Liquid Gas for Fuel Cells

Sustainable, Clean, and Silent Power Generation

SUSTAINABLE GROWTH & INNOVATION - DECEMBER 2023

WLPGA

LPG EXCEPTIONAL ENERGY

The World LPG Association

The World LPG Association (WLPGA) promotes the use of LPG to foster a safer, cleaner, healthier and more prosperous world. WLPGA is the authoritative voice of the global LPG industry and represents the full LPG value chain. The WLPGA brings together over 300 private and public companies operating in more than 125 countries involved in one, several or all activities of the industry; develops long-term partnerships with international organisations; and implements projects on local and global scales. The association was established in 1987 and granted Special Consultative Status with the United Nations Economic and Social Council in 1989.

The WLPGA mission statement forms the four principal goals of the WLPGA in the current period, namely Advocacy, to advocate LPG as part of the solution to future energy challenges; Safety & Business Improvement, to support safe, efficient, and responsible business; Sustainable Growth and Innovation, to encourage sustainable growth and innovation in the business and Communications to effectively communicate and raise awareness of LPG.

Acknowledgments

This report has been developed by the Innovation & Technology Network of WLPGA.

There could be views expressed in this document that are not necessarily shared by all contributors.

Key contributors:

George Nikolaou, NaTco/Liquid Gas Europe
Nikos Xydas from WLPGA coordinated this project.

Disclaimer

Liquid Gas

for

Fuel Cells

Sustainable, Clean, and Silent
Power Generation

Contents Page

Introduction

The aim of this report is to promote understanding amongst the LPG industry and beyond of the technical possibilities, applications, and market potential of Liquid Gas for fuel cells. Ultimately, the goal is to inform the LPG community of the numerous opportunities in the various related segments, current developments in the technology of fuel cell market technology general advances with Liquid Gas, and actions to be taken by the LPG industry.

The main objective, besides giving a bird's-eye view snapshot of the fuel cell market as a whole, is to present the role of Liquid Gas in the fuel cell market and potential synergies and to serve as a starting point for discussions and decisions about Liquid Gas and fuel cell technology.

This report contains:

- **Chapter One** provides an overview of the various fuel cell technologies, main manufacturers, and main fuel cell market applications.
- **Chapter Two** provides selective case studies of Liquid Gas fuel cell market applications.
- **Chapter Three** provides a roadmap with a technology overview, identifies barriers, and explores market opportunities for Liquid Gas fuel cells. Finally, it provides high-level recommendations to stakeholders.

Executive Summary

The world today is in an era of unprecedented change, where protecting the environment is a global concern. The LPG industry envisions a future where it can meet growing energy demands in an environmentally sustainable way.

Liquid Gas fuel cells are an area of interest and research and are portrayed as an answer to the world's urgent need for alternative and clean energy solutions. The integration of Liquid Gas into fuel cell technology has the potential to offer a number of benefits, including reduced emissions, improved efficiency and versatility in various applications.

Key drivers fostering the expansion of Liquid Gas fuel cell technology based on trends up to that point:

- **Clean Energy Demand and Climate Change Mitigation Goals**: Increasing global awareness of environmental issues and the demand for cleaner energy alternatives drive interest in Liquid Gas fuel cells as they offer a low-emission option, contributing to sustainability goals and reducing the carbon footprint.
- **Regional Adoption and Policies:** The adoption of Liquid Gas fuel cells may be influenced by regional energy policies, incentives, and regulations. Supportive policies and clean energy targets, can incentivise businesses and consumers to adopt Liquid Gas fuel cell technologies. The regulatory landscape will play a crucial role in shaping the market trajectory.
- **Advancements in Fuel Cell Technology:** Continued advancements in fuel cell technology, including proton exchange membrane (PEM) and solid oxide fuel cells (SOFCs), contribute to the growth of the Liquid Gas fuel cell market. Improvements in efficiency, durability, and cost-effectiveness will play a crucial role in making Liquid Gas fuel cells more competitive with other power generation technologies.
- **Energy Security, Resilience and Global Events:** Liquid Gas fuel cells enhance energy security by providing decentralised power generation. This is crucial in regions prone to power outages or those seeking greater energy resilience. Applications in critical infrastructure and emergency services benefit from reliable backup power. Unexpected events such as natural disasters, pandemics, or geopolitical shifts can have ripple effects on energy markets, including Liquid Gas. These events can influence supply chains, market dynamics, and investment decisions.
- **Versatility in Applications:** The versatility of Liquid Gas fuel cells allows them to be employed in various applications, including stationary power generation, backup power, combined heat and power (CHP) systems, and off-grid scenarios. This broad range of applications increases their market potential.
- **Economic Viability:** The economic feasibility of Liquid Gas fuel cells, including factors such as system costs, operational efficiency, and maintenance requirements, contributes to their growth.
- **Lack of adequate hydrogen infrastructure**: While the lack of hydrogen infrastructure may present challenges for hydrogen fuel cells, it opens doors for Liquid Gas fuel cells. These opportunities can contribute to a more diverse and flexible energy landscape, particularly in regions where hydrogen infrastructure is not yet fully developed.
- **Integration with Renewable LPG:** The integration of renewable LPG, produced from sustainable sources or through advanced processes, further enhances the environmental credentials of Liquid Gas fuel cells.

Other advantages of Liquid Gas fuel cells include: high energy density, silent operation, lack of moving parts that frequently wear out or break down and robust design making them operate in the harshest conditions.

Factors hampering the growth of Liquid Gas fuel cells:

- **Cost Considerations:** The initial cost of Liquid Gas fuel cell systems and related components such as catalysts are relatively high. High upfront costs are a barrier to adoption, especially in markets where cost-effectiveness is a significant factor in decision-making.

- **Scaling Issues:** Scaling up the production and deployment of Liquid Gas fuel cell systems to meet increasing demand can be a logistical challenge. Issues related to mass production, supply chain management, and economies of scale need to be addressed for widespread adoption.
- **Limited Awareness and Education:** Lack of awareness and understanding about Liquid Gas fuel cells among consumers, businesses, and policymakers impedes their adoption.
- **Technological Challenges:** Despite advancements, there may still be technological challenges in terms of the efficiency, durability, and performance of Liquid Gas fuel cells.
- **The European Chemicals Agency (ECHA) is soon planning to ban polyfluoroalkyl substances (PFAS).** This ban would have destructive effects on the fuel cell industry and could also jeopardise the Liquid Gas fuel cell market growth.

Liquid Gas has an energy density (46.4 MJ kg^{-1}, 22.8 MJ l^{-1}) and can be reformed to hydrogen at 200°C to 350°C. Liquid Gas is in a gas state at standard temperature and pressure, but it can be more easily compressed, stored, and transported as it is liquid at a pressure of about 10 bars.

A fuel cell generates electricity by using two electrodes, a cathode, and an anode, to pass charged ions through an electrolyte. The electrolyte conducts ions but not electricity. The electricity resulting from this process is thus freed and conducted to the electric load via an external circuit. As Liquid Gas fuel cells generate electricity through chemical reactions rather than combustion, they can achieve much higher efficiency than traditional power generation methods such as steam turbines and internal combustion engines.

Working Principles of Fuel Cells

The most important fuel cell types are shown in Figure 1, along with the points of origin of the reaction products on the anode or cathode side and the direction and type of ion transport through the electrolyte. Between them, the various fuel cell types cover a wide temperature range. Low operating temperatures allow for a dynamic load response, while high temperatures favour continuous loads. In addition, the electrolytes of the high-temperature fuel cells are more resistant to impurities and to variations in fuel quality.

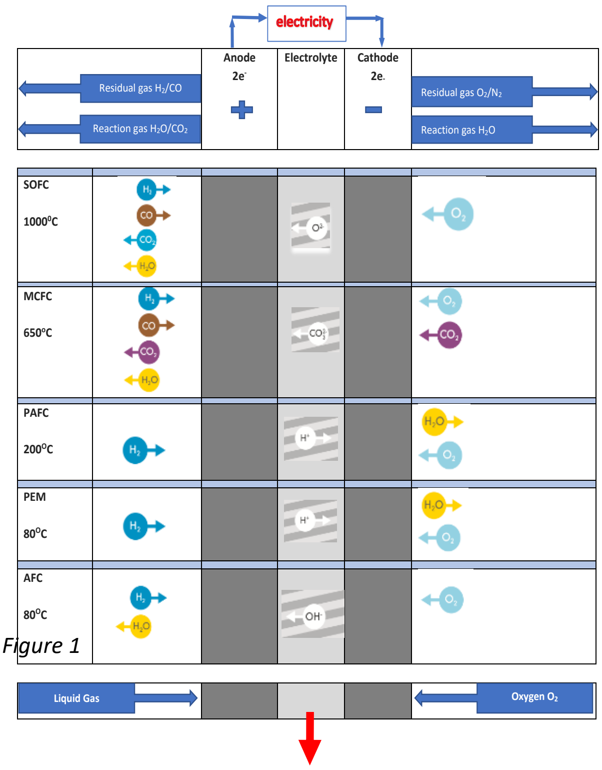


Figure 1

In PEMFC and PAFC, the water that occurs is drawn off at the cathode. In the case of the AFC and the high-temperature SOFC and MCFC cells, by contrast, the reaction products of the fuels supplied on the anode side leave the cell again on the same side. A special feature of the AFC is that it gives off product water via the electrolyte, causing the electrolyte to be diluted.

Air, or pure oxygen, is supplied at the cathode as an oxidant. Correspondingly, nitrogen and oxygen occur as residual gases at the cathode outlet. The fuel for the fuel cell can either be used directly in the fuel cell or prepared from various hydrogen-rich intermediates, such as Liquid Gas, via reforming. Depending on the operating temperature, reforming takes place internally or externally.

The number of fuel cell manufacturers is growing, with many of them already manufacturing Liquid Gas fuel cells, such as MTU CFU Solution, Ansaldo Fuel Cell, Helbio SA, Sunfire, Kyocera, Ishikawajima-Harima Heavy Industries, Technology Management, Inc. (TMI), GenCell, Adaptive Energy, Atrex Energy, H-Power Corp., IdaTech, ENEOS, Panasonic etc.
Liquid Gas could achieve a great market share in the fuel cell market as it provides a readily available source of power for remote facilities, installations, and residences away from the electricity grid that lack access to a natural gas network and have a need for a reliable or higher quality electric service. Currently, many of these potential customers generate onsite power using reciprocating engine generators and sometimes must finance transmission line extensions, which can be very costly to avoid power shortages. Besides electricity, the only by-products a fuel cell generates are water and useful heat. When fuel cells are sited near the point of energy use, heat can be captured for heating, called combined heat and power [CHP] or cogeneration, or even cooling and refrigeration, resulting in system efficiencies of 90% or greater. CHP allows users to reduce or eliminate the need for boilers or water heaters and their associated costs and emissions. There are many cases around the world where Liquid Gas fuel cells have been successfully implemented in different markets, such as railways, telecom, oil and gas, critical operations, and electric power generation.

Liquid Gas is key in accelerating clean energy fuel cell technology and is a promising alternative energy source for diverse applications. The ability to combine multiple units in parallel allows fuel cell power generator systems to handle varying load requirements.

The adoption of Liquid Gas fuel cells may depend on factors such as cost, efficiency, and local infrastructure. Additionally, advancements in fuel cell technology and the availability of rLPG can further enhance the environmental sustainability of these applications. The potential market opportunities for Liquid Gas fuel cells, which were briefly touched upon in the report, can be subdivided into the following:

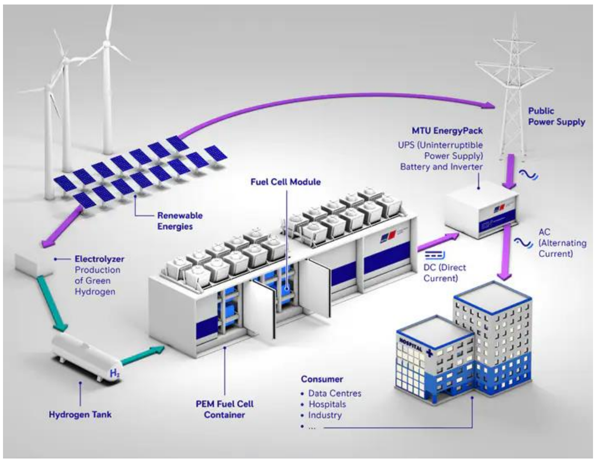
- **Residential and small scale combined heat and power (CHP):** Liquid Gas can fuel cells can be used in residential settings for CHP applications. These systems provide both electricity and heat for space heating or water heating, offering high efficiency and potential energy cost savings for homeowners.
- **Backup Power Systems**: Liquid Gas fuel cells can be used as backup power systems for critical infrastructure, such as data centres, hospitals, and other facilities. They provide a reliable source of power during grid outages.
- **Auxiliary Power Units (APU)s**: APUs provide onboard electricity and heat in various applications. APUs are secondary power sources, typically used in vehicles, aircraft, and other mobile or stationary settings, to supply electricity, heat, or air conditioning independently of the main power source.
- **Commercial and Industrial CHP:** Liquid fuel cells can be integrated into CHP systems to provide electricity and heat for various processes.
- **Remote and Off Grid Areas:** In remote or off-grid areas where access to conventional power sources is limited, Liquid Gas fuel cells can serve as a reliable and independent power solution. This includes applications in remote telecommunications towers, research stations, or rural electrification projects.
- **Telecommunication Infrastructure:** Liquid Gas fuel cells are used to provide backup power for telecommunication towers in areas with unreliable grid power. The reliable and continuous power supply is crucial for maintaining communication services.
- **Forklifts or Material Handling Vehicles**: Liquid Gas fuel cells can be integrated into material handling equipment, such as forklifts and warehouse vehicles. This application offers advantages over traditional lead-acid batteries, including faster refuelling times and longer operating hours.
- **Recreational Vehicles (RVs) and Boats**: Liquid Gas fuel cells can be employed in RVs and boats as a clean and efficient power source for on-board electrical systems. They offer a quieter and more environmentally friendly alternative to traditional generators.
- **Portable Power Systems:** Portable Liquid Gas fuel cells are used for various applications, such as camping, outdoor events, and emergency situations. These compact systems provide a convenient and clean power source in locations without access to traditional electricity.

- SOFC technology with Liquid Gas is available for deployment today, and as tested in various cases they have high reliability, low maintenance costs after continuous operation, and a more ecological approach when combined with renewable sources such as solar or wind.

BioLPG and r-DME create strong potential for the future cell market.

Liquid Gas can effectively overcome many of the key obstacles facing hydrogen today, like availability, fuelling infrastructure, and price, and serve as the key stepping stone.

The engagement of manufacturers, industry associations, and other players can be instrumental in driving growth in the market; helping products commercialise and raising consumer and policy-maker awareness. Initiatives and projects will have a positive impact on Liquid Gas fuel cells, helping product concepts to reach commercialisation, raising the profile with policymakers and end-users, and ensuring the inclusion of technologies in regulations and incentive schemes.



Source: Rolls-Royce's Power Systems

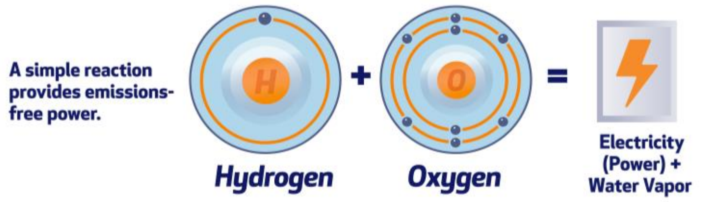
While the Liquid Gas fuel cell market growth is currently slow, continued research and the rapid pace of development will create a vibrant market for fuel cells. There is no doubt that the prospects for fuel cells as a replacement for traditional fossil fuels are generally very good, even if the acceptance of this good and innovative technology is still in its infancy. The LPG industry can play a critical role in ensuring that development efforts include Liquid Gas fuel cells to shape the market and set the stage for the industry's future success. As the huge investments in the development of fuel cells by both governments and the private sector show, the market potential is enormous, and Liquid Gas can secure a share of this market.

Chapter One

This section of the report examines the major types of fuel cells and explores fuel reformer technology and its major applications in different market segments.

1.1. The fuel cell principle

A fuel cell is a device that generates electricity through the reverse electrolysis chemical reaction, in which hydrogen and oxygen react to produce water and electricity. The fuel for fuel cells is hydrogen and oxygen. Hydrogen can be a gas from water electrolysis or produced by reforming Liquid Gas, while oxygen is taken in from the atmosphere. As it generates electricity, the fuel cell also produces heat at the same time through the chemical reactions of hydrogen and oxygen, without burning fuel. There are many opportunities for its commercialisation in a diverse range of applications as a new, highly efficient energy system.



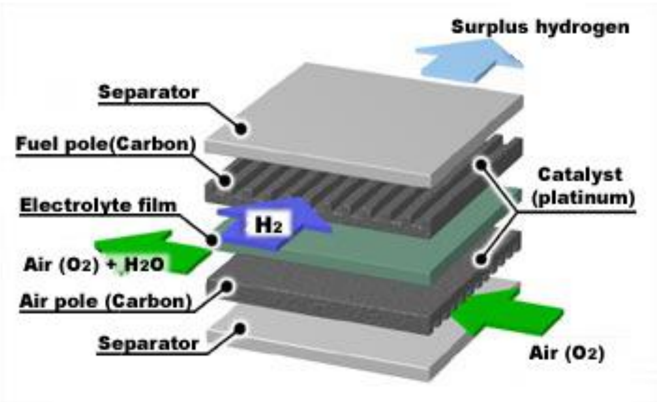
Source: CHFCA

Basic fuel cell structure

The component unit of a fuel cell is called a "cell" or "unit cell." Similar to a flat dry-cell battery, a fuel cell consists of a cathode (air electrode) and an anode (fuel electrode), as well as a thin plastic sheet (electrolyte) placed between the two electrodes.

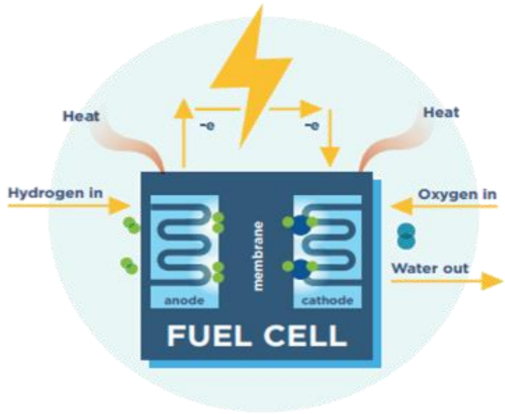
Mechanism of a fuel cell

A fuel cell consists of an electrolyte between two electrodes and a conducting wire linking the two electrodes. Hydrogen fed to one electrode (the fuel electrode) divides into hydrogen ions and electrons on the electrode. Hydrogen ions flow through the electrolyte to the other electrode, to which air is fed (the air electrode). Electrons flow from the fuel electrode to the air electrode through the conducting wire linking the two electrodes. At this time, the electrical current flows in the opposite direction. At the air electrode, the hydrogen ions react with the oxygen and electrons to produce water and heat. As there are no moving parts, fuel cells operate silently and with extremely high reliability.



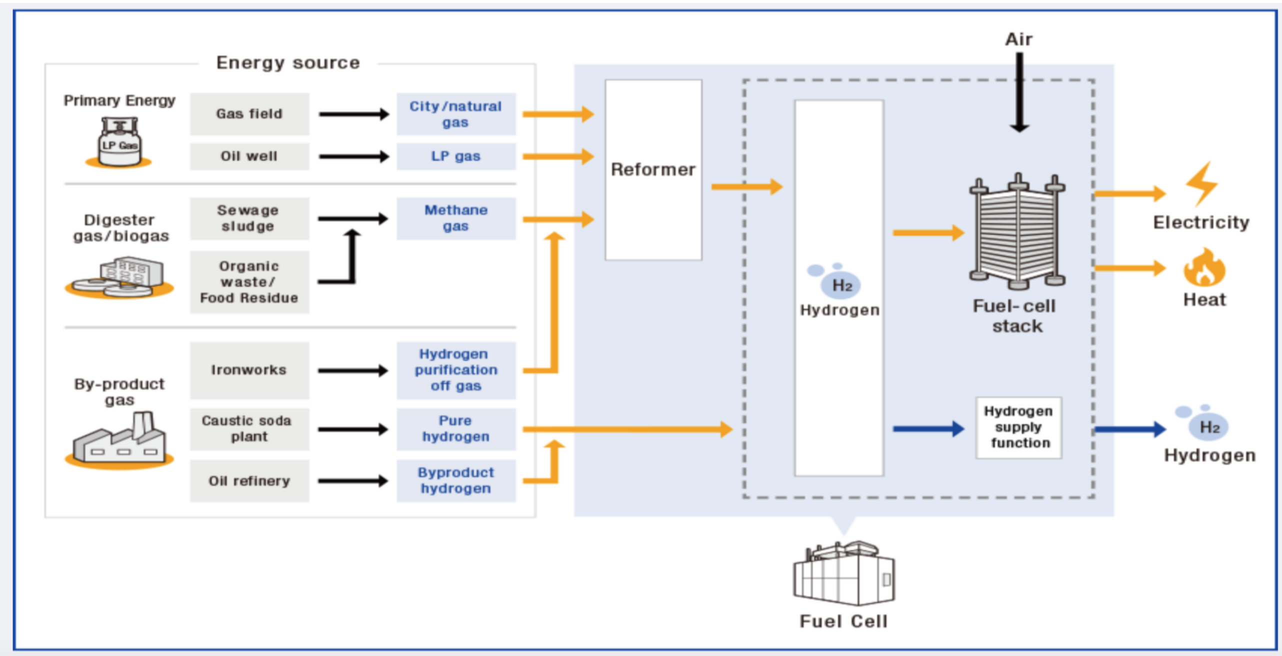
Source: Fuel Cell Commercialisation

- The hydrogen atoms enter at the anode.
- The atoms are stripped of their electrons in the anode.
- The positively charged protons pass through the mebrane to the cathode and the negatively charged electrons are forced through a circuit, generating electricity.
- After passing through the circuit , the electrons combine with the protons and oxyden from the air to generate the fuel cell's byproducts: water and heat.



Source: Fuel Cell and Hydrogen Association

Fuel cells are operable with multiple sources of energy, such as Liquid Gas, digester gas, and biogas



Source: www.fujielectric.com

1.2. Driving Forces for Liquid Gas Fuel Cells

The demand for Liquid Gas fuel cells will increase due to various laws and regulations on carbon emissions. Low emissions, excellent efficiency, fuel flexibility, energy security, durability, scalability, and silent operation are all advantages of this technology.

Advantages of Liquid Gas Fuel Cells

- **Robust design:** This can be beneficial when operated in harsh environments. They are compact and occupy minimal space.
- **Low Noise and Vibration:** Liquid gas fuel cells, operate with low noise levels and minimal vibration. This characteristic is advantageous for applications where quiet and smooth operation is desirable, such as in residential and commercial settings.
- **Longer Operating Life:** Liquid Gas fuel cells can have a longer operating life compared to some other power generation technologies. This is due to the absence of moving parts and the electrochemical nature of the energy conversion process.
- **Fuel Security:** Liquid Gas is a storable and transportable fuel, providing a degree of energy security. The ability to store Liquid Gas for extended periods without degradation makes it suitable for backup power applications and emergency situations.
- **Remote monitoring and control:** For many models, this saves users time and money by not having to travel to the site.
- **Fuel availability:** Liquid Gas is a widely available and easily accessible fuel. The existing infrastructure for Liquid Gas distribution can be leveraged for fuel cell applications, making it convenient for various industries and applications.
- **Modular Design:** Many Liquid Gas fuel cell systems are designed with modularity in mind. This allows for scalability, enabling users to install systems of varying sizes to meet specific power demands. The modular design makes Liquid Gas fuel cells adaptable to a range of applications with different energy requirements. Individual fuel cells can be joined with one another to form stacks. In turn, these stacks can be combined into larger systems.
- **Excellent efficiency:** No combustion is required to create electricity, which is therefore more efficient and delivers more usable energy for the same amount of fuel.
- **Lower operational costs:** Compared to batteries and internal combustion generators, fuel cells save money. They eliminate the need to change, charge, and manage batteries, subsequently reducing labour, time, space, and peak power demands. The units run longer than lead-acid batteries and can be fuelled in as little as three minutes, substantially reducing vehicle and personnel downtime.
- **Higher Energy Density:** Liquid Gas has a higher energy density compared to many other fuels. This means that a relatively small volume of Liquid Gas can contain a significant amount of energy, contributing to the overall efficiency of the fuel cell.
- **Temperature tolerance:** Fuel cells do not degrade a high temperature and their range can be between - 40°C and +50°C without any cooling required.
- **Low Operating Temperatures:** Some types of Liquid Gas fuel cells operate at lower temperatures compared to certain other fuel cell technologies. Lower operating temperatures can contribute to higher efficiency and reduced energy losses.
- **Reduced Greenhouse Gas Emissions:** Liquid Gas fuel cells, when using Liquid Gas derived from renewable sources can contribute to lower greenhouse gas emissions compared to traditional combustion-based power generation methods. The electrochemical conversion process in fuel cells produces electricity with minimal emissions of air pollutants.

- **Quick Start-Up and Response:** Liquid Gas fuel cells can have relatively quick start-up times, allowing for rapid response to changes in electricity demand. This characteristic makes them suitable for applications where flexibility in power generation is important.
- **Reliability and Longevity:** With proper maintenance, Liquid Gas fuel cells can offer reliable and long-lasting operation. This is important for applications requiring consistent and uninterrupted power supply.

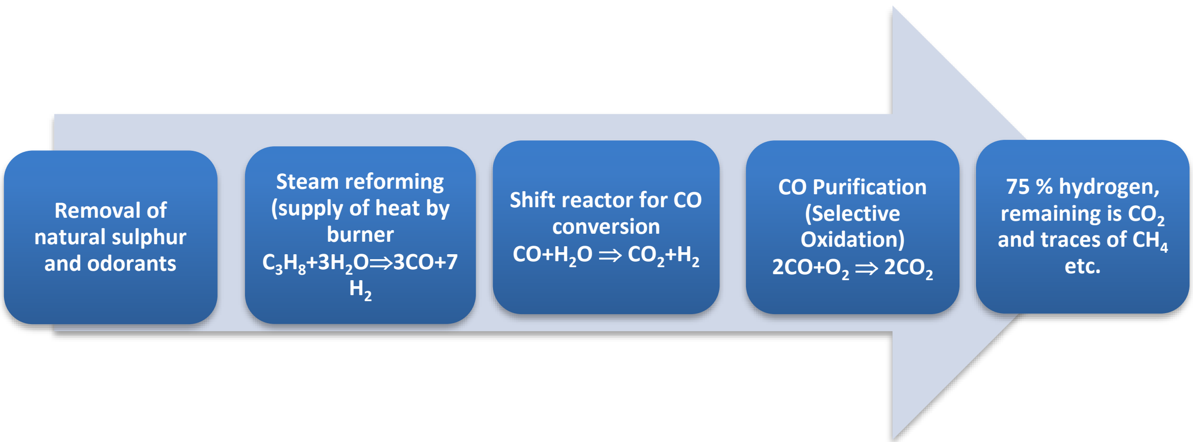
These benefits collectively make Liquid Gas fuel cells an attractive and environmentally friendly option for power generation in various applications, offering a balance between efficiency, versatility, and reduced environmental impact. It's important to consider that the specific benefits of Liquid Gas fuel cells can depend on factors such as the type of fuel cell technology used, the application, and the infrastructure.

1.3. Reforming Liquid Gas to Hydrogen

Liquid Gas can be steam-reformed to hydrogen. The emissions from this process can be reduced by capturing and permanently storing the CO_2 coming from the Steam Reforming (SR) process. During the SR process, high-pressure steam (H_2O) reacts with Liquid Gas and produces hydrogen (H_2) and CO_2. In this hydrogen-making process, the CO_2 can be captured and transported to geological storage sites either onshore or offshore. An estimated 71%-92% of CO_2 produced during the process can be captured and stored (CCS) thereby lowering the emissions from hydrogen production.

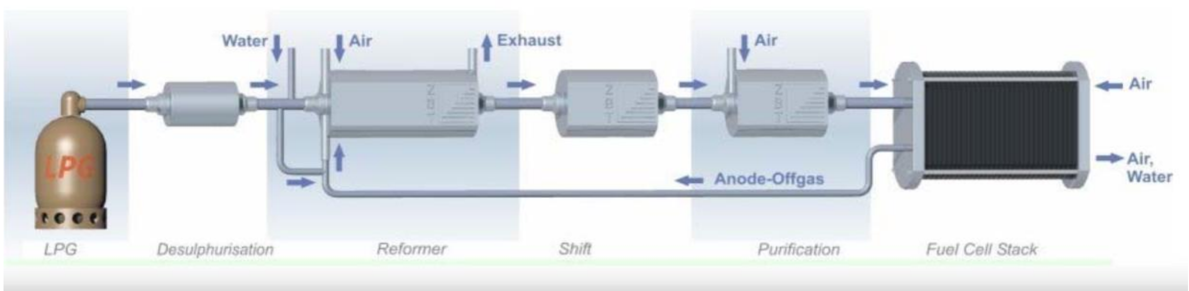
Liquid Gas can be steam-reformed to hydrogen, albeit at milder temperatures of 200°C to 350°C. The lower temperatures reduce the energy requirement, and hence the carbon footprint, for producing hydrogen from Liquid Gas. Converting Liquid Gas to hydrogen provides a way to capture these carbon dioxide emissions at the source. When the hydrogen product of an SR is purified, the main impurity is carbon dioxide. This is captured at the source, and the carbon dioxide can then be sold into the commodity carbon dioxide market for use in carbonated beverages and refrigeration. There are other uses for the carbon dioxide, but it could be pumped back into the ground and sequestered.

Process of reforming Liquid Gas into hydrogen



Hydrogen rich gas is used energetically in a fuel cell stack.

- The remaining gas (Off Gas) is re-fed to the burner of the reformer (approx. 45% H2, 45% CO_2, 3% CH4, 7% N2)
- Gas process efficiency is ~75% using Liquid Gas in the burner and about 90% using the off-gas from the fuel cell stack.

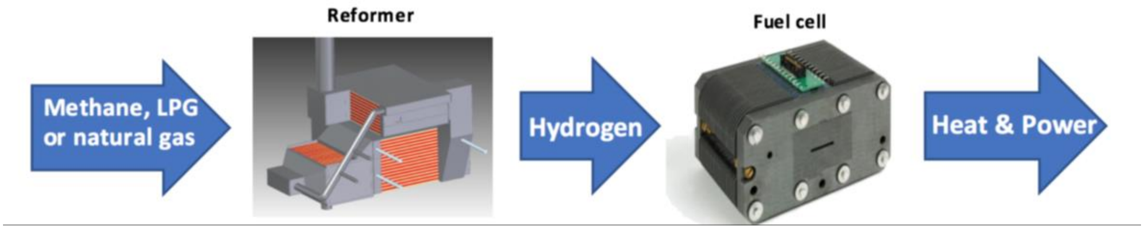


Source: zbt-duisburg

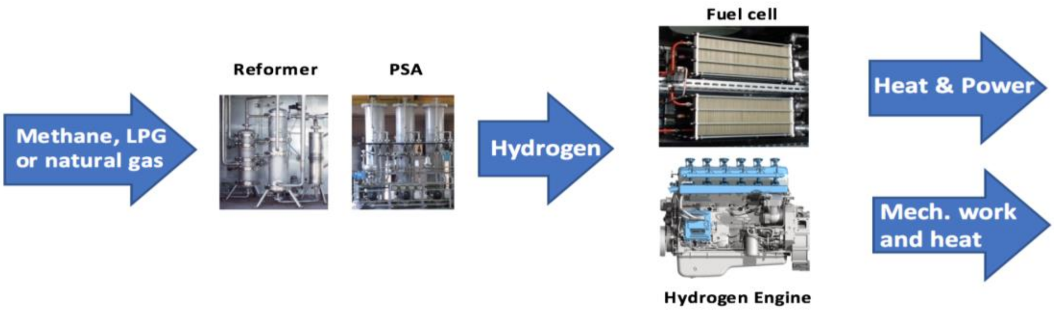
Reformers and Energy Systems of two basic designs

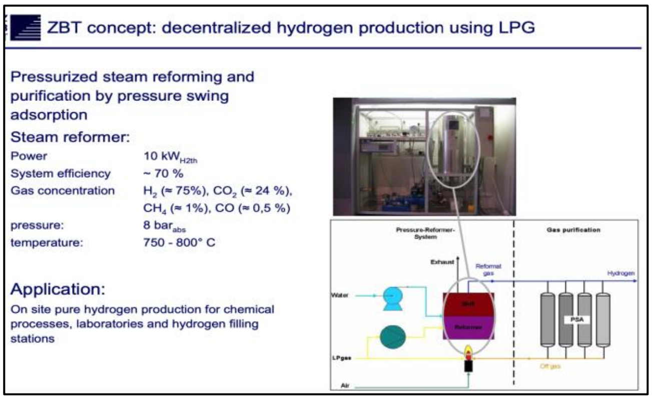
Reformers are provided in two different configurations, adapted for different types of fuel cells and market segments but based on the same principle of catalytic, flame-less steam reforming:

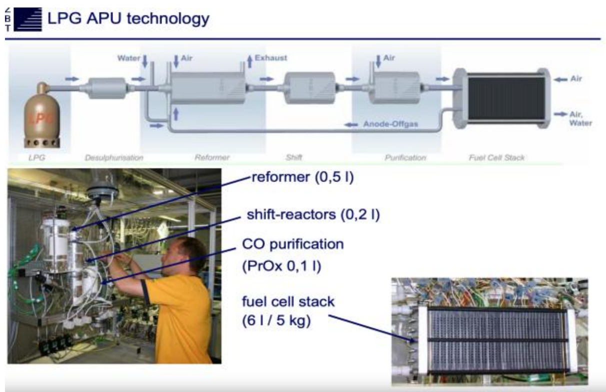
Compact plate design for mass-produced consumer products, primarily for Combined Heat and Power (CHP) systems in the power range of 1-5 KW electrical power and secondly for power units and battery charges, known as Auxiliary Power Units (APU). In this embodiment, the reformer works under low pressure and can be integrated with fuel cells powered by the generated reformate, i.e., hydrogen, where CO is removed but CO is allowed to pass through both the reformer and the fuel cell.



Tubular design for hydrogen processors with a capacity of 10-500 Nm3/h, where the application requirements are very high for the purity of the hydrogen. The reformer operates under 8-10 bar pressure, which enables efficient purification up to 99.999%, in so–called PSA (Pressure Swing Adsorption). With this combination of technologies, hydrogen of the required quality can be offered to industrial processes, CHP-systems, as fuel for fuel cell vehicles (passenger, cars, buses, trucks, forklifts, ships, trains, etc.) and for hydrogen powered combustion engines.







Source: eZelleron GmbH Group Exhibit Hydrogen + Fuel Cells

1.4. Fuel Cell Technologies

A variety of fuel cell types are available, and their names reflect the materials used in the electrolyte membrane. The properties of the membrane affect the permissible operating temperature, the nature of electrochemical reactions, and fuel purity requirements. Depending on the fuel cell type, an electrical efficiency of 50–55% is achieved. Some fuel cell types operate at high temperatures, enabling heat recovery and an increased electrical efficiency of about 60%. High-temperature fuel cell types such as Solid Oxide Fuel Cells (SOFC) run on Liquid Gas but low-temperature fuel cells such as Proton Exchange Membrane (PEM) need hydrogen as fuel. If hydrogen is not used directly for a PEM fuel cell, a reforming stage using Liquid Gas needs to be deployed upstream to produce hydrogen. Fuel cells with low operational temperatures are more tolerant of dynamic load variations than high temperature fuel cells.

1.4.1. Phosphoric Acid Fuel Cell (PAFC)

The Phosphoric Acid Fuel Cell (PAFC) was the first fuel cell with higher temperatures, operating at temperatures up to 200°C. The increased temperature means that the excess heat from the fuel cell is of such a quality that it can be utilised, increasing the overall efficiency of the fuel cell from around 40% (electrical efficiency) up to 80%.

PAFCs can utilise hydrogen-rich fuels, and LPG (propane or butane) is one of the potential fuels for these cells. The reforming of LPG into hydrogen-rich gas is typically done in a separate reformer unit before feeding it into the fuel cell stack.

PAFC has an electrolyte of phosphoric acid in a silicon carbide structure and electrodes made of platinum dispersed on carbon, a schematic presentation of this is given in Figure 2.

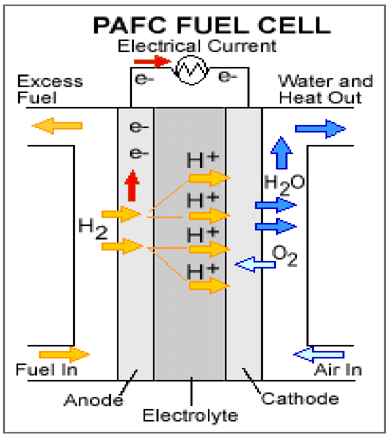


Figure 2: Schematic of a PAFC

The electrode reactions are the following:

Anode reaction: $2H_2 \rightarrow 4H^+ + 4e^-$

Cathode reaction: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$

Total reaction: $2H_2 + O_2 \rightarrow 2H_2O$

Due to the higher temperatures, other fuel sources than pure hydrogen can be used. This includes Liquid Gas. Liquid Gas needs to be reformed at a separate stage before the PAFC. A PAFC system for the use of Liquid Gas would include both a reformer and a heat recovery system (Figure 3).

In a PAFC the heat recovery system will typically be a steam turbine. The reforming will be a steam reforming that converts Liquid Gas to carbon monoxide, CH_4, and hydrogen. Steam reforming of Liquid Gas can be represented by the following endothermic reactions.

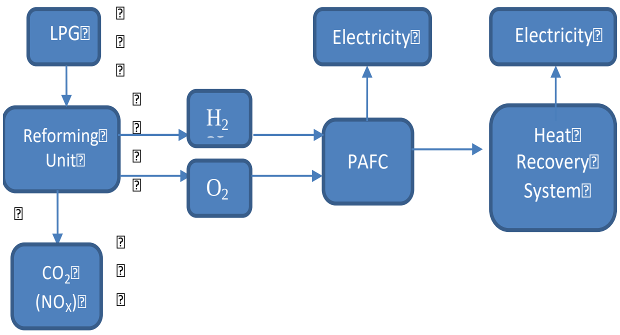


Figure 3: Flow chart of a PAFC fuel cell

Steam reforming:

$C_3H_8 + 3H_2O \rightarrow 3CO + 7H_2$ $\Delta H^o = 498$ kJ/mol

$C_4H_{10} + 4H_2O \rightarrow 4CO + 9H_2$ $\Delta H^o = 650$ kJ/mol

which are accompanied by the moderately exothermic and thermodynamically limited water-gas-shift (WGS) reaction for further converting to CO_2 and more hydrogen:

$CO + H_2O \leftrightarrow CO_2 + H_2$ $\Delta H^o = -41.1$ kJ/mol

Benefits and Challenges

The efficiency of the PAFC itself is relatively low, around 40%, but including heat recovery, the efficiency can be as high as 80%. The higher temperature in the PAFC also makes it less sensitive to CO poisoning and other contaminants than other fuel cells using platinum catalysts. The system has a low power density and will thus be large and heavy. The moderate temperature makes start-up slower than for low-temperature fuel cells, but the PAFC is less prone to the negative effects of cycling than the higher-temperature fuel cells. PAFC efficiency is only slightly higher than that of combustion-based power plants, which typically operate at around 33% efficiency. PAFCs are also less powerful than other fuel cells, given the same weight and volume. As a result, these fuel cells are typically large and heavy. PAFCs are also expensive. They require much higher loadings of expensive platinum catalysts than other types of fuel cells do, which raises the cost.

Applications

PAFCs are typically used in a cogeneration mode to not only produce electricity but also heat that can be captured to assist heating and cooling. PAFCs are often seen in high-energy demand applications, such as hospitals, schools and manufacturing and processing centres. PAFCs have been used for stationary power generators with output in the 100 kW to 400 kW range and are also finding application in large vehicles such as buses.

Major manufacturers include:

- Doosan Fuel Cell America Inc.
- Fuji Electric.
- DRDO (India) with PAFC based air-independent propulsion for integration into Kalvari-class submarines.

Source: *PureCell System 400 CEP*

1.4.2. Molten Carbonate Fuel Cell (MCFC)

Molten Carbonate fuel cells (MCFC), Figure 4, use high-temperature compounds of salt (like sodium or magnesium) carbonates (chemically, CO_3) as the electrolyte. Efficiency ranges from 60-80%, and the operating temperature is about 650 degrees C. Units with outputs up to 2 megawatts (MW) have been constructed, and designs exist for units up to 100 MW. The anode is normally a nickel alloy, and the cathode is normally nickel oxide with lithium incorporated into the structure.

This high temperature allows MCFCs to utilise non-platinum catalysts through a process called ‘internal reforming, decreasing overall system cost. The high temperature makes the MCFC flexible in terms of the choice of fuel such as Liquid Gas. A reforming unit is not needed, as the reforming occurs in the fuel cell itself. Using hydrocarbons leads to CO_2 emissions. As no air is present where the reforming takes place at the anode, the reforming is

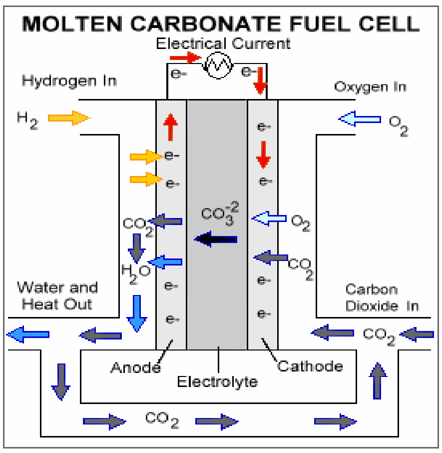


Figure 4: Schematic of a MCFC

not a source for NO_x emissions, but the subsequent heat and energy recovery systems have the potential for some NO_x emissions.

Fuel cell reactions

Anode reaction: $2H_2 + 2CO_3^{2-} \rightarrow 2H_2O + 2CO_2 + 4e^-$

Cathode reaction: $O_2 + 2CO_2 + 4e^- \rightarrow 2CO_3^{2-}$

Total reaction for fuel cell: $2H_2 + O_2 \rightarrow 2H_2O$

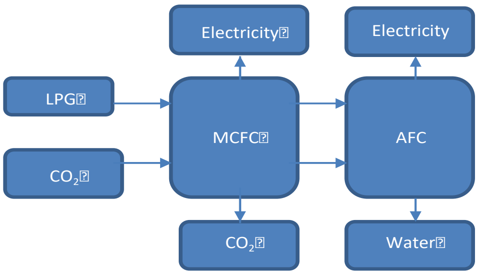


Figure 5: Flow chart for a MCFC

MCFC is suitable for a heat recovery system. The flue gases can be used in an afterburner or a gas turbine, and more energy can be extracted in a steam turbine. The electrical efficiency is around 50%, but the total efficiency of an MCFC can be as high as 85%. A flowchart for a MCFC using Liquid Gas is given in Figure 5.

Benefits and Challenges

The MCFC is a highly efficient fuel cell, with a low-cost catalyst and electrolyte and high flexibility towards fuels and contaminants. The high temperature makes it suitable for energy recovery systems, but it also makes it vulnerable to negative cycling effects like corrosion and cracking of components. The MCFC has a slow start-up and is less flexible towards changing power demands than low temperature fuel cells.

The primary disadvantage of current MCFC technology is durability. The high temperatures at which these cells operate, and the corrosive electrolyte used accelerate component breakdown and corrosion, decreasing cell life.

The MCFCs are likely to occupy the same market segment as SOFCs. They run slightly cooler at 650°C, making their combination with a gas turbine less simple, but the operating temperature could be raised if necessary. Whether this would bring about material problems is an important issue. The primary difference between the MCFC and the SOFC is the need for CO_2 recirculation in the MCFC system, meaning that it is difficult to design one below about 250 KW. This removes the market for domestic-scale power.

Source: Fuel Cell Energy

Applications

These fuel cells are typically deployed in stationary applications, providing high-quality primary and back-up power to utilities and businesses. Molten carbonate fuel cells (MCFCs) are currently being developed for natural gas and coal-based power plants for electrical utility, industrial, and military applications.

1.4.3. Solid Acid Fuel Cell (SOFC)

Solid Acid Fuel Cells (SOFCs) use a hard, ceramic compound of metal (like calcium or zirconium) oxides (chemically, O_2) as an electrolyte. SOFCs can achieve electrical efficiencies of 50% to 60% and 70-80% in CHP applications, and operating temperatures are about 1,000°C. Cell output is up to 100 kW. At such high temperatures, a reformer is not required to extract hydrogen from the fuel, and waste heat can be recycled to make additional electricity. However, the high-temperature limits applications of SOFC units, and they tend to be rather large. While solid electrolytes cannot leak, they can crack. A schematic representation of a SOFC is given in Figure 6.

The SOFC shows the same flexibility towards fuels, such as Liquid Gas. The reforming to syngas (hydrogen and carbon monoxide) occurs within the fuel cell. Unlike the MCFC, the SOFC does not require CO_2 to be added at the cathode. This is the reaction that happens in the SOFC:

Steam reforming: $CH_4 + H_2O \rightarrow CO + 3H_2$

Water-gas-shift: $CO + H_2O \rightarrow CO_2 + H_2$

Total reaction from reforming: $CH + 2H\ O \rightarrow CO + 4H_2$

Fuel cell reactions

Anode reaction: $2H_2 + 2O^{2-} \rightarrow 2H_2O + 4e^-$

Cathode reaction: $O_2 + 4e^- \rightarrow 2O^{2-}$

Total reaction for fuel cell: $2H_2 + O_2 \rightarrow 2H_2O$

A flowchart for a SOFC using Liquid Gas is given in Figure 8. The electrical efficiency of a SOFC is high, about 60%, but can be increased to as high as 85% or higher if a heat recovery system is applied.

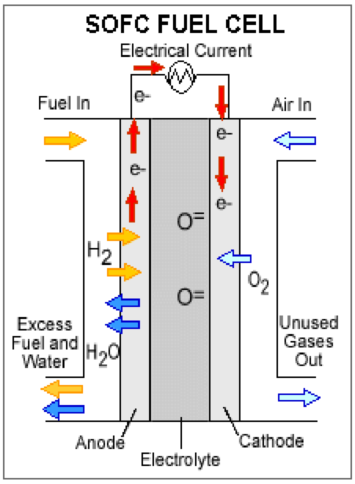


Figure 6: Schematic of a SOFC

There are two possible geometries for SOFCs: planar and tubular. In a planer SFOC (Figure 7), each cell is a flat plate, with each component of the cell laid upon each other. The tubular SOFC (Figure 7), is formed as a tube, with one electrode being the inner tube and the outer tube being the other electrode, and the electrolyte between them. Even though the tubular SOFC is more stable for thermal cycling, the planar SOFC is considered the more favourable design due to its higher energy density and the fact that it is easier to produce. Combining SOFCs with batteries will reduce thermal strain and ensure a more flexible operation.

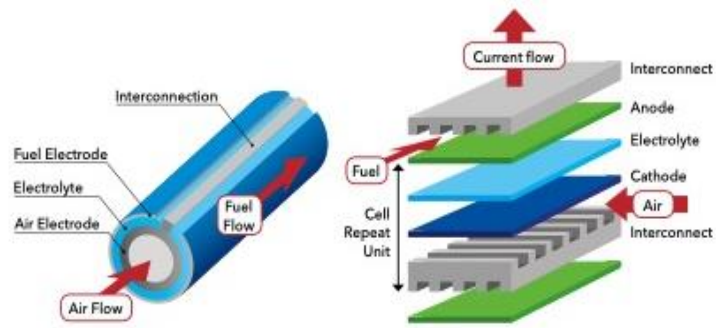


Figure 7: Cell structure of tubular (A) and planar B solid oxide fuel cell

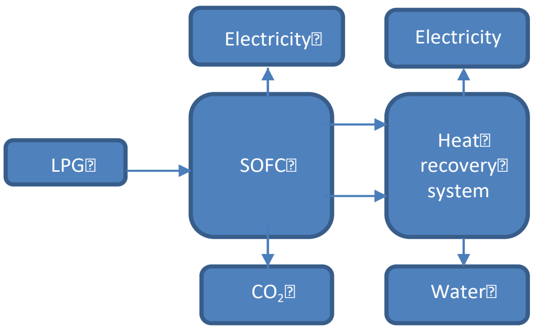


Figure 8: Flow Chart for a SOFC

Benefits and Challenges

SPFCs have high power density, rapid start-up, and low-temperature operation, making them ideal for use in transport and battery replacement, among other things. They are currently expensive, as is any technology in the initial phase, but the synergies that may be derived from the automotive mass-manufacture of many SPFC components could bring the price down well below that of competing alternatives.

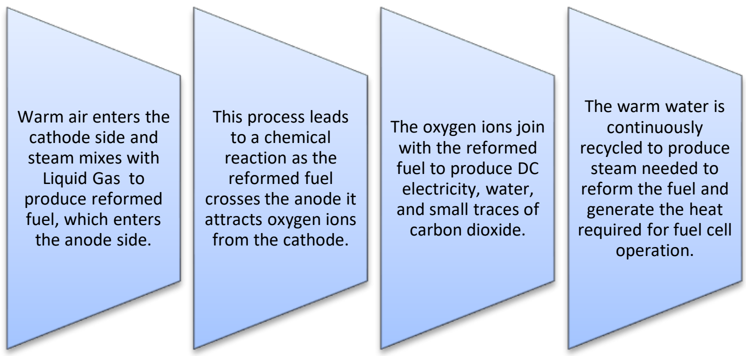
Applications

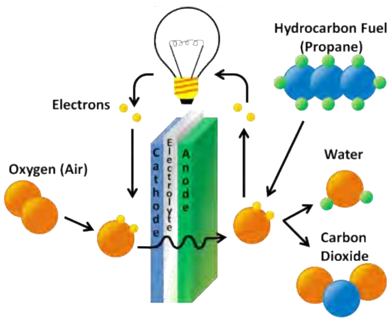
SOFCs operate at high temperatures and therefore lend themselves to applications in which this high-temperature heat can be used. This heat can be used in two basic ways, for heating processes such as those in industry or possibly in homes, or for integration with turbines for additional electricity production. SOFCs are generally used in large-scale power production on shore, with capacities of up to 10 MW. Specific applications in which SOFCs may be used are in decentralised electricity generation of 250 KW to 30 MW; industrial cogeneration of 1-30 MW; or domestic applications of close to 5 KW. As mentioned previously, high-temperature fuel cells are also flexible in their fuelling, which may make them a good future choice for locations without dedicated natural gas grids. Several projects have been looking into SOFCs for maritime use. SOFCs are being used in a range of applications, from small residential auxiliary power units supplying heat and power to homes to large-scale stationary power generators for larger buildings and businesses.

Source: Bloomenergy

Liquid Gas SOFC operation

A SOFC is an electrochemical reaction device that converts fuel and air into electricity without combustion. A SOFC is comprised of three parts: an electrolyte, an anode, and a cathode. The electrolyte is a solid ceramic material, and the anode and cathode parts feature coatings of electrolyte.





Solid oxide fuel cells produce electricity through the movement of electrons

A solid oxide fuel cell utilises the movement of electrons and generates electricity in a few basic steps.

- Liquid Gas goes through a steam-reforming process. This chemical reaction produces hydrogen (H2), carbon monoxide (CO), carbon dioxide (CO_2), and steam (H2O). There will be some unreformed natural gas left in the mix as well.
- The mix of elements from the reformer enters the fuel cell at the anode side. Meanwhile, air (including oxygen) enters the fuel cell at the cathode side.
- Oxygen in the air combines with free electrons to form oxide ions at the cathode. Oxide ions with free electrons

travel from the cathode to the anode through the electrolyte.

- At the anode, oxide ions react with hydrogen to form water (steam) and with carbon monoxide (CO) forming carbon dioxide (CO_2).
- Reactions covered in the previous step release free electrons. These free electrons travel to the cathode through the external electrical circuit, producing electricity.

Applications for key alternative energy uses

- Uninterruptible power for critical transportation infrastructure, such as railway crossings, signals and switches.
- Hybrid off-grid power (including solar, wind, or other renewables) for remote applications like back-country radio networks or aviation and weather-monitoring equipment.
- Reliable uptimes for solar-powered trailers that provide mobile surveillance, environmental monitoring, communications, and other critical functions.
- Power production in case harsh weather interrupts production.

Manufacturers

- Adaptive Energy
- Sunfire
- Watt
- Upstart
- Redox
- h2e Power

Case Study

Adaptive Energy's Performer Series P250i is a Liquid Gas-powered solid oxide fuel cell that provides low-watt backup or off-grid power in remote, harsh conditions. It integrates with wind, solar, or other alternative technologies because of its fuel efficiency. One 20-pound Liquid Gas tank provides eight hours of runtime. The P250i can operate in temperatures ranging from minus 40 degrees C to 50 degrees C, so it excels in extreme cold. It is highly durable due to the proprietary microtubular stack that provides built-in redundancy. These benefits, plus the availability of Liquid Gas make the P250i ideal for off-grid locations where fuel must be airlifted.

Sunfire-Remote

SUNFIRE REMOTE
Off-grid power
for remote infrastructures

Sunfire-Home

SUNFIRE HOME
Clean electricity and heat
for single-family homes

1.4.4. Other Fuel Cell Technologies that can use Liquid Gas

1.4.4.1. Alkaline Fuel Cell

The alkaline fuel cell has a long history in space programmes, primarily because it was the first to be sufficiently developed. Alkaline fuel cells operate on compressed hydrogen and oxygen. They generally use a solution of potassium hydroxide (chemically, KOH) in water as their electrolyte (Figure 8). Efficiency is about 70%, and the operating temperature is 150 to 200 degrees. Cell output ranges from 300 watts (W) to 5 kilowatts (kW). The AFC consists normally of a nickel anode, a silver cathode, and an alkaline electrolyte. The fuel is hydrogen (H_2), and oxygen (O_2), and hydroxide (OH-), are transported through the electrolyte from the cathode to the anode. The hydrogen and oxygen need to be pure to avoid degradation of the AFC. See Figure 9 below for a schematic of an AFC, and Figure 10 for a flow chart for the AFC process.

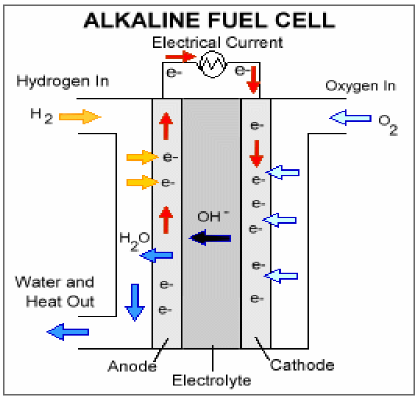


Figure 9: Schematic of an AFC

The AFC consumes hydrogen and oxygen and produces energy and water. On the NASA space shuttle, the AFC was also used as a source of water and heat. The main reactions that are occurring are the following:

Anode reaction: $2H_2 + 4OH^- \rightarrow 4H_2O + 4e^-$

Cathode reaction: $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$

Total reaction: $2H_2 + O_2 \rightarrow 2H_2O$

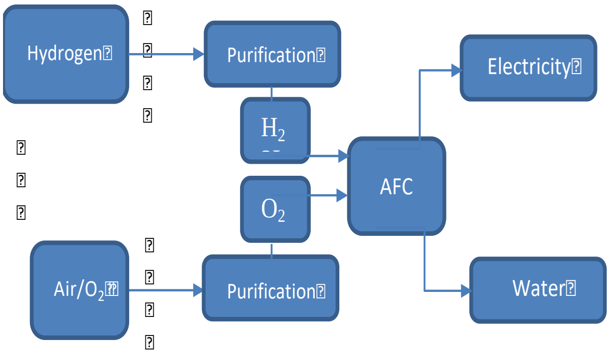


Figure 10: Flow chart of an alkaline fuel cell

Benefits and Challenges

AFC is a low-cost fuel cell with low-cost catalysts and readily available electrolytes. It can operate at room temperature, which is beneficial from a safety perspective but also ensures that the requirements for the material used are less stringent and less expensive. The operation of the AFC is flexible, and a cold start is possible. Water is the only by-product of the AFC, no other emissions. The AFC has a moderate efficiency, 50-60%, and no need for fuel reforming or heat recovery systems. The major concern for the AFC is CO_2 poisoning. CO_2 in the fuel will react with the alkaline electrolyte, reducing the efficiency and eventually leading to precipitation and blocking of the cell by potassium carbonate.

$2KOH + CO_2 \rightarrow K_2CO_3 + H_2O$

Because of this, the AFC requires pure oxygen and pure hydrogen to function in an optimal range over a prolonged period. If air is to be used, removing CO_2 is necessary, and other fuels than hydrogen is not recommended as long as substantial purification is performed before injection into the AFC.

Applications

The AFC is one of the most efficient types of fuel cells, with a potential of 60% electrical efficiency and 80% to 90% in CHP applications. AFCs use hydrogen as a fuel source, though they are highly sensitive and can fail when exposed to carbon dioxide, which is why they are primarily used in controlled aerospace and underwater applications. The first fuel cell driven passenger ship, the Hydra, was driven by a 5 kW AFC.

1.4.4.2. Direct Methanol Fuel Cell (DMFC)

DMFCs use a polymer membrane as an electrolyte and, commonly, a platinum catalyst as well. The DCFC uses methanol directly without prior reforming to hydrogen. The DMFC has a polymer membrane electrolyte. The electrodes have a platinum-ruthenium catalyst that can directly utilise the hydrogen in methanol (CH_3OH) to generate electricity. A schematic of the DMFC is given in Figure 11.

DMFC is generally good for delivering a small amount of electricity over a prolonged period of time, and power outputs of up to 5 KW are the norm. The DMFC normally operates between 50 and 120 °C. Higher temperatures and pressures can increase cell efficiency, but they will also lead to higher overall losses in the system, so the benefit is lost.

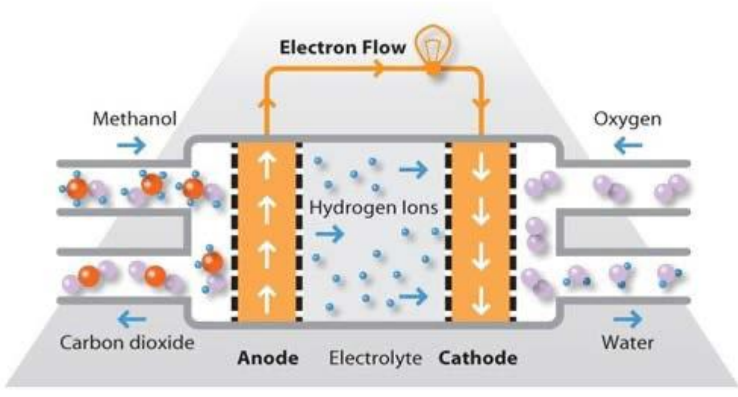


Figure 11: Schematic of a DMFC

The DMFC uses a weak methanol in water solution (3%) as fuel. As methanol is the fuel, the oxidation at the anode leads to CO_2 emissions. The main reactions in the DMFC are:

Anode reaction: $CH_3OH+2H_2O \rightarrow 6H^+ + CO_2 + 6e^-$

Cathode reaction: $3/2O_2 + 6H^+ + 6e^- \rightarrow 3H_2O$

Total reaction: $CH_3OH + 3/2\ O_2 \rightarrow CO_2 + 2H_2O$

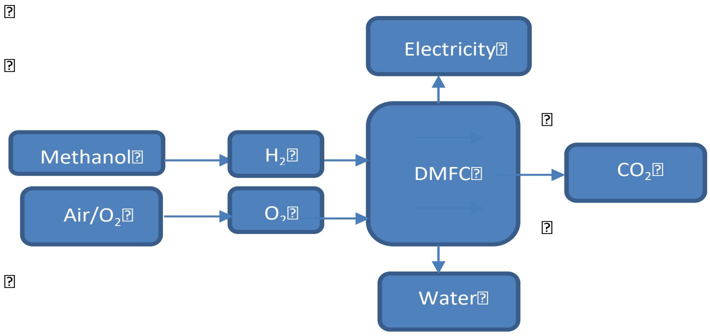


Figure 12: Flow chart for a direct methanol fuel cell system

Benefits and Challenges

The DMFC uses methanol directly without any need for reforming. This is a fuel with an energy density that is easy to handle, and store compared with hydrogen. Using methanol also leads to CO_2 emissions, but DMFC has no NO_x emissions. The efficiency of a DMFC is low, around 20%. Also, the major challenge with DMFC is methanol cross-over, which means that methanol crosses over the membrane to the cathode, where it reacts directly with oxygen. This leads to a reduction in cell efficiency.

Applications

Applications of DMFCs range from small electronics, such as battery chargers and laptops, to larger applications like stationary power for telecommunications backup.

1.4.4.3. Proton Exchange Membrane Fuel Cell (PEMFC)

PEMFCs use a polymer membrane for their electrolyte and platinum for their catalyst. What distinguishes these fuel cells from others is PEMFC's ability to operate at cooler temperatures relative to other types of fuel cells, between 27 and 95° C. PEMFCs operate between 40% to 60% efficiency and are capable of handling large and sudden shifts in power output. A schematic of the PEMFC is given in Figure 12 below.

The PEMFC uses hydrogen and oxygen and produces water in addition to electricity and heat. If other fuel sources than hydrogen are to be used, they need to be converted to hydrogen prior to injection to the PEMFC. For hydrocarbons, this means steam reforming and water-gas-shift. In the PEMFC, the main reactions that are occurring are the following: Anode reaction: $2H_2 \rightarrow 4H^+ + 4e^-$

Cathode reaction: $O_2 + 4H^+ + 4e^- \rightarrow 4H_2O$

Total reaction: $2H_2 + O_2 \rightarrow 2H_2O$

A flowchart for a PEMFC using hydrogen is given in Figure 13.

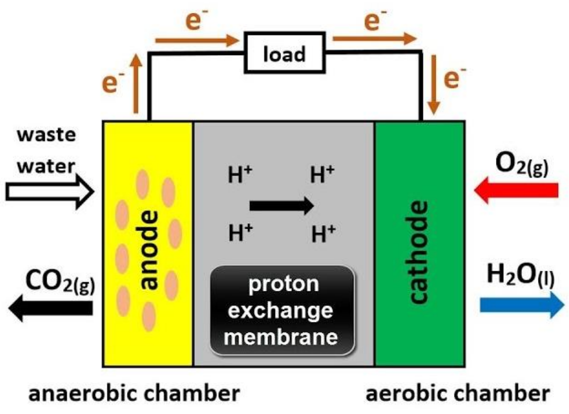


Figure 13: Schematic of a proton exchange membrane

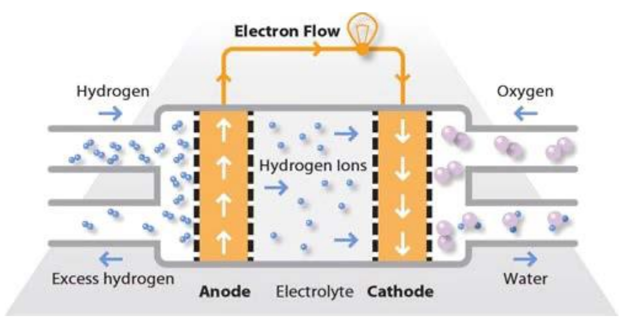
Benefits and Challenges

The PEMFC has a high power-to-weight ratio (100- 1000W/kg), a low operating temperature that allows for flexible operation, and less stringent material requirements that make it a suitable fuel cell for transportation. The efficiency of the PEMFC system is moderate, 50 -60% and excess heat is of such a quality that heat recovery is not feasible. Also, the low temperature leads to a complex system for water management to ensure efficient operation of the PEMFC.

The platinum catalyst has a higher cost, and it can be poisoned by carbon monoxide (CO) and sulphur (S). A pure hydrogen source is needed, but the PEMFC is not as sensitive to poisoning as the AFC. Hydrocarbons can be used as fuel for PEMFC, but a separate steam reforming and subsequent water-gas-shift system are required to make hydrogen of the necessary purity. If hydrogen is used as a fuel, the PEMFC emits only water. CO_2 and low levels of NO_X are emitted if hydrocarbons are used as fuel.

Further development

There is continuous development of the PEMFC to improve operation flexibility and durability and reduce cost. New membrane materials, such as Metal-Organic frameworks, and reducing catalyst loading are part of this development.



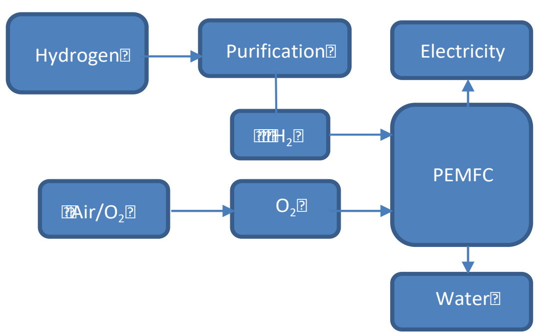


Figure 13: Schematic of a proton exchange

Figure 14: Flow chart for PEM fuel cell system

Applications

PEMFCs have been extensively used in many applications, they are used in several cars, the Alsterwasser passenger ship with a power output of 96 kW, and German Type 212A class submarines with modules ranging from 30 to 50 KW each. It has also been used on other ships with power levels ranging from 12 to 60 KW.

Additionally, PEMFCs can be scaled in stationary applications for use in telecommunications, data centres, and residential markets. PEMFCs are well-suited for cars and other specialty vehicles such as forklifts that need to quickly start up or accelerate.

The modules currently have a size of up to 120 KW, and the physical size is small, which is positive for applications in transport and remarkably, for marine use. This makes PEM fuel cells a good candidate for transportation applications ranging from trucks and buses to trains and boats.

Ban on perfluorinated and polyfluorinated chemicals (PFAS)

On 7th February 2023, a new restriction proposal was published by the European Chemicals Agency (ECHA). The restriction proposal seeks a ban on both the use and production of PFAS in order to reduce the risks these substances pose to humans and the environment. PFASs are used in various key components of fuel cells and electrolytic cells. These include things such as the PEM, which is made of the polymer perfluorosulfonic acid these days (perfluorosulfonic acid is one representative of the PFAS group of substances). PFSA is the proton-conducting material in the fuel cell membrane and the electrolyte membrane and enables the transport of protons with simultaneous spatial separation of hydrogen and oxygen or their partial reactions. The proton-conducting polymer membrane is an essential core component and therefore necessary for polymer electrolyte membrane fuel cells and for electrolytic cells. There are currently no technically mature alternatives for these key components, as only PFSA ionomers have reached the level of technological maturity needed for these functions in the demanding environments in which fuel cells or electrolysers are found. Alternative materials based on non-fluorinated hydrocarbon polymers are at an early stage of development and cannot be qualified for commercial use because various technical parameters do not reach those of PFSA materials.

1.4.4.4. Zinc-Air Fuel Cell (ZAFC)

In this type of fuel cell, there is a gas diffusion electrode, a zinc anode separated by electrolyte, and a mechanical separator. Oxygen is reduced to hydroxide, which combines with oxidised zinc, generating electrons in the process. This fuel cell was created in the United States for use in vehicles. The electrolyte is an aqueous alkali solution such as potassium hydroxide, and the electrode reactions are as follows:

Anode: $Zn+2OH^- \rightarrow Zn(OH)_2+2e^-$
Cathode: $O_2+2H_2O+4e^- \rightarrow 4OH^-$
Overall Reaction: $2Zn+O_2+2H_2O \rightarrow 4Zn(OH)_2$

It is used as an alternative fuel for vehicles.

1.4.5. Summary of Fuel Cell Technologies

PAFC, MCFC, and SOFC are available commercially with Liquid Gas or AFC, PEMFC are near commercialisation.

Fuel Cell Type	Electrolyte type	Operating temperature (ºC)	Catalyst Type	Module Power levels (kW)	Lifetime	Fuel	Emissions	Efficiency	Key advantages	Key weaknesses	Areas of application
PEM	Proton Exchange Membrane	50-100	Platimum	Up to 200 KW	Moderate	Liquid Gas Hydrogen	No	50-60% (electrical) 40% reformed fuel	Quick start Work at room temperature Air as oxidant	Sensitive to CO Reactants need to be humidified Expensive catalyst	Vehicle power Portable power Back- up power Distributed Generation
AFC	Alkaline	90-100	Nickel/ Silver	Up to 500 KW	Moderate	Liquid Gas High purity Hydrogen	No	50-60% (electrical)	Quick start Work at room temperature	Need pure oxygen as oxidant	Aerospace Military Backup power
PAFC	Phosphoric Acid	150-200	Platinum	100-400 KW	Excellent	Liquid Gas LNG Methanol Diesel Hydrogen	CO_2 and low levels of NO_X if carbon fuel is used.	40% (electrical) 80% (with heat recovery)	Insensitive to CO_2	Sensitive to CO Slow start	Distributed Generation
SOFC	Solid Oxide	650-1000	LaMno3/ LaCoO3	20-60 KW	Moderate	Liquid Gas LNG Methanol Diesel Hydrogen	CO_2 and low levels of NO_X if carbon fuel is used.	60% (electrical) 85% (with heat recovery)	Air as oxidant High energy efficiency	High operating temperature	Large Distributed Generation Portable power
MCFC	Molton Carbonate	600-700	Nickel	Up to 500 KW	Good	Liquid Gas LNG Methanol Diesel Hydrogen	CO_2 and low levels of NO_X if carbon fuel is used.	50% (electrical) 85% (with heat recovery)	Air as oxidant High energy efficiency	High operating temperature	Large Distributed Generation

Low temperature Fuel Cells (AFC, PEMFC, PAFC)	High temperature Fuel Cells (MCFC, SOFC)
▶ Incorporate precious metal electrocatalysts to improve performance. ▶ Exhibit fast dynamic response and short start-up times. ▶ PAFCs have the potential to operate 40,000 hours and even 70,000 hours. Additionally, because they can perform well at partial loads, they can provide higher quality power. ▶ PEM fuel cells can come online quicker than internal combustion engines.	▶ Increased operating temperature reduces the need for expensive electrocatalysts. ▶ Generate useful 'waste' heat and are therefore well suited to co-generation applications. ▶ Exhibit long start-up times and are sensitive to thermal transients. ▶ Require expensive and exotic construction materials to withstand the operating temperature, particularly in the balance of the plant (piping, heat exchangers, etc.). ▶ Reliability and durability are concerns, again due to the operating temperature. ▶ They can be integrated with a gas turbine, offering high efficiency combined cycles. ▶ They are only at the initial stage. MCFC and SOFC offer tremendous potential in industrial CHP applications because the thermal energy recovered through a CHP system is of high enough quality to power industrial applications. Additionally, industrial applications can maximise the use of thermal energy.

1.5. Main Manufacturers

The table below includes larger manufacturers - players in the field of fuel cell technology. The companies in green offer Liquid Gas powered fuel cells as well.

Region	Company	Field of Interest	Fuel Cell type
Canada	Hydrogenics	Hydrogen	PEMFC
Europe	Hexis (micro-CHP)	Hydrogen, natural gas, city gas, biogas	SOFC
Europe	Siemens Power Generation, Inc	H2 + CO, natural gas, jet fuel, diesel	SOFC
Europe	Nedstack	Hydrogen	PEMFC
Europe	MTU CFU Solution	Waste gas, LPG natural gas	MCFC
Europe	Ansaldo Fuel Cell	Waste gas, LPG natural gas	MCFC
Europe	Solid Power	Natural gas, bio-methane	SOFC
Europe	AFC Energy	Direct hydrogen or cracked ammonia	AFC
Europe	AFC Energy	Direct hydrogen or cracked ammonia	AAEMFC
Europe	EFOY	Methanol	DMFC
Europe	Intelligent Energy	Hydrogen	PEMFC
Europe	Helbio SA	N, Biogas, Propane/LPG, Ethanol	PEMFC
Europe	H2Planet	Hydrogen	PEMFC
Europe	EFOY	Hydrogen	PEMFC
Europe	Sunfire Fuel Cell	LPG/Propane or natural gas, biogas	SOFC
Europe	CeresPower	City Gas	SOFC
Europe	Viessmann	LPG, Natural Gas	SOFC
Europe	Panasonic	Hydrogen	MCFC
Japan	Mitsubishi Hitachi PowerSystems	City gas	SOFC
Japan	Panasonic	Natural Gas	PEMFC
Japan	Aisin	Natural Gas	SOFC
Japan	Kyocera	Utility-supplied gas or LPG	SOFC
Japan	Toshiba	Petroleum gas, biogas, town gas	PEMFC
Japan	Ishikawajima-Harima Heavy Industries	Waste gas, LPG, natural gas, Ammonia	SOFC, PEMFC, MCFC
Japan	Fuji Electric	City gas, Biogas, Pure hydrogen	PEMFC, PAFC
Korea	Posco Energy	LNG, Biogas, SNG	MCFC
USA	Technology Management, Inc.(TMI)	Natural Gas, Biogas, LPG, Ethanol	SOFC
USA	GenCell	Waste gas, LP gas natural gas	MCFC, PEMFC
USA	Power Innovations	Hydrogen	PEMFC
USA	Adaptive Energy	Natural Gas, Propane	SOFC
USA	Altergy	Hydrogen - Methanol	PEMFC
USA	Atrex Energy	Natural Gas, Propane	SOFC
USA	Bloom Energy	Natural Gas, Directed Biogas	SOFC
USA	Doosan Fuel Cell America (HyAxiom)	Natural Gas, LPG	PAFC
USA	FuelCell Energy	Natural Gas	MCFC
USA	Plug Power	Hydrogen	PEMFC
USA	Watt Fuel Cell	Natural Gas	SOFC
USA	Fuel Cell Technologies (FCT)	Biogas, natural gas, methanol	PEMFC,PAFC, DMFC
USA	Ballard Power Systems	Hydrogen	PEMFC
USA	FuelCell Energy	Biogas, natural gas, methanol	MCFC-SOFC
USA	UTC Power	Natural Gas, Hydrogen	PAFC - PEMFC
USA	H-Power Corp.	Natural gas, hydrogen, propane	PEMFC
USA	IdaTech	Natural gas, propane, methanol	PEMFC
USA	RedWawk Energy	Natural Gas, propane	SOFC, PEM, AFC

1.6. Fuel Cell vs. Photovoltaic vs. Engine Power Generator

While the applications of fuel cells, solar, and engine-based power generators may be very similar, there are distinct differences between each technology. Each one has its benefits and inherent problems.

Photovoltaic (PV) arrays create electricity by converting sunlight into electricity. They usually must be used in conjunction with storage batteries and only make electricity when directly exposed to sunlight. PV arrays only make power during daylight hours and when directly exposed. If obstructed by any foliage, buildings, etc. that would cast a shadow on the arrays, the output is dramatically reduced.

Engine Based-Power Generator is a device that converts mechanical energy into electrical energy. These generators are usually turned by an integrated piston-type internal combustion engine that uses gasoline, diesel, or Liquid Gas as a fuel source to produce electricity. As long as it has fuel, it will continue to produce electricity until mechanical failure occurs. They must have lube oil servicing and be manually started and stopped. Generators tend to be noisy and are extremely prone to theft or vandalism.

A Fuel Cell is a device that converts the chemical energy from an external fuel into electricity through a chemical reaction with oxygen or an oxidising agent. It is like a generator with no moving parts. It is usually used in conjunction with storage batteries. It will continue to produce electricity as long as it has fuel and air.

Fuel Cells	Photovoltaic Systems (PV)s	Engine Power Generation
Advantages **High Efficiency**: Fuel cells can achieve high efficiency, especially in CHP applications, where the waste heat is utilised. **Low Environmental Impact**: Fuel cells produce less emissions, with water vapor as the primary byproduct. **Quiet Operation:** Fuel cells operate silently compared to traditional engines. **Challenges:** **High Initial Costs:** The initial cost of fuel cell systems can be relatively high. **Hydrogen Infrastructure:** Hydrogen fuel cells require an infrastructure for hydrogen production, storage, and distribution. **Durability:** Some types of fuel cells may have durability issues, requiring careful maintenance.	**Advantages** **Renewable Energy Source**: PV systems harness solar energy, a renewable resource. **Low Operating Costs**: Once installed, PV systems have minimal operating costs and low maintenance requirements. **Reduced Environmental Impact:** PV systems produce electricity without emitting greenhouse gases during operation. **Challenges** **Intermittency:** Solar power is intermittent, dependent on weather conditions and daylight hours. **Energy Storage**: Additional systems (e.g., batteries) are needed for energy storage to address intermittent power generation. **Land Use:** Large-scale PV installations may require significant land area.	**Advantages** **Proven Technology:** Internal combustion engines are well-established and widely used. **Versatility:** Engine generators can run on various fuels, including liquid gas, natural gas, diesel, and gasoline. **Quick Response:** Engines can quickly respond to changes in demand, making them suitable for applications with variable loads. **Challenges:** **Fuel Dependence:** Traditional engines rely on fossil fuels, contributing to air pollution and greenhouse gas emissions. **Lower Efficiency:** Internal combustion engines are generally less efficient than fuel cells, especially in CHP applications. **Noise and Vibration:** Engines can be noisy and generate vibrations during operation.

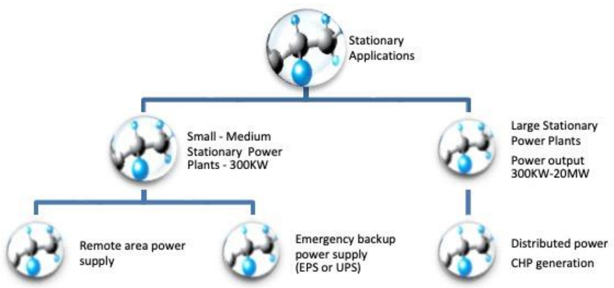
The choice between fuel cells, photovoltaic (PV) systems, and traditional engine power generation depends on various factors, including application, efficiency, environmental impact, and specific requirements. In many cases, a combination of these technologies or hybrid systems may be employed to leverage the strengths of each while mitigating their respective weaknesses. Advances in technology and ongoing research continue to influence the landscape of power generation options.

1.7. Fuel Cell Market Applications

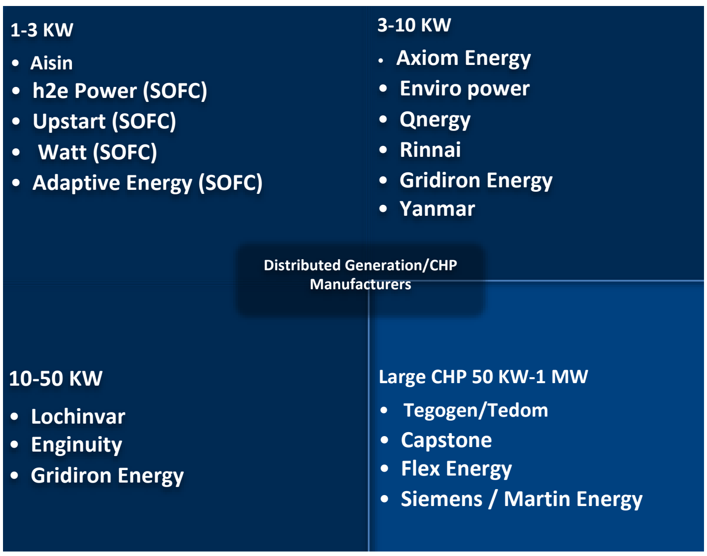
1.7.1. Stationary Applications

The stationary sector includes fuel cell systems that operate at a fixed location for **primary power, backup power, or CHP**. Fuel cells are being developed for both large-scale (100 kW and over) and small-scale (up to 100 kW) applications and deployed to a wide range of customers, including retail operations, data centres, residences, telecommunications, utilities, and many more. Due to their low maintenance and emission-free operation, fuel cells already represent an economical alternative to conventional generators in some areas. In residential energy supply, fuel cell units generate heat and electricity at the same time.

A strong driver for several of the stationary applications is "resilience," which reflects the ability of a system to absorb unexpected events (such as blackouts) via distributed power plants for grid stabilisation and backup. The stationary fuel cell sector represented >70% of the fuel cell market size and was valued at $4.58 billion in 2021. It is projected to grow from $5.90 billion in 2022 to $36.41 billion by 2029, according to Fortune Business Insights.



PEMFCs and SOFCs are mostly used, however, MCFCs, AFCs, and PAFCs can also be used. In fact, both low and high- and high-temperature fuel cells could, in principle, be utilised for stationary applications. While low-temperature fuel cells have the advantage that are usually faster during start-up, high-temperature systems such as SOFCs and MCFCs produce heat that can be directly used for other applications, and they can also operate directly on fuel without external reforming, reaching a higher efficiency than low-temperature systems.



As can be seen from the figure below, we can identify two main power plants: large stationary power plants (power output from 300 kW up to 20 MW) and medium stationary power plants (power output from a few Watts up to ten kW for small stationary power plants and from ten kW up to 300 kW for medium stationary power plants). Moreover, stationary fuel cells, depending on their features, may be used for many applications, either as the primary power source instead of the grid or in places where the grid cannot reach to provide supplemental power in hybrid power systems with photovoltaics, batteries, capacitors, or wind turbines, providing primary or secondary power (distributed power or CHP generation) or as a backup (emergency backup power supply (EPS) or UPS). PEMFCs and SOFCs can be mostly used in small-scale systems with Liquid Gas as fuel. In contrast to private homes, industrial plants, hotels, and hospitals have significantly higher energy demands. This can be met by fuel cell-powered combined heat and power (CHP) plants, which have the potential to gradually replace engine-powered plants due to their better efficiency and elimination of pollutants. MCFCs and SOFCs can be predominantly used, operating at high temperatures with Liquid Gas.

1.7.1.1. Industrial Applications

The main applications for the industrial use of FCs are prime power, CHP, and tri-generation, mainly for new office builds, retail parks, hospitals, universities, or data centres. Because of the higher electrical efficiency of HT-FCs, MCFCs, and SOFCs are usually used for such applications. PAFCs, PEFCs, and recently AFCs have been used to a lesser extent. Furthermore, the reduced gas reforming effort in HT-FCs allows biogas from landfills, biomass, and digester sources to be used as fuel. Natural gas is the dominant fuel; however, Liquid Gas is also extensively used.

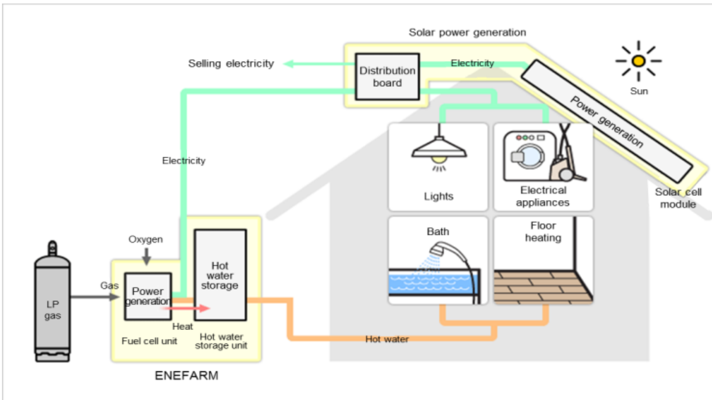
The prime power market for large stationary fuel cells is led by three players:

- Bloom Energy
- FCE
- Doosan

1.7.1.2. Residential Applications

Residential CHP units produce heat and power mainly for single-family houses. In comparison to conventional CHP technologies (ICE, Sterling Engine) FC systems lead to significant reductions in CO_2-emissions (about 1–2.5 tons/year/house).

Liquid Gas is primarily used as the fuel for residential CHP applications. Both PEFCs (quick start-up, power modulation, direct hot water) and SOFCs (internal reforming, high temperature heat) are used for this application.



Japan is in a leading position in the market introduction for residential CHP fuel systems. The Japanese ENE-Farm programme was responsible for over 400,000 micro-CHP fuel cell installations (until the end of June 2021). This is the largest worldwide deployment programme, and it reflects the long and outstanding commitment of both the Japanese government and the Japanese industry to form a ‘Hydrogen Society’.

House energy supply with fuel cell systems

Today’s technology
- House heating supply with Liquid Gas burner systems
- Heating and cooking

Tomorrow’s application with fuel cells
- Mini CHP systems (Combined Heat & Power) as house energy supply

Companies working on fuel cell house CHP systems powered by Liquid Gas

- Vaillant, Plug Power (Germany / USA)
- Sulzer Hexis (Switzerland)
- Viessmann (Germany)
- Idatech, RWE, Buderus/Bosch (USA, Germany) efc, Brötje, Baxi (Germany, UK)
- Other internationally (Korea, Japan)

1.7.1.3. Back- up and off-grid Power

FC systems for back-up and off- grid applications are quite similar, except for the fuel tank capacity; back-up systems for emergency use need lower fuel capacity.

Backup systems are used for areas such as server banks, data centres, telematics, traffic controls, tunnels, mines, hospitals, environmental protection, pipelines, disaster control, IT, tele-communications, or signalling. Back-up power supply (BPS) systems are generally categorised as either uninterruptible power supply (UPS) or emergency power supply (EPS) systems. In order to be able to bridge longer periods of power failures, the mostly battery-operated UPS systems are typically extended by EPS systems.

In contrast to competing battery technologies, fuel cells decouple energy and power. Furthermore, they have a longer lifetime, lower service requirements, and lower operating costs than batteries and do not suffer from self-discharge. Moreover, due to the short operating time of power backup systems, F-durability issues are less important compared to CHP-applications.

SUNFIRE HOME RESIDENTIAL INSTALLATIONS IN GERMANY

Previously, diesel generators with appropriately dimensioned diesel tanks were typically used on site. However, a whole series of favourable characteristics make fuel cell technology very attractive for deployment as back-up power supplies:

- Fast and safe start-up in the event of a power failure
- Low maintenance requirements and minimal aging tendency in standby mode
- Power output can be regulated over a wide range while maintaining a high degree of efficiency
- No degradation of fuels

Typical fuel cell backup power units for telecom applications are in the range of two to ten kW. The fuel capacity on site of such applications must be large enough to cover the required autonomous operation time, which can amount to several days of continuous operation.

Fuel cell applications and system suitability

Application	Processor	Fuel
Short Run Backup (4-6 Hrs)	Direct Hydrogen or Electrolyser	Bottled hydrogen or grid electricity for electrolysis
Poor Grid Sites (Total daily blackout hrs 7-18 hrs) with frequent short blackouts in a day	Direct Hydrogen	Bottled hydrogen
Poor Grid Sites (Total daily blackout hrs 7-18 hrs) with long non-frequent blackouts in a day	Reformer based or Direct Hydrogen	Hydrocarbon fuel - such as methanol/LPG/ammonia or bottled hydrogen
Off-Grid Sites (Continuous Power)	Direct Hydrogen Reformer based	Bottled hydrogen or hydrocarbon fuel such as methanol/LPG/ammonia

1.7.2. Portable Power

Portable fuel cells encompass those fuel cells designed to be moved, including auxiliary power units (APU) of lower power.

The portable applications range in the power requirement from 25 W to about 5 kW. Military applications are a special field of portable fuel cell applications. This market covers mainly the 4C applications (Computer, Cordless Phone, Camera, Cordless Tools). Power supplies for notebooks and mobile phones are based on DMFCs and H2-PEFCs in the power region of ~5 W and 75 W.

1.7.2.1. Power Supply for Recreational Vehicles and Specialty Markets

These markets comprise long-term power supply applications such as caravans, RVs, sailing boats, energy supply for remote sensor or relay stations, etc., with restricted site access. For example, in a vacation place outdoor camping area, the use of a fuel cell for electrical power instead of a diesel generator, avoiding harmful emissions, helps to preserve the environment and causes no problems with noise to other people in the environment. To avoid challenges related to gas processing, systems powered by Liquid Gas are based on high-temperature PEFC technologies such as those developed by EnyMotion (EnyWare B500, 500 W using bioethanol), Truma (VeGA, 250 W using Liquid Gas), or on SOFC technology such as the Liquid Gas -powered RP-20 system from Acumentrics (500 W, start-up time <1 h).

Leisure market applications (bottle market)
Applications:

- Camping, caravanning
- Sailing, yachting
- Remote applications, allotment gardens

Today's technology with Liquid Gas

- Liquid Gas powered vehicles
- Heat supply
- Cooking and cooling

Tomorrow's application with fuel cells

- Portable/onboard power supply for vehicles (APU)

1.7.3. Auxiliary Power Units (APUs)

The need for auxiliary power in recreational boats and truck applications is widespread. An auxiliary power unit (APU) that works independently of the engine based on fuel cell technology is an attractive solution. Such APUs, already available on ships or trucks, require no infrastructure modification or fuel storage. Liquid Gas is already available on many vessels for cooking, refrigeration, and heating. The fuel cell provides an efficient and environmentally friendly means for the power supply by boosting efficiency while minimising noise, vibration, and pollution.

1.7.4. Marine Vessels

Maritime fuel cell applications are still in the prototyping and developing stages, even though the maritime sector is under huge pressure to reduce emissions.

The recreational maritime industry is calling for more electric-powered ships by striving for low-noise and low emission energy usage on board. The use of fuel cells in shipping is still in its infancy. Fuel cells combined with Liquid Gas can efficiently reduce and even eliminate emissions and noise, while energy efficiency can be increased if they are used in combination with conventional combustion engines. Furthermore, fuel cells have other potential benefits, such as reduced maintenance, modular and flexible design, and improved part-load efficiency. However, fuel cells come with drawbacks such as continuing high costs, durability limitations, and space constraints.

For application on deep-sea ships, which can more easily accommodate waste heat recovery solutions, high-temperature fuel cell systems such as SOFC may be explored, as a large proportion of their energy consumption relates to propulsion at a steady speed over long distances. Apart from the potential efficiency increase, fuel cells have other potential benefits such as reduced noise, reduced maintenance needs, modular and flexible design, and improved part-load operation efficiency. However, fuel cells come with significant disadvantages related to cost and durability.
Currently, SOFCs involve about ten times the CAPEX of internal combustion engines per kW installed and have a much shorter lifetime. Laboratory tests indicate that SOFCs can achieve significantly higher efficiencies than conventional engines, but this has not yet been demonstrated on a ship. The pilot projects underway have the potential to demonstrate SOFCs' real operational efficiency over the next three to five years.

Case study
MSC Europe to install the world's first LNG-fuelled fuel cell solution

Similar to the examples of LNG-powered fuel cells, equally well, Liquid Gas can be used for similar applications. In this example powered by LNG, SOFC technology will deliver electrical efficiency up to 60% and will also eliminate nitrogen oxide, sulphur oxide and fine particulate emissions. In addition, it will reduce greenhouse gas emissions by approximately 30% compared to conventional dual-fuel LNG engines. MSC Europe will be the world's first cruise ship to use SOFC technology (image: MSC Cruises). Chantiers de l'Atlantique will install the world's first LNG-fuelled fuel cell solution aboard the new MSC Europa.

Shell consortium

Similarly, to the above LNG example, a consortium led by Shell aims to design, manufacture, and install a 600-kilowatt (kW) SOFC auxiliary power unit on an LNG carrier for a year of testing in 2025. The trial seeks to test the technology's decarbonisation potential, prove its scalability as a propulsion solution for shipping, and enable wider industry acceptance of fuel cells.

1.7.5. Bio Liquid Gas use in a SOFC to power the auxiliary load of a locomotive

Diesel compression ignition engines are the motive power of choice for railway vehicles due to their higher power for a given speed and displacement and higher efficiency. In the UK, 90% of all locomotives use diesel engines, and overall, 30% of all rolling stock uses diesel engines. Railway vehicle operators are seeking ways to reduce the tailpipe emissions of their vehicles, reduce fuel consumption, lower their operating costs and for when fossil fuels are used also lower the net carbon dioxide emissions of their operations. In the UK, there is intent to replace all diesel-only operated railway vehicles by 2040.

Colas Rail UK's Freight Business has collaborated with G-Volution Ltd to decarbonise locomotive operations by using SOFC running on near net zero carbon emission Bio Liquid Gas (Bio-LPG) to generate power for auxiliary loads.

With most locomotives heavily reliant on diesel and a major source of our carbon emissions, Colas Rail UK partnered with G-Volution on a project to install a SOFC into a Class 37 locomotive to power the auxiliary systems. Route simulations by the University of Birmingham using a 35kW SOFC show that a typical Class 37 operation using two locomotives will save on average 50 tonnes (12%) of CO_2e per year and combined with an average 8% reduction in fuel costs. Other benefits brought by this approach are improved air quality (zero particulate matter and nitrogen oxides are produced by the SOFC) and a significant reduction in noise and engine idling.

Key advantages

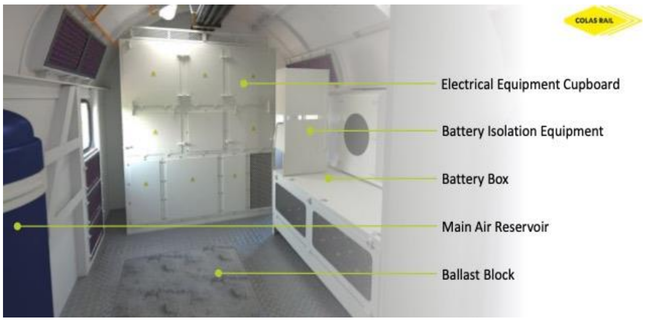
- r-Liquid Gas SOFC is more efficient than diesel engines.
- Removing auxiliary/parasitic loads from the diesel engine lowers the locomotive's fuel consumption and tailpipe emissions.
- The diesel engine can be switched off during dwell and stabling times, with the SOFC providing the power required for cab lighting, heating, locomotive control systems, and railway signalling and communication equipment. There is no need to keep the engine, idling thus lowering fuel consumption, and exhaust emissions

and improving local air quality as a result.

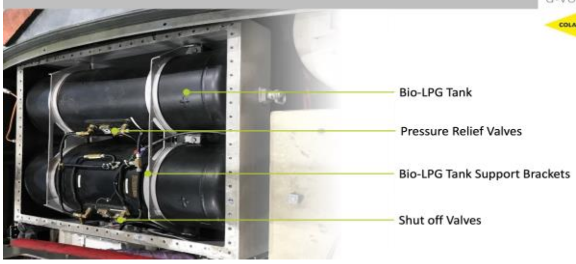
- It aligns perfectly with the dual-fuel evolution of the locomotive's diesel/compression ignition engine. Both the SOFC powering the auxiliary load (at higher efficiency than the engine) and the locomotive's diesel engine can share the new r-Liquid Gas fuel tanks installed on the locomotive.

Potential impact

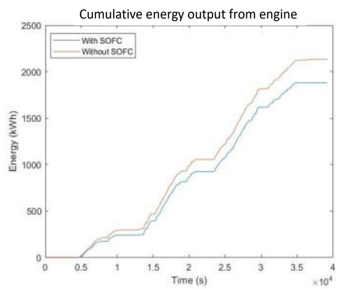
- Lower fuel consumption and improved exhaust emissions from the locomotive's diesel engine.
- Overall lower fuel consumption for the locomotive by shifting the provision of auxiliary load from the engine to the Liquid Gas or r-Liquid Gas fuelled SOFC.
- Lower carbon emissions from the locomotive.
- Improvement in local air quality by eliminating the need to idle the engine to provide the auxiliary load during dwell and stabling times.
- New use of Liquid Gas and r-Liquid Gas for railways.
- New Liquid Gas and r-Liquid Gas supply chain and infrastructure opportunities.



Vehicle Integration Concept – Bio-LPG Storage

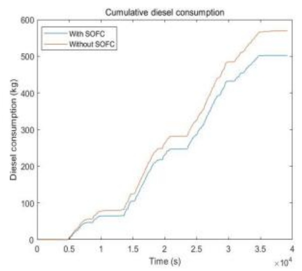


Energy from engine



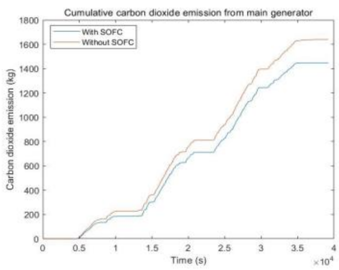
- Baseline Energy Without SOFC:
  total energy from engine = 2,133.61 kWh
- With SOFC:
  energy from engine = 1,880.40 kWh
  energy from SOFC = 253.21 kWh

Fuel Savings per Locomotive per day



- Without SOFC:
  total diesel consumption = 570.21 kg
- With SOFC:
  total diesel consumption = 501.91 kg
  Bio propane consumption = 32.77 kg

Carbon dioxide reduction (CO2e)



- With SOFC:
  total CO_2 emission = 1,445.99 kg (diesel)+0.0701 kg (propane)= 1,446.06 kg
- Without SOFC:
  total CO_2 emission = 1,640.7 kg
- **a 12% reduction**

Annualised savings per Locomotive

Results	With SOFC
Fuel Cost Savings %	8%
Fuel Cost Savings £ per annum	£12,000
CO2e savings %	12%
CO2e savings per annum	50.5 tonnes (£10,300, DfT TAG central CO2e prices)

Assumptions	Unit
Cost for bio propane	36p/litre
Cost for gasoil	87p/litre
CO2 emissions from bio propane	0.0021kg/litre
CO2 emissions from gasoil	2.76kg/litre
Days of operation	260 days

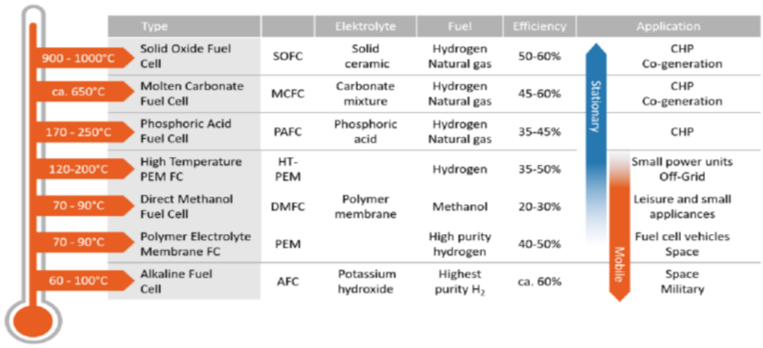
1.7.6. DME to power hydrogen fuel-cell electric vehicles

DME as a hydrogen vector

DME can decarbonise transportation as a hydrogen vector. DME is an excellent carrier molecule for transporting hydrogen to power a new generation of light- and heavy-duty, fuel-cell electric vehicles and to provide increased supplies of renewable hydrogen:

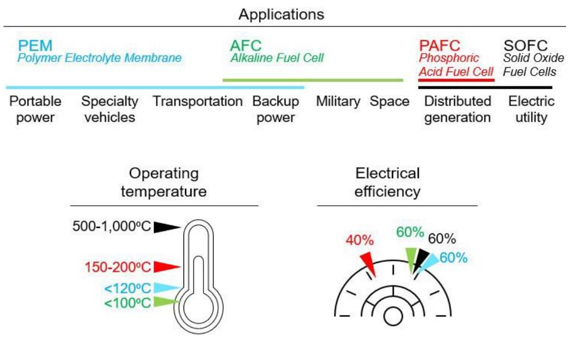
- DME is particularly dense in hydrogen, with six hydrogen atoms on each DME molecule.
- DME can be made from a wide variety of renewable feedstocks, creating a new pathway for renewable hydrogen production.
- DME liquefies at low pressure (~73 psi), making it much easier and less expensive to transport than hydrogen, which can be compressed at up to 10,000 psi of pressure.

These qualities mean that the roll-out of increased DME production, DME-powered trucks, and blending DME with Liquid Gas can also accelerate the expansion of hydrogen fuelling infrastructure. As trucking fleets begin to use DME as a diesel replacement and/or blend it with Liquid Gas, the same equipment and feedstocks can also be used to bring DME directly to hydrogen fuelling stations, where it can easily be converted to power fuel cell electric vehicles as well. With DME engines and trucks in development now, Liquid Gas/DME blending tests moving forward, and hydrogen vehicles pushing into the market, these three fuels can quickly become natural allies – three different applications for the same molecule DME.



	Type		Elektrolyte	Fuel	Efficiency	Application
900 - 1000°C	Solid Oxide Fuel Cell	SOFC	Solid ceramic	Hydrogen Natural gas	50-60%	CHP Co-generation
ca. 650°C	Molten Carbonate Fuel Cell	MCFC	Carbonate mixture	Hydrogen Natural gas	45-60%	CHP Co-generation
170 - 250°C	Phosphoric Acid Fuel Cell	PAFC	Phosphoric acid	Hydrogen Natural gas	35-45%	CHP
120-200°C	High Temperature PEM FC	HT-PEM		Hydrogen	35-50%	Small power units Off-Grid
70 - 90°C	Direct Methanol Fuel Cell	DMFC	Polymer membrane	Methanol	20-30%	Leisure and small applicances
70 - 90°C	Polymer Electrolyte Membrane FC	PEM		High purity hydrogen	40-50%	Fuel cell vehicles Space
60 - 100°C	Alkaline Fuel Cell	AFC	Potassium hydroxide	Highest purity H_2	ca. 60%	Space Military

1.7.7. Summary of Fuel Cell Technologies and their applications



Source: U.S. Department of Energy. (November 2015). Comparison of Fuel Cell Technologies. Retrieved from https://www.energy.gov/

Fuel cell technology and types of fuel cells – Comparison of different types of fuel cells

Application type	Portable	Stationary	Transport
Definition	Units that are built into, or charge up, products that are designed to be moved, including small auxiliarypower units (APU)	Units that provideelectricity (and sometimes heat) but are not designed be moved	Units that provide propulsive power or range extension to a vehicle
Typical power range	1W to 20 kW	0.5 kW to 2 MW	1 kW to 300 kW
Typical technology	PEMFC, DMFC, SOFC	PEMFC, MCFC, AFC, SOFC PAFC	PEMFC, DMFC

Example	Small 'movable 'APUs (campervans, boats, lighting) Military applications (portable soldier-borne power, skid-mounted generators) Portable products (torches, battery chargers), small personal electronics (mp3 players)	Large stationary prime power and combined heat and power (CHP) Small stationary micro-CHP Uninterruptible power supplies (UPS) Larger 'permanent 'APUs (e.g., trucks and ships)	Materials handling vehicles Fuel cell electric vehicles (FCEV) Trucks and buses Rail vehicles Autonomous vehicles (air, land, or water)

Chapter Two

Case Studies- Selected Industries

Around the world, the fuel cell footprint has increased steadily over the years, with different countries or regions initially focusing on specific sector and a large portfolio of Liquid Gas Fuel Cell applications with high levels of technological maturity is available for deployment today.

- United States: fuel cell powered light-duty vehicles, material handling equipment (MHE), large-scale stationary fuel cell installations, and small-scale fuel cell systems for backup power.
- Japan: small-scale fuel cell residential installations (ENE-Farm), fuel cell powered light-duty vehicles.
- South Korea: multi-megawatt fuel cell power parks
- China: fuel cell powered buses
- Europe: fuel cell powered buses, large-scale electrolyser/power-to-gas projects, small-scale fuel cell residential installations (ENE-Field)

Other countries are involved in research, development, and deployment of fuel cells, and there is global interest and investment in fuel cells production to meet broad global decarbonisation goals. There are great opportunities for use of Liquid Gas Fuel cells in different areas of applications.

2.1. Railway

Rail Signals and Crossings

Liquid Gas fuel cells are used by railways as backup power to prevent power outages. They often replace generators, which require high maintenance, are loud, and prone to theft.

Cathodic Protection

Millions of miles of pipeline around the world distribute critical liquids and gases and a key threat is corrosion, which can erode the integrity of pipeline and storage tanks. Cathodic protection prevents this via a small electrical current. However, they often require specialised skills and routine monitoring to maintain power, ensuring these systems stay on and remain effective.

Sunfire

Power Generator for Deutsche Bahn Traffic lights and barriers

Customer: Deutsche Bahn AG

Location: Germany

Deutsche Bahn relies on Sunfire-Remote. Since 2017, power generators have been supplying systems for traffic lights and barriers at level crossings. They take over the hard work that used to be done by maintenance workers. Nowadays, the level crossings can be monitored remotely. Deutsche Bahn benefits from the flexible application possibilities of power generators. Using available renewable sources, our customer combines Sunfire-Remote with photovoltaic systems. While solar energy is sufficient to provide the necessary power in the summer, fuel cells take over in the dark winter months.

Challenges:

Outages can put lives in danger. The technical solution must be as reliable as the human workforce.

Benefits:

- Technical solution in place of physical work
- Extended fuel cell life and lower fuel consumption due to hybrid design
- Remote monitoring of system parameters, fuel level, and battery charge

Ultra Electronics USSI

Liquid Gas-powered fuel cell systems support railway signals

Customer: RedHawk Energy Systems of Pataskala,

Location: Ohio

The Liquid Gas-powered P250i fuel cell system from Ultra Electronics USSI provides 250 watts of 24/7 backup power for railway signals and crossings. The fuel cell system recharges battery banks at railway installations. The system contains a secure compartment for Liquid Gas along with a telematics communication system to remotely monitor the system's status and fuel level.

Benefits:

- Run time using two standard Liquid GAs grill cylinders ranges from 130 to 160 hours. Larger tanks can be used to provide longer run times.
- This technology allows for the railway signals and crossings to run for days, weeks and months on backup power.
- The P250i fuel cell can be used as a backup to AC power or integrated into a solar- or wind-powered system.

2.2. Telecommunications

Telecommunications providers rely on backup power to maintain a constant power supply and to ensure the operability of cell towers. In telecommunication stations, fuel cells offer many advantages which include reliability, low maintenance costs, reduced frequency of refuelling and reduced cost. Liquid Gas meets the special requirements in hard-to-reach areas. The system offers a perfect tandem with photovoltaic systems. In summer, solar energy can be used, while fuel cells reliably maintain operation in the dark winter months. Such a hybrid application is sustainable and extends maintenance intervals.

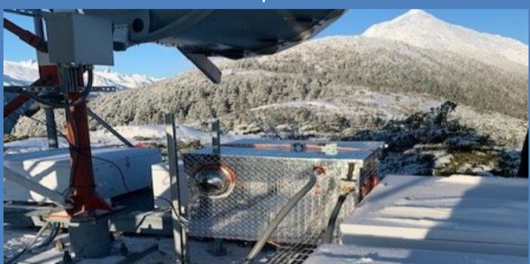
Sunfire
Customer: Leading U.S.A Telecom network operator

Location: Telecommunications in Alaska
The Sunfire remote Liquid Gas fuel cells are a mature solution. Since 2014, they have proven their reliable operation even in harsh environmental conditions. The possibility of remote monitoring and control as well as the combinability with photovoltaics for effective power supply in the summer months make this solution the first choice for our customer. Microwave radio stations ensure that even the most remote areas of Alaska are supplied with telephone and broadband Internet services. In the past, problems arose with the power supply for these applications. Thermoelectric generators repeatedly proved inefficient, while fuel cells did not always work reliably. As a result, the leading U.S. grid operator opted for a long-term solution with fuel cells

Challenges:

The station can be reached only by helicopter. Limited accessibility in winter. Rough climate with frequent weather changes. Temperatures from -30 °C to + +35 °C. High humidity.

Benefits:
- remote control and monitoring
- fewer service flights
- easy commissioning and operation
- efficient power generation
- reduced fuel consumption



Sunfire
Customer: Leading German telecommunications provider

Location: Germany
The telecommunications sector is highly dependent on a flawless infrastructure at all times. Even off-grid systems such as radio repair stations must be continuously supplied with power. In the search for contemporary solutions, the industry pays attention not only to reliability and maintenance effort, but also to climate protection. –RemoWiyh the fuel cell it has proven that CO_2 emissions can not only be reduced to a quarter compared to diesel engines, but that an additional 90% can even be saved when operating with Bio-Liquid Gas.

Challenges:

Reduce CO_2 footprint and provide sustainable fuels

Benefits:
- compared to the CO_2 emission value of mains electricity in Germany, the device thus saved 80 % of the emissions
- with bio–Liquid Gas additional saving of 90 % CO_2 emissions

2.3. Oil and Gas

In critical infrastructures such as the oil and gas industry, safety and reliability are critical. But factors such as cost efficiency and emissions are also playing an increasingly important role. Liquid Gas fuel cells are ideal for these infrastructures.

Power for Sabah – Sarawak Gas pipeline block valve stations.

Customer: Petronas
Location: Borneo, Sabah State (Malaysia)

Sunfire-Remote delivers its full output even under tropical conditions. It has replaced the previous inefficient power generators with only 3% efficiency at block valve stations on Petronas' Sabah-Sarawak gas pipeline since 2022. Sunfire-Remote reliably provides power for block valve operation as well as SCADA and communications equipment. CO_2 emissions can thus be reduced by up to 90 %.

Sunfire remote fuel cells reduce emissions in the oil and gas industry.

Challenges:
Robust, reliable and low-pollution power supply at remote block valve stations

Benefits:
- Reduction of greenhouse gas emissions by up to 90 % compared to the previous energy supply.
- Long maintenance intervals of 10,000 operating hours
- Integration into existing SCADA

2.4. Critical Infrastructure Safety

Power insecurity puts millions of people at risk of harm during weather disasters. Blackouts can knock power plants offline, crippling water treatment facilities, cellular networks, and other critical infrastructure. Liquid Gas fuel cells are ideal for organisations that need more rugged and flexible power options, especially for off-grid use cases. This is because Liquid Gas fuel cells operate even in the harshest of conditions with little maintenance. And thanks to being a quiet, clean, and dependable power solution, Liquid Gas-powered solid oxide fuel cells work in a wide variety of applications.

Sunfire
Power for nighttime signals on wind turbines

Customer: Leading European wind park provider
Location: Spanien

Night marker lights are essential for modern and powerful wind turbines. One of the world's leading wind farm developers and installers relies on Liquid Gas fuel cell generators to provide clean power for air traffic obstacle lighting during the construction of wind turbines. The hybrid PV systems have been passed from project to project across Europe since 2014.

Challenge**:**
Robust, reliable and low-pollution power supply for air traffic obstacle lighting during construction.

Benefits:
• Hybrid PV configuration
• Hassle-free operation
• Easy transfer to new construction sites
• Long refuelling and maintenance intervals
• Remote monitoring of energy supply

2.5. Remote Power Supply

Sunfire Remote:
Clean Power at Mount Everest Base Camp (5,000 m height)

Customer: Furtenbach Abenteuer GmbH
Location: Mount Everest Base Camp

In 2018, Sunfire for the entire season supplied power to Mount Everest Base Camp. As the Himalayas are a sensitive environment, our customer required a sustainable solution to replace a diesel generator.

Challenge:
Extreme environmental conditions, demanding logistics

Benefits:
- Low fuel consumption due to high efficiency
- The use of readily available fuels, compact units facilitates transportation.
- Low noise level and low emissions

Sunfire Remote:
AFE power supply for music festival lighting)

Customer : 3,000 Grad Festival
Location: Germany

Sunfire-Remote offers a serious alternative that is also significantly more environmentally friendly. People who go to festivals want to enjoy the feeling of freedom. But with a clear conscience. Sustainability is an important issue, especially for the younger generation. Sunfire-Remote helped festival-goers find their way in the dark by generating electricity for a floodlight pole.

Challenges:
Trouble-free and clean power supply for lighting the tent area and washrooms.

Benefits:
quiet and clean operation

2.6. Construction Vehicles

Calor has partnered with Adelan, a global developer of microtubular solid oxide fuel cell (mSOFC) technology, to help pave the way for a cleaner, low-carbon construction vehicles.

With the construction sector accounting for almost a quarter of all global carbon emissions, a more sustainable replacement to diesel is needed. Adelan is aiming to deploy its unique microporous SOFC technology as an alternative to diesel-fuelled internal combustion engines. Adelan's mSOFC can use Liquid Gas or renewable hydrocarbons such as rDME andr Liquid Gas. Futuria DME has been shown to deliver CO2 savings of up to 74% compared to diesel. This project partnership paves the way for more sustainable, cleaner energy source for the next generation of construction vehicles.

2.7. Leisure Recreational Vehicles (RV)

This Innovate UK funded project CATALYST examined the feasibility of a new Adelan device in the field of fuel cells. The invention enables more economic clean portable power generation in vehicles such as campervans and blue light vehicles (e.g., ambulances), reducing air pollution emissions. With a new fuel cell design, Adelan reduced the parts count and costs of a portable system to accelerate the penetration of this technology into portable generator markets. The University of Birmingham supported the project by developing sealant and metal interconnect materials.

Source: Adelan

2.8. Full-Sail Power for the Outward-Bound

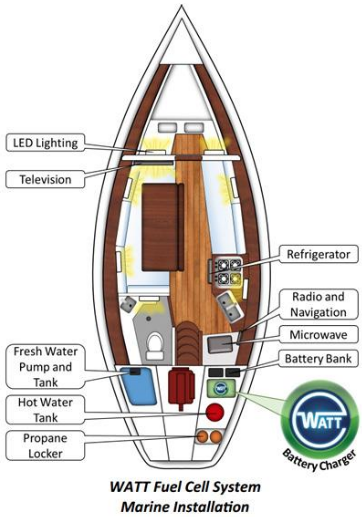
Sailing yachts and boats

Boats longer than 10m need a supplementary power generator for power and/or heat production when docked or in the occasion of failure of the main engine. Fuel cells fuelled with Liquid Gas generate on-board power **and offer** the same attractive characteristics as in any other mobile application: reliable, economical, quiet, vibration-free, and emission-free operation. From starting the engines to supplying power to all electronic systems and lighting keeping all of the marine batteries and battery banks charged at sea. There is no noise and no dangerous emissions.

Manufacturer

WATT

Unlike typical generators, WATT quietly and efficiently creates clean energy with no toxic fumes. WATT's innovative fuel cell system operates on Liquid Gas and integrates seamlessly to manage your renewable power sources, there is no need to dock and plug in to charge. With up to 1,000 watts of output, WATT is ideal for keeping all systems go for both short outings and long cruises.



Source: WATT

Advantages

1. Full-Sail Power for the Outward-Bound
2. Integrated Power Control in Uncontrollable Conditions
3. Complete Flexibility and Peace of Mind

Working and generating the power you need, so you remain safe at sea

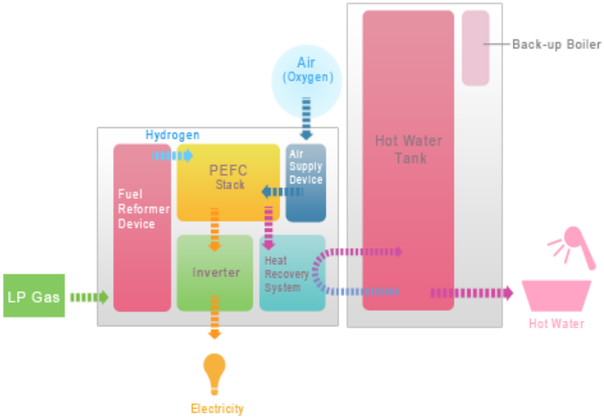
2.9. Electric Power Generation

EneFarm Home Fuel Cell

The residential fuel cell Ene-Farm is a cogeneration system that takes hydrogen from Liquid Gas and city gas and conducts a chemical reaction with oxygen in the air to generate electricity while simultaneously using waste heat to supply hot water. Ene-Farm power generation covers approximately 70% of the electricity used by households, contributing to a reduction in the amount of grid electricity purchased and a reduction in peak demand. In comparison to conventional electrical supply grid systems, it has the capability for a very high efficiency ratio and a significant reduction in CO_2 gas emissions.

Source: ENE-FARM

The Ene-Farm generation capacity ranges from 0.3kW to 1kW of electricity, enough to cover the normal power requirements for home electric appliance standby power, and power is drawn from the electric utility's power grid only when this power is insufficient. In theoret calculations, about 60% of typical electric power demands for a normal household will be by the Ene-Farm. In addition, a power system that raises the self-sufficiency ratio even higher is being developed by combining it with solar power generation devices ("DOUBLE GENERATION").



The hot water supply unit holds 200 litres of heated water at 65ºC and when the hot water is used up, auxiliary heat source equipment comes online, preventing running out of hot water. The hot water generated by the system is used in the kitchen, bath, floor heating, mist-sauna, and the like, providing a comfortable daily lifestyle.

The government has also taken notice of the high environmental performance of the ENE-Farm, and it is making all-out efforts towards the installation of 2.5 million units by the year 2030 through the introduction of tax incentives and by defraying costs and other measures.

Korea: New Plant Started with ‘LPG-LNG Dual Model’ of Doosan Fuel Cell

This project is designed to construct a 12.32MW (0.44MW * 28Unit) fuel cell plant named ‘Bitgoeul-ECO Plant’ with 81.5 billion KRW on the idle premises of Gwangju 1st sewage treatment plant, the first commercialisation case of LPG-LNG Dual Model of Doosan Fuel Cell.

This plant will supply 95,000 MWh a year, which can power approximately 33,000 households in the city.

- Project: Bitgoeul-ECO Plant
- MW: 12.3MW (0.44MW*28Unit)
- Construction Period: February 2021 – August 2022

M400 LPG-NG The dual model produces electricity and heat in places without natural gas pipes by using Liquid Gas which is easy to store and transport. It is designed to be applied to isolated regions and national infrastructure facilities.

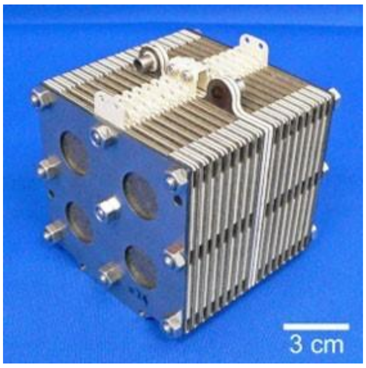
2.10. Drone with SOFC

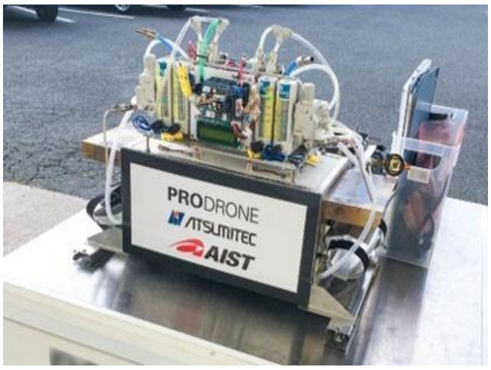
Japanese companies and research institutes have developed and demonstrated world's first solid oxide fuel cell drone using Liquid Gas. The drone uses Elcogen's solid oxide cells.

Developed SOFC system uses Liquid Gas and light weight SOFC stack enabling power generation in the air. By supplying SOFC system and secondary batteries to the drone, flight and working time are extended.

In addition, Liquid Gas can be stably reformed to hydrogen or carbon monoxide inside the electrode even when the drone's power load changes significantly. Since it is driven by a general-purpose and easy-to-carry Liquid Gas, it is expected to contribute to the fields of logistics, infrastructure inspection, disaster response, etc. even in areas before hydrogen infrastructure development.

Source: Elcogen





Chapter Three

Roadmap

3.1. Market Outlook on Technology

There are many technological advancements, mainly focusing on the mass manufacture of SOFC. Below are presented some developments in fuel cell technology.

Alkaline Fuel Cells (AFC)

AFCs can be produced relatively inexpensively as they do not use precious metals in their electrodes. However, unlike other fuel cells, carbon dioxide can create serious performance degradation. Consequently, the perceived attractiveness of the technology is diminishing and very few manufactures are actively developing the technology particularly in the U.S.A.

Phosphoric Acid Fuel Cells (PAFC)

PAFC are the most commercially established fuel cell in the market. However, much of the development of these fuel cells is mostly appropriate for larger-scale applications and due to raw material costs, extensive and mass Liquid Gas fuel cell production seems unlikely in the near term.

Molten Carbonate Fuel Cells (MCFC)

MCFCs are a high-temperature technology and are expected to operate at up to 50% electrical efficiency and this high efficiency offers fuel cost advantages in prime power applications. The high-temperature operation is ideal for industrial combined heat and power applications, but this high temperature also leads to a decrease in the durability of the fuel cell components in today's products. Manufacturers are currently exploring new materials and designs, which will increase the cell life without decreasing performance. While the MCFC internal reformation is capable of handling Liquid Gas, doing so requires different operating conditions than those for natural gas. These large applications generally have large fuel needs and have natural gas readily available making natural gas an obvious fuel choice. To enter this market, it would be up to the LPG industry to encourage MCFC manufacturers to develop the systems and specifications to operate at maximum efficiency using Liquids Gas.

Solid Oxide Fuel Cells (SOFC)

The SOFC holds a large market share of the competing fuel cell technologies. The SOFC is a high-temperature fuel cell, and this operation temperature also makes the internal reformation of fuels possible. Additionally, high-temperature operation removes the need for precious metal catalysts, which offers cost benefits. The SOFC is anticipated to have electrical efficiencies of 50% to 60% in Distributed Generation (DG) applications, which will provide lifecycle cost advantages in prime power uses. It should also be noted that SOFCs are the most sulphur-resistant fuel cell technology. While the SOFC internal reformation should be capable of handling Liquid Gas, the same issue of fuel choice applies here, as with MCFC applications. The earliest products in this technology class are in the 150-kW range. The high-temperature internal reformation process increases start-up times and makes load following more difficult.

Consequently, the units are more suited to supplying base load power. The high-temperature operation is ideal for industrial combined heat and power applications, but this high temperature also leads to a decrease in the durability of the fuel cell components. SOFC with Liquid Gas is available at a large scale.

Proton Exchange Membrane (PEM) Fuel Cells

Based on the rural market penetration of the Liquid Gas industry, the stage of development of the PEM technology, and its operating characteristics, the PEMFC offers the best opportunity to increase Liquid Gas sales. PEMFCs are the most common type of fuel cell being developed. PEMFC offers a variety of advantages to the market. It operates below 95ºC, which makes it ideal for mobile applications. This low operating temperature facilitates fast unit start-up times. This quick start capability should help PEMFCs enter the standby power market. One of the most attractive characteristics of the PEMFC is its ability to handle transient or fluctuating loads. The PEMFC provides high quality partial load operation, meaning its efficiency improves at lower load levels, and is relatively constant down to one quarter of the unit's rated capacity. This translates to good power quality in load following conditions. These qualities will make the PEMFC desirable in stand-alone applications, high quality power applications, and applications serving transient loads. PEMFCs are relatively simple to manufacture, which should facilitate cost reductions when they reach mass production. Mass production will be necessary to enter the mainstream market. Based on the rural market penetration of the Liquid Gas industry, the stage of development of the PEMFC technology, and its operating characteristics, the PEMFC offers the best opportunity to increase Liquid Gas sales however ban on perfluorinated and polyfluorinated chemicals (PFAS) under discussion will be a drawback.

Liquid Gas-powered Solid Oxide Fuel Cells – Case Study

SOFCs produce considerable temperatures as part of the electrochemical process. That fact makes it possible to integrate a reformer with a fuel cell to produce hydrogen at the source. This means fuel cells using already low-carbon Liquid Gas can chemically produce hydrogen. Traditionally, a solution like this would add significant costs and additional complexity but a commercially attractive approach has now emerged with a novel fuel cell architecture that makes it possible to use gaseous fuels like Liquid Gas without the need for a reformer.

Adelan Ltd., the microtubular SOFC (mSOFC) uses an ingenious internal structure to produce hydrogen from Liquid Gas. mSOFCs offer a dependable and reliable source of electricity in even the most remote locations so long as an appropriate fuel can be sourced. Furthermore, the ability of this technology to use almost any clean fuel offers considerable opportunity for immediate and widespread fuel cell uptake.

Liquid Gas SOFC technology :

- **Available for deployment at megawatt-scale today.**
- **Enables renewable available fuels like Liquid Gas.**
- **High reliability, low maintenance costs after continuous operation.**
- **Ecological approach when combined with Renewable sources.**

3.2 Barriers to Growth

There are several specific barriers which determine the size of the market opportunity. Key issues are highlighted below.

- The capital cost of fuel cells is likely to remain high during the early years of market development.
- Some of the currently available fuel cell technologies are still in the prototype stage and not yet validated.
- The manufacturing cost of catalysts is very high.
- Hydrogen, which is the main fuel and driver for fuel cells, is expensive to produce and not widely available this creates low interest for further investment from stakeholders.
- Liquid Gas fuel cell systems have some difficulty following load demand fluctuations in transient load applications. Currently, overcoming this weakness requires the utilisation of alternatives such as battery banks, which add cost.
- The unregulated presence of sulphur in Liquid Gas places added demands on reformers for low-temperature (PEM) fuel cells, as the system must be over engineered to handle varying levels of sulphur. While this is not technically a problem, it does make the reformers more expensive and potentially increase the frequency of maintenance. However, ECHA's Committee for Socio-Economic Analysis (SEAC)'s support for a gradual ban on per- and polyfluoroalkyl substances (PFAS) will impact development and investment of the PEM fuel cells.
- Other elements found in Liquid Gas such as propylene, ethane, and butane also present technical challenges in the reformation process. Varying levels of ethane and butane can be accommodated as well, though they may lower the throughput of the reformer.

3.3 Market Opportunities

Due to its low carbon potential, fuel cell power is likely to be central to the future energy mix of many modern economies. Fuel cells are a viable solution for cities to reduce their emissions and realise their green energy transition.

According to the Global Fuel Cell industry report, the global market for fuel cells is expected to reach USD 14.6 billion by 2027. The top destinations in this regard are the USA, China, Japan, and Korea, while the Netherlands and France stand out in Europe.

Fuel cells have numerous competitive advantages, which should enable the technology to expand its market.
As the cost of fuel cells comes down and reliability increases, market opportunities for Liquid Gas-powered fuel cells will continue to grow. The use of fuel cells in CHP applications promises to further increase and broaden their adoption. For instance, the exploration of using SOFCs in the trucking industry to power the refrigeration elements could prove to be an attractive opportunity to drive the sale of Liquid Gas. The development of residential fuel cell parks, which supply whole neighbourhoods with power and reduce congestion on the transmission system, maybe another opportunity. Below are highlighted opportunities for the Liquid Gas fuel cell industry. The Liquid Gas industry should focus on high-value fuel cell applications. Such applications should avoid direct competition with low-cost grid electricity or natural gas.

BioLPG can further reduce the carbon footprint for customers and towards transition to net zero.

3.3.1 Residential and small-scale CHP

Combined heat and power (CHP) systems using Liquid Gas Fuel Cells can be deployed in different use cases for local heat and power provision. Micro-CHPs (mCHPs) for residential are the most advanced market segment to date.

Liquid Gas fuel cells can have a good potential for CHP applications, more specifically:

Existing residential customers. These homes normally use photovoltaic systems (PV) with batteries and backup generators as their primary source of power. The typical PV system averages about 2.5 kW. The typical backup generator is 4-12 kW. Potential Liquid Gas fuel cells can replace the PV system or just the generator. Given the peak load requirement of a household, fuel cells will likely be combined with battery storage to meet peak loads. Because of the quiet operation and emission-free operation of fuel cells, it is possible that many customers will be willing to switch to a fuel cell generator. The likely prospects in this group have a less reliable power supply, perhaps because they are on the edge of the electric grid, requiring local supplemental or backup power generation. Currently, many of these potential customers generate power on-site using reciprocating engine generators or must incur line extensions, which can be costly. Liquid Gas fuel cells offer these rural customers an efficient and environmentally friendly alternative source. Liquid Gas fuel cells also have additional properties as a distributed power generation source that can be useful to rural utilities to mitigate shortages and provide an alternative to costly expansion of the power distribution system. Liquid Gas fuel cells will compete with more clean forms of energy, such as photovoltaic (PV) systems.

Remote new construction. In this case, a Liquid Gas fuel cell could serve as an alternative to expanding the power grid to meet the needs of remote customers and could potentially serve a range of facilities, such as a residential neighbourhood or farm. This scenario could create a market for larger-capacity fuel cells and thus hold the potential for greater economies of scale.

3.3.2 Backup Power Systems

Safety-critical infrastructure worldwide has a need for constant reliable power because a loss of power can cause significant financial losses. These industries include data centres, brokerage operations, financial transaction centres such as credit card sales authorisation centres, hospitals, airports, fire stations, wastewater treatment plants, rail signals, crossings, telecommunications centres airline reservation operations, etc. For these businesses, consistent, reliable power is more valuable because the loss of power causes greater financial harm to businesses than any increased cost of electricity. These units are installed to provide service when power is out or when there are fluctuations in voltage or frequency. Typical backup units are 40-80 kW and are generally used exclusively for backup generation.

Other advantages of fuel cells for backup power include:

- Operating efficiencies are around 50%.
- Scalable and modular to operate in parallel.
- Wider operating temperature range (-5^{O}C to 50^{O}C).
- Indoor or outdoor use with a minimal footprint.
- Longer life with no moving parts.

3.3.3 Auxiliary Power Units (APUs)

Liquid Gas fuel cells can be used in Auxiliary Power Units (APUs) to provide onboard electricity and heat in various applications. APUs are secondary power sources, typically used in vehicles, aircraft, and other mobile or stationary settings, to supply electricity, heat, or air conditioning independently of the main power source. Some examples include:

Automotive Applications: Liquid Gas fuel cells can be used as APUs in automotive settings, providing auxiliary power for electric vehicles (EVs) or traditional internal combustion engine vehicles. In EVs, an APU with a Liquid Gas fuel cell can act as a range extender, charging the vehicle's battery when needed, thereby alleviating concerns related to range anxiety.

Truck and Transport Industry: Liquid Gas fuel cells can serve as APUs in trucks and other commercial vehicles. They can power onboard systems, such as air conditioning, heating, and electronics, without the need for the main engine to run continuously during rest stops or overnight stays. This helps reduce fuel consumption and emissions.

Marine Applications: Liquid Gas fuel cells in APUs can be used in marine environments to provide auxiliary power for boats and ships. This is particularly beneficial during periods when the main engine is not in use, such as when the vessel is docked or anchored.

Construction and Industrial Equipment: Liquid Gas fuel cells can be integrated into the APUs of construction and industrial equipment, providing auxiliary power for lights, tools, and other electrical systems. This can contribute to energy efficiency and reduced emissions on job sites.

The truck APU market represents a very interesting market opportunity for Liquid Gas fuel cells. A typical class 8 truck idles approximately 1,800 hours per year. This excessive idling occurs when truckers leave their engines running to power their sleeper cab conveniences, such as air conditioning and television, or to provide power to the large refrigerator units for trucks carrying temperature-sensitive loads. This idling has a tremendous financial impact on the trucking industry. According to the EPA, idling trucks will consume $1.0 billion in diesel fuel and produce 11 million tons of CO_2 and approximately 180,000 tons of NOx per year. As fuel cells provide better electrical efficiency than an idling truck engine, Liquid Gas costs to power a fuel cell APU could be lower than the diesel fuel costs required to keep the engine running. Use of an APU also eliminates significant wear and tear caused during idling, and therefore, provides another financial incentive to use an APU. Additionally, many states in the USA are now offering grants or rebates for NOx emission reduction technologies. Texas is currently paying roughly $5,000/ton of NOx reduced.

3.3.4 Commercial and Industrial CHP

Upscaled CHP systems can be used in larger public or commercial buildings (e.g., office buildings, public schools, etc.). They can also be deployed for industrial use to replace less efficient turbines or combustion systems. Due to the different operating temperatures of fuel cells, they offer varying opportunities for combined heat and power (CHP) applications. While PEM fuel cells operate at lower temperatures, they can provide sufficient waste heat for use in operations that coincide with hot water demand, such as hot water heating. The high-quality waste heat and energy generated by these fuel cells can be used for heat exchange systems for cooling and refrigeration as well as industrial applications. Additionally, because large industrial customers can negotiate time of use rates, DG CHP can be used to offset electricity demand during high-priced peak load hours. This potential opens vast markets such as restaurants, warehouses, supermarkets, and schools.

3.3.5 Remote and Off Grid Areas

In remote or off-grid areas where access to conventional power sources is limited, Liquid Gas fuel cells can serve as a reliable and independent power solution. Off-grid power, and power generation sets are additional fuel cell application areas in the stationary sector and can also provide off-grid power supply for remote areas such as islands, mountain refuges, industrial sites, mining facilities, and telecommunication infrastructures. Liquid Gas fuel cell power generation sets offer a reliable power source for the remote operation of smaller applications (e.g., generators for construction, and cooling for refrigerated containers). Scientific research stations in remote locations, such as polar regions or deserts, can use Liquid Gas fuel cells to meet their energy needs. Stations dedicated to environmental monitoring, such as air quality monitoring or wildlife observation, can utilise Liquid Gas fuel cells for continuous and autonomous power supply in remote areas.

3.3.6 Telecommunication infrastructure

A very interesting market for Liquid Gas fuel cells is the telecommunications industry. Telecommunications providers rely on backup power to maintain a constant power supply, to prevent power outages, and to ensure the operability of cell towers, equipment, and networks. The backup power supply that best meets these objectives is fuel cell technology.

Control Office Facilities: The major wireless communications companies are already exploring the potential of fuel cells to meet the power needs of these towers, especially in remote areas. The typical facility requires 100–300 kW. Fuel cells that effectively employ CHP systems could be a cost-effective source of prime power for many of these remote facilities. PAFC, MCFC, and SOFC seem to be the leading candidates to fill this market niche.

Relay Stations: These towers require about 25-40 kW of power. As many of these towers are in remote locations, it may be practical to use Liquid Gas fuel cells rather than pay the cost of building feeder lines to interconnect with the electric grid.

Battery Replacement: Telecommunications towers must have at least four hours of emergency backup power, typically batteries, in case of power loss. Small fuel cell units, approximately 5 kW, are needed as a cost-effective and reliable replacement for these emergency backup battery systems. As these systems are only required to have the capacity to operate four hours per year, this appears to be a market for the Liquid Gas industry.

3.3.7 Forklifts or Material Handling Vehicles (MHVs)

Forklifts are the largest single type of fuel cell operated vehicle in use today. In USA, there are already in use more than 15,000 and Japan plans to have 30,000 fuel cells powered MHV's in use by 2030.

Forklift represents a very interesting market opportunity for Liquid Gas fuel cells for many reasons. Most indoor forklifts are electric, which require expensive batteries and extensive down time for recharging. Internal combustion engines currently power most of the non-electric forklifts so Liquid Gas fuel cells are a logical choice once they are price competitive. The forklift market makes up the largest market for electric vehicles worldwide. Many of these trucks operate 24 hours a day, seven days a week, making this a potentially lucrative niche market for Liquid Gas fuel cells.

3.3.8 Recreational Vehicles

The Recreational Vehicle Industry Association estimates RV represents one of the largest markets for small-scale DG. RV ownership has increased over 62% in the last twenty years with a record 11.2 million RV owning households. Additionally, 9.6 million families plan to buy an RV within the next five years. RVs are typically equipped with 5-20 kW systems for air conditioning, electric ranges, power lights, etc. The units are typically fuelled by diesel or gas, from the same fuel source as the engine. Liquid Gas is often used for heating and cooking and could be used to power a fuel cell generator. Additionally, Liquid Gas is available at most of the larger RV rest stops and camping areas.

3.3.9 Boat Market

Liquid Gas-powered fuel cells in the boating industry offer attractive characteristics. The quiet, reliable, emission free operation is a huge potential draw for consumers. Boats over 30 feet are typical candidates for generators. These generators range between 5-30 kW in size. Boats frequently utilise Liquid Gas for heating and cooking applications so adding generation to this list is feasible. It is worthwhile to note that some vessels are now using Liquid Gas propulsion systems. Boats in this sector of the market have a transient load, which depends on what appliances are running from the generator, fuel cells with internal batteries are expected to handle these loads following requirements.

3.3.10 Portable Power Systems

Portable Liquid Gas fuel cells are used for various applications, such as camping, outdoor events, and emergency situations. These compact systems provide a convenient and clean power source in locations without access to traditional electricity.

3.4 The Way Forward

This report is a snapshot in time. There have been decades of R&D, investment, testing, and innovation by countless government agencies, companies, universities, laboratories, research facilities, and customers, all working towards the common goal of a decarbonised energy network that includes fuel cell technologies.

To increase the adoption of Liquid Gas fuel cells in the market, a combination of strategic actions, partnerships, and advocacy efforts is essential. Here are some next steps and recommendations:

In the years ahead, efforts to achieve the commercialisation of different kinds of fuel cell applications must be stepped up in the Liquid Gas industry. Although several fuel cell applications are readily available for deployment today, others still require further technological development. For all applications, achieving substantially higher deployment volumes to cut costs and drive commercialisation is the main challenge to overcome in the coming years, mainly in Europe.

Policy Advocacy

- Engagement with policymakers and key decision-makers (EU, national, and local) to advocate for supportive regulations, and incentives that encourage the adoption of Liquid Gas fuel cells.
- Participation in policy discussions and alignment with government initiatives can create a favourable market environment. Lawmakers must understand the advantages, of Liquid Gas particularly its superior environmental performance, to ensure proper consideration in environmental regulations.
- Development of an overall EU fuel cell sector strategy or roadmap.

Partnerships and Collaborations

- Intensified dialogue with manufacturers and stakeholders on further market development needs.
- Collaboration with manufacturers on how to improve the commercial availability of LPG fuel cell applications and accelerate further market development.

Pilot Programmes and Demonstration projects

- Identification of projects or initiatives showcasing the effectiveness and benefits of Liquid Gas fuel cells in various applications, such as residential CHP systems, backup power, and off-grid solutions. Successful demonstrations can build confidence among potential users and investors.
- Investigation on additional Liquid Gas fuel cell opportunities in the 100+ kW market.

Advancements in Fuel Cell Technology

- Investment in research and development to enhance the efficiency, durability, and performance of Liquid Gas fuel cells. Continuous technological advancements will make Liquid Gas fuel cells more competitive and appealing to a wider range of applications.
- Work with reformer manufacturers to ensure that the reformers are developed to use Liquid Gas.

Market Diversification

- Identification of new market segments and applications where LPG fuel cells can provide unique value. This may include targeting specific industries, regions, or niche applications that align with the strengths of LPG fuel cell technology.
- Promotion of Liquid Gas fuel cell forklift and fuel cell APU development.

Cost Competitiveness

- Adoption of Liquid Gas fuel cells across sectors would lead to economies of scale and a decline in cost. Large-scale fuel cell production and sufficiently widespread sales would make these technologies more competitive.
- Deployment of Liquid Gas fuel cells across multiple sectors in parallel will help drive such scale economies and synergies. Liquid Gas fuel cells can play an important role in decarbonising a wide range of sectors, including shipping, power, data centres, steel, and gas distribution.

Communication and Customer Testimonial

- Implementation of targeted communication campaigns to raise awareness among businesses, consumers, and policymakers about the benefits and applications of Liquid Gas fuel cells.
- Dissemination of information through various channels, including workshops, webinars, and industry events.
- Collection and showcase success stories and testimonials from satisfied customers who have adopted Liquid Gas fuel cells.
- Communication of positive feedback and real-world examples can build trust and credibility among potential investors. Fuel cell manufacturers should view Liquid Gas fuel cells as attractive sources of revenue that are strategically important because of their growing numbers.

Integration with Renewable LPG

- Promotion of rLPG, which is produced using renewable energy sources. This aligns with sustainability goals and can enhance the environmental profile of Liquid Gas fuel cells.

By combining these recommendations, companies and stakeholders in the LPG fuel cell industry can work collaboratively to increase awareness, address challenges, and foster a conducive environment for the widespread adoption of Liquid Gas fuel cells in various sectors.

The momentum behind fuel cell development is strong. However, faster action is required to create demand for low-emission Liquid Gas fuel cells and unlock investment that can accelerate production scale-up and bring down the costs of fuel cell technologies for producing and using Liquid Gas.

While Liquid Gas fuel cell market growth is currently slow, continued research and the rapid pace of development will create a vibrant market for fuel cells.

Global LPG industry because it has the opportunity to leverage its existing infrastructure, its existing knowledge, and its existing workforce to move other molecules, create new lines of business, and, in some cases, lower the carbon footprint. LPG companies making investments in the hydrogen space and in other markets can leverage their knowledge of logistics and how to move other products, particularly Liquid Gas products.

References

- https://www.energy.gov/eere/fuelcells/fuel-cell-basics
- https://www.fchea.org/fuelcells
- https://dokumen.tips/documents/shell-hydrogen-study-energy-of-the-future-and-fuel-cell-technology-uwe-schabla.html
- https://www.lpgasmagazine.com/renewable-fuel-producer-hydrogen-opens-opportunities-for-propane/
- https://www.fchea.org/fuelcells
- https://sunfire-fuel-cells.de/en//
- https://thechemistrynotes.com/fuel-cell/
- https://www.powermag.com/understanding-fuel-cells-and-their-role-in-the-green-energy-revolution/
- https://www.energy.gov/eere/wipo/downloads/fuel-cells-backup-power-telecommunications-facilities-fact-sheet/
- https://www.doosanfuelcell.com/en/media-center/medi-0101_view/?id=33
- https://fuelcellsworks.com/news/korea-new-plant-started-with-lpg-lng-dual-model-of-doosan-fuel-cell//
- https://www.rrapier.com/2020/06/how-propane-can-help-transition-to-a-low-carbon-future/
- https://americanhistory.si.edu/fuelcells/basics.htm
- https://sigens.de/en/what-is-a-fuel-cell/#:~:text=Due%20to%20their%20low%2Dmaintenance,electricity%20at%20the%20same%20time.
- https://www.lpgasmagazine.com/renewable-fuel-producer-hydrogen-opens-opportunities-for-propane/
- https://www.rrapier.com/2020/06/how-propane-can-help-transition-to-a-low-carbon-future/
- https://propane.com/environment/stories/propane-is-key-to-accelerating-clean-energy-fuel-celltechnology/#:~:text=Solid%20Oxide%20Fuel%20Cells%20(SOFC,propane%20can%20chemically%20produce%20hydrogen.
- https://www.fortunebusinessinsights.com/industry-reports/fuel-cell-market-100733

Abbreviations

AFC	Alkaline Fuel Cell
APU	Auxiliary Power Units
BOG	“Boil-Off” Gas
CO2	Carbon Dioxide
DMFC	Direct Methanol Fuel Cell
DG	Distributed Generation
ECHA	European Chemical Agency
kWh	Kilowatt hour
LNG	Liquefied Natural Gas
MFCs	Microbial fuel cells
MCFC	Molten Carbonate Fuel Cell
SOFC	Solid Oxide Fuel Cell
NG	Natural Gas
NOx	Nitrogen Oxides
PAFC	Phosphoric Acid Fuel Cell
PEMFC	Proton Exchange Membrane Fuel Cell
PM	Particulate Matter
RV	Recreational Vehicle
ZAFC	Zinc-Air Fuel Cell

Copyright

WORLD LPG ASSOCIATION
182 avenue Charles de Gaulle
92200 Neuilly-sur-Seine - France
www.wlpga.org
@WorldLPGAssoc
#ExceptionalEnergy