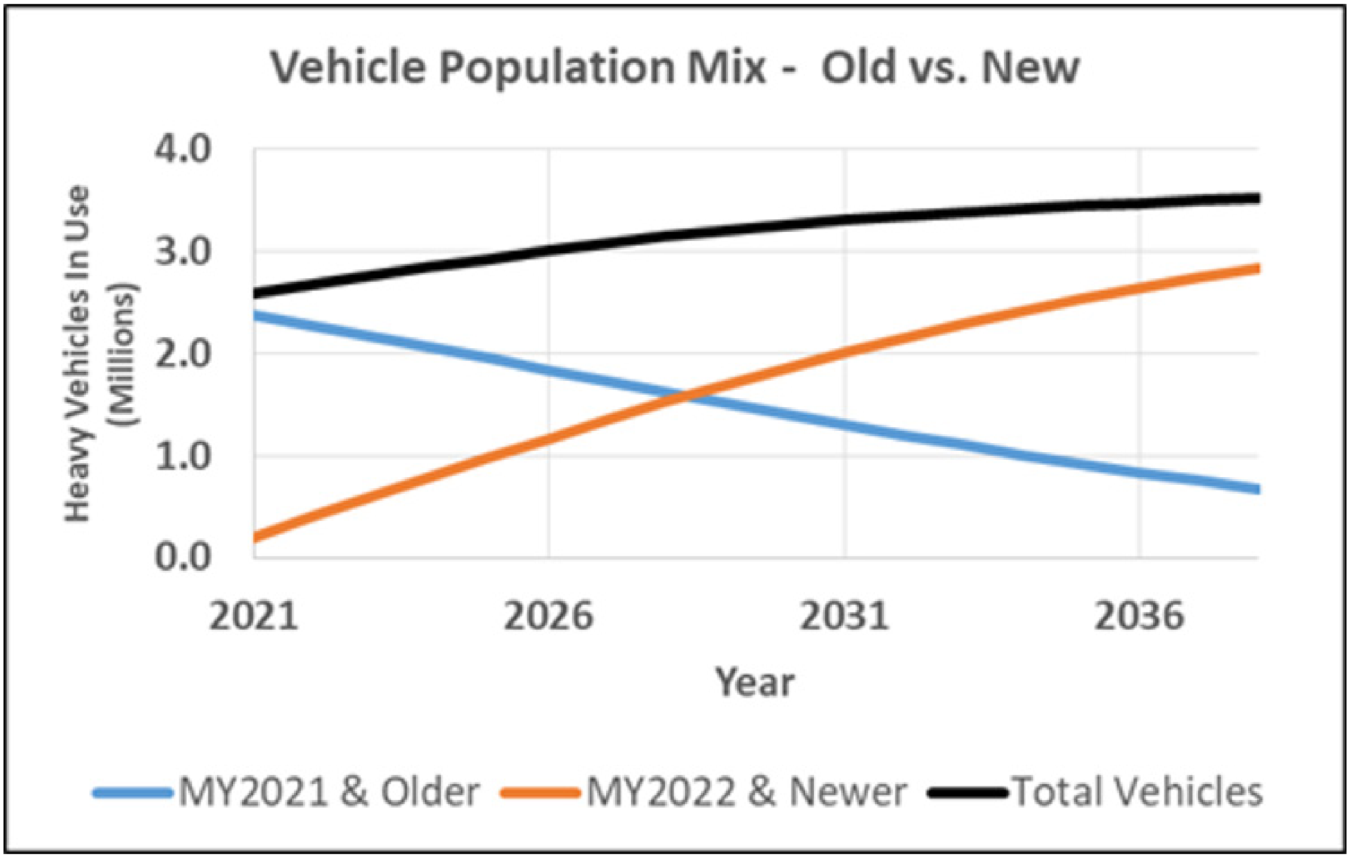
The truck manufacturing marketplace is entirely about supply and demand. The annual trucking market demand for new vehicles and the annual trucking manufacturing output range from 150,000 to 300,000 vehicles per year.

In 2020, manufacturers are starting essentially at zero production of Class 8 fuel cell trucks. In 2030, 30% of new Class 8 vehicles would optimistically be approximately 100,000 vehicles a year. There are an estimated 1.8 million Class 8 trucks hauling freight trailers in the United States today. In total, there may be up to 4 million Class 8 vehicles registered in the United States with the lives of those vehicles ranging from 12 to 20 years or more.

Trucks are long-term capital investment tools. Commercial vehicle populations change slowly. The vehicles have long life spans. It can take 20 years or more for a new technology to completely supplant an existing one through normal market attrition. NACFE illustrates this in assuming a typical annual production rate for all Class 8 vehicles starting in 2021 and how long it takes for attrition to retire out the older model years. (See Figure ES 7.) The top line also illustrates that market demand for capacity is expected to increase over time, placing additional pressure on the number of vehicles needed to be in operation.

FIGURE ES 7

EXAMPLE VEHICLE MODEL YEAR MARKET PENETRATION OVER TIME (MIHELIC)



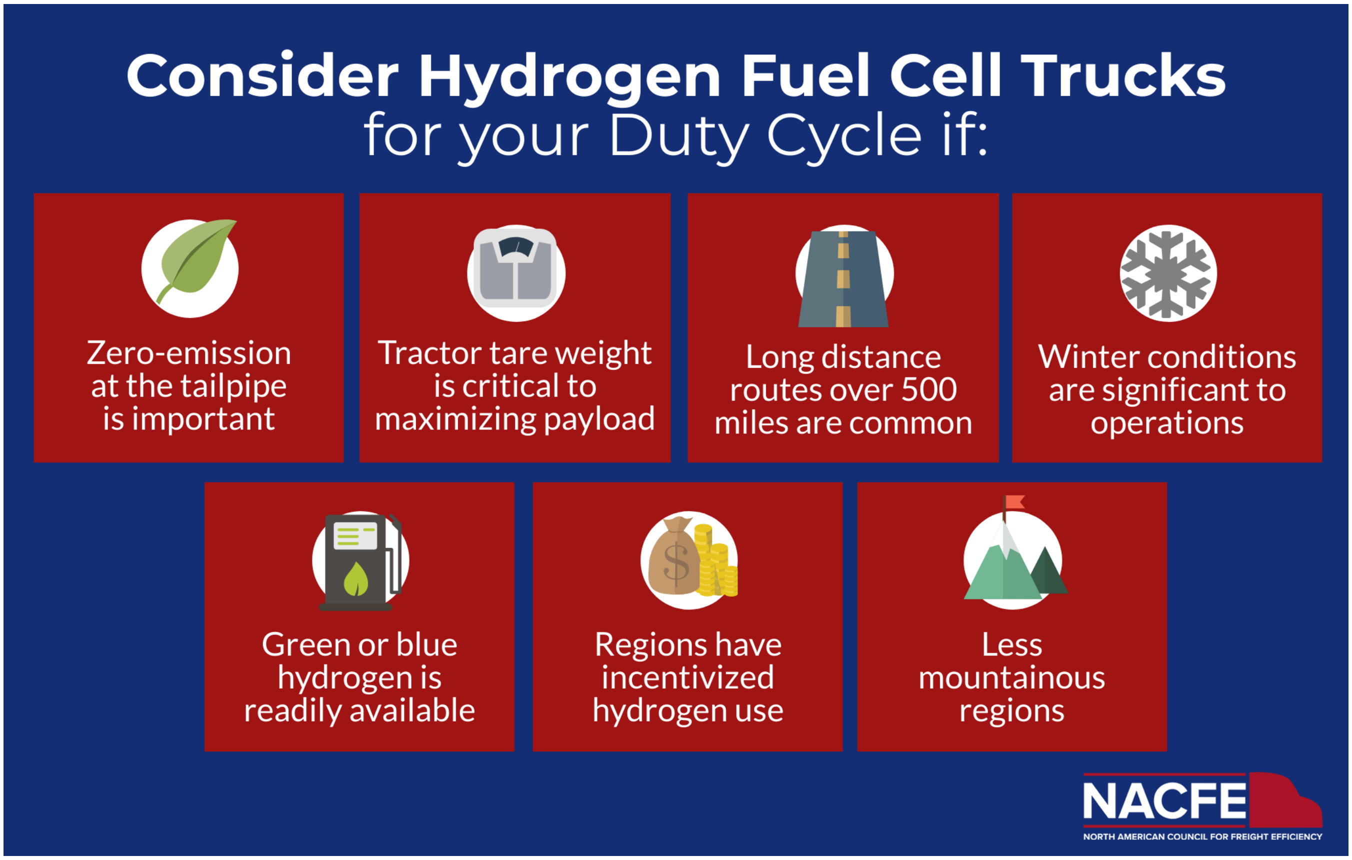
"It will take a village for hydrogen to scale quickly and trucking won't deliver scale alone, industries and utilities will need to participate heavily to scale quickly and drive down costs."

— Patrick Molloy, Senior Associate, Rocky Mountain Institute

Cost comparison baselines are changing. While decades of experience with diesel trucks make it easy for fleets and manufacturers to know today's baseline diesel truck cost, tomorrow's baseline must be based on battery electric vehicles. As zero-emissions vehicle regulations propagate across North America, the option of employing a diesel in particular markets will disappear. California is the first state to enact these prohibitions, but the 15-state MOU highlights that others are not far behind. The baseline will become the battery electric truck. However, battery electric trucks will not be enough. Fleets and manufacturers will realize the need for hydrogen fuel cell electric vehicles (FCEVs) as well. (See Figure ES 8.)

FIGURE ES 8

WHEN TO CONSIDER HYDROGEN FUEL CELL TRUCKS FOR YOUR DUTY CYCLE (NACFE)



This brings the discussion to efficiency comparison. As Steve Hanley of CleanTechnica summarized, "Making electricity to electrolyze hydrogen which is then used in fuel cells to power vehicles is not as efficient as making electricity and using it to power vehicles directly in the first place. Every time energy gets converted from one form to another, there are losses. The more transformations there are, the more losses occur."

The argument is not as simple as comparing efficiency, because hydrogen is a regional question, it is a systemic discussion well beyond just comparing Truck A to Truck B. Hydrogen is a commitment to a dramatically different regional economy. It impacts planning for jobs, exports, imports, quality of life factors, environmental factors, trade agreements, GDP, and more. Countries are wrestling with a revolution in energy where the two lead contenders transport that electricity by electrons and by hydrogen molecules.

"The costs of hydrogen, vehicles, and hydrogen production all must come down significantly to make hydrogen economically competitive with alternatives. Industry advocates and researchers are confident that these costs will be reduced through scale and innovation over time."

— Mike Roeth, Executive Director, North American Council for Freight Efficiency

NACFE has described the interim of freight hauling before we arrive at the future net-zero freight system as the "messy middle." That transition will see multiple alternative fuel powertrains in use as manufacturers and fleets try to keep the nation's freight moving while the requirements migrate to being first net-zero emissions and ultimately true-zero emissions.

The commercial vehicle marketplace is all about supply and demand—all the alternatives will be in play to fill demand. In time, the supply of zero-emissions vehicles and the associated infrastructure to support them will become a reality. However, in the near- and mid-term, freight still needs to be delivered daily.

Alternative fuel systems outlined in NACFE's Guidance Report: Viable Class 7/8 Electric, Hybrid, and Alternative Fuel Tractors, will be in use regionally to fill the need. Investments in these technologies will have life spans, and those investments may slow the ultimate transition to later true-zero emissions choices, but the freight has to be delivered daily.

North America's experience in 2020 with ramifications of the COVID-19 pandemic has emphasized that freight has no choice, fleets cannot wait, and freight must get through daily. Waiting for the perfect solution is not an option for freight haulers and truck manufacturers. Instead, investments need to be made each year based on choosing better and better available solutions.

Long-term, a hydrogen future also will be an electric future, as the two are intertwined. Just as an FCEV is a combination of a hydrogen fuel cell and a BEV, the marketplace will likely have both solutions in quantity, as they are optimized for different duty cycles, uses, and regions.

The technology of both is mature enough for truck manufacturers to begin production, but immature enough that first owners should not expect problem-free use. Decades of experience with battery electric vehicles and fuel cells for buses and cars has matured the technology to an extent, but real-world fleet use for commercial freight is different, and there will be a learning curve for all involved.

Scaling both BEV and FCEV use are tied together; the innovations in the infrastructure and distribution of energy are linked, both requiring significant growth in environmentally responsible energy production. Scale will bring cost reduction, as is expected in technology deployments. Where there is a path to improving profitability, innovation naturally occurs.

The US Department of Energy summarizes why hydrogen is a solution in its 2020 Hydrogen Program Plan:

> *Hydrogen is part of a comprehensive energy portfolio that can enable energy security and resiliency and provide economic value and environmental benefits for diverse applications across multiple sectors. Hydrogen can be derived from a variety of domestically available primary sources, including renewables; fossil fuels with carbon capture, utilization, and storage (CCUS); and nuclear power. Diverse, sustainable, and abundant domestic resources are essential for the nation to: 1) provide for a variety of end uses and a range of energy needs, 2) reduce dependency on single or limited resources, 3) retain energy independence and expand opportunities for net exports, and 4) be prepared for future scenarios where resources, end-use needs, and constraints may change significantly. Flexibility is a key asset and hydrogen provides that opportunity.*

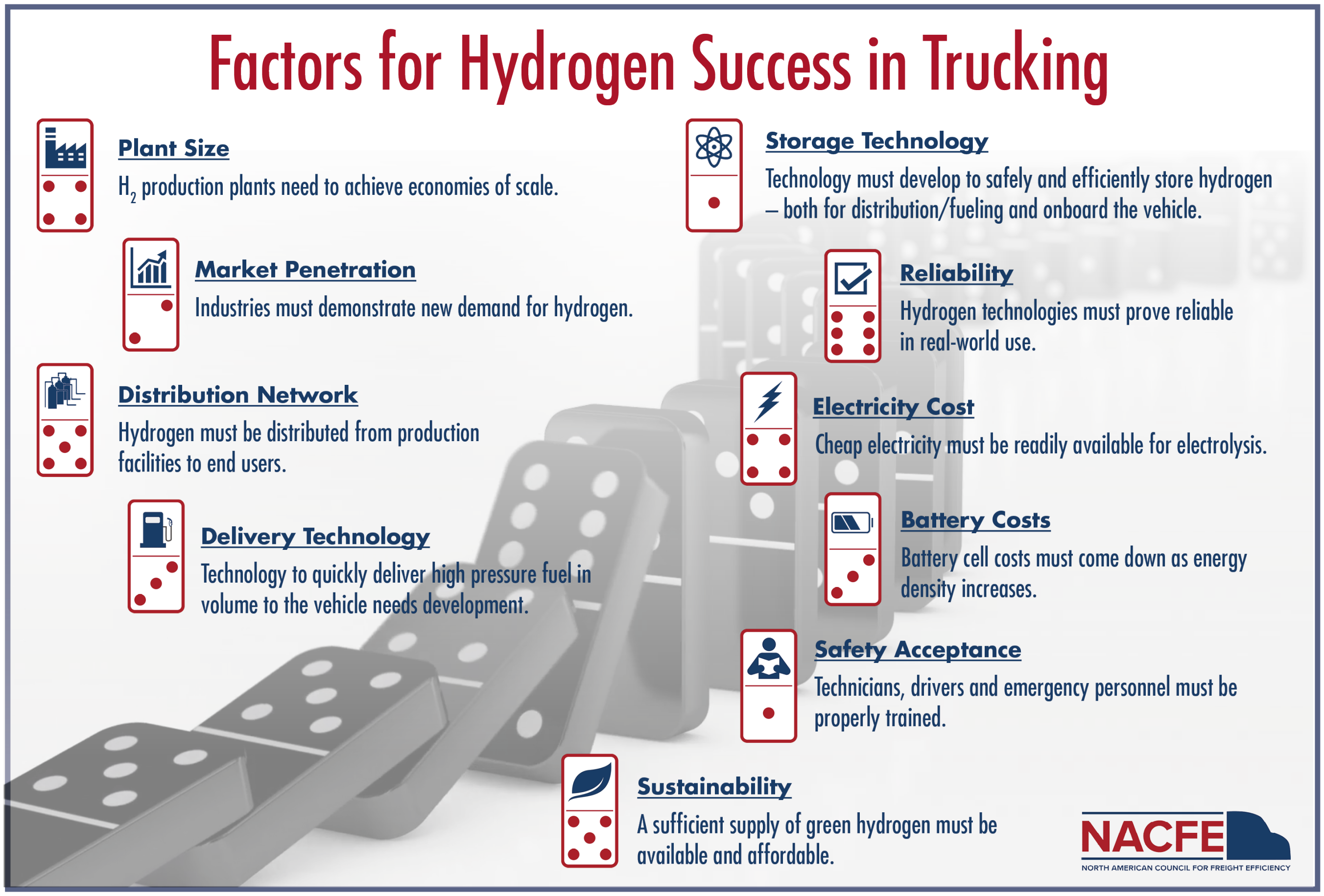
Hydrogen truck viability in the marketplace depends on a number of factors falling into place—dominos if you will—that need to fall right for the costs to make sense in the long run. (See Figure ES 9.)

"Hydrogen fuel cell heavy-duty trucks are technically viable. The technology has been going through decades of maturation on buses, cars and industrial uses. Adapting fuel cells to heavy-duty trucks will invariably have a learning curve as all new technologies do, but fuel cells are much further along in production use and are not a brand-new technology."

– Kevin Otto, Electrification Technical Lead, North American Council for Freight Efficiency

FIGURE ES 9

HYDROGEN SUCCESS DEPENDS ON MANY FACTORS (NACFE)



Today, there are but a handful of prototype fuel cell demonstrator trucks purpose built to be successful in specific duty cycles. Production level vehicles, outside of a few in Switzerland, have not hit the North American market and OEMs are projecting they will not start production in any quantities until the 2023–2025 timeframe. It is for this reason that NACFE has not taken a deep dive into specific FCEV vehicles as there are no production vehicles available today with any field history with fleets. These pilot vehicles are discussed in the body of the report as they are relevant to specific regions.

NACFE concludes there are five major findings supported by the research for this report.

- 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.

NACFE started this research looking to evaluate the viability of commercial hydrogen fuel cell trucks. It was readily apparent that the topic is much bigger than the trucks. We conclude that it takes a village for hydrogen to scale quickly. Trucking is not the primary mechanism, industries and utilities will need to participate heavily to scale rapidly. If the hydrogen is there, the use for heavy truck transportation will come. This paper highlights the complexity of the hydrogen future.

THE FULL REPORT

The full report is available at www.nacfe.org and includes 235 references; and 102 NACFE graphics. See the Table of Contents for more information on the full report:

1 Table of Contents

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 Rocky Mountain Institute (RMI) on a variety of projects including the Run on Less fuel efficiency demonstration series, electric trucks, emissions reductions, and low-carbon supply chains.

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Rocky Mountain Institute (RMI)—an independent nonprofit founded in 1982—transforms global energy use to create a clean, prosperous, and secure low-carbon future. It engages businesses, communities, institutions, and entrepreneurs to accelerate the adoption of market-based solutions that cost-effectively shift from fossil fuels to efficiency and renewables. RMI has offices in Basalt and Boulder, Colorado; New York City; the San Francisco Bay Area; Washington, D.C.; and Beijing.

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Trucking Efficiency is an exciting opportunity for fleets, manufacturers, and other trucking industry stakeholders.

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