**Gore Electrolysis Technologies**
Enhancing Hydrogen
Production Efficiency

# MINIMIZING LCOH WITH ADVANCED PROTON EXCHANGE MEMBRANES

## Table of Contents

*What do a French steel mill, a North Sea offshore wind plant, and a Spanish hydrogen production hub have in common?*

*For Proton Exchange Membrane (PEM) water electrolysis to become a viable pathway for green hydrogen production, the levelized cost of hydrogen (LCOH) must come down. The goal of this study was to investigate the impact of the PEM on the LCOH for three use cases: a dedicated hydrogen production powered by nuclear for a French steel mill; a green hydrogen production facility powered by offshore wind in the North Sea; and a local hydrogen production hub in Spain powered by a photovoltaic system. The study compares the GORE® PEM M275.80 to a state-of-the-art comparable product on the market (Market PEM) as well as against Alkaline electrolysis. The simulation shows that Gore's PEM technology is superior in each of the three use cases and offers the lowest LCOH due to its high cell efficiency.*

## 1. Introduction

The clean energy economy is evolving rapidly, but faster progress is needed to meet international climate and energy goals. PEM water electrolysis must become more efficient to become a viable green hydrogen production pathway at scale. Currently, the cost of green hydrogen produced through electrolysis (\$4.5-12/kg $H_2$)[1] is significantly higher than that of grey hydrogen generated through steam methane reforming (\$0.98-2.93/kg $H_2$)[2]. The challenge is minimizing the LCOH to make it more affordable for off-takers.

There are many studies focusing on LCOH reduction considering different regional and economical factors. However, as a leading PEM supplier, we wanted to investigate PEM attributes and their impact on reducing LCOH.

We partnered with FEV Consulting, a global leader in technical and management consulting with deep expertise in the energy sector, including hydrogen systems. An electrolyzer "material to system level" model was developed to assess system efficiency improvements relative to membrane property changes. This model evaluates cost reductions directly linked to material attributes (Figure 1) in three representative use cases.

Figure 1.

This paper will introduce each use case before detailing the modeling approach and the respective membrane attributes used in the calculations. The results of the assessment and their implications are summarized in the conclusion.

---

1-2. Green Hydrogen to Undercut Gray Sibling by End of Decade, Kamala Schelling, BloombergNEF, 2023, https://www.bnef.com

*Together, improving life*

# 2. From material properties to system output

## 2.1 Use case identification

Three distinct use cases were selected (Figure 2) for the electrolyzer system simulation. Each use case is defined by a) electrolyzer capacity, b) load profile, c) hydrogen purity and pressure requirements and d) operation strategy.

Figure 2.

### Use Case #1

**DIRECT $H_2$ PRODUCTION AND UTILIZATION IN STEEL MAKING POWERED BY GRID**

- **"Fixed" $H_2$ demand**
- **Power: Via grid from nuclear or Power Purchase Agreements**
- **Electrolyzer system operated at ambient conditions**
- **Sale of $O_2$ at €24.5/t**
- **Location: France**

### Use Case #2

**LARGE-SCALE GREEN $H_2$ PRODUCTION FOR DIVERSE OFF-TAKERS POWERED BY OFFSHORE WIND**

- **$H_2$ production for multiple off-takers**
- **Power: Offshore wind**
- **PEM Electrolyzer system operated at differential pressure**
- **Sale of $O_2$ at €24.5/t**
- **Location: Germany**

### Use Case #3

**LOCAL $H_2$ PRODUCTION HUB FOR TRANSPORT POWERED BY PHOTOVOLTAICS (PV)**

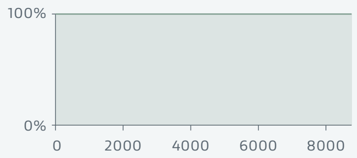
- **$H_2$ production for mobile off-takers**
- **Power: Photovoltaic**
- **PEM Electrolyzer system operated at differential pressure**
- **No $O_2$ revenues considered**
- **Location: Spain**

### Use Case Requirements

**Electrolyzer Capacity**
- PEM system adjusted to match 500 MW Alkaline system based on efficiency

**Load Profile**
- Steady-state, continuous electrolyzer operation
- Reference plant: GravityHy, France

**Electricity load profile over year [h]**



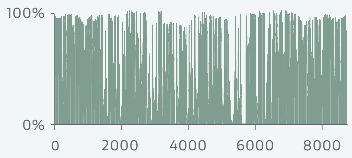
**Hydrogen Purity & Pressure**
- $H_2$ purity: 99.8%
- $H_2$ pressure: min. 4.5 bar

**Operation Strategy**
- Consecutive maintenance intervals are considered to ensure a steady hydrogen supply.
- Fixed hydrogen output throughout the year.
- Maintenance (1 week per year) is done consecutively for individual modules.
- System compensates the downtime of one module by increasing the operation point / current density.

**Electrolyzer Capacity**
- 100 MW onshore electrolyzer for all systems

**Load Profile**
- Electrolyzer follows renewables profile
- Reference wind park: Dan Tysk, Germany

**Electricity load profile over year [h]**



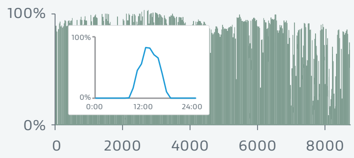
**Hydrogen Purity & Pressure**
- $H_2$ purity: Grade A (≥98%)
- $H_2$ pressure: 30 bar

**Operation Strategy**
- An efficiency-optimized operation strategy for each of the electrolyzer-membrane combinations is considered.
- Individual modules will shut down if the efficiency of the remaining system can be improved.
- Modules in operation will run on a similar current density.

**Electrolyzer Capacity**
- 20 MW electrolyzer for all systems

**Load Profile**
- Electrolyzer follows renewables profile
- Reference solar park: Guillena, Spain

**Electricity load profile over year [h]**



**Hydrogen Purity & Pressure**
- $H_2$ purity: Grade A (≥98%)
- $H_2$ pressure: 30 bar

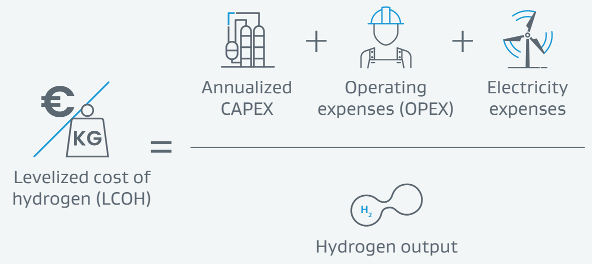
**Operation Strategy**
- Only one module considered for Use Case #3
- Complete shutdown of production plant once part load limit is reached.
- Volatile load profile is a key characteristic.

## 2.2 LCOH calculation

### 2.2.1 Definition

The LCOH is defined as the equivalent cost per unit of hydrogen at which the project achieves a Net Present Value equal to zero (Figure 3).

Figure 3.



To calculate the LCOH for each of the three use cases, the following assumptions were made:

### 2.2.2 CAPEX

For this LCOH calculation, CAPEX is split into:

- **Cost for a 20 MW module** (identical across all use cases) consisting of: Electrolyzer Stack, Balance of Plant (BOP) Module, Power Electronics Module
- **Cost groups** which scale with plant size/use case: Power Electronics System, Compressor, Cooling, Piping, Instrumentation, Engineering, Construction Cost

### 2.2.3 OPEX

Operational expenses include all annual costs like Operation & Maintenance, stack replacement and water costs. For the sake of simplicity, "oxygen revenue" was also included under OPEX.

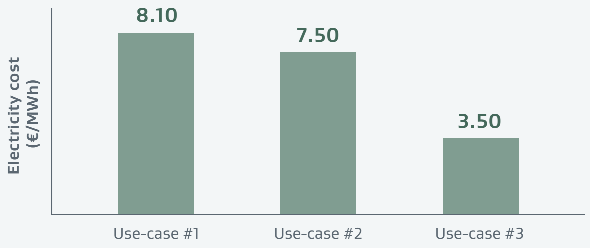
### 2.2.4 Electricity expenses

Electricity expenses are shown in Figure 4 per use case. **For Use Case #1**, assumptions for levelized cost of electricity (LCOE) are based on electricity prices for industrial customers for power-purchase agreements or direct nuclear power in France.

**For Use Cases #2 and #3**, assumptions for LCOE are based on a direct coupling of the renewable energy source and electrolyzer system. Surplus electricity is not considered within the LCOH calculation.

Figure 4.

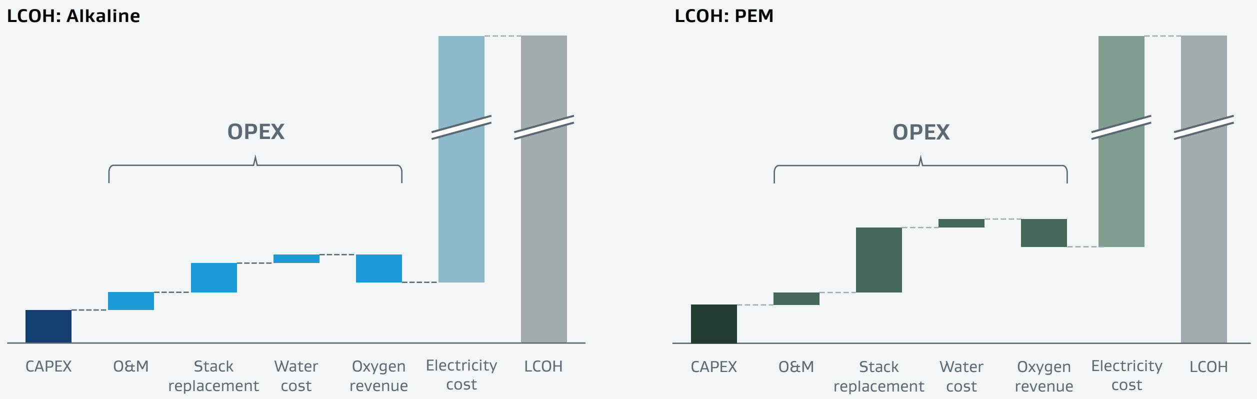
**LCOE as defined for each use case:**



### 2.2.5 Specific system characteristics and use-case implications

The LCOH calculation accommodates different systems characteristics and use case implications. The illustration represents the assumptions used to calculate CAPEX and OPEX. Electricity costs are influenced by use case scenario and membrane combination, and resultant LCOH will vary (Figure 5).

Figure 5.


**LCOH: Alkaline**

**LCOH: PEM**

- No residual value of the system considered (System lifetime: 25 years)
- Stack replacement cost are depreciated linearly
- Average LCOH over the system's lifetime

## 3. Membrane attributes[3,4]

The key PEM attributes that contribute to the overall efficiency of an electrolysis cell are **proton resistance** and **hydrogen permeation resistance**.

The cell efficiency ($\varepsilon_{tot\ H_2}$) is the product of the voltage (or electric) efficiency ($\varepsilon_V$) and the faradaic efficiency ($\varepsilon_F$) (Figure 6).

Figure 6.

$$\varepsilon_{tot\ H_2} = \varepsilon_V \cdot \varepsilon_F$$

The PEM proton resistance affects the voltage efficiency. The hydrogen permeation resistance affects the faradaic efficiency.

These attributes were evaluated on Gore's PEM M275.80 and Market PEM and inputted into the FEV cell model to simulate system and overall efficiencies according to the different use cases. For alkaline electrolysis, a benchmark performance cell was used for the comparison with PEM electrolysis.

### 3.1 Voltage efficiency

The voltage efficiency ($\varepsilon_v$) can be defined as the ratio between the thermoneutral voltage ($E_{th}$) and the measured cell voltage ($E_{cell}$) (Figure 7).

Figure 7.

$$\varepsilon_V = \frac{E_{th}}{E_{cell}}$$

The measured cell voltage ($E_{cell}$) is composed of the reversible voltage ($E_{re\ v}$) (required to split the water molecules), the ohmic overpotential ($\eta_{iR}$), the kinetic overpotential ($\eta_{kin}$) and the transport overpotential ($\eta_{rest}$) (Figure 8).

Figure 8.

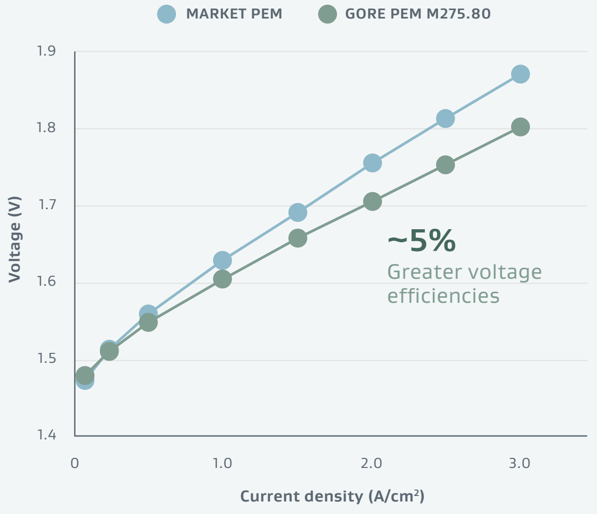
$$E_{cell}(j) = E_{re\ v} + \eta_{iR}(j) + \eta_{kin}(j) + \eta_{rest}(j)$$

A key component of the ohmic overpotential is the **membrane proton resistance** that is typically normalized over the electrochemically active area and has units of mOhm*cm².

**Therefore, the lower the membrane proton resistance, the lower the ohmic overpotential and thus the higher the voltage efficiency.**

Gore's PEM M275.80 offers ~5% greater cell voltage efficiencies over other PEM. This reduces the amount of electricity required to produce 1 kg of Hydrogen by ~5% (Figure 9).

Figure 9.



### 3.2 Faradaic Efficiency

The electrolysis process produces hydrogen on the cathode electrode. However, a fraction of this produced hydrogen can permeate through the membrane and is not captured with the volume of produced hydrogen.

Additionally—although of lower importance—oxygen produced on the anode side can permeate through the membrane and react on the cathode catalyst with hydrogen to form water. This further reduces the actual hydrogen production volume.

The faradaic efficiency ($\varepsilon_F$) can be defined as the ratio between the usable volume of produced hydrogen ($\dot{m}_{re\ H_2}$) and the total volume of hydrogen ($\dot{m}_{id\ H_2}$) produced (Figure 10).

Figure 10.

$$\varepsilon_F = \frac{\dot{m}_{re\ H_2}}{\dot{m}_{id\ H_2}}$$

Therefore, membrane resistance to hydrogen permeation is a critical attribute for the faradaic efficiency and can be represented in the units of kPacm²/mA.

**The lower the membrane hydrogen permeation, the higher the faradaic efficiency.**

### 3.3 Differences between Gore and Market PEM

Proton resistance and hydrogen permeation resistance are therefore two critical membrane attributes that impact the efficiency of the electrolysis cell. However, both attributes are interdependent, and cannot be individually maximized.

Gore's PEM M275.80 was developed to provide significant improvement in proton resistance compared to the Market PEM (Figure 11), accepting a slight reduction in hydrogen permeation resistance. Across a wide range of operating conditions, this would lead to a more efficient system overall.

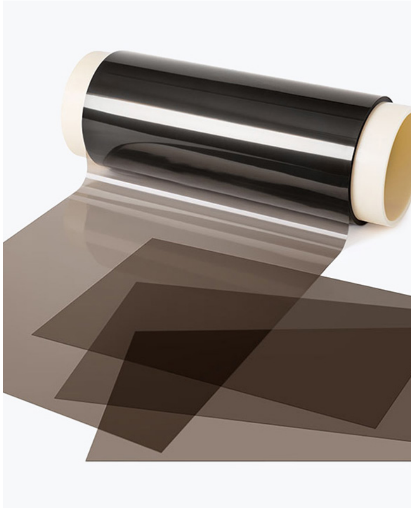
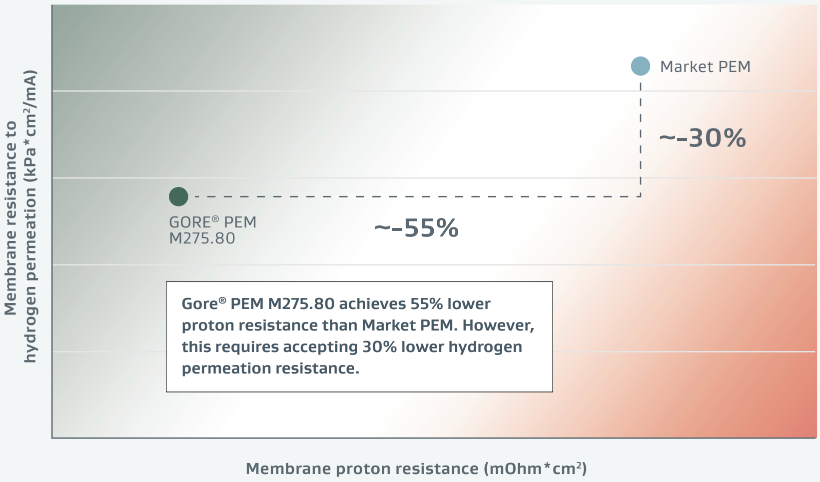


Figure 11.



Gore® PEM M275.80 achieves 55% lower proton resistance than Market PEM. However, this requires accepting 30% lower hydrogen permeation resistance.

---

Literature reference for equations and efficiency definitions:
3. Garbe et al., Electrochim. Acta 377 (2021) 138046
4. Efficiency – Electrolysis, White paper, Dr. Philipp Lettenmeier, Siemens Energy Global GmbH & Co. KG, 2020

# 4. Simulation results

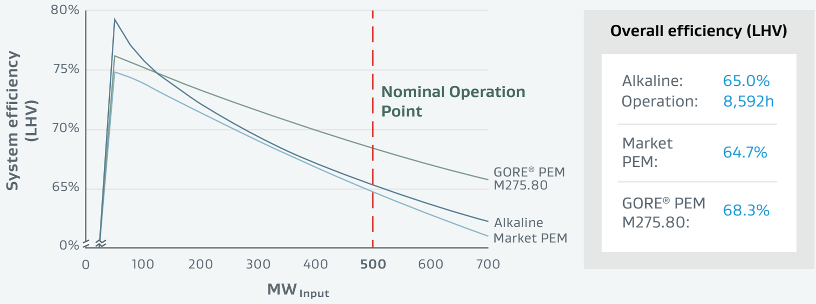
## 4.1 Efficiency & LCOH output for Use Case #1

USE CASE #1 RESULT

### DIRECT $H_2$ PRODUCTION AND UTILIZATION IN STEEL MAKING POWERED BY GRID

### 4.1.1 System output

Figure 12.

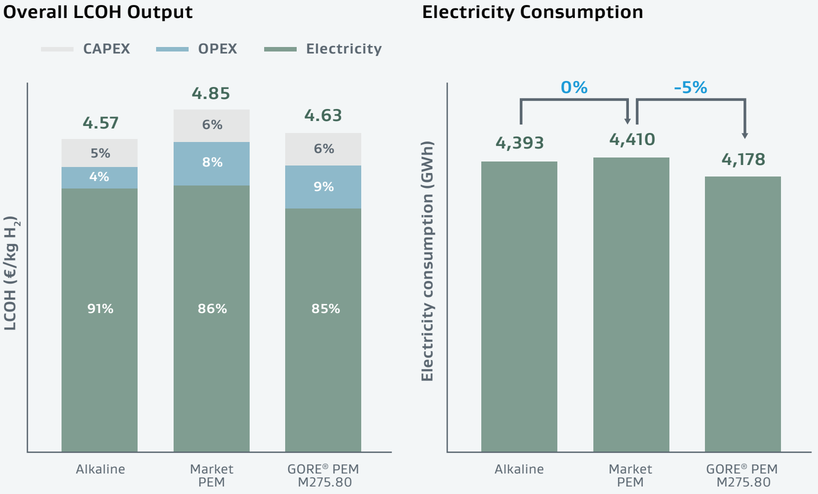


Overall efficiency considering operating strategy and profile; system efficiency represents efficiency at a given operating point.

GORE® PEM M275.80 enables the highest system efficiency around the nominal operation point, followed by Alkaline. Part load is not considered relevant in this use case (Figure 12).

### 4.1.2 LCOH output

Figure 13.



GORE® PEM M275.80 is about 5% more efficient and therefore shows about 5% less electricity consumption vs. Market PEM & Alkaline (Figure 13).

The efficiency improvement of Gore's PEM M275.80 results in a significant reduction in LCOH compared to Market PEM. In this large-scale use case, approximately 85,000 tons of hydrogen are produced per year. Therefore, every €0.01/kg saved would lead to €850,000 in annual electricity cost savings.

On the other hand, the efficiency improvements are offset by higher CAPEX in PEM systems compared to Alkaline. To make PEM systems more competitive against Alkaline on the basis of LCOH, further PEM system CAPEX reductions and efficiency improvements are necessary for this use case.

## 4.2 Efficiency & LCOH output for Use Case #2

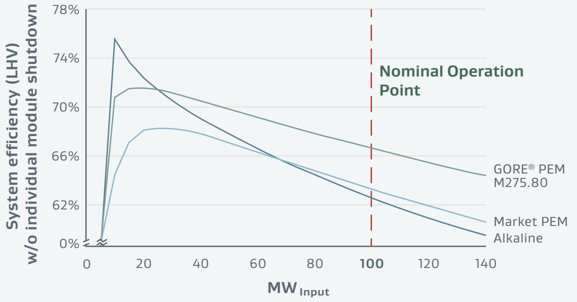
USE CASE #2 RESULT

### LARGE-SCALE GREEN $H_2$ PRODUCTION FOR DIVERSE OFF-TAKERS POWERED BY OFFSHORE WIND

### 4.2.1 System output

Gore's PEM M275.80 enables the highest efficiency at nominal power. At low part load, Alkaline may become more efficient (Figure 14).

Figure 14.



**Overall efficiency (LHV)**

| | |
|---|---|
| Alkaline:<br>FLH: | 63.8%<br>5,651h |
| Market PEM: | 64.1% |
| GORE® PEM M275.80: | 67.4% |

Overall efficiency considering operating strategy and profile; system efficiency represents efficiency at a given operating point.

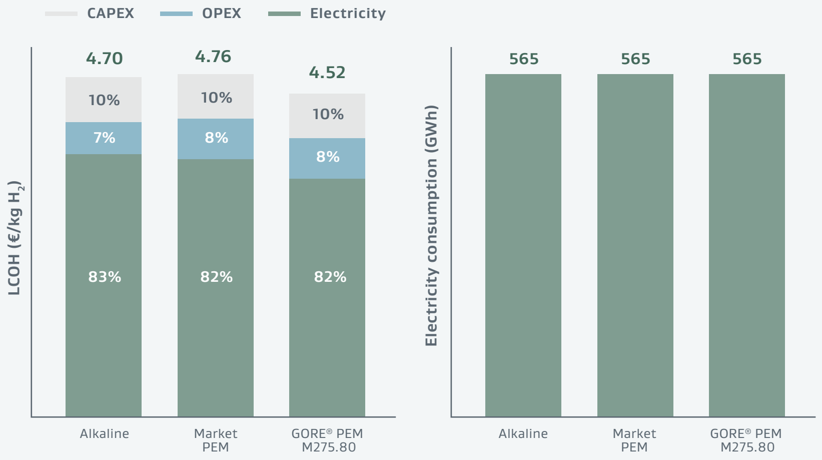
Overall, GORE® PEM M275.80 demonstrates best system performance, followed by Alkaline.

### 4.2.2 LCOH output

Figure 15.

**Overall LCOH Output**

**Electricity Consumption**



System efficiency is crucial as electricity expenditures account for over 80% of the LCOH (Figure 15).

The highest system efficiency can be enabled with Gore's PEM M275.80 over a wide range of load supporting partial load flexibility as needed for an offshore wind powered electrolyzer (Figure 14).

System efficiency improvements achieved while using the highly conductive GORE® PEM M275.80 result in a reduction of the LCOH by €0.18 and €0.24/kg $H_2$ when compared to Alkaline and Market PEM respectively. For the given use case of an offshore windpark with a 100 MW electrolyzer wherein 11,400 tons of hydrogen are produced per year, this translates to annual savings of €2.1M and €2.7M.

## 4.3 Efficiency & LCOH output for Use Case #3

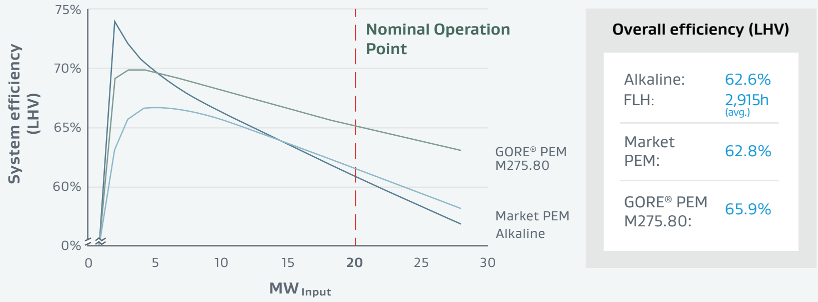
USE CASE #3 RESULT

# LOCAL $H_2$ PRODUCTION HUB FOR TRANSPORT POWERED BY PHOTOVOLTAICS

### 4.3.1 System output

Similar performance characteristics as Use Case #2, but generally lower efficiency due to hydrogen compression to 200 bar (Figure 16).

Figure 16.

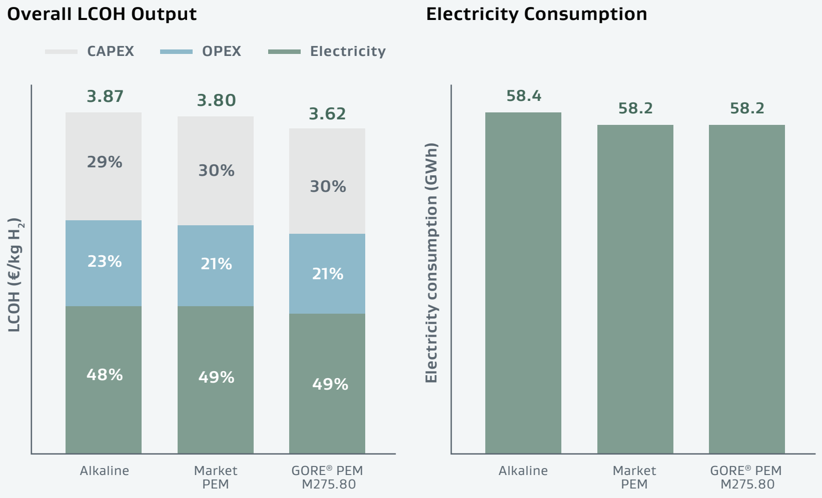


Overall efficiency considering operating strategy and profile; system efficiency represents efficiency at a given operating point.

Pressurized operations of PEM electrolyzers allows higher system efficiencies than Alkaline.

### 4.3.2 LCOH output

Figure 17.



Even at relatively low FLH, electricity expenditures account for about 50% of the LCOH.

The highest system efficiency can be enabled with Gore's PEM M275.80 over a wide range of load supporting partial load flexibility as needed for an photovoltaic powered electrolyzer (Figure 16).

System efficiency improvements achieved while using the highly conductive GORE® PEM M275.80 result in a reduction of the LCOH by €0.25 and €0.18/kg $H_2$ when compared to the Alkaline and Market PEM respectively. For the given use case of a photovoltaic hub with a 20 MW electrolyzer wherein 1,150 tons of hydrogen are produced per year, this translates to annual savings of €290,000 and €210,000.

## 5. Conclusion and path forward

In summary, the analysis underscores electricity costs as the primary cost driver in all three use case scenarios. The simulations demonstrate that the right PEM can minimize energy consumption and therefore significantly reduce LCOH.

### Comparing Gore PEM to Market PEM

The GORE® PEM M275.80 boasts 5% greater voltage efficiency over Market PEM, resulting in approximately 3% higher efficiency across all scenarios. LCOH was reduced by between €0.22-0.24/kg $H_2$ depending on the use case. In Use Case #1 (green steel production), this translates to annual savings of €18.7 million.

It's worth noting that highly conductive PEMs with reduced membrane proton resistance offer heightened voltage efficiencies. However, safe operation requires mitigation for durability and hydrogen crossover.

Here, innovations such as unique ionomers and thin membrane construction play a pivotal role. Such features enhance conductance and voltage efficiency while mitigating those performance trade-offs between efficiency, durability and safety.

To further optimize overall system performance, additives can minimize hydrogen crossover and improve chemical durability. Membrane reinforcements support thin yet mechanically robust membranes.

### Comparing GORE® PEM M275.80 to Alkaline

Use Cases #2 and #3 demonstrate a potential LCOH reduction of 5% or ~€0.20/kg $H_2$.

In Use Case #1, additional CAPEX and efficiency requirements are required to achieve competitive LCOH against Alkaline systems.

### Looking ahead

Gore is dedicated to advancing our PEM technology to maximize cell efficiencies while meeting market durability and safety requirements. Our goal is to further lower LCOH and position our PEM as the most cost-effective alternative solution across various use cases compared to other PEM and Alkaline systems.

We are also committed to exploring additional use case scenarios and expanding project parameters; for example, systems outside Europe, or encompassing storage and transportation applications. This will generate deeper insights into the potential impact of advanced PEM products on reducing LCOH.

In collaboration with our partners, we are actively working to acquire reliable degradation data to inform the LCOH model and ensure sustained efficiency improvements over the long term.

Further improvements to the model may include accounting for potential system optimizations with our new PEM technology and how efficiency improvements might affect stack replacement and degradation assumptions. This could offer insights into additional cost enhancements over time.

Lastly, there is a need to study other variables and their interactions on efficiency and ultimately LCOH. Sensitivity studies have been conducted on operating current densities, membrane hydrogen permeation resistances and degradation rates, and more work is required to understand wider system inputs.

Gore's development strategy is founded on innovation, collaboration, and simulation. By advancing our products, working with partners to collect degradation data, and refining scenario models to ensure sustained efficiency improvements, we are dedicated to ensuring the long-term success of PEM technology.

**FEV Consulting** is the management consulting arm of the FEV Group and act as a bridge between strategy and technology. The company combines many years of experience in top management consulting with deep product understanding and technical know-how. As part of the mobility and energy ecosystem, it integrates different industry-specific capabilities. This enables FEV Consulting to create sustainable product and strategy solutions for some of the most pressing and complex issues facing today's enterprises.

For more information, please visit fev-consulting.com

**Authors**

**Amr Kobaisy**
**New Product Development Manager**

**Oliver Teller**
**Product Manager PEM Water Electrolysis**

**Co-author**

**Daniela Thienel**
**Marketing Manager**

To delve deeper into Gore and its PEM water electrolysis technologies,
please visit **gore.com/products/gore-pem-water-electrolysis**.

## Gore's Sustainability Commitment

Gore emphasizes eco-friendly and safe manufacturing processes, guided by ISO 14001, avoiding PFOS/PFOA, and incorporating waste management practices like precious-metal recovery, ePTFE recycling, and multiple waste-reduction streams. Our products comply with REACH and RoHS standards, and do not emit PFOS/PFOA during use.

For more information, please visit **gore.com/about/responsible-enterprise**

## About Gore

W. L. Gore & Associates is a global material science company dedicated to transforming industries and improving lives. The organization is committed to accelerating the world's transition to clean energy by leveraging the potential of hydrogen. As the market leader in Proton Exchange Membranes (PEM) and through successful collaborations with key fuel cell OEMs including Hyundai and Toyota, W. L. Gore & Associates possesses the technical and production capabilities to drive PEM Water Electrolysis into the commercial mainstream.

For more information, please visit **gore.com/alt-energy**

**FOR INDUSTRIAL USE ONLY. Not for use in food, drug, cosmetic or medical device manufacturing, processing, or packaging operations.**

W. L. Gore & Associates, Inc. is certified according to ISO 9001.

**INTERNATIONAL CONTACTS**

| | | | | | |
|---|---|---|---|---|---|
| **United States** | +1 410 476 2699 | **China** | +86 21 5172 8299 | **Korea** | +82 2 393 3411 |
| **Germany** | +49 89 4612 0 | **Japan** | +81 3 6746 2570 | | |

**gore.com/alt-energy**