DOE | Alkaline Fuel Cell & High Temperature Membranes Enable New Market Opportunities

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1.0 Introduction & Methodology

1. Introduction

Fuel cells are classified primarily by the type of electrolyte they use[1]. Alkaline fuel cells (AFC) use a solution of potassium hydroxide in water (KOH) as the electrolyte and a variety of non-precious metals as the catalyst. By comparison the more familiar polymer electrolyte membrane (PEM) fuel cells use a solid polymer as the electrolyte and platinum (a precious metal) as the catalyst. Although PEM fuel cells are the most developed, due to the high cost of platinum and its limited availability, alternatives are actively being sought for application in hydrogen fuel cells.

Fuel cell classification by electrolyte has implications for both performance and applications. **Alkaline fuel cells hold the promise of continued cost reduction and the ability to expand the range of applications to include military, space, backup power and transportation. AFCs match the typical stack size of PEM (1kW-100 kW), as well as the electrical efficiency (60%). However, challenges remain for AFCs with respect to sensitivity to CO_2 in fuel and air; electrolyte management (aqueous) and electrolyte conductivity (polymer).**

The purpose of this report is to highlight emerging markets not only for anion exchange membranes (AEM), but also for high temperature membranes for PEM fuel cells in three temperature ranges of interest (80-120C) (120-240C) and (>200C). Anion Exchange Membranes are solid polymer electrolyte membranes that contain positive ionic groups and mobile negatively charged ions.

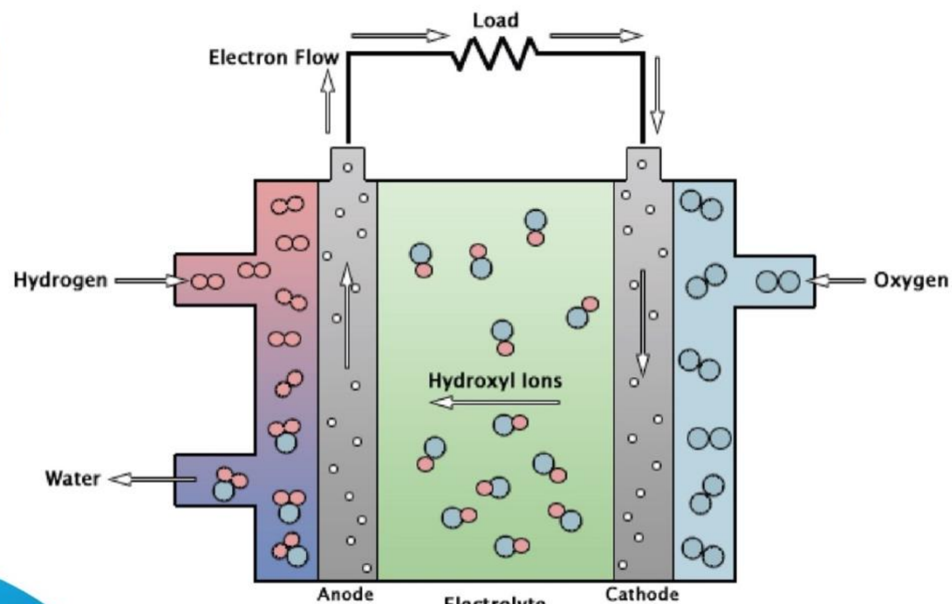
1.1 Methodology

Both secondary and primary market research methods were used to identify emerging markets for anion exchange membranes. Secondary market research made use of information from two subscription databases (BCC Research and MarketsandMarkets) as well as publicly available information. To gain a perspective on which markets held the most near-term promise for AEM, a small sample of U.S. organizations were contacted by email and phone, to gain their perspective. Given the brevity of time, only secondary market research was conducted to identify emerging market opportunities for PEM membranes working in the higher temperature ranges. Throughout this report, the results of primary market research are interspersed without attribution.

TABLE 1: Sample size and response rate by organization type

Organization Type	Outreach	Data Collected	Response Rate
Small Business conducting AEM R&D	22	4	18%
Universities conducting AEM R&D	14	4	29%
Industry	4	2	50%
Federal Lab	3	1	33%
TOTAL	**43**	**11**	**26%**

2.0 Anion Exchange Membranes



2.0 Anion Exchange Membranes

The original introduction of alkaline fuel cells in 1939 used aqueous liquid potassium hydroxide as the electrolyte[2]. However, today's Anion Exchange Membranes (AEM) use polymer electrolyte membranes, thus replacing the use of an aqueous solution and enabling a solid-state alkaline fuel cell[3]. A wide variety of synthetic and naturally-derived materials can be used to produce the AEM and are described in a 2021 publication by Hren, Masa et al[4]. The challenge that will enable the market for the use of AEM to grow is the ability to maintain a lower temperature and produce it at a lower cost than PEM[5]. Other issues were noted in a report produced by IRENA.[6]

> *"… performance is not yet as good as expected, mostly due to low AEM conductivity, poor electrode architectures and slow catalyst kinetics. Performance enhancement is typically achieved by tuning membrane conductivity properties, or by adding a supporting electrolyte (e.g. KOH or sodium bicarbonate [NaHCO3]). Such tuning could lead to decreased durability, however. The OH ion is intrinsically three-fold slower (lower conductivity) than H+ protons within PEM, which forces AEM developers to either make thinner membranes, or ones with higher charge density."*

Market Size for AEM

The result is that the market for anion-exchange membranes is currently very small. According to a 2019 press release by Market Intellica **the global AEM market value was $485M in 2014, $520M in 2019 and expected to reach 550M by 2024[7] with an emphasis on applications with fuel cells.** However, a 2020 press release by Transparency Market Research[8] highlighted a different application of AEMs in **battery applications**. They announced that the overall ion exchange market was growing based on the promise that AEMs would be able to meet the demand in battery applications.[9] A recent article by Tsehaye, Misigna et al provides a literature review and talks to the prospects for anion-exchange membranes in **alkali metal-air batteries.**[10] According to Transparency Market Research:

> *"Cation exchange membranes and AEMs are acquiring prominence in zinc-air applications. As such, cation exchange membranes are predicted to dictate the second-highest revenue among all charge types in the market landscape. Various advantages of AEMs such as minimizing zincate ion permeation toward the air electrode are generating incremental opportunities for companies in the ion exchange membrane market. Apart from zinc-air batteries, manufacturers are increasing the applicability of cation exchange membranes and AEMs in vanadium redox flow batteries."*[11]

This same report indicates that demand for anion exchange membranes is high due to the fact that AEM can be used in **water purification and electrolysis.** In this application, competition stems from less expensive cation exchange membranes.

2.1 Hydrogen Fuel Cell Applications of AEM

A hydrogen fuel cell uses hydrogen as the fuel in an electrochemical process that combines hydrogen and oxygen to produce electricity with water and heat as by-products. Fuel cells do not require the combustion of fossil fuels and therefore don't generate green-house gas emissions. However, currently the production of the hydrogen used in hydrogen fuel cells derives from fossil fuel sources (methane gas reforming) and according to TWI, will take decades before most hydrogen can be secured from other sources.[12]

Another process that holds great promise for the future is the reverse process which uses **electrolysis to produce "green" hydroge**n and oxygen from water and can use a wide range of renewable energy resources to produce hydrogen. However, globally only a very small percentage of hydrogen is currently formed in this fashion (less than 5%) and it is expensive to produce.[13] Currently green hydrogen is two to three times more expensive than hydrogen produced from fossil fuels in combination with carbon capture and storage (CSS). However, a recent report by the International Renewable Energy Agency (IRENA)[14] predicts that green hydrogen should be cost competitive by 2030, given the falling costs of wind and solar production.

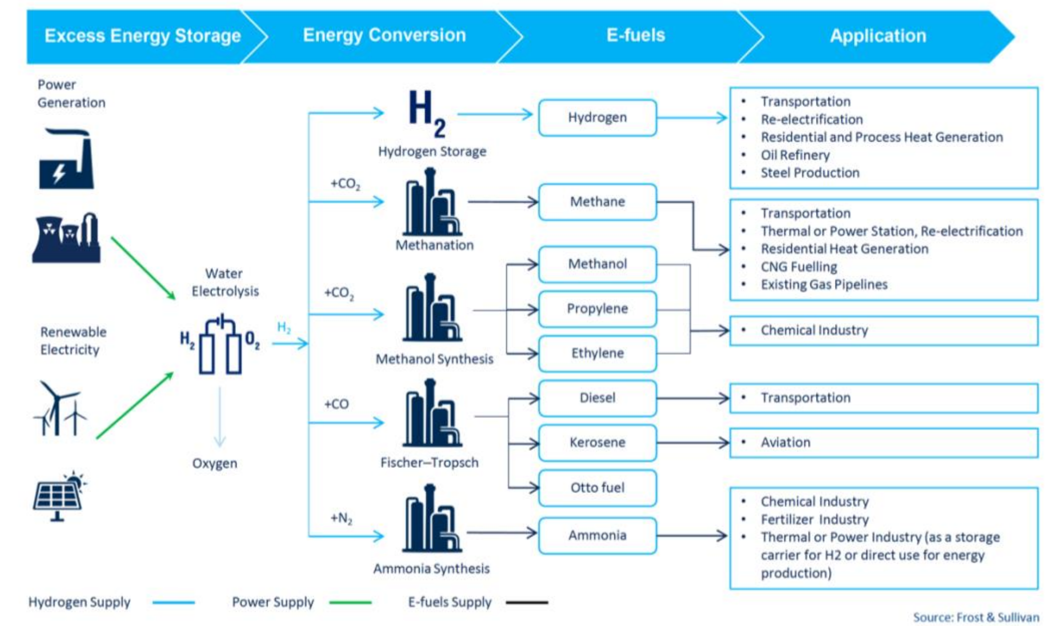
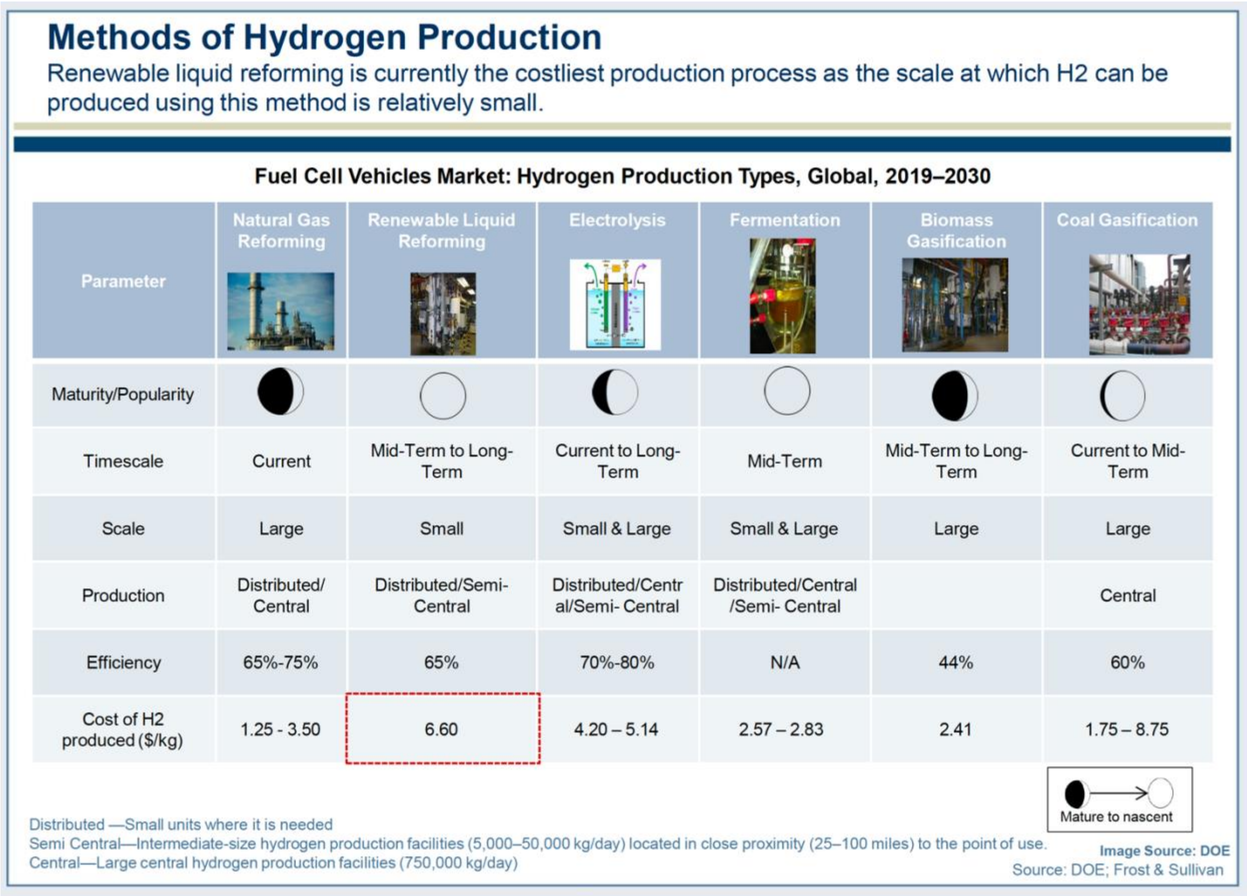


FIGURE 1: Power-to-X: Technological Chain, Global, 2020[15]

The concept of Power-to-X used in Figure 2 makes the point that there are many different ways to generate fuels for use with a wide range of end-use applications.

The end-use application for which hydrogen is most urgently in demand is ground transportation. Both the United States and China have a national milestone of 1 million Fuel Cell Electric Vehicles (FCEV) by 2030. **The leading automotive companies producing FCEV include Hyandai-Kai, Toyota, Honda, BMW, GM, Ford, Renault, Audi and Nissan**. The current cost of fuel based on method of production is represented in the following figure.



Methods of Hydrogen Production

Renewable liquid reforming is currently the costliest production process as the scale at which H2 can be produced using this method is relatively small.

Fuel Cell Vehicles Market: Hydrogen Production Types, Global, 2019–2030

Parameter	Natural Gas Reforming	Renewable Liquid Reforming	Electrolysis	Fermentation	Biomass Gasification	Coal Gasification
Maturity/Popularity						
Timescale	Current	Mid-Term to Long-Term	Current to Long-Term	Mid-Term	Mid-Term to Long-Term	Current to Mid-Term
Scale	Large	Small	Small & Large	Small & Large	Large	Large
Production	Distributed/ Central	Distributed/Semi-Central	Distributed/Central/Semi- Central	Distributed/Central /Semi- Central		Central
Efficiency	65%-75%	65%	70%-80%	N/A	44%	60%
Cost of H2 produced ($/kg)	1.25 - 3.50	6.60	4.20 – 5.14	2.57 – 2.83	2.41	1.75 – 8.75

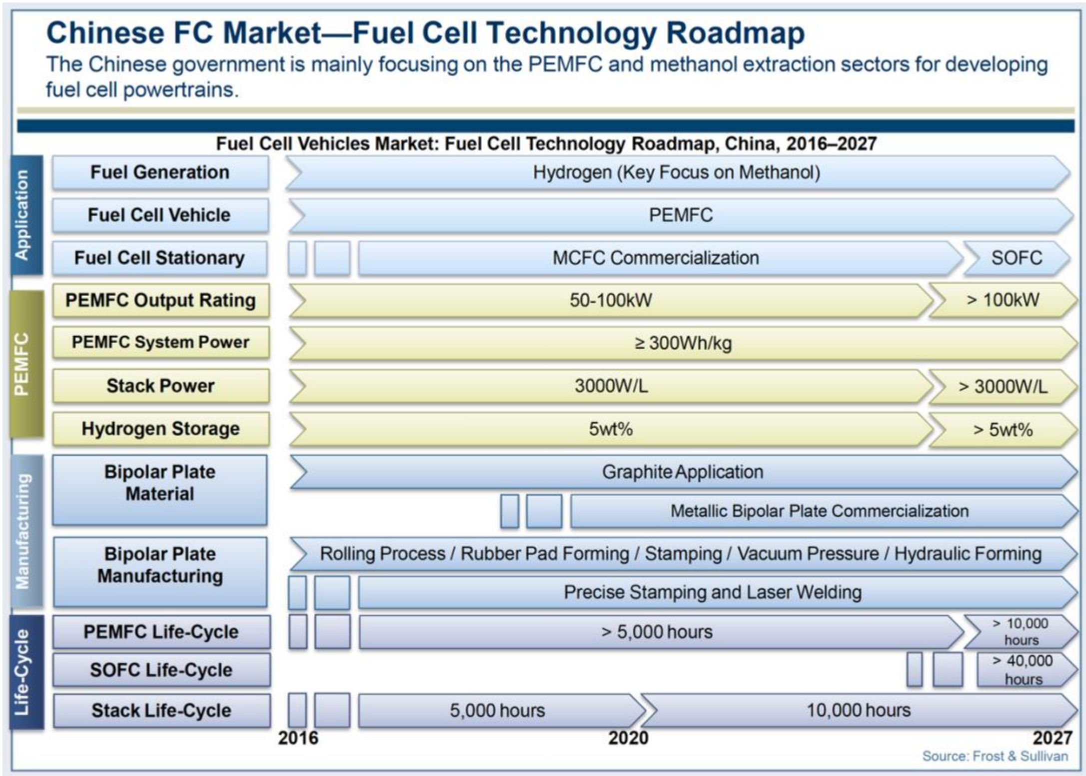
Mature to nascent

Distributed —Small units where it is needed
Semi Central—Intermediate-size hydrogen production facilities (5,000–50,000 kg/day) located in close proximity (25–100 miles) to the point of use.
Central—Large central hydrogen production facilities (750,000 kg/day)

Image Source: DOE
Source: DOE; Frost & Sullivan

FIGURE 2: Methods of Hydrogen Production[16]

As China is the second largest producer of H2 next to the U.S., the fuel cell technology roadmap for China between 2016 and 2027 is included. [17] **The major producers of H2 in China include Air Liquide (57.3% share), Air Products (34.66% share) and Linde (6.05% share).**



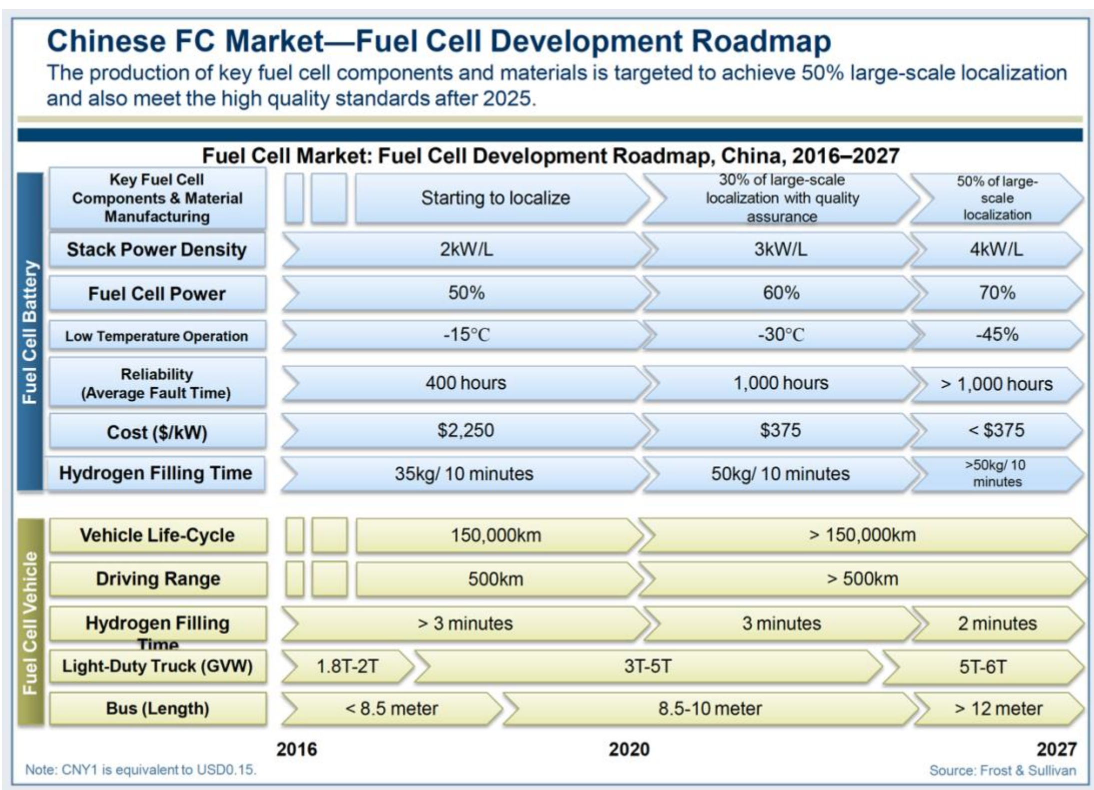


FIGURE 3: China's Fuel Cell Development Roadmap

2.2 Alkaline Electrolyzer Uses of AEM

Electrolysis is the process of using electricity to split water into hydrogen and oxygen. Like fuel cells, electrolyzers consist of an anode and cathode separated by an electrolyte. Different types of electrolyte materials can be used including polymer electrolyte membranes (PEM), alkaline electrolyzers (AEM) and solid oxide electrolyzers.

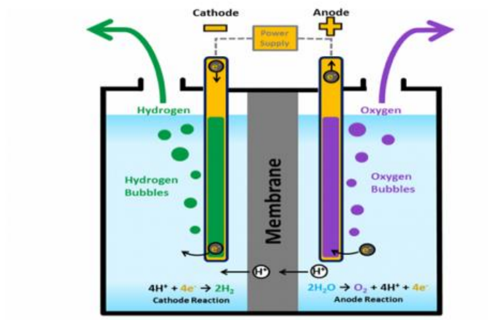


FIGURE 4: Electrolysis Process
Source Department of Energy[18]

There is the potential to use renewable energy as the source of power generation. However, according to the Department of Energy "today's grid electricity is not the ideal source of electricity for electrolysis because most of the electricity is generated using technologies that result in greenhouse gas emission and are energy intensive. Electricity generation using renewable or nuclear energy technologies, either separate from the grid, or as a growing portion of the grid mix, is a possible option to overcome these limitations for hydrogen production via electrolysis."[19] A recent report by Frost and Sullivan contrasts the performance of alkaline electrolysis, PEM electrolysis and solid oxide electrolysis[20].

Power-to-X Technology: Electrolysis Technologies, Global, 2020						
Technology	Advantages	Limitations	Efficiency	Lifetime	TRL*	Capital cost, $/kW$_{el}$
Alkaline Electrolysis	• High unit modularity • Most mature technology • Simple and robust • High reliability and durability • Possibility to operate at elevated pressure • High hydrogen production yield • Energy-efficient electrolysis	• Require high input of electrical energy • Relatively low current density • Short lifetime • High maintenance costs • Not totally appropriate for operation using transient power sources	58%-80%	90,000-100,000 hours	9	700-1,500
Polymer electrolyte Membrane (PEM) Electrolysis	• Fast start-up, shutdown, can sustain on/off cycles • Integration with RES • On-site, on-demand generation, ability to operate in part-load and overload conditions • More efficient at a high current density	• Require high input of electrical energy • Require power source • High system cost due to platinum-based family catalysts and proton exchange membrane	64%-89%	60,000-100,000 hours	7-9	900-2,500
Solid Oxide Electrolysis	• High conversion efficiency • Reduction in electric energy input • Can be used with high-temperature heat sources, such as nuclear or geothermal power	• High system cost • Technology is in demo stage • Low lifetime and reliability • Elements toxicity • Need for constant operation • Long start-up times and break-in times	90%-98%	25,000 hours	5-7	1,800-6,400

*TRL – Technology Readiness Level

Source: Frost & Sullivan

FIGURE 5: Comparative Analysis of Electrolysis Technologies[21]

The Frost and Sullivan report clarifies that

> ***Low-temperature electrolysis*** *is carried at low temperature, and hydrogen produced by electrolyzing water due to the passage of an electric current. There are two commercially available technologies, namely alkaline electrolysis (employs aqueous alkaline electrolyte) and polymer electrolyte membrane electrolysis (employs solid electrolyte).*
>
> *•**High-temperature electrolysis** is carried at high temperature, and hydrogen produced by electrolyzing steam. In this process, in addition to the electric current, some heat is used (up to 1/3rd of energy required for the production of hydrogen). Currently, solid oxide electrolysis is only one of the near-commercial high-temperature technologies.*[22]

2.3 Alkaline Battery Uses of AEM

Although both fuel cells and batteries can be used as power sources batteries store energy, rather than create it.

> *"A key operating difference between batteries and fuel cells is that batteries have a charge and a discharge cycle, while fuel cells produce electricity continuously as long as their fuel is available, Batteries are useful in applications where they can be recharged. Fuel cells are a better option when there is no way to recharge batteries…. Fuel cell can be refueled while operational, since the tank is separate. On the other hand, a battery cannot be charged and discharged simultaneously."*[23]

There are many different classes of batteries including alkaline batteries which derive energy from the reaction between zinc metal and manganese dioxide. Alkaline batteries have a higher energy density and longer shelf life, yet provide the same voltage as other batteries. **Alkaline batteries account for 80% of batteries manufactured in the U.S**. In recent years there has been increased interest in zinc-air batteries because of their energy density in combination with low-cost and the environmental friendliness of Zn, a non-toxic element[24]. Many different types of membranes are being developed and tested to improve performance including AEM.

Another alkaline battery in which AEM can be used is the alkaline-based organic redox flow battery. This type of battery is attracting significant attention because it can retain the advantages of vanadium redox flow batteries but replaces vanadium (which is expensive) with a less costly and readily synthesized organic compound. According to a recent article in the Journal of Power Sources[25] an alternative is needed to lithium-ion batteries used in stationary energy storage because of the high maintenance costs and the limited availability of lithium. Redox flow batteries have emerged as a candidate to address the sustainable energy requirements.

> In summary, the literature indicates that improved alkaline anion exchange membranes will facilitate advances not only with hydrogen **fuel cells,** but also with **alkali metal-air batteries** and with **electrolyzers.**

3.0 The Role of AEM in the ion exchange membrane market and the hydrogen market

Ion exchange membranes are widely used by industry and have many commercial uses including water purification (desalination, water softening, etc.), separation, and pre-concentration of food products and pharmaceutical products and in the manufacture of basic chemical products. However, it is important to keep in mind that there are many different types of ion exchange membranes used in these applications including (1) cation-exchange membranes, (2) amphoteric ion-exchange membranes, (3) anion exchange membranes, (4) bipolar membranes, and (5) mosaic ion-exchange membranes.[26] Anion exchange membranes currently represent a small segment of the overall ion exchange membrane market.

As anion exchange membranes can be used to generate hydrogen using an electrolysis process, **AEMs hold the promise of being more widely used in the global hydrogen production industry, as part of the "hydrogen economy." However, it is important to keep in mind that the anion exchange membrane component of the hydrogen generation market is very small and not currently cost effective.** According to an October 2020 publication by Frost and Sullivan entitled Growth Opportunities in the Hydrogen Market for the Global Power Sector:

"Progress toward the hydrogen economy is driven by the sustainability agenda that seeks to decarbonise power, transport and industry. ***However, all 71 million tons of the hydrogen produced now is based on fossil fuels (so called grey hydrogen). On current policies, grey hydrogen will account for 75%—meaning 126 million tons—of the production in 2030****. This will deliver minimal environmental benefits, and highlights the urgent need to massively increase investment in sustainable hydrogen sources.*

One option would be blue hydrogen generated from Carbon Capture Utilisation & Storage (CCUS). This would reduce overall carbon emissions, but Carbon Capture &Storage (CCS) is an energy-intensive process and the technology has struggled for commercial acceptance; *massive investment would be needed to make it a viable option. Green hydrogen is the more desirable outcome, where the hydrogen is generated from carbon-free sources. This is a focus area in Europe and could drive the next wave of investment in renewable generation in the region."*[27]

AEM manufacturers such as Evonik, see the promise that AEMs hold in a new hydrogen economy (See Figure 6). End use applications that currently used carbon-based fuels such as aircraft, ships, cars are seen as the ultimate market as well as industries that use hydrogen during production processes.

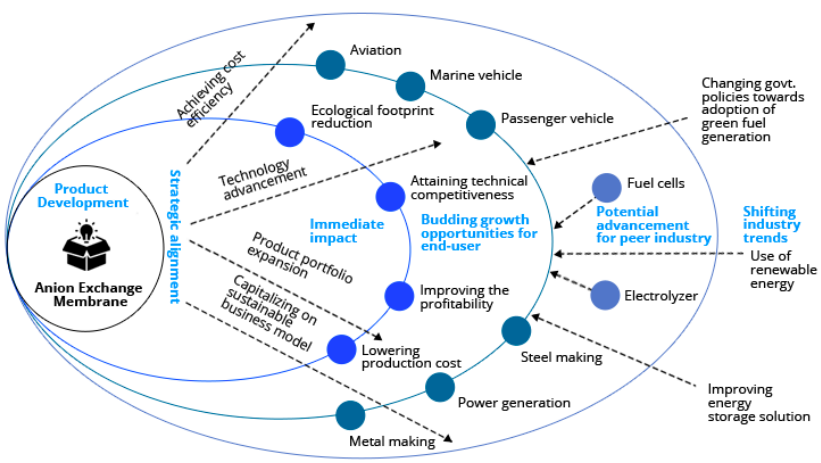


FIGURE 6: The possible impact of AEM on End-Use applications
Source: Evonik[28]

To put the role of AEM in context,[29] the following graphic represents the role that membranes play in the PEM Transport Supply Chain structure with European companies. Although a PEM membrane is used (not AEM), the graphic clearly demonstrates the integration of components and players that serve as system integrators by sub-component, subsystem and finally fuel cell integration.

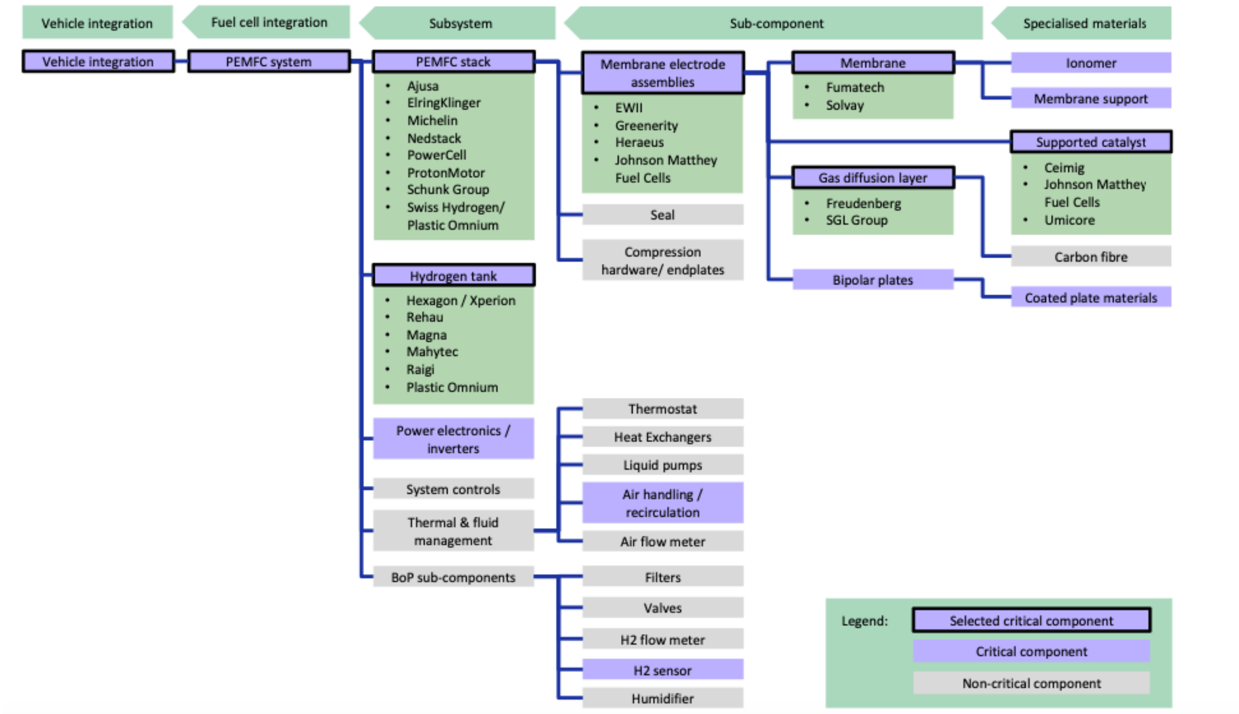
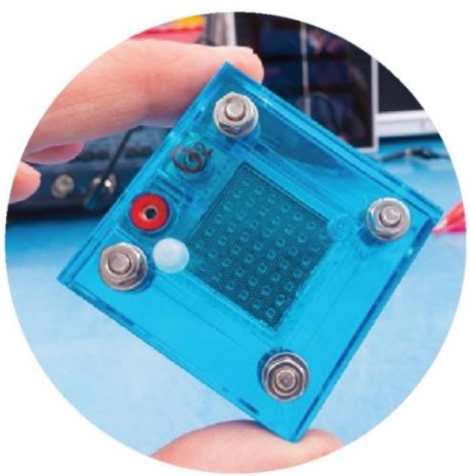


FIGURE 7: Integration of membranes into subcomponents and subsystems *Source: E4tech (UK) Ltd for FCH 2 JU in partnership with Ecorys and Strategic Analysis Inc.*[30]

3.0 The Role of AEM in the Ion Exchange Membrane Market & the Hydrogen Economy



3.1 The Role of AEM in the Electrolyzer Market

The method known as alkaline electrolysis has been in commercial use since the middle of the 20th century. It uses a cell with a cathode, an anode and an electrolyte based on a solution of caustic salts, most often KOH and NaOH electrolytes. When voltage is applied, water decomposes in the alkaline solution[31] [32]Hydrogen is formed at the cathode and oxygen at the anode. The hydrogen obtained must then be cleaned, dried and potentially compressed. The electrolyte is a liquid which adds more equipment and processes to splitting out the hydrogen

Water electrolysis is the reaction of splitting water molecules into hydrogen and oxygen. There are two main water electrolysis technologies that produce H2 at low temperatures, which can be distinguished by the electrolyte used in the electrolysis cell; Alkaline electrolysis (AE) and proton exchange membrane (PEM) electrolysis. Alkaline electrolysis is a mature technology for H2 production up to MW scale and represents the most widely used electrolytic technology on a commercial level worldwide.[33] However the use of anion exchange membranes in this application and solid oxide is relatively new and currently at the lab scale[34] [35]. The 2020 report produced by the International Renewable Energy Agency (IRENA) is a “must read” for anyone entertaining how to reduce the cost of scaling up the use of AEM membranes in this application.

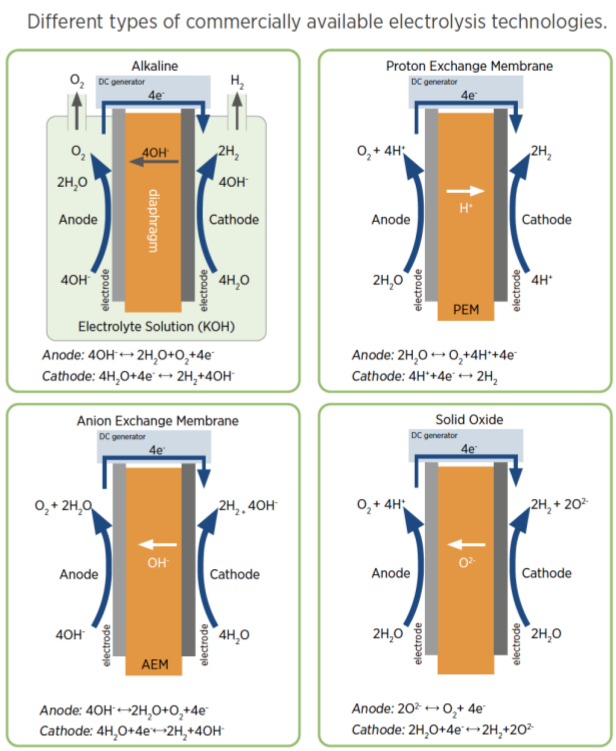


FIGURE 8: Established and new electrolysis technologies

Source: IRENA, 2020

The **Hydrogen Generation Market** report by MarketsandMarkets includes the DOE technical targets and cost contributions for hydrogen production from water electrolysis.

Table 2: Technical Targets: Distributed Water Electrolysis Hydrogen Production

Characteristics	Unit	2011 Status	2015 Target	2020 Target
Hydrogen levelized cost (production only)	USD/kg	4.2	3.9	2.3
Electrolyzer system capital cost	USD/kg	0.7	0.5	0.5
System energy efficiency	% (LHV)	67	72	75
Stack energy efficiency	% (LHV)	74	76	77

Source: MarketsandMarkets

Another promising approach is referred to as **unitized regenerative fuel cells (URFC) or reversible fuel cells.** In this system, electrochemical cells are used both as electrolyzers and fuel cells[36].

4.0 Key Players

4.0 Key Players

4.1. Companies in the U.S. Anion Exchange Market

In the U.S. a number of universities and small businesses are focused on addressing many of the technical challenges of anion exchange membranes for use in fuel cells, batteries and electrolyzers.

Table 3: Small Businesses and Universities working on AEM

Universities	Small Business
Cornell	ALCHEMR, Inc.
Georgia Institute of Technology	Amsen Technologies, LLC
Massachusetts Institute of Technology	Bettergy Corporation
New York University	Dioxide Materials, Inc
Northestern University	Ecolectro, Inc.
Penn State	Giner, Inc.
Princeton University	Innosense, LLC
Rensselaer Polytchnica Institute	Lynntech, Inc.
Stanford University	Opus 12
University of Connecticut	Precision Combustion, Inc.
University of Delaware	Storagenergy Technologies, Inc.
University of Southern California, Los Angeles	TDA Research, Inc.
Univrsity of South Carolina	Tetramer technologies, Inc.
Washington University	Versogen
	Xergy Inc.

4.2. Companies in the Global Anion Exchange Market

The largest manufacturers to date of anion exchange membranes include Shandong Tianwei Membrane Technology Company, Astom Corporation,[37] Enapter and Evonik. The largest membrane manufacturer in the U.S. for health and industrial applications is 3M which has been working with the Department of Energy for many years with funding through ARPA-E.

Shandong Tianewi Membrane Technology Company

Little information is available on this company, which some analysts list as a major supplier of AEM. According to a listing of Chinese companies,[38] this firm is backed by the **Shandong Ocean Chemical Industry Scientific Research Institute** and the **University of Science and Technology of China**. The company also is said to have financial backing from **Shandong High-tech Investment Company** and **Weifang Venture Capital Investment Company.** It is a member of the Membrane Industry Association of China, a 400+ industry association. No information is available on the size of the company. Its products are listed as homogeneous anion exchange membrane, homogeneous cation exchange membrane, diffusion dialysis devices, homogeneous membrane electrodialysis devices and bipolar membrane water electrolysis devices which are mainly used in wet metallurgy, non-ferrous metal processing, waste acid recovery, brackish water desalination, seawater concentration, chemical separation, water treatment and other fields.

Astom Corporation

ASTOM Corporation was formed through the merger of two firms: **Tokuyama Corporation** and **Asahi Kasei Corporation** and brought together their capabilities with hydrocarbon-based ion exchange membranes and electrodialysis equipment divisions. The company has developed a unique design for some of the membranes that it sells (tubular rather than flat panel). A detailed product catalog can be downloaded from this site. The end use applications that ASTOM has targeted include: salt production; food/pharmaceuticals; drinking water production; waste solution treatment; acid/alkali recovery and other applications including membranes for batteries; desalination of deep sea water.

Enapter

Enapter has its origins as an Italian company called **ACTA Spa** which specialized in research and development of fuel cells and AEM electrolysis. ACTA which was later renamed **Heliocentris** Italy entered the Alternative Investment Market of the London Stock Exchange in 2004[39]. The company had a very rocky start and eventually, after more than a decade went bankrupt. However, according to **Sebastian-Justus Schmidt,** owner of Enapter, as early as 2007 a small team of chemical engineers began to focus on alkaline water electrolysis. In an August 2020 Enapter White Paper,[40] the company describes how AEM is a game changer in the electrolysis industry and **cites P.I. Hoon T. Chung from Los Alamos National Lab who indicates that it has the potential to offer >75% stack cost reduction**[41].

> *"AEM technology produces hydrogen at high purity in cells using a solid polymeric anion exchange membrane. The stack is made up of multiple cells connect-ed in series, each of which has a cathodic half-cell separated from an anodic half-cell by an anion exchange membrane. The anodic half-cell is filled with dilute KOH (alkaline) electrolyte solution. The cathodic half-cell has no liquid and produces hydrogen by electrolysis from water that permeates through the membrane from the anodic half-cell.*
>
> *Oxygen evolves from the anodic side and is transported away by the circulat-ing electrolyte. Hydrogen is produced under pressure (typically 35 bar) and is already extremely dry and pure (~99.9%). Enapter's ancillary dryer module can increase hydrogen purity to >99.999%. As hydrogen is generated, the anodic half-cell side is topped up with purified water. Completely deionised water is not needed.*
>
> *AEM electrolysis technology is recognised by a leading independent scientific review1 and the US Department of Energy for its distinct position in the field of electrolysis2. AEM water*

electrolysis combines the advantages of PEM and TA electrolysis, making it best positioned to meet green hydrogen cost reductions."

Today, Enapter has products in 33 countries. Its AEM Electrolyser is described as a plug & play AEM electrolyser module that can turn renewable electricity and water into green hydrogen. Enapter's Electrolyzer is compact and standardized. Up to 70 electrolyzers can be stacked in a 20 foot container to create an AEM cluster. The company maintains that this configuration is ideal for refueling stations, industrial uses and for others needing large amounts of hydrogen. For more information see the **Product spec sheet.**

Evonik

Evonik, a German company, is one of the world's leading chemical companies. The company is active in more than 100 countries and in 2020 it generated sales of €12.2 billion and an operating profit (adjusted EBITDA) of €1.9 billion. Evonik employs more than 33,000 employees. The company has an interest in green hydrogen as a key raw material for the chemical industry. Researchers at the Creavis facility have developed a novel anion exchange membrane (AEM). " A consortium of highly qualified partners from industry and research organizations will plan, construct, and test an AEM electrolysis system based on the new membranes from Evonik. CHANNEL stands for **C**ost-efficient **H**ydrogen production unit based on **AN**ion**N** exchange membrane **El**ectrolysis. **The project will run for three years and will receive funding of around €2 million from the European Union's Horizon 2020 research program. In addition to Evonik, which is providing the AEM membrane, the other project partners are Shell (Netherlands; hydrogen user), Enapter (Italy; plant engineer for the electrolyzer), Forschungszentrum Jülich (Germany; R&D on membrane-electrode assemblies), the Norwegian University of Science and Technology (NTNU; catalysts), and SINTEF, an independent research organization in Norway, which is responsible for project coordination.** The consortium therefore covers the entire value chain for the production of green hydrogen."[42] For more information about this initiative, see the original request for proposals.

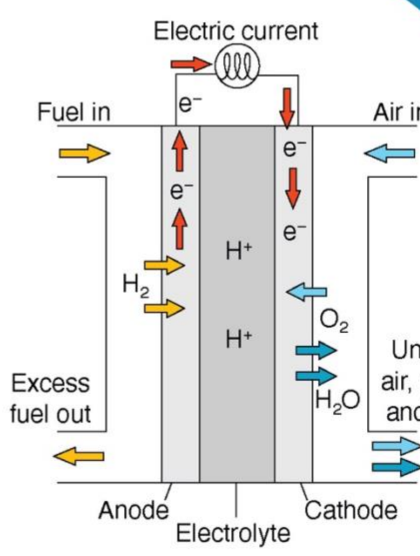
3M

3M has been actively involved with the Department of Energy conducting research on AEM since 2015. Funded research and results can be seen in DOE's annual reviews.[43] [44] [45] The following is a description of the research that 3M presented at the 2021 ARPA-E conference.

"3M will develop a new anion exchange membrane (AEM) technology with widespread applications in fuel cells, electrolyzers, and flow batteries. Unlike many proton exchange membrane (PEM) applications, the team's AEM will operate in an alkaline environment, which means lower-cost electrodes can be used. The team plans to engineer a membrane that simultaneously meets key goals for resistance, mechanical and chemical stability, and cost. They will do this by focusing on simple, hydroxide-stable polymers, such as polyethylene, and stable cations, such as tetraalkylammonium and imidazolium groups.

Positively-charged cation side chains attached to the polymer backbone will facilitate passage of hydroxide ions through the electrolyte, resulting in enhanced ionic conductivity. The proposed polymer chemistry is envisioned to be low cost and can be used in alkaline environments, and can be processed into mechanically robust membrane composites. This membrane technology has the potential to enable high volume, low-cost production of AEMs. The impact of this project can be transformational as the commercial availability of high-quality AEMs has been a limiting factor in developing AEM-based devices."

5.0 Perspectives on Near Term Opportunities for AEM



5.0 Perspectives on Near Term Opportunities for AEM

As the markets for the use of anion exchange membranes are emerging, primary market research was used to determine which applications research scientists believed were exerting the most market pull. A summary of their responses is listed in Table 4. The overall concurrence is that the strongest market pull is with water electrolysis. A cautionary notes is worth mentioning. According to the United Nations more than two billion people live in countries experiencing high water stress due to insufficient potable water. As hydrogen production using water electrolysis will require large amounts of water – it should be anticipated that a hydrogen economy will put additional stress on this resource[46].

Table 4: Market Pull Responses from the Research Community

		Where do you see Market Pull	Strongest market potential	What will it take to accelerate adoption
1	Small Business	• Water Electrolysis • CO2 Electrolysis • Fuel Cells	• Water Electrolysis	• Stop internal politics
2	Small business	• Green Hydrogen • Water Electrolysis • High Standard Commercial AEM	• Water Electrolysis	• Scale-up
3	Large business	• Water Electrolysis • Low Cost AEM • Research Communities	• Water Electrolysis • Potentially, flow batteries	• Credible PGM free performance and durability, equal to PEM. • Total system cost reduction. • No US fluoropolymer makers, limited to hydrocarbon-based ionomers. • Durability
4	Large business	• Water Electrolysis • CO2 Electrolysis • Electrochemical Reactors • industrial Water Treatment	• Water Electrolysis	• Stable AEM membrane with high iconic capacity
5	University	• Water Electrolysis • CO2 Electrolysis • Green Hydrogen	• Green Hydrogen • Water Electrolysis • CO2 Electrolysis • H2/BR storage batteries	• Industry Awareness
6	University	• Hydrogen Electrolysis	• Hydrogen Electrolysis	• Scale-up • Durability • Cannister/role-to-role design • Manufacturing • Membrane redesign
7	University	• Water Electrolysis • C02 Electrolysis • Hydrogen Fuel Cells	• Transportation Fuel Cells • Desalinators/Water Purification	• ID Optimal Ionomer Chemistries • Thermal Stability

		• Desalinators/Water Purification		
8	Small business	• Water Electrolysis • Co2 Electrolysis	• Water Electrolysis • Co2 Electrolysis	• Scale-up • Improve QC in Batch variation in commercial manufacturing • Scale up optimized synthetic procedures for high performance AEMs
9	Small business	• Water Electrolysis • Co2 Electrolysis • Desalinators/Water Purification	• Water Electrolysis	• Improve stability and activity
10	University	• Metals recovery • Electrodialysis • Fuel cells and • Water electrolyzers	• Electrolysis (assume water)	• in-cell durability
11	National Laboratory.	• Water electrolysis • Fuel Cells • Back-up power	• Water Electrolysis	• Durability • Improved C02 scrubbing • Develop C02 tolerant AEM • Improve Water management schemes

6.0 The High Temperature PEM Market

6.0 The high Temperature PEM Market

This section of the report addresses the interest in higher temperature PEM operating in three ranges (80-120C) (120-240C) and (>200C). Current perfluorosulfonic acid (PFSA) PEM membranes, such as Nafion® and Aquivion® represent the state-of-the-art, but there is a need to increase the operating temperature to improve mass transport, avoid catalyst poisoning and electrode flooding, increase efficiency, and reduce the cost and complexity of the system. However, PSFAs-based PEM membranes, such as those previously noted, exhibit lower mechanical and chemical stability, as well as proton conductivity at lower relative humidity and temperatures above 80°C.[47] BCC Research notes three key advantages of high-temperature PEM fuel cell (HTPEMFC) membranes including: (1) Higher operating temperature PEMFC operate with smaller cooling elements, which is especially good for automobile applications; (2) Higher operating temperature membranes allows for more efficient heat for PEMFC stationary applications; and (3) Higher temperature membrane is more tolerant to carbon monoxide poisoning, which reduces need for ultra-pure hydrogen feed[48]**.**

The DOE High Temperature Membrane Working Group calls out targets for automotive and stationary applications. The DOE notes that operating PEM fuel cell stacks at higher temperatures, including 120°C for transportation and 150°C for stationary applications including Combustion Heat and Power (CHP) , would yield significant energy benefits.[49]

Having looked at numerous analysts reports, current reports do not appear to segment the PEM market using HTPEMFC as a descriptor. However, that may be changing as on June 13, 2021 there was a press release for a new market research report entitled **Global High Temperature Proton Exchange Membrane (HTPEM) Market Growth 2021 – 2026**[50] . This signals that other market research firms are likely to follow. That said, it is clear from the literature that is available that solid performance at higher temperatures will allow PEM fuel cells to expand application to larger vehicles including ships, trains, aircraft, and large stationary applications. According to an April 15, 2020 Tech Snapshot[51] from Los Alamos National Laboratory the advantage of higher temperature PEM with **no humidification can lead to a reduction in radiator size, elimination of humidifying control units and enhanced reaction kinetics for iproved power performance at operatin temperatures greater than 100C.**

Figure 9 puts in perspective that PMFC is but one of the myriad of technologies that are vying to provide the best solution for applications in the fuel cell market . Alternative technologies operating in this space include **alkaline fuel cells (AFC), direct carbon fuel cells (DCFC), enzymatic biofuel cell (EFC), molten carbonate fuel cells (MCFC), protonic ceramic fuel cell (PCFC), solid acid fuel cell (SAFC) and zinc-air fuel cell (ZAFC).**

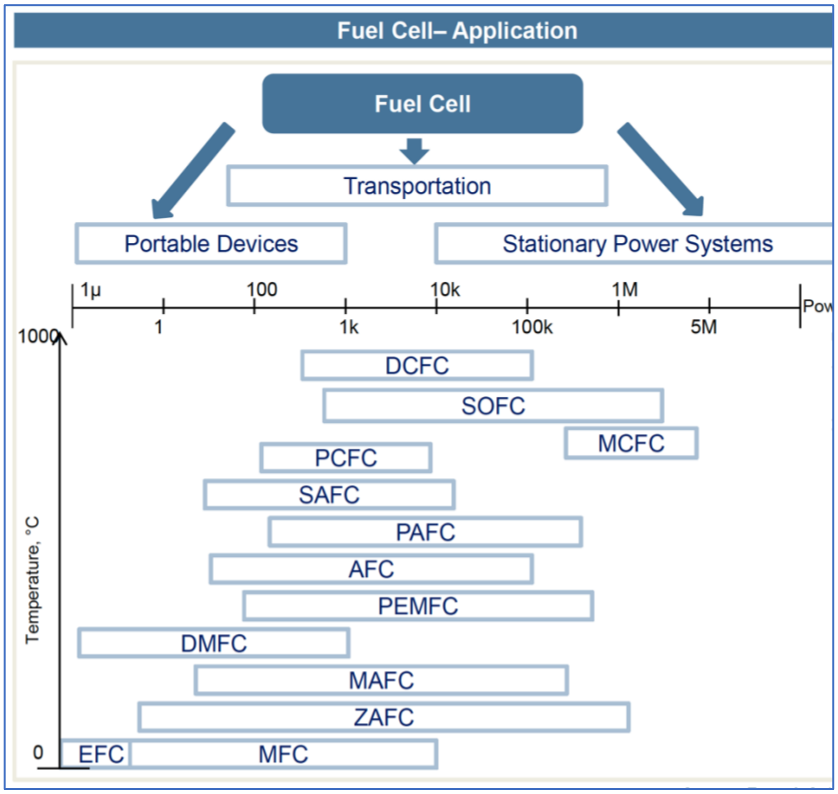


FIGURE 9: Technological Advancements and Emerging Applications of Fuel Cell[52]

6.1. Universities and Small Business Working in High Temp PEM Research

In the United States, a number of universities and small businesses are focused on addressing the technical challenges of high temperature membranes for use in fuel cells, batteries and electrolyzers. The need is for fuel cell membranes designed for operation at temperatures greater than 80°C - more specifically, ≈ 120°C for automotive applications, and for stationary applications, at T ≥150°C.

TABLE 5: Small Businesses and Universities Working on High Temp Membranes

Universities	Small Businesses
Rochester Institute of Technology	Advent Technologies Holdings, Inc.
North Dakota State University	Akron Polymer Systems, Inc.
University of North Dakota	Amsen Technologies LLC
University of South Carolina	Celadyne Technologies, Inc.
University at Buffalo	CertainTech, Inc.
University of Connecticut	FuelCell Energy, Inc.
University of Texas	Giner, Inc.
University of Texas at Austin	Ion Power
University of California at Irvine	Media and Process Technology Inc.
University of Louisiana	NanoSonic Inc.
Louisiana State University	NEI Corporation
SUNY Buffalo	Nuvant Systems, Inc.

Michigan Technological University	OxEon Energy LLC
University of Delaware	Tetramer Technologies LLC
University of Arizona	Xergy Inc.
University of Mexico (in partnership with Los Alamos National Lab (LANL))	
Northeastern University College of Science	

6.2 HTPEM Membrane Developers

This is not a comprehensive list, rather a list of those that surfaced in the development of this report.

Fumatech

Fumatech has developed high temp membrane materials with application in HTPEMFCs. The company's sources speak to two materials that can be used for this kind of technology, both of which are based on poly-benzimidazole (PBI) molecules. Fumapem® AP is the more classic PBI version and the newer one is ultra-high molecular weight fumapem® AM. Per Fumatech sources "While the fumapem® AP suits well the wet anode operation, fumapem® AM is advantageous for operation with equalized humidity on both cathode and anode side and for its superb durability against temperature above 170 °C. Both membranes feature very good thermo-durability and conductivity. Very high level of performance can be achieved with both of them over period of 3,000-20,000 hrs, depending on operational condition."[53]

HyPoint Targeting Hydrogen Aviation Market

HyPoint utilizes compressed air for both cooling and oxygen supply to deliver a high-temperature (HTPEM) fuel cell system that is three times lighter than comparable liquid-cooled low-temperature (LTPEM) fuel cell systems. The company also leverages a number of technical innovations including lightweight bipolar plates and a highly conductive, corrosion-resistant coating in order to radically outperform existing systems. Consequently, HyPoint is able to deliver up to a 50% reduction in total cost of ownership for aircraft makers; allowing them to create practical, cost-effective zero-emission vehicles. For more on HyPoint's approach, one can review the company's recently released white paper, at detailed in a newly-released Technical White Paper. Per the source, HyPoint is developing relationships with major eAircraft and eVTOL (including air taxi and cargo drone), manufacturers, and has secured nearly $2M in R&D contracts. Company sources offer the following LTPEM and HTPEM comparison table:

TABLE 7: Comparison of HTPEM and LTPEM
Source: HyPoint[54]

Parameter	LTPEM	HTPEM	Comments
Temperature Range	≤ 80°C	140–180°C	Even broader range for shorter periods of time. Easy to cool in any environmental conditions.
Electrolyte	Water	Phosphoric acid	
Humidity control	Critical	Unnecessary	HTPEM permits short overheating → more reliable in an emergency
Impurity Tolerance	CO: ppm levels	CO: several percent	HTPEM is more tolerant of other impurities as well, all resulting in a lower operational cost.
Membrane chemistry	Fluorocarbon → higher cost	Hydrocarbon → lower cost	Lower capital cost
Durability	5000–10000 h	5000–20000 h	20,000 hours achieved in a lab
Stack design	Standard	Simplified	No gas humidification, simpler cooling system

Blue World Technologies & Clayton Power: HTPEM for Stationary and APU Applications

May 2021 data indicates that Blue World Technologies and Clayton Power have joined forces to develop a small-scale mobile methanol fuel cell solution for auxiliary power and stationary applications. Their goal is to develop a solution in the 5 to 15-kilowatt power range. The methanol fuel cell solution represents a combination of Blue World Technologies proprietary high-temperature proton exchange membrane (HTPEM) technology, and Clayton Powers lithium-ion battery solution, to provide an instant- and continuous power supply. The project effort is supported by Danish Energy Agency through the EUDP (Danish Energy Technology Development and Demonstration Program) and includes Aalborg University as a key knowledge partner. The ultimate goal is to develop a compact, flexible, and modular solution in the power range between 5-15kW making it perfect for installation onboard heavy-duty trucks. The solution would allow trucks to generate silent and vibration-free energy powering appliances (air conditioning, TV, microwave, refrigeration and other equipment) during vehicle stops. Moreover, the solution could also be used as a portable/mobile generator supplying power beyond the grid for tools and equipment at construction sites, telecommunication sites, remote medical facilities, and other off-grid needs. Sources indicate that the fuel cell power unit has zero particle emission and has a net-zero carbon operation when powered with methanol from renewable sources.[55]

Advent Technologies

U.S. based Advent Technologies Holdings, Inc. develops, manufactures, and assembles critical components for fuel cells and advanced energy systems in the renewable energy sector. The company is headquartered in Boston, Massachusetts, with offices in the San Francisco Bay Area and Europe. Advent Technologies holds over 120 patents issued (or pending) for its fuel cell technology, and also holds the IP for next-generation high-temperature proton exchange membranes (HT-PEM) that enable various fuels to function at high temperatures under extreme conditions, with application in automotive, maritime, aviation, and power generation sectors.[56]

HTPEMFC Partnership: Advent, LANL, BNL and NREL

According to April 2021 revealed a new partnership comprising Los Alamos National Laboratory, Advent Technology Holdings Inc., Brookhaven National Laboratory, and the National Renewable Energy Laboratory (NREL), toward the development over the next few years to bring to HTPEMFCs to market. Per the source, HTPEMFCs have potential to revolutionize the heavy-duty transportation industry; allowing ships to run on renewable methanol or ammonia, airplanes to run on dimethyl ether or hydrogen, and off-grid power generators to work with low- or zero-carbon fuels that are easily transportable to remote locations. The project received funding from the DOE's Hydrogen and Fuel Cell Technologies Office, through the L'Innovator ("Lab Innovator") Pilot Program.[57]

SerEnergy

SerEnergy provides fully integrated power generator solutions based on the HTPEM fuel cell technology.[58] This private Denmark based company was established in 2006. SerEnergy designs, manufactures and sells HTPEMFC stacks and fuel cell power modules for system integrators. Moreover, sources suggest the world's first piloted aircraft capable of taking off using only power from a fuel cell system, the Antares DLR-H2, was powered by Serenergy fuel cells.[59]

Research on PBI-Based PEMS for HTFC: Current Status and Prospects

Authors from North Dakota State University and the Energy & Environmental Research Center at University of North Dakota, released the following report in Dec. 2020 "Polybenzimidazole-Based Polymer Electrolyte Membranes for High-Temperature Fuel Cells: Current Status and Prospects." Per the report, the authors conclude that integration of acid-doped PBI membranes into fuel cell devices is expected to grow rapidly. The integration supports HTPEMFCs, offering key advantages over Nafion® and other membranes based on hydrated polymers. The operating temperatures of acid-doped PBI membranes are much higher, and therefore provide several advantages relating CO tolerance of catalyst layers, and more. The source notes that substantial efforts have been dedicated to the investigation on PBI membranes, which has led to breakthroughs for PEMFCs, and highlights of research in this space are provided.

LANL & HTPEMFC Electrode Composition

2020 data indicates that researchers at Los Alamos National Laboratory (LANL) have developed an HTPEMFC electrode composition that improves fuel cell performance under anhydrous conditions above 100 °C. The solution has demonstrated great durability in humidified conditions under 100 °C as well. The technology holds promise for use in fuel cells for heavy duty vehicles while retaining utility for portable and stationary power applications. LANL research believe that in coming years this flexibility may be a breakthrough improvement over conventional compositions. Specific to market opportunities, LANL sources note potential for vehicle applications, marine and dockside power as well.[60]

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