GORE® Fuel Cell Technologies
Optimizing TCO for
Fuel Cell Trucks

EMPOWERING THE FUTURE: PEMFC ADVANCEMENTS FOR DIESEL ENGINE TRANSITION

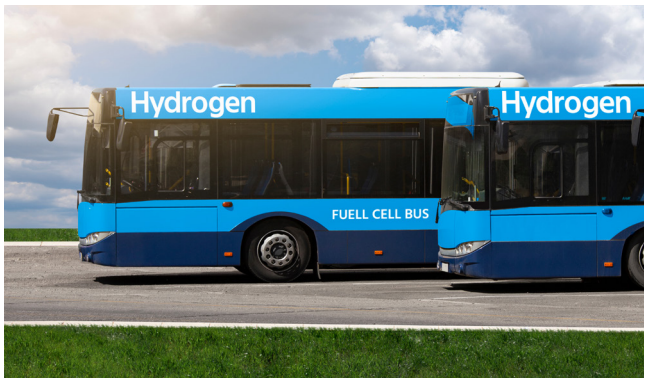
Q&A WITH SIMON CLEGHORN

Heavy-duty vehicles (HDV) can leverage PEM fuel cell technology to great effect — but require new solutions to address their demanding operating requirements. We spoke to Simon Cleghorn, currently a Global Product Specialist in Gore's Clean Energy business unit with 28 years' fuel cell experience, about how Gore's advanced materials expertise can deliver high performance while lowering total cost of ownership (TCO).

What is the current status of PEM fuel cells in the transportation sector?

Proton exchange membrane (PEM) fuel cells have been in development for passenger vehicles for over two decades, with many technical and commercial successes. As a result, PEM fuel cells can offer an attractive alternative to conventional internal combustion engines (ICE), with similar driving experience, range and fueling times — and zero tailpipe emissions.

More recently, PEM fuel cells have started to generate more interest in the heavy-duty vehicle (HDV) and commercial transport sectors, thanks to their unique benefits in terms of both power and energy[1] compared to lithium-ion batteries[2]. Combined with their lower mass and volume, short refueling times and long range, PEM fuel cells provide a major opportunity to decarbonize the long-haul, heavy-duty transport sector.



Several niche markets, such as material handling applications (i.e. forklifts) and some focused commercial transportation applications (passenger buses, trucks, and vans) are already in operation. Given that road freight vehicles account for 5% of all global carbon emissions[3], the race to replace conventional HDV diesel engines is on.

What are the requirements for commercializing fuel cells in HDVs?

The operating requirements of HDV use cases present far greater challenges for PEM technology compared to passenger vehicles. With longer lifetimes, higher-temperature operation, and greater power requirements, the current limitations and failure mechanisms of PEM in light-duty vehicles (LDVs) can be exacerbated in HDVs.

1. New roads and challenges for fuel cells in heavy-duty transportation, Cullen, David A., Neyerlin, K. C., Ahluwalia, Rajesh K., Mukundan, Rangachary, More, Karren L., Borup, Rodney L., Weber, Adam Z., Myers, Deborah J., and Kusoglu, Ahmet., United States: N. p., 2021, https://www.nature.com/articles/s41560-021-00775-z
2. The Future of Hydrogen, International Energy Agency, June 2019, https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf
3. CO_2 and Greenhouse Gas Emission, Hannah Ritchie, Max Roser and Pablo Rosado, 2020, https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions

Together, improving life

GORE

Figure 1 illustrates some of the high-level differences in requirements for fuel cell systems when comparing heavy-duty and passenger vehicles. Typically, fuel cell engines for heavy-duty vehicles (FCHDVs) may require 3x greater power output (300kW) than fuel cell passenger vehicles (100kW) with an expected lifetime almost four times longer (30,000 hours vs. 8,000 hours)[4] to achieve the service life of the incumbent diesel technology of 1 million miles of operation.

Figure 1.

Comparison of fuel cell system requirement for passenger vehicles and long-haul heavy-duty vehicles.

100kW	**Fuel Cell Power**	200 - 300kW
8,000 hrs.	**Lifetime**	30,000 hrs.
$30 per kW	**Fuel Cell Systems Cost Target**	$60 per kW
65 %	**Efficiency Target**	> 70 %

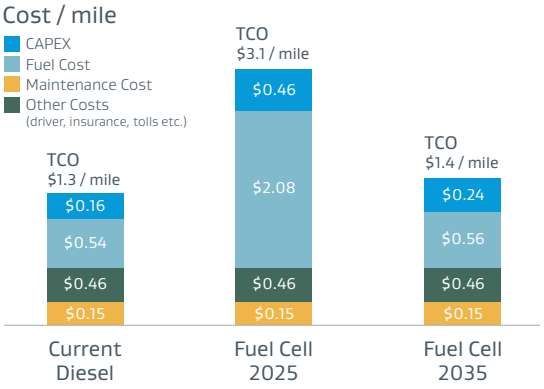
From a cost perspective, the focus for passenger vehicles is typically initial purchase price. For HDVs, the total cost of the asset over its operational life — or the total cost of ownership (TCO) — is considered the most critical metric to define business attractiveness.

This results in more demanding requirements for vehicle efficiency to minimize fuel cost, but a relaxation in the acceptable purchase cost for the engine. According to the US Department of Energy (DOE) estimates, the fuel cell systems cost target increases from $3,000 (or $30/kW) for a passenger car to $18,000 (or $60/kW) for a HDV.

We estimate that currently, the TCO for today's fuel cell HDVs is approximately 2-3 times higher than ICE (Figure 2)[5] based on a simple model developed with publicly available data from fuel cell truck OEM announcements, industry reports and DOE published targets. (Based on the lack of industry experience for operating fuel cells, we assume that maintenance cost and other costs such as drivers, insurance and tolls are independent of the technological solution.)

Figure 2.

Results of a simple total cost of ownership model comparing diesel and fuel cell long haul heavy duty vehicles.



Key Assumptions	Current Fuel Cell	Fuel Cell 2035
Fuel Cell Cost ($ /kW)	160	80
Fuel Cost ($ / Kg)	15	5
Fuel Efficiency (Mile / Kg)	7.2	9
System Life (years)	3 - 5	10
Rebate / Subsidy	Yes	No

This graph highlights that lowering TCO to achieve cost parity requires a multi-faceted approach, driven by action and engagement throughout the value chain from product development through to public policy and industry regulation.

From the perspective of innovation, addressing the following factors is important to achieving cost parity with diesel engines:

- **Decrease hydrogen fuel cost over the life of the vehicle** by increasing the fuel cell system's fuel efficiency above the estimated[6] 7.2 miles/kg of hydrogen, alongside the assumed decreases in hydrogen unit cost to $5/kg (from the current estimate of $15/kg).
- **Decrease initial systems** cost to offset the future elimination of subsidies which are available today[7]. We assume this can be accomplished by a combination of decreasing fuel cell systems cost ($160/kW)[8] and hydrogen tank costs ($1000/kg of H_2 stored) to achieve the DOE published targets[9] ($80/kW and $400/kg of H_2 stored).

4 – 5. Leveraging Advancements in Proton Exchange Membranes to Address the Challenges of Replacing Diesel Engines, Simon Cleghorn, W.L. Gore & Associates presentation for Mobex.io. May 11 2023
6. Nikola matures as an electric truck manufacturer, FreightWaves, March 17 2023, https://www.freightwaves.com/news/nikola-matures-as-an-electric-truck-manufacturer
7. Clean Heavy-Duty Vehicle Program, EPA, August 30 2023, https://www.epa.gov/inflation-reduction-act/clean-heavy-duty-vehicle-program
8. Hydrogen Program Record, DOE, May 23 2023, https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/23002-hd-fuel-cell-system-cost-2022.pdf
9.Hydrogen Storage Cost Analysis, DOE, June 2022, https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review22/st235_houchins_2022_p-pdf.pdf?Status=Master

- **Increasing systems life** (miles driven) to achieve a 10-year lifetime. Today we are not aware of any publicly available data reported on the life of current FCHDVs. Demonstrations are underway, such as drayage trucking fleets in Southern California[10] and food distribution trucks in Texas[11], both serving real-world customers to prove commercial viability. Therefore, we have assumed current fuel cell life is about 30 to 50% of the ultimate service life.

What are the development challenges and how does Gore approach TCO?

The fuel cost is the largest single contributor to the TCO of the FCHDV across all modeled scenarios — indicating that developers should focus their future investments in this area.

At the same time, we also recognize that significant time and money is required to determine the material requirements and operational strategies that can enable 10 years of FCHDV operation.

As OEM systems developers work towards solving the problem of minimizing TCO, they will very likely encounter trade-offs to optimize the needs for fuel efficiency and operational lifetime in this complex and multi-dimensional system. This is made even more challenging by the relative immaturity of fuel cell technology as it is applied to HDV applications.

At Gore we have over 25 years of fuel cell industry experience and PEM material expertise. Our goal is to apply this PEM capability and partner with R&D engineers to accelerate the development of competitive fuel cell stacks and systems which optimize trade-offs and create a compelling competitive TCO.

As one of the only PEM manufacturers integrated into commercial fuel cell vehicle production in the world, we understand our customers' challenges and the markets they are operating in.

How can Gore's PEM help lower TCO?

As a PEM developer, we see multiple pathways in this complex system where PEM attributes can impact the key contributors to TCO for HDV applications (Figure 3).

At Gore we believe that there are five critical PEM attributes — membrane resistance, mechanical durability, chemical durability, gas permeability and price — that can influence TCO by impacting system design, efficiency and cost.

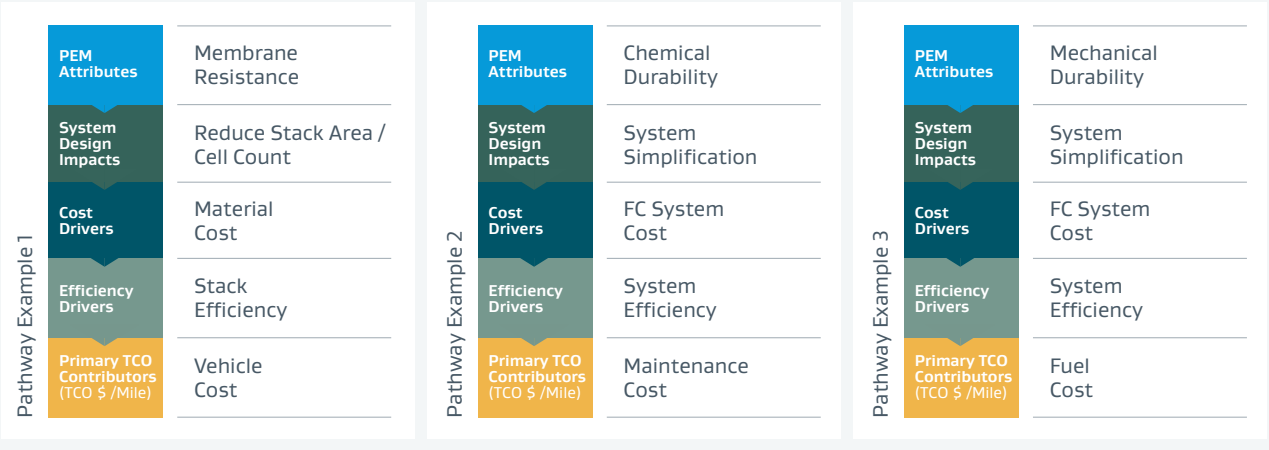
These are examples of potential pathways and how different attributes affect TCO:

- **Decreased proton resistance** of the PEM can result in reducing the stack size and therefore systems cost — and ultimately, vehicle cost. Alternatively, decreased proton resistance can also increase voltage efficiency, thus increasing fuel efficiency and

10. FCEV Drayage Trucks Prove Themselves in LA Port Demonstration..., Heavy Duty Trucking, September 22 2022, https://www.truckinginfo.com/10181655/fcev-drayage-trucks-prove-themselves-in-la-port-demonstration-project
11. Hyzon Motors Successfully Completes First Customer Demo..., PR Newswire, August 30 2023, https://www.prnewswire.com/news-releases/hyzon-motors-successfully-completes-first-customer-demo-of-liquid-hydrogen-fuel-cell-electric-truck-301913272.html

Figure 3.

Multiple pathways where PEM attributes can impact the key contributor to TCO.



decreasing fuel costs over a vehicle's lifetime. This highlights how enhancing a single PEM attribute can optimize TCO in several different ways.

- Likewise, **higher PEM mechanical durability** can enable simplification of fuel cell systems through reducing system controls to protect the PEM or allowing for a small battery and putting greater reliance on the load following capability of the fuel cell. Here, TCO may be impacted by the decreased weight of the systems or the decreased systems cost.
- **Higher PEM chemical durability** allows the FC stack to withstand harsh operating conditions, and therefore the systems controls or the cooling systems' design can be simplified.

These examples illustrate that this is a complex and multi-faceted problem, where any advancement in any single PEM attribute can be leveraged in multiple ways to lower the vehicle TCO — while managing potential performance trade-offs, such as PEM resistance and mechanical durability in the two previous examples.

Gore's expertise lies in our engineering capabilities. We understand how to optimize PEM attributes and reduce trade-offs depending on key customer requirements, based on data and insights from advanced testing and development experience over the last few decades.

Our goal as a PEM developer is to provide systems engineers a choice of materials and design solutions, and therefore potential engineering pathways to solve for TCO when considering the needs of their different HDV use cases.

We believe this process can unlock multiple approaches to reducing TCO, which may be use-case dependent or contingent upon the availability of regional subsidies or local hydrogen fuel costs.

How else can Gore help lower TCO?

Gore's fuel cell experience and enterprise-wide capabilities offer our customers highly valued fuel cell solutions beyond the material attributes of our PEM.

Our global supply security and production output can deliver industry-leading volumes of high-quality PEM to lower manufacturing and raw material costs for OEMs.

Our recent process innovations and subsequent capital investments in precise coating have enabled the rapid production of GORE-SELECT® Membranes with increased quality, greater uniformity and wider width. This gives fuel cell stack manufacturers greater flexibility over their downstream processing and ultimately increased confidence in the performance of their products over the desired service life.

Our advanced testing and failure mode analysis capabilities — carried out in close collaboration with our customers — provide critical insights into problem solving and the future vectors for product development. A deeper understanding of our products' fitness-for-use helps identify the right investment strategy and accelerate time-to-market.

In a dynamic, competitive and rapidly-evolving fuel cell industry, this can make all the difference.

What is the future outlook for Fuel Cell HDVs?

Given its major contribution to global greenhouse gas emissions, and in line with worldwide commitments to net-zero targets, the traffic in the transportation sector is moving in one direction: zero-emission.

However, despite their environmental benefits, fuel cell HDVs will only achieve large-scale adoption if they can deliver economic benefits, and prove to be a viable commercial alternative to diesel engines.

Despite the challenging and complex ecosystem, the signs are positive. A McKinsey report projects significant reductions in TCO for fuel cell HDVs by 2040, thanks to advancements and associated cost

reductions in technology, increased vehicle production scale, and infrastructure deployments.

Under the right market conditions, 85% of new medium- and heavy-duty truck sales in US, EU, and China could be zero-emission powertrains (both battery and fuel cell) within two decades.[12]

At Gore, we're passionate about partnering with our customers to solve their development challenges. With a high-performance PEM that helps lower TCO, stack and system manufacturers can feel confident in cost-effective fuel cell solutions that succeed in harsh operating conditions — and a competitive market.

12. Preparing the world for zero emission trucks, McKinsey Center for Future Mobility, September 2022, https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/preparing-the-world-for-zero-emission-trucks

About the Author:

Simon Cleghorn
E scleghorn@wlgore.com

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.

For more information, please visit **gore.com**

INTERNATIONAL CONTACTS

Australia	+61 2 9473 6800	**India**	+91 22 6768 7000	**Singapore**	+65 6733 2882
China	+86 21 5172 8299	**Japan**	+81 3 6746 2570	**South America**	+55 11 5502 7800
EMEA	+49 89 4612 2211	**Korea**	+82 2 393 3411	**Taiwan**	+886 2 2173 7799
Germany	+49 89 4612 0	**Mexico**	+52 81 8288 1283	**USA**	+1 410 476 2699

W. L. Gore & Associates, Inc.
201 Airport Road, Elkton, MD 21922
T +1 800 523 4673 **F** +1 410 506 8585 **E** performancesolutions@wlgore.com
gore.com/alt-energy

AES-36-MIS-US-JAN24