GORE ePTFE PEM Automotive Industry
White Paper

The role of an ePTFE-reinforced Polymer Electrolyte Membrane (PEM) in the Automotive Fuel Cell Market

Introduction

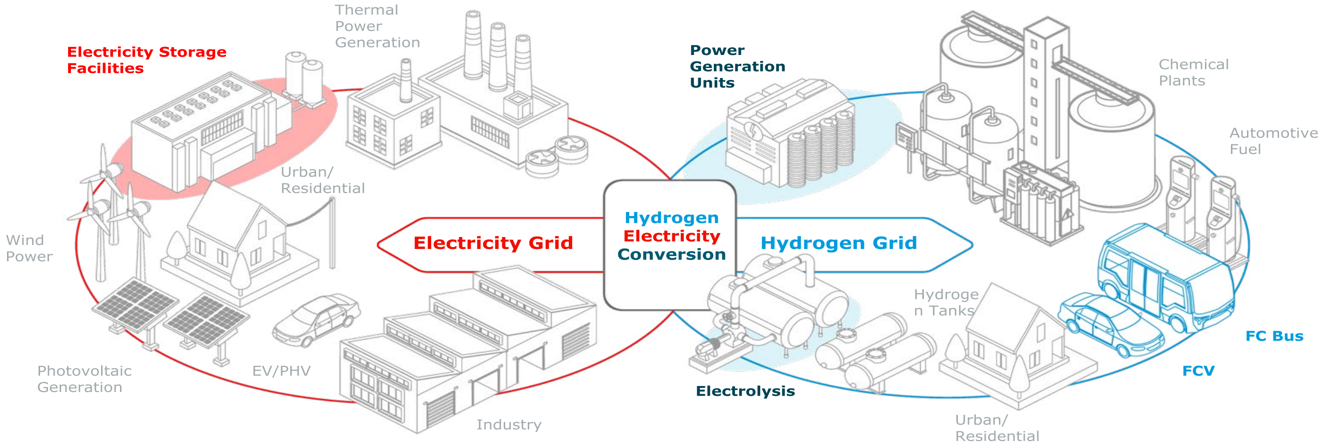
Hydrogen holds the key to a clean energy future. It is a critical catalyst in our transition from fossil fuels to a more sustainable, low-carbon global energy future.

The transportation sector has a major role to play in the adoption and commercialization of hydrogen-based energy. From passenger cars to commercial vehicles to long-haul logistics across air, land and sea, transportation applications are leading the growth of the hydrogen economy.

Fuel cell technology is the driving force behind the hydrogen-electricity conversion. There are several types of fuel cell technologies, and decades of development have demonstrated that proton exchange membrane (PEM) fuel cells are the leading technology for the automotive and transportation sector.

PEM offers high power density, low weight, and low volume compared to other fuel cell types such as alkaline, direct methanol, and phosphoric acid.

Figure 1: Hydrogen Electricity Conversion[a]



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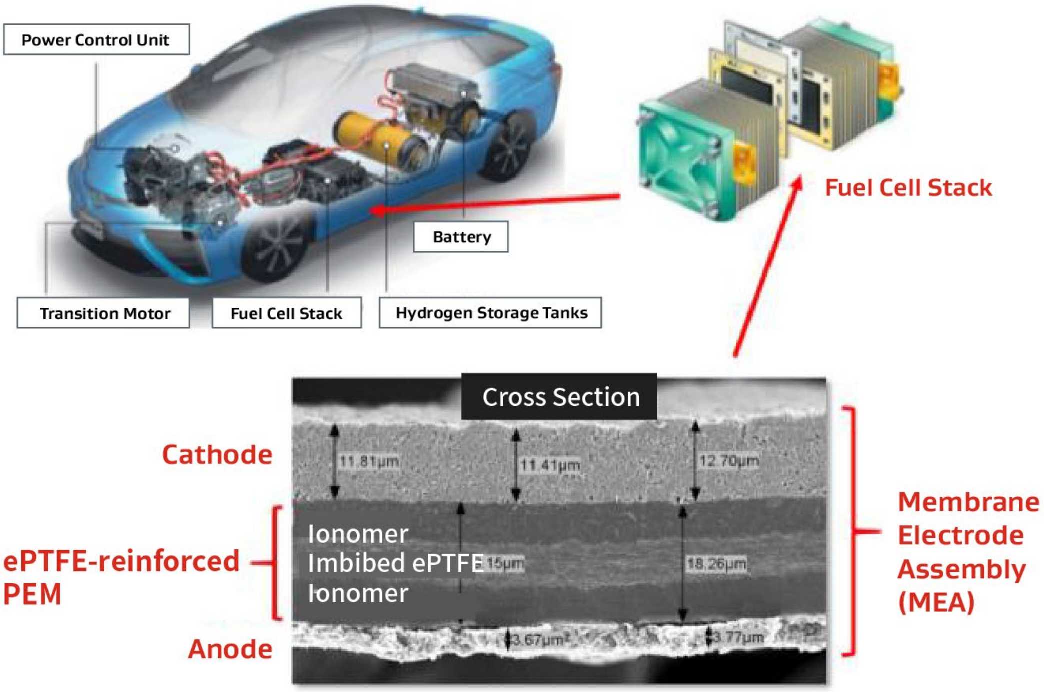
a. Fueling The Future Of Mobility, Deloitte China, 2022, https://www2.deloitte.com/content/dam/Deloitte/cn/Documents/finance/deloitte-cn-fueling-the-future-of-mobility-en-200101.pdf

Together, improving life

Figure 2: An MEA at the center of the fuel cell stack

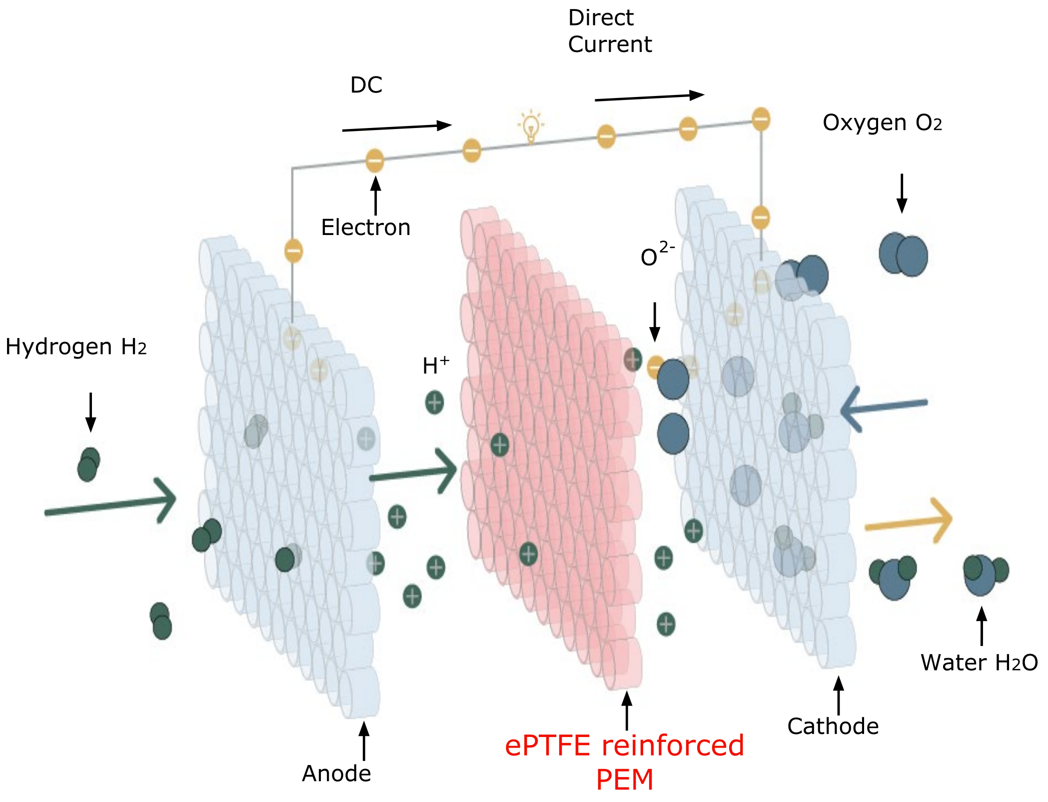


Each fuel cell stack consists of several hundred membrane electrode assemblies (MEAs) depending on the power of the stack. Each MEA consists of an anode and cathode electrode on either side of a PEM. The MEA is at the heart of the fuel cell and is responsible for the electrochemical conversion of fuel to electrical energy.

In fuel cell operation, hydrogen fuel enters on the anode side of the cell where it reacts at the anode catalyst and separates into protons and electrons. The protons pass through the ionically conducting PEM to the cathode side to combine with oxygen, and with the help of a catalyst, produce water. The electrons, which cannot pass through the membrane, flow from the fuel cell to form a current, generating power (Figure 3).

The PEM is a core component of the fuel cell. The performance of the PEM is highly dependent upon the stack and systems design and critically the operating conditions the PEM experiences. Nevertheless, this tiny piece of technology is at the heart of the fuel cell vehicle movement – and thus, powering the global shift towards clean energy.

Figure 3: An ePTFE-reinforced PEM is at the heart of the MEA.



PEM REQUIREMENTS IN THE AUTOMOTIVE FUEL CELL MARKET

Zero carbon emissions, long driving range (300-400 miles) and quick fueling times (3-5 minutes) make fuel cell electric vehicles (FCEVs) an attractive prospect for the future of transportation.

However, to fully realize their potential, fuel cells must not only be commercially viable, but genuinely competitive against conventional combustion engines: a well-established technology with massive economies of scale.

For PEM technology to achieve large-scale adoption in the automotive industry, it must address manufacturer's requirements in three broad categories:

1. **Performance**
2. **Reliability**
3. **Cost**

These three categories are interdependent; shifts in one attribute may involve trade-offs in another.

PERFORMANCE

This category considers the fundamental attributes that describe how a PEM performs in a fuel cell stack under varying operating conditions (relative humidity (RH), temperature, duty cycles, and so on).

Proton Conductance & Power Density

Power density is a major factor in the performance of fuel cell vehicles. One factor influencing power density is the PEM's proton conductance; conversely, resistance to this proton transport is a significant factor in determining overall stack and system efficiency.

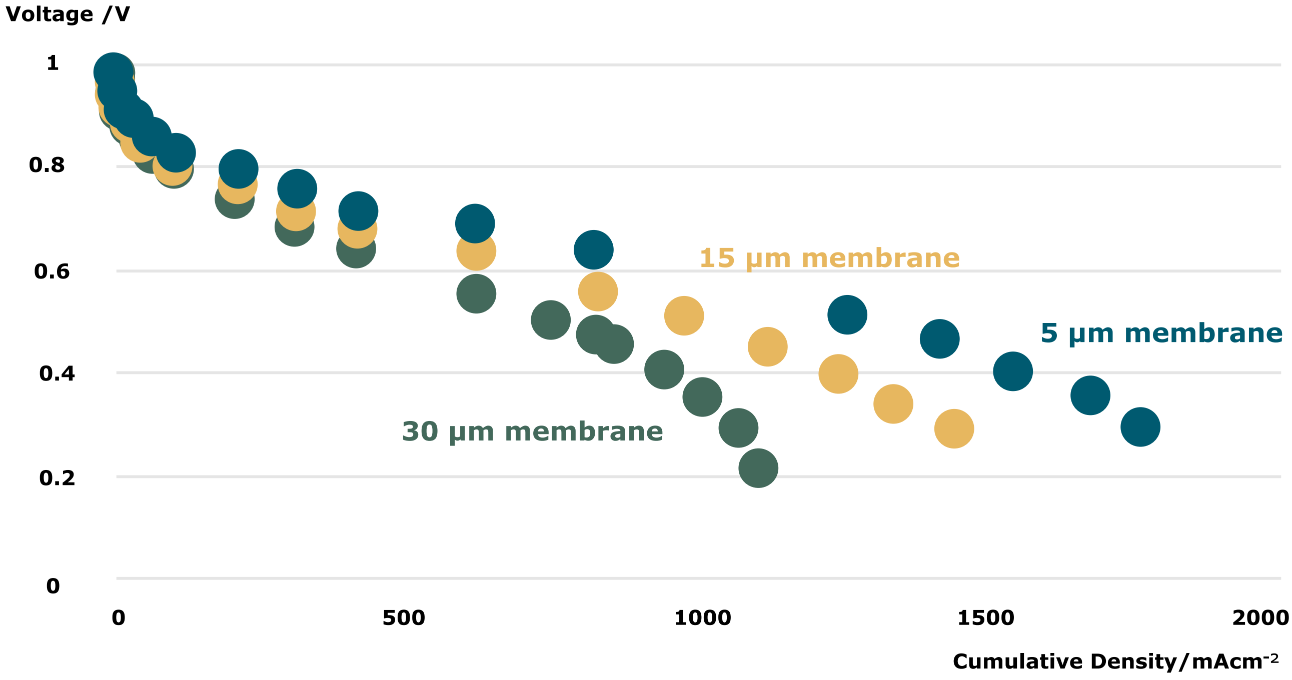
Proton conductance is mainly affected by the type of ionomer used, the membrane reinforcement structure and the thickness of the PEM itself.

These same factors also influence the rate of water transport through the PEM. For example, a thinner PEM has low proton resistance, resulting in higher power density. Thinner membranes also have higher water transport, which results in high performance in low RH conditions.

However, a thinner membrane traditionally means a trade-off against gas crossover and mechanical durability – both of which negatively affect performance in the longer run.

Reinforcing the PEM with expanded polytetrafluoroethylene – or ePTFE – is one solution that significantly reduces this trade-off. Based on decades of development, Gore's ePTFE-reinforced composite membrane technology demonstrates higher performance over a longer PEM lifecycle – even in extreme operating conditions.

Figure 4: High Current Density Output



As industry cost pressures and performance requirements increase, research and development efforts should focus on thinner and stronger PEMs, enabling even greater power density and greater durability while mitigating performance trade-offs.

This development and design must be performed in consideration of other attributes, as we'll explore further on.

Durability

Fuel cell durability in real-world environments is another critical performance factor for FCEVs. The U.S. Department of Energy has set lifetime targets of 5,000 hours – approximately 150,000 miles – of driving under realistic conditions.

There are two types of durability that PEM design must consider to meet these targets.

Mechanical Durability

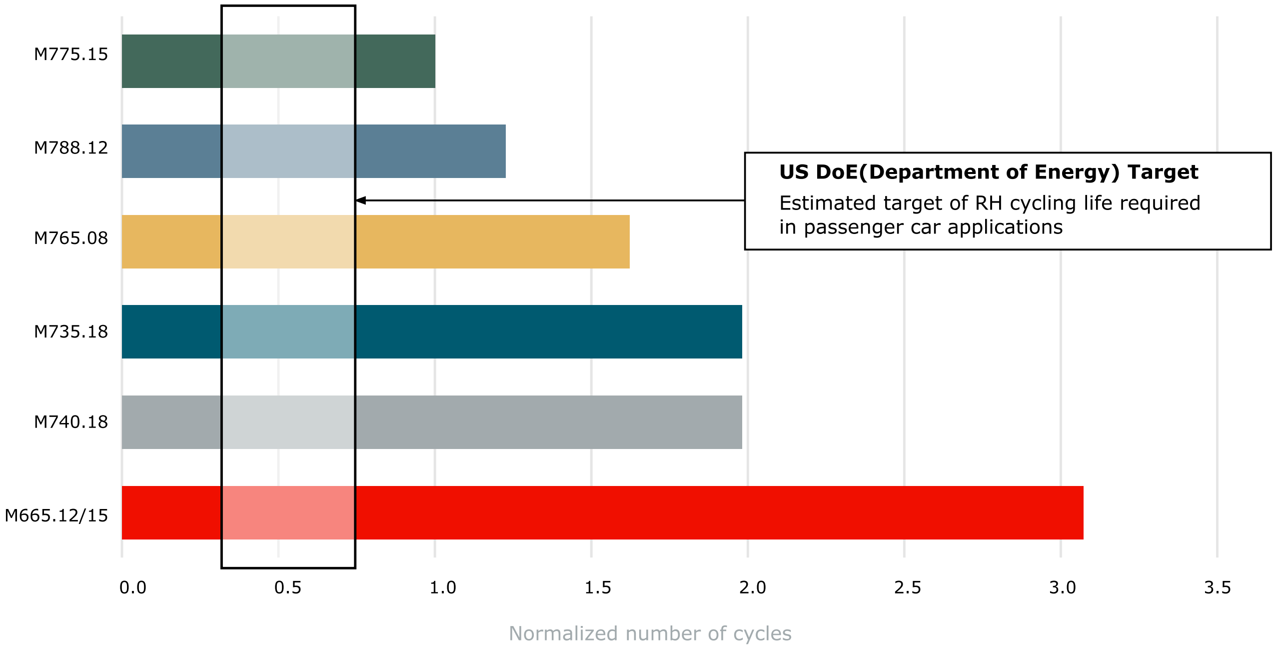
Relative humidity (RH) cycling during operation causes mechanical degradation of the PEM. Increasing and decreasing RH causes the PEM to swell and shrink, leading to cracks and holes in the MEA.

Over time, this can lead to increasing gas cross-over and efficiency loss – and then ultimately catastrophic failure – of the fuel cell stack. Traditionally, unreinforced PEMs were made thicker to increase their durability, resulting in lower proton conductance and therefore power density.

Now it is widely accepted in the industry that a chemically stable ePTFE-reinforced membrane significantly reduces this in-plane swelling, improving RH cycling durability, and extending the stack life. This allows thinner, but mechanically stronger PEMs to be developed, therefore breaking a trade-off, that provides both high proton conductance and greater mechanical durability.

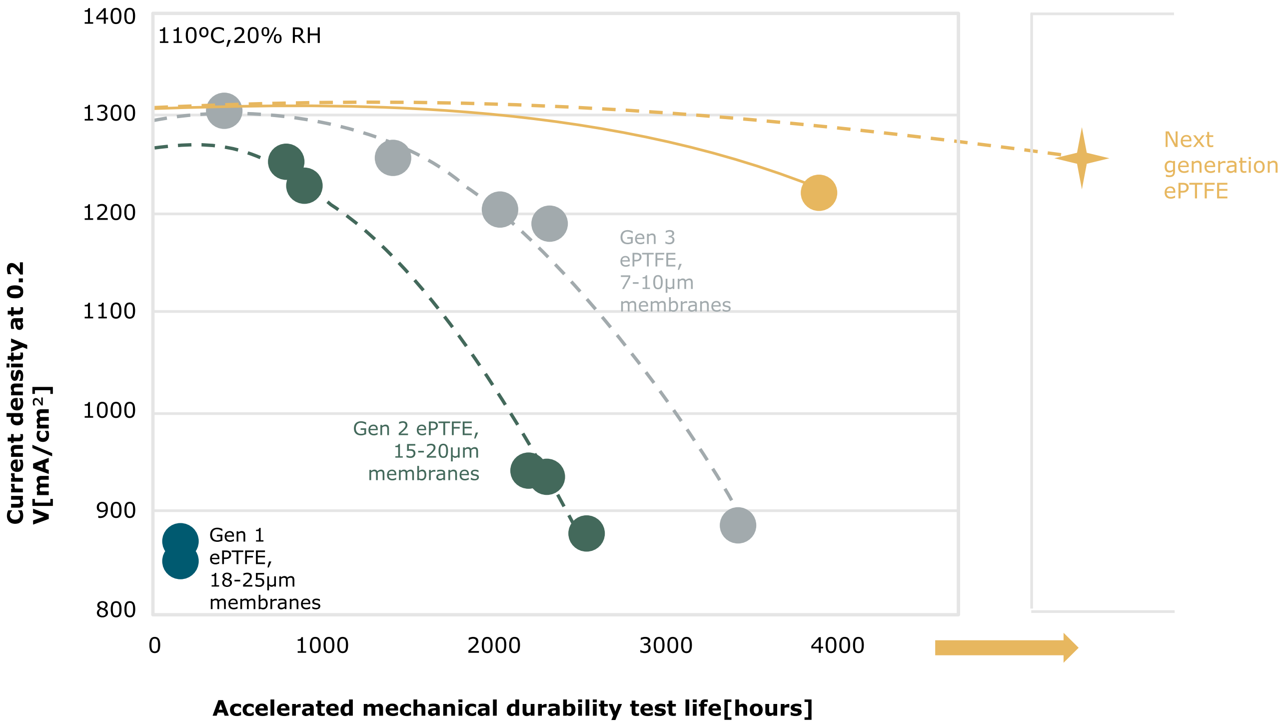
Not all ePTFE-reinforced membranes are created equal. Different designs provide different benefits (and trade-offs) to different applications. Gore's advanced PEM portfolio demonstrates the ability to cover a broad spectrum of mechanical durability and power density requirements.

Figure 5: GORE RH (Relative Humidity Cycling Test)



Developing future generations of PEM technology to have higher power density and mechanical durability at the same time will be a crucial factor in ensuring the industry's commercial viability by lowering total cost of ownership (to be discussed in later sections).

Figure 6: Gore's ePTFE technology improves the mechanical durability of the PEM



Chemical Durability

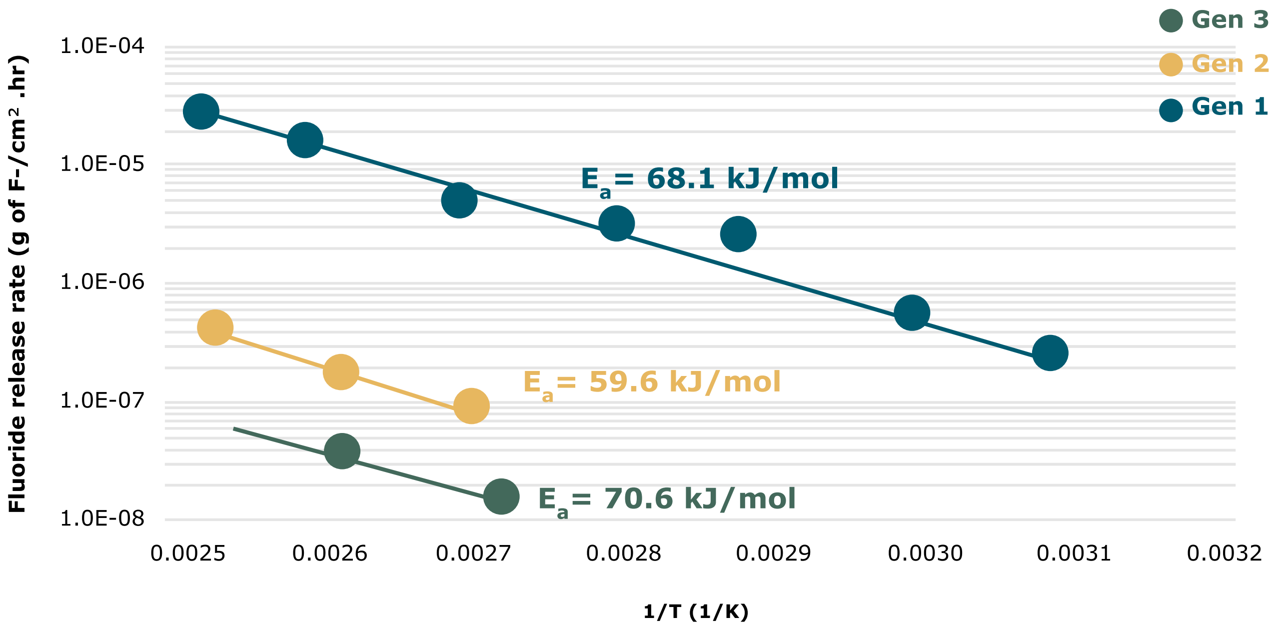
The fuel cell operates in a harsh chemical environment. Harmful radicals generated during the fuel cell's operation can react with the ionomer and result in ionomer loss. This degradation can cause continuous loss in fuel cell performance, increases gas cross-over and ultimately failure of the PEM and fuel cell.

As the ionomer degrades, it breaks down to form hydrogen fluoride, which can be measured in the product water; hence fluoride release is a common metric used to measure PEM chemical durability.

A PEM's chemical durability is affected by both the properties of the PEM and the operating environment of the PEM . For example, temperature has a huge impact on degradation, with tests showing fluoride release rates (FFR) increasing roughly 10x with a 30-degree change in temperature. (Figure 7)

However, using appropriate additive technology has shown to significantly improve the chemical durability of the PEM. (Figure 7)

Figure 7: Fluoride release rate in 70% RH OCV (Open Circuit Voltage) hold



Gas Crossover

While a key function of the PEM is to transport protons, it is equally important that the PEM keeps the hydrogen and oxygen gases separate.

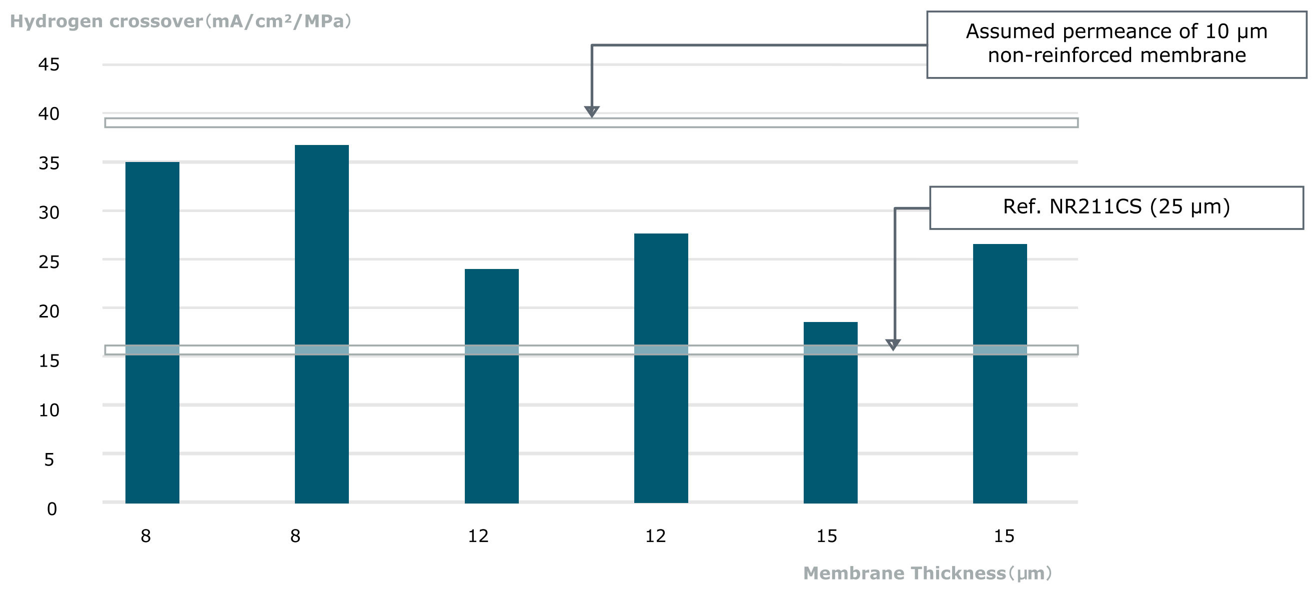
As much as the goal is to facilitate the efficient electrochemical conversion of hydrogen and oxygen, it is critical to eliminate (as much as possible) fuel inefficiency by these gases permeating through the membrane. Nitrogen crossover can also accumulate at the anode flow fields, lowering the hydrogen concentration and resulting in local fuel starvation[a].

As mentioned earlier, thinner membranes – the preferred option for power density – traditionally have a higher level of gas crossover, leading to performance decline.

Gore’s newer generation of thin PEMs with a unique ePTFE structure have been able to mitigate this trade-off, reducing gas crossover while delivering higher power density.

a. Kocha, Shyam S. et al. “Characterization Of Gas Crossover And Its Implications In PEM Fuel Cells”. Aiche Journal, vol 52, no. 5, 2006, pp. 1916-1925. Wiley, https://doi.org/10.1002/aic.10780

Figure 8: Hydrogen Permeability



Given that gas crossover affects fuel efficiency, this attribute will become increasingly important to OEMs as the industry grows and shifts from systems costs to operational costs. Fuel cell manufacturers will need to focus R&D efforts on breaking through the 'performance vs. permeability' trade-off.

High Temperature Environments

External temperatures don't just affect fluoride release rates. High-temperature operations are a growing focus of OEMS, who share a common goal of reducing radiator size and therefore decreasing costs.

However, high temperatures are a hostile operating environment for PEM, causing performance deterioration, decreased durability, and accelerated PEM degradation.

A thinner PEM helps to improve performance at high temperatures, and so the effectiveness of the ePTFE reinforcement structure will determine the relative effects on durability.

PEM Performance: Customize to Optimize

These performance factors are all inter-related, and R&D efforts and PEM design must be undertaken with a holistic approach towards understanding how they work with, and trade off against, each other.

As the fuel cell industry matures, PEM suppliers must demonstrate expertise in materials, and their interactions with other MEA and stack components and fuel cell operating strategies to enable the optimization of the systems for power, durability and cost.

RELIABILITY

PEM **performanc**e is concerned with measuring a single or a small number of data points.

PEM **reliability** looks at the bigger picture: the long-term PEM supply in mass production volumes.

We'll define reliability per the Oxford Dictionary: "the quality of being trustworthy or performing consistently well".

As the fuel cell industry moves into the mass production phase, we must consider the very different requirements at this level compared to R&D. Small sample batches of high-performing products are not enough to meet growing global demand.

PEM manufacturers must ensure high manufacturing yields of consistently high-performing products – at minimal cost impact and quality risk – to ensure a reliable supply. There are several factors to consider:

Product Quality & Consistency

'Quality' is a broad concept that covers many bases, from incoming defective parts per million (DPPM) of components, to the technical definition of 'reliability': the probability that a component will continue to work for a specified length of time.

This is calculated as: $R_{(t)} = e^{-\lambda t}$

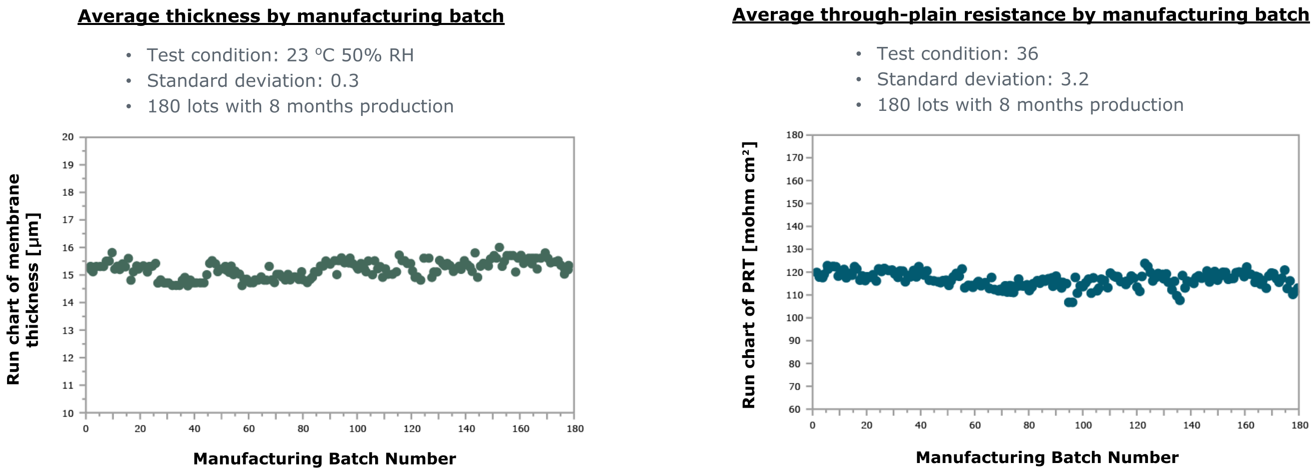
Where R is the percentage probability of failure, λ is the intrinsic failure rate (failures/hour) and MBTF (mean time between failure) is 1/ λ.

The intrinsic failure rate of a system is the summation of all the failure rates of its components. Thus, the system's reliability is limited by the component with the highest failure rate – so the focus should be on this weakest link.

This brings us to PEM. Although measuring product attributes does not guarantee non-failure, it's a good indication of product uniformity and process consistency that greatly reduces the risk of random failures. In turn, this enables MEA or stack makers to have more control and less variability in their processes, leading to a lower probability of failure.

In high-volume production environments, this is essential to reduce the risks of low process yields and incurring downstream costs related to product quality.

Figure 9: Gore PEM mass production data over 180 lots and 8 months of production



Average thickness by manufacturing batch

- Test condition: 23 °C 50% RH
- Standard deviation: 0.3
- 180 lots with 8 months production

Average through-plain resistance by manufacturing batch

- Test condition: 36
- Standard deviation: 3.2
- 180 lots with 8 months production

Capacity & Supply Security

Another consideration in this category is the reliability of the supply of PEM components, in terms of the availability of raw materials and the ability to produce PEM in the quantities required for a rapidly growing market.

The critical components of PEM are the ionomer, ePTFE reinforcement, backer, and additives. Because the fuel cell industry was still in the R&D stage of development until recently, there are very few PEM producers with established, proven, and reliable raw material supply chains based on deep R&D initiatives and secure partnerships with sub-suppliers.

Equally, not many suppliers have the capacity to manufacture PEM in the quantities required to meet the needs of the industry. Building new capacity requires large investments – in terms of cost, time, and experience – to scale up to the level required to provide a consistent, reliable supply.

Leading PEM suppliers have a certain level of vertical integration to streamline their operations, manage costs, and manage quality control. For example, Gore has leveraged its core ePTFE reinforcement expertise to develop, manufacture, and design its PEM products.

It is important to not only consider the availability of capacity, but how stable and proven that capacity is.

Track Record

There are extremely high costs associated with designing, building, and evaluating fuel cell stacks and systems. ‘First movers’ – (leading industry players) – typically invest ahead of the market to validate a PEM’s performance and suitability for a fuel cell application. While not all stacks and systems are designed in the same way, this approach is nevertheless a good benchmark of a PEM’s performance.

Using products with established materials, made with proven processes, and demonstrated to work in end-use systems is critical to reduce risk to the downstream value chain. This risk is significant when considering the small margin for error when competing in a developing market.

For example, China’s upgraded fuel cell subsidy program[a], established in 2020 and lasting for four years, has diminishing value each year despite higher technical requirements and policy targets. A new penalties system is enforced after a mid-year review.

Clearly, the value chain has limited opportunities to fully capture the benefits of this policy and establish a market foothold. Companies with an advantage in technology, cost-effectiveness, and proven PEM supply would therefore stand to benefit the most.

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[a] “China Fuel Cell “Subsidy” Policy: Game Plan Breakdown - Energy Iceberg”. Energy Iceberg, 2022,https://energyiceberg.com/china-fuel-cell-subsidy-design/.

COST

Hydrogen fuel cells promise an alternative, sustainable energy solution to meet global decarbonization targets – transforming everything from transit systems to entire industries to the very air that we breathe.

However, to make the net-zero vision a reality, it must be commercially viable in the long term. Currently, hydrogen fuel cells have yet to achieve cost parity with internal combustion engine vehicles (ICEVs) or battery electric vehicles (BEVs).

This is largely due to economies of scale and the typically high cost of the raw materials used to manufacture PEM.

Ionomers used to make thin membranes with a lower gas crossover are generally expensive. Additional components such as the electrodes, gas diffusion layer, and bipolar plates are also pricey and increase the size – and therefore the cost – of the fuel cell stack.

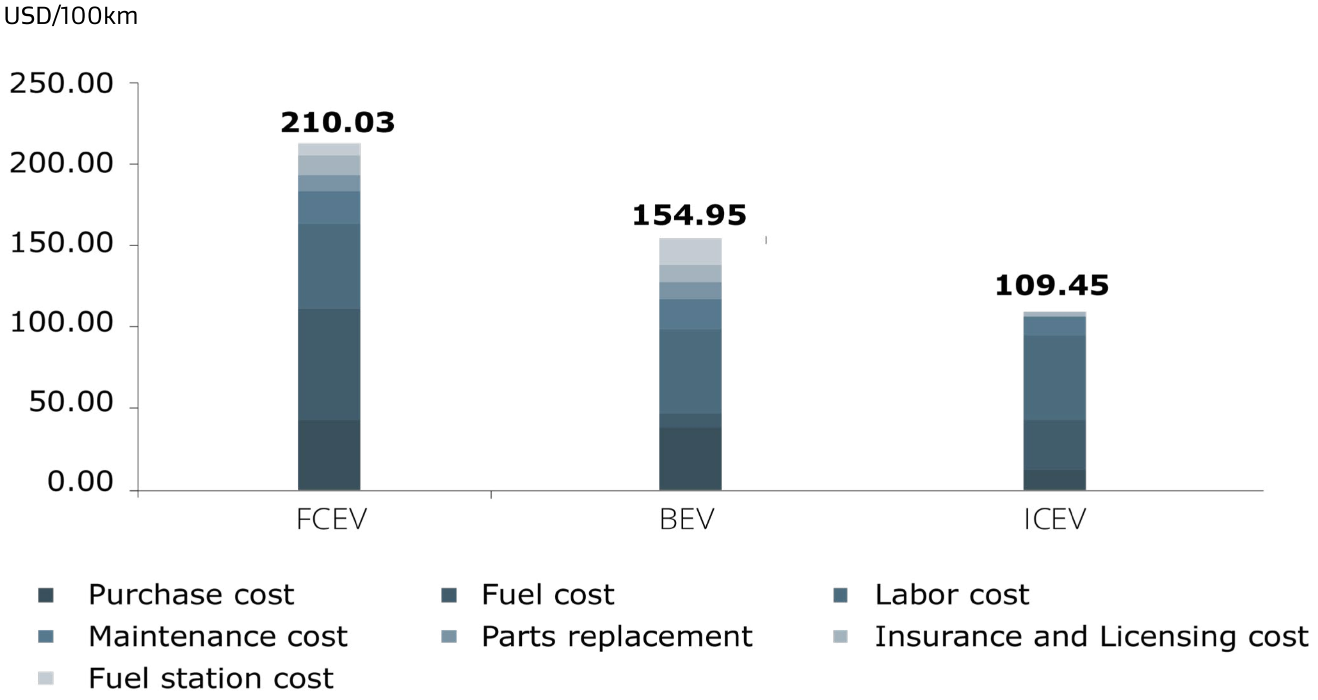
High production costs to manufacturers are passed on to the commercial vehicle price for consumers, resulting in FCEVs that are too expensive to compete with BEVs and ICEVs.

To reach cost parity, production volumes must increase – which cannot happen if material costs remain high.

This is recognised at national policy levels, across the world, with more than $500 billion in global investment[a] and 66 countries committing to sustainable energy transition. 8 out of the world's 10 largest economies have committed to net-zero emissions by 2050.

Regulations and financial support cannot last indefinitely, so there must be a cost reduction strategy along the fuel cell value chain.

Figure 10: System costs for FCEV, BEV & ICEV



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[a] "Fostering Effective Energy Transition". World Economic Forum, 2022, https://www3.weforum.org/docs/WEF_Fostering_Effective_Energy_Transition_2021.pdf

Traditional cost reduction strategies consider individual components' cost contribution and set targets to drive a total cost reduction.

However – as we've noted with the interdependent nature of fuel cell stack components and their attributes – a more holistic approach, looking at the total cost of ownership (TCO) is more appropriate in this instance.

The first step in establishing a measure of TCO is understanding the user's needs. For example:

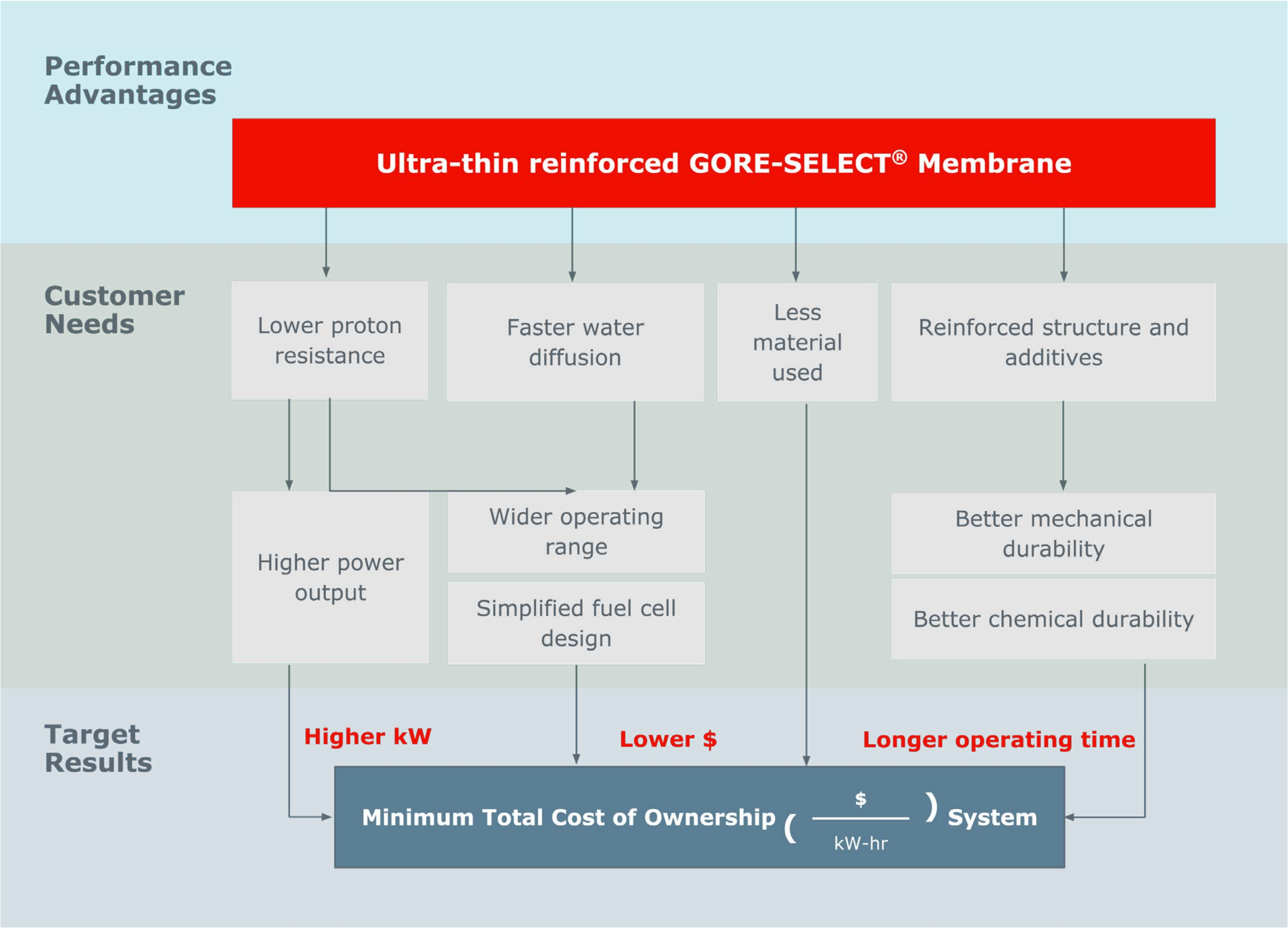
- What are the attributes that affect the final cost of a fuel cell system?
- How do we put a dollar value to a PEM that can generate higher power?
- Would it be better to have a lower cost PEM with a trade-off against power?

Again, each component seldom works in isolation and there are other factors to consider. A thinner, ePTFE-reinforced PEM can still generate high power and enable faster water diffusion, which improves operation in low RH operating conditions. This allows for a wider operating temperature range. An ePTFE-reinforced membrane is more durable and longer-lasting, lowering the total cost of a system over its lifetime.

A thinner PEM also, naturally, means less raw materials, and therefore lower component material costs – not only for the PEM itself, but for other stack components, leading to a smaller, lighter (and cheaper) stack of similar power.

Thinner PEM can also be manufactured and shipped in greater volumes from a fixed raw material supply.

Figure 11: Gore-SELECT® Membranes offer performance advantages that combine to contribute to a lower TCO



Although fuel cell systems are currently more expensive than battery electric vehicles (BEVs) and internal combustion engine vehicles (ICEVs), recent research and TCO analysis demonstrates extremely encouraging results for the future[a].

From a TCO perspective, FCEVs are forecasted to become cheaper than BEVs by 2026, and less than ICEVs around 2027 – overall, a 50% decline in the TCO of FCEVs over the next decade. This is driven by several acquisition and operational factors:

- Vehicle build cost will decline as technology matures and economies of scale improve
- Raw material cost will drop with more highly developed sourcing and supply chains
- Significant decrease in cost of hydrogen fuel, due to increased global usage of renewable energies in production and development of infrastructure and transport mechanisms
- Increased public and private sector investment, subsidies, and incentives
- Upwards pricing pressure on ICE vehicles through restrictions, higher emission standards, or outright market bans on pure ICEs

By the researchers' own admission, these forecasts may even be conservative. As we have seen with emerging technologies, production volumes increase and costs decrease even more dramatically than expected. As global interest in fuel cell technology grows, these curves may shift exponentially.

And in the very center of it all: a thinner, stronger, ePTFE-reinforced PEM enabling a longer-lasting, more powerful fuel cell stack.

[a] Fueling The Future Of Mobility, Deloitte China, 2022, https://www2.deloitte.com/content/dam/Deloitte/cn/Documents/finance/deloitte-cn-fueling-the-future-of-mobility-en-200101.pdf

LOOKING AHEAD TO A BRIGHTER, CLEANER FUTURE

An ePTFE-reinforced PEM is at the core of the fuel cell stack – and at the heart of the clean energy movement. Through efficient product design and reliable manufacturing, it has direct and causal impact to the operation, durability, and reliability of a fuel cell system; and therefore, how commercially viable that system can be.

The fuel cell automotive industry has made huge progress in the last decade and promises to take even greater leaps forward in the next 10 years. FCEVs are an extremely attractive solution in commercial and heavy-duty transportation applications, thanks to characteristics such as long range, fast refueling, and high energy density – and of course, zero emissions.

As the climate emergency remains near the top of the global policy agenda, hydrogen presents the most sustainable solution for a clean energy future – and the automotive fuel cell industry will drive that movement.

Companies and manufacturers with an interest in this sector need a partner with an outstanding track record, R&D and process expertise, and the supply security to deliver on that promise.

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