GORE® Fuel Cell Technologies
Decarbonizing Automotive Applications

ADDRESSING THE CHALLENGES FOR PEM FUEL CELLS IN HEAVY-DUTY VEHICLES

As the automotive industry pursues alternative energy solutions to contribute towards global decarbonization, the heavy-duty vehicle (HDV) segment has become a focus for proton exchange membrane (PEM) fuel cell technology solutions. However, HDVs have very challenging cost and operational requirements. This article explores the application of PEM fuel cells in HDVs and how Gore's advanced materials expertise can deliver high performance while lowering total cost of ownership (TCO).

PEM's potential in transportation applications

As the second-largest carbon-polluting sector worldwide, responsible for over 20% of global greenhouse gas emissions (Figure 1), transportation has a major role to play in achieving the world's decarbonization goals.

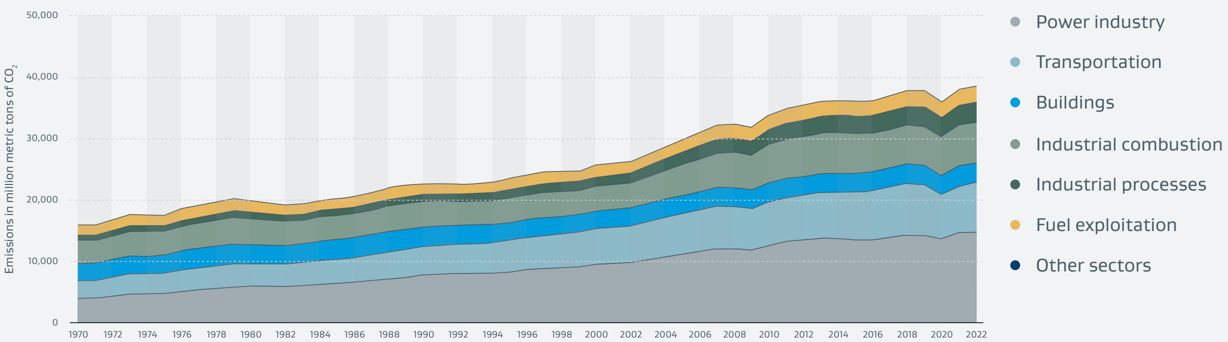
Hydrogen has been explored and developed as an alternative fuel source for several decades. This interest has rapidly accelerated in recent years as public and private interest groups across the world place greater emphasis — and investment — into renewable energy policies and projects to achieve the global targets for decreasing greenhouse gas (GHG) emissions.

Proton exchange membrane fuel cells (PEMFC) are the most attractive hydrogen energy conversion technology available today for powering mobility applications. Light-duty fuel cell vehicles (LDV) from OEMs such as Toyota, Hyundai and Honda have demonstrated vehicles with similar driving experience, range and refueling times to conventional internal combustion engines (ICE) and the benefit of zero tailpipe emissions.

Figure 1.

Global carbon dioxide emissions by sector

in million metric tons of carbon dioxide



Global CO_2 emissions 1970-2022, by sector, Statista, 2023, https://www.statista.com/statistics/276480/world-carbon-dioxide-emissions-by-sector/

In materials handling applications such as forklifts, PEMFCs can displace battery technology thanks to their increased productivity due to faster refueling capabilities — a valuable proposition in this cost-sensitive environment. There are estimated to be over 40,000 hydrogen powered forklift trucks[1] in operation today.

Meeting the performance challenges of fuel cells in heavy-duty vehicles

Following the promising progress for fuel cells in LDVs, the focus for PEMFC's development has shifted towards the heavy-duty transportation sector, where battery technology may not be able to compete as a zero-emission solution. Heavy-duty vehicles (HDV), trains, marine and aviation applications require high power density and long range capabilities; thus, PEMFC's capabilities are generating significant interest as diesel engine replacements in these sectors.

The heavy-duty segment shares a critical responsibility to lower carbon emissions; while HDVs represent just 10% of the vehicles on the road, they generate more than 25% of total carbon emissions from the transportation sector[2].

Furthermore, as the adoption of battery solutions for LDVs accelerates – hybrid and electric vehicles now make up 16% of all LDV sales in the US[3] – emissions from HDVs will represent a greater share of total transportation emissions. Hence, the pressure to implement alternative energy solutions for this vehicle sector will increase.

In the US, there is strong support for the transition to 'clean vehicles' at the state and federal level. In April 2023, the Environmental Protection Agency (EPA) announced more stringent CO_2 standards for HDVs starting from 2027 to reduce greenhouse gas emissions from this segment. The California Air Resources Board (CARB) has introduced comprehensive regulations to encourage the adoption of zero-emisision vehicles (ZEV)[4], in support of the state's executive order mandating a full transition to heavy-duty ZEVs by 2045 (Figure 2). 16 other US states have followed California's lead, signing a collective agreement to make all new sales of medium- and heavy-duty trucks ZEVs by 2050[5].

Figure 2.

California's Electric Vehicle Goals

2025	**1.5 Million** EVs Sold	**250,000** Chargers Installed	**200 Public** Hydrogen Stations
2030	**5 Million** EVs Sold		
2035	**100%** Electric Sales for New Passenger Vehicles	**100%** Electric Operations for Drayage Trucks and Off-road Vehicles & Equipment	
2045	**100%** Electric Operations for Medium- and Heavy-duty Vehicles		

California Energy Commission Announces Nation's 1st Incentive Project For Zero-Emission Truck & Bus Infrastructure, CleanTechnica, 2021, https://cleantechnica.com/2021/04/13/california-energy-commission-announces-nations-1st-incentive-project-for-zero-emission-truck-bus-infrastructure/

From an economic perspective, the focus for decarbonizing the heavy-duty transportation industry will be addressing total cost of ownership (TCO). While the short refueling times, longer range, and greater power and energy density compared to lithium-ion batteries favor PEMFC solutions to demonstrate lowest

1. A quantitative risk assessment of hydrogen fuel cell forklifts, International Journal of Hydrogen Energy, 2023, https://www.sciencedirect.com/science/article/abs/pii/S0360319923006547
2. How to Eliminate Pollution from Heavy-Duty Vehicles, Union of Concerned Scientists, 2022, https://www.ucsusa.org/resources/heavy-duty-vehicles-and-nox
3. Electric vehicles and hybrids make up 16% of U.S. light-duty vehicle sales, U.S. Energy Information Administration, 2023, https://www.eia.gov/todayinenergy/detail.php?id=60321
4. Advanced Clean Fleets, California Air Resources Board, https://ww2.arb.ca.gov/our-work/programs/advanced-clean-fleets/about
5. Multi-State Medium- and Heavy-Duty Zero Emission Vehicle Memorandum of Understanding, N.C. Department of Transportation, 2020, https://www.ncdot.gov/initiatives-policies/environmental/climate-change/Documents/zev-memorandum-of-understanding.pdf

TCO to decarbonize heavy-duty applications, they may also enable easier deployment of a hydrogen fueling infrastructure compared to LDVs.

With more predictable routes for dedicated fleets, fewer refueling stations may be required to support fuel cell adoption. Infrastructure costs could be further reduced by implementing a "hub-and-spoke" model to serve fixed routes from a single centralized hydrogen refueling station located at industrial clusters[6].

While HDV applications could lend themselves to addressing the infrastructure problem, there are numerous challenges for the fuel cell stack itself. At the core of the stack, the PEM must also play its critical role to enable a fuel cell engine with a competitive TCO. The operating requirements of HDVs present new and demanding challenges for PEM technology:

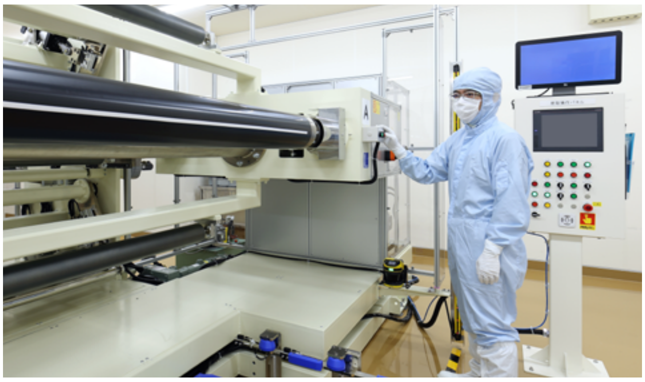
- Lifetime expectations are at least 4x greater than LDVs.
- Freight haulage demands greater power output.
- Long periods of high-power operation result in higher-temperature operating conditions.
- High fuel efficiency is required to provide competitive fuel costs.

The longer lifetime requirements at higher temperatures compared to LDVs should exacerbate the performance limitations and decay mechanisms that the PEM experiences in HDV applications:

- Greater cumulative mechanical stress causing fatigue failures. As a result, membrane reinforcement may be critical to maintaining membrane integrity over the longer HDV lifecycle.
- Higher temperatures, especially at low relative humidity, will accelerate chemical attack of the membrane. This highlights the importance of PEM design considerations such as ionomer attributes, PEM thickness and additive function.
- Furthermore, long-life requirements can lead to greater risk of cumulative contamination and corrosion within the fuel cell. In turn, this can greatly accelerate chemical degradation of the ionomer component of the PEM.

GORE-SELECT® Membranes: High-performance PEM solutions

With decades of investment in deep science and advanced material development, Gore has evolved as an industry leader in PEM technology. A culture of continuous innovation and technical expertise has supported the development of unique GORE-SELECT® Membranes with a market-leading combination of durability and power density.



At its core, the GORE-SELECT® Membrane's unique reinforcement structure can enable very strong and thin PEM with a lower ionomer content. Our latest iterations have decreased membrane resistance while enhancing mechanical properties. In tandem, Gore has also developed successive generations of PEM additive technologies with significant reductions in chemical degradation rates. The result is PEM that allows for greater power density over a longer life cycle.

The PEM functionality can be a major contributor to the determination of TCO for fuel cell systems manufacturers. Gore's thinner, stronger PEM can deliver higher power output and greater fuel efficiency over a longer lifetime, mitigating initial system capital and operating costs and therefore lowering TCO.

6. The Future of Hydrogen, IEA, 2019, https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf

Gore: A Legacy of Fuel Cell Leadership

Gore has been developing and supplying PEMs for fuel cells for over 25 years. Today, we are recognized as the world's leading PEM supplier based on our unique capability to manufacture thin, high power, and strong, durable composite reinforced PEMs. Our global business network covers 28 sales offices, 2 R&D facilities, and a world-class manufacturing plant.

Since the Fuel Cell Business Unit was established in 1995, Gore has manufactured millions of square meters of PEM and enabled over 60,000 fuel cell vehicles globally. Notably, Gore is the sole PEM supplier for the first- and second-generation Toyota MIRAIs, Honda Clarity, and Hyundai NEXO.

Gore's advanced suite of analytical and testing capabilities – some of which have become industry standards – allows us to understand our product's fitness for use in a range of end-applications. We collaborate closely with our customers to identify their specific requirements and find the most cost-effective solutions to protect their investments.

Gore's fuel cell products are not limited to automotive applications, and are also widely used in numerous other applications such as commercial vehicles, stationary power, material handling (forklifts), rails and marine projects.

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Simon Cleghorn is currently a Global Product Specialist at W. L. Gore & Associates. He is a PhD electrochemist with close to 28 years' experience working in the field of proton exchange membranes for fuel cells and other applications.

If you wish to learn more about Gore and its GORE-SELECT® Membrane technology, please visit https://www.gore.com/alt-energy.

About Gore

W. L. Gore & Associates is a global materials science company dedicated to transforming industries and improving lives. Since 1958, Gore has solved complex technical challenges in demanding environments — from outer space to the world's highest peaks to the inner workings of the human body. With more than 13,000 Associates and a strong, team-oriented culture, Gore generates annual revenues of $4.8 billion.

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AES-35-MIS-US-JAN24