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Review Paper

Grand Challenges in Fuel cell Technology towards Resource Recovery

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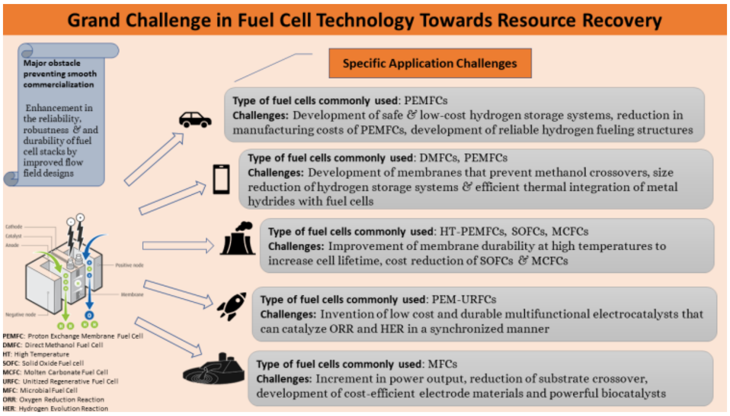
ABSTRACT

Fuel cells are perceived as promising candidates for bridging the gap between the future clean energy path and the current 'dirty energy' path. Amongst a miscellany of fuel cell types, PEMFCs are utilized in several applications by virtue of their greater energy density and ecofriendly nature (if hydrogen is the fuel). Certain fuel cell types such as the PEMFCs can be employed to not only generate power, but also as electrolyzers to harvest oxygen and hydrogen for space applications. The recovered oxygen can be used to meet oxygen requirements in the spacecrafts while the recovered hydrogen can be used to generate electricity. Other types of fuel cells (e.g., the microbial fuel cell (MFC)) simultaneously works to treat the wastewater and produce electricity. However, there are several challenges that hinder fuel cells from reaching their full potential. Large scale commercialization still requires the unraveling the technical issues that dent their reliability, durability, and robustness. Hence, major challenges in resource recovery remain to exist, such as the high cost, shortage of suitable noble catalysts, and reduced lifespan. The hurdle of technical problems should be overcome first to gain public trust; thereby, catalyzing the expansive commercial roll out of fuel cells and more intensive research towards resource recovery can be suitably promoted.

KEYWORDS: Fuel cells; Advantages; Energy; Challenges; Hydrogen Energy.

GRAPHICAL ABSTRACT



Grand Challenge in Fuel Cell Technology Towards Resource Recovery

Major obstacle preventing smooth commercialization

Enhancement in the reliability, robustness & and durability of fuel cell stacks by improved flow field designs

Specific Application Challenges

Type of fuel cells commonly used: PEMFCs
Challenges: Development of safe & low-cost hydrogen storage systems, reduction in manufacturing costs of PEMFCs, development of reliable hydrogen fueling structures

Type of fuel cells commonly used: DMFCs, PEMFCs
Challenges: Development of membranes that prevent methanol crossovers, size reduction of hydrogen storage systems & efficient thermal integration of metal hydrides with fuel cells

Type of fuel cells commonly used: HT-PEMFCs, SOFCs, MCFCs
Challenges: Improvement of membrane durability at high temperatures to increase cell lifetime, cost reduction of SOFCs & MCFCs

Type of fuel cells commonly used: PEM-URFCs
Challenges: Invention of low cost and durable multifunctional electrocatalysts that can catalyze ORR and HER in a synchronized manner

Type of fuel cells commonly used: MFCs
Challenges: Increment in power output, reduction of substrate crossover, development of cost-efficient electrode materials and powerful biocatalysts

PEMFC: Proton Exchange Membrane Fuel Cell
DMFC: Direct Methanol Fuel Cell
HT: High Temperature
SOFC: Solid Oxide Fuel cell
MCFC: Molten Carbonate Fuel Cell
URFC: Unitized Regenerative Fuel Cell
MFC: Microbial Fuel Cell
ORR: Oxygen Reduction Reaction
HER: Hydrogen Evolution Reaction

HIGHLIGHTS

- Fuel cells are promising candidates for power generation with zero to low carbon footprint.
- Fuel cells are ideal for stationery and transportation sectors due to numerous advantages.
- Large scale commercialization still requires the unraveling the technical issues such as durability, and cost.

1. Introduction

Transition towards the generation and conversion of clean energy requires the improvement of current renewable energy-based technologies. Increasing dependence and application of fossil fuels, initiated by escalating world energy demands, have resulted in severe environmental problems including climate change and global warming (Tawalbeh et al., 2022a). Importantly, repercussions of fossil fuel emissions are said to be "unlocalized" where even though the developed nations are responsible for the emissions, it is the developing nations that suffer as evidenced by recent devastations in South Asia (Perera, 2018) (Khokhar, 2022). Fuel cells have immense potential in catalyzing the shift towards cleaner energy sources and can also be utilized as efficient power generators and converters. Besides environmental benefits,

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such as reducing CO2 emissions, fuel cell systems are known to operate with greater efficiencies as well (Akinyele et al., 2020).

Fuel cells work on the basic principle of directly converting the chemical energy of the fuel into electrical energy via redox reactions. Hydrogen, methanol, and hydrocarbons are mostly used as fuels, that are fed to the anode, while oxygen and sometimes halogens are used as oxidants and fed to the cathode (Sazali et al., 2020). Hydrogen fuel cells are receiving special attention since they produce water as biproducts making them ecofriendly sources (Tawalbeh et al., 2022b). The fuel cell was first described by Sir William Groove in 1839 in which hydrogen and oxygen were utilized to produce electricity using platinum electrodes (Thomas et al., 2020). Since then, a variety of fuel cells utilizing various fuels and electrolytes that work on a range of operating temperatures have been developed. Table 1 (Qussay et al., 2021) (Menshikov et al., 2021) (Ferriday and Middleton, 2021) (Xu et al., 2022a) lists and compares the common fuel cell types. Additionally, some fuel cells can also recover and produce valuable resources and products whilst also generating energy such as the microbial fuel cell (MFC). Even though, fuel cells are extremely promising candidates to act as the bridge between current fossil fuel dependence and the future clean energy world there are several challenges that prevent their wide-spread commercial roll out and their utilization in resource recovery. This article aims to address the current status of fuel cells in the market today, explain the major large scale technical challenges, and finally state specific application challenges namely in the transportation, portable, stationary, space and wastewater treatment fields.

Table 1
Different types of fuel cells (Qussay et al., 2021; Menshikov et al., 2021; Ferriday and Middleton, 2021; Xu et al., 2022)

Fuel cell type	Fuel	Electrolyte	Operating temperature	Applications
Polymeric Electrolyte Membrane Fuel Cells (PEMFCs)	Pure Hydrogen, Methanol, Ethanol Formic acid (Menshikov et al., 2021)	Solid Polymeric Membrane (Usually Nafion Membranes)	60-120ºC	Transportation, Portable, Stationery and Space
Alkaline Fuel Cells (AFCs)	Pure Hydrogen, Liquid Hydrocarbons	Sodium Hydroxide, Potassium Hydroxide	40-70ºC (Ferriday and Middleton, 2021)	Space, Transportation and Stationery (standalone power generators)
Phosphoric Acid Fuel Cells (PAFCs)	Hydrogen, Hydrogen rich gases	Phosphoric Acid	150-220ºC	Stationary (Combined Heat & Power)
Molten Carbonate Fuel Cells (MCFCs)	Natural Gas	Molten Lithium and Potassium Carbonates	550-700ºC	Stationary (Combined Heat and power), Transportation (Trains and boats)
Solid Oxide Fuel Cell	Hydrocarbons, Alcohol, Solid Carbon, and Ammonia (Xu et al., 2022)	yttria-stabilized zirconia (YSZ)	600-1100ºC	Stationary (Cogeneration and Standalone Power Generators), Transportation (Trains & Boats)

2. Current Status of Fuel Cells

Fuel cell technology has undergone rapid advancements since its discovery, particularly in the development of construction materials and the fuel type employed. Such advancements have enabled the application of fuel cells in widespread industries including transportation, power generation, medical and wastewater treatment (Fan et al., 2021) (Mendonça et al., 2021) (Jeon et al., 2019) (Dwivedi et al., 2022). In the transportation sector, PEMFC type is dominating because of their all-solid structure, and the high energy density by weight of hydrogen gas (Osman et al., 2022). This makes them suitable for heavy weight carriers such as buses. As of 2021, there are more than 60 fuel cell buses in Europe and about 30 fuel cell buses operated in China in 2017 driven by the Chinese New Vehicle program (Fan et al., 2021). Additionally, Foshan in China can produce 5000 fuel cell buses per year making it the largest fuel cell bus project (Kendall, 2018). In the power generation sector, SOFCs are used as standalone power generators or in hybrid with other power generators because they can tolerate higher operating temperatures, about 1000oC, thereby making them preferable specially when using fossil-based fuels such as methane, butane, and gasoline (Mendonça et al., 2021). In the previous systems, internal reforming of the fuel is possible. SOFCs also exhibit the advantage of no noise pollution, since there are no moving parts involved. In 2017, Kyocera, a Japanese company used 700 W cell stacks in the pursuit of the first 3 kW SOFC for institutional cogeneration (Mendonça et al., 2021). The utilization of fuel cells as portable energy generating devices is also emerging because they offer the luxury of compact designs and light weight, thus, having the ability to produce greater amount of energy compared to the battery. Passive direct methanol fuel cells (PDMFC) are being utilized in hearing aid devices and have recently been introduced into the market (de Sá et al., 2022). High energy conversion efficiency, high energy density, simple construction and operation provides them with an edge over battery-based devices. In conclusion, fuel cells are viewed as one of the devices towards the transition into cleaner energy sources and reducing carbon emissions. However, there are major technical challenges that still limit their widespread commercialization as discussed in the coming sections.

3. Large Scale Technical Challenges

It is important to address the technical hurdles of fuel cells to better appreciate reasons as to why the fuel cells have not yet achieved the same level of trust as IC engines. Compared to individual cells, stacks have lower reliability, and durability when the same material type and catalyst is used as the individual cell. The degradation of materials and catalysts in the stacks, sparked by poor water management and thermal issues in the case of PEMFC for example, and the non-homogenous contact between cathode and interconnectors in the case of SOFC (Wu et al., 2020) (Fang et al., 2020). Thus, overshadows the main reasons as to why scalability problems are emerging. In the case of hydrogen fuel cells, uneven flow distribution of reactants is one of the major problems that is prohibiting large-scale technical success. This issue arises from the difficulty of keeping all the cells of the stack at a uniform flow rate and pressure drop (Wang et al., 2018). The failure of any individual cell may occur due to flowrates dropping below or elevating above design values leading to non-uniform reaction kinetics. This results in temperatures either increasing or reducing significantly causing excessive water production and ultimately flooding in the cell (Nimir et al., 2021).

Excessive increase in temperatures accelerates the membrane material degradation (Nauman et al., 2022). Mechanical failure arises from the creation of hotspots. These mechanical failures may in turn lead to cell blockages causing a cascading effect on the other cells in the stack because they start to experience uneven reactions as well. Thus, the failure of an individual cell ultimately aggravates the problem leading to overall stack failure. Therefore, the reliability, durability and robustness of the fuel cell stack is considerably reduced compared to the individual cell. It is imperative that attention be shifted to the development of flow field designs in pursuit of ensuring uniform reactants flow to all the cells.

3.1. Specific Applications' challenges

3.1.1. Challenges in Transportation

PEMFCs dominate the automotive industry due to several advantages as previously discussed in this context. Nonetheless, development of safe and low-cost hydrogen storage systems is still one of the main challenges faced by hydrogen based PEMFCs (Al-Othman et al., 2022). Additionally, there is a scarcity of reliable hydrogen fueling infra structures around the world (Mohammed et al., 2019) (Cigolotti et al., 2021a). A reliable hydrogen fueling network is extremely vital because PEMFCs rely on high purity hydrogen for durable and efficient functioning (Wang et al. 2021). Besides this, the high cost of PEM fuel cell systems in electric vehicles is another major challenge (Thompson et al., 2018). Battery electric vehicles have been gaining attention due to the decrease in lithium-ion battery costs (Cullen et al., 2021). With stiff competitions from other technologies, it is crucial that fuel cells also undergo capital cost reductions soon to ensure their market presence. Finally, cold start issue is another applicational challenge where, at temperatures are below 0oC, water freezes, that occupies pore spaces and blocks the supply of fuel; thereby, damaging fuel cell components (Kocher et al., 2021). One of the available ways to mitigate this issue is by inserting a hybrid battery to warm up the stack allowing liquid water to flow, when temperature rises above 0oC, via capillary action (Wang et al., 2021).

3.1.2. Challenges in Portable Applications

Among the types of PEMFCs, direct methanol fuel cells (DMFCs) are utilized in the portable power generation market because of their high energy density, silent operation, immediate refilling and self-discharge, long operational duration (Youssef et al., 2018). They can be employed in any portable electronic devices that work on batteries such as laptops, mobile phones and ear pods. In terms of their application challenges, the efficiency of DEMFCs is deteriorated due to methanol crossover where the fuel permeates through the membrane reaching the cathode side causing a combustion reaction rather than an electrochemical reaction (de Sá et al., 2022). Once this happens at the cathode, oxygen reduction is also reduced, because methanol is blocking the catalyst active sites. Carbon monoxide poisoning of the catalyst also takes place due to the incomplete oxidation of methanol at the cathode which ultimately leads to a reduction in cell output. Alternative membranes can be employed to prevent crossovers (Yogarathinam et al., 2022).

Upcoming portable electric devices are expected to have reduced sizes; thereby, requiring high power densities. Fuel cells have undoubtedly the potential to meet the high-power density demand, but the current challenge lies in reducing the size of hydrogen storage systems to meet the market demand of upcoming portable electric devices. Metal hybrids appear to be promising solid state hydrogen storage materials that allow greater volumetric hydrogen storage densities to be reached (Andersson and Grönkvist, 2019). Simply, metals that can absorb hydrogen reversibly are termed as metal hybrids. Even though metal hybrids offer a safe, compact, and efficient method of gaseous hydrogen storage, but the efficient thermal integration with fuel cells is still a challenge given the exothermic and endothermic nature of absorption and desorption reactions (Han et al., 2020).

3.1.3. Challenges in Stationary Power Generation Applications

Hydrocarbon and renewable energy sources are currently promising to power isolated and remote areas (Mohammed et al., 2019). Applications involving combined heat and power generation (CHP), high temperature-PEMFCs (HT-PEMFCs), that operate at higher temperature ranges 100-200oC, are exploited instead of the conventional low temperature ones because of simple plate designs, greater tolerance to fuel impurities, rapid reaction kinetics, and superior water management (Xu et al., 2021) (Haider et al., 2021). Although the power production and efficiency of this fuel cell is high, their low durability sparked by the unsatisfactory performance of the membranes, at high temperatures, is major obstacle towards their mass-market roll out (Salam et al. 2020). The lifetime of the membrane directly effects the lifetime of the gasket, the catalyst, and the electrode plate. Hence, reduction in the durability of the membrane will also affect the durability of the aforementioned materials. With the current state of the art, elevated temperatures do not only cause PEM dehydration, but also the Nafion membrane itself degrades (Liu et al., 2019) (Legree et al., 2020) (Pistono and Rice, 2020) (Wu et al., 2020). Further operation at elevated temperatures, leads to further dehydration of the membrane causing increased transfer of hydrogen fuel that causes damage to the relevant materials; consequently, reducing the durability of the PEMFC overall.

Although high temperature membranes (e.g., Polybenzimidazole (PBI) based membranes) solve the problem of dehydration at elevated temperatures, the inevitable persistence of free radicals is major challenge that reduces the cell activity (Haider et al., 2021). A potential way forward is the utilization of acid-based membranes given their superior conductivity and high stability at elevated temperatures. Researchers attempted to develop novel membranes that exhibit high conductivity and thermal stability above 100oC rendering them highly attractive for operations at elevated temperatures (Alashkar et al., 2022). With regards to other fuel cell types, the primary barrier towards large-scale utilization, in this field, is high cost (Cigolotti and Genovese, 2021b). Although cost reductions are important, it is essential that ingenious marketing tactics also be employed such as starting with smaller stationary fuel cell systems before tapping on the large market to ensure developers are familiarized with problems encountered in emerging technologies allowing them to reduce the costs of such smaller systems first.

3.1.4. Challenges in Space Applications

NASA has long utilized fuel cells to power electronic devices and store energy in space shuttles (Baroutaji et al., 2019). Although solar energy is expected to be the primary source of energy to power shuttles in space, its transient characteristics deter it from continuously supplying power (Zhang et al., 2021). Power sources like batteries are heavy and carry the risk of toxic material leakage and explosions (Pu et al., 2021). Hence, fuel cells are promising candidates to replace existing batteries. Regenerative Fuel Cells (RFC) are utilized for space applications as renewable energy storage and converter devices because of their rapid startup and shutdown, high energy density, less self-discharge issues, ecofriendly nature, reduced environmental impact and long-life capabilities (Omrani and Shabani, 2019) (Gayen et al., 2021). The RFCs contain both water electrolysis cell and a fuel cell device. The fuel cell produces electricity and H2O by utilizing H2 and O2 for the redox reactions while the water electrolysis cell splits the H2O to regenerate the H2 and O2 in case PEM RFCs are used. Additionally, the generated O2 could be utilized as a secondary source to meet the oxygen supply needs of the spacecraft (Pu et al., 2021). More specifically, unitized RFC (URFC) are preferred because they utilize bifunctional electrocatalysts for oxygen electrodes to perform both the backward and forward reactions; consequently, requiring only one electrochemical cell and thus, reducing the spatial requirements and cost making them ideal for space applications (Wang et al., 2018) (Vincent et al., 2020).

The current electrocatalysts employed in URFCs, however, are limited to expensive noble metals namely, platinum and rhodium, which acts as a deterrent to their large-scale commercial roll out (Yu et al., 2020) (Zhou et al., 2018). Furthermore, there is an absence of materials, in the market, that can catalyze the reactions, namely the oxygen reduction reaction, and hydrogen evolution reaction in a synchronized manner (Zhang et al., 2019) (Yang et al., 2019). In general, the main challenge is to reduce the cost of the URFC by developing low cost, durable and efficient multi-functional electrocatalysts that will aid in reducing the complexity of catalyst layers (Peng et al., 2021). Finally, further studies are needed to analyze URFCs performance in extreme conditions in space of low temperature, pressure, and gravity to completely realize their potential in space applications (Pu et al. 2021).

3.1.5. Challenges in Wastewater Treatment

Microbial fuel cells (MFCs) are a novel type of fuel cells that can generate electricity and simultaneously eliminate pollutants from wastewater (Guo et al., 2020). Pollutants such as carbon, phosphorous, and nitrogen are first stabilized in MFC chambers after which the trapped chemical energy in these compounds is used to produce electricity (Tang et al., 2019). In terms of their structure, they contain a cathode and an anode that is separated by a semi-permeable membrane and utilize microbes that not only catalyze the release of electrons, from organic substrates, but also aid in transferring electrons to the electron receptors at the anode (Vishwanathan, 2021). Generally, sludge digesters are utilized in wastewater treatment plants to treat the waste and recover energy. However, with the utilization of MFCs, both the wastewater treatment and energy recovery take place in one unit. Compared to other wastewater treatment technologies, such as chemical treatment, aerobic filtration, anaerobic filtration membrane filtration, MFCs have advantages of energy recovery, valuable product recovery, reduced sludge production, lower operational costs, and superior resistance to environmental damages (Nosek et al., 2020). The main challenges with regards to large scale implementation of MFCs lie in increasing the power output, reducing the initial cost, ensuring stability of the power output, and reducing substrate crossover that reduces columbic efficiency (Koroglu et al., 2018). Further research should focus on the development of cost-efficient electrode materials and more powerful biocatalysts to increase efficiency (Tawalbeh et al., 2022c). Additionally, the application of automatic control systems should be investigated in pursuit of simplifying the process and increasing system reliability (Guo et al., 2020).

4. Final Remarks

Fuel cells have immense potential in catalyzing the transition towards cleaner energy sources. They are efficient energy generators and converters that can also be used to recover valuable resources. A common challenge noted in the above applications is the cost reduction. Cost effective electrode materials in MFCs and alternative PEM membranes should be researched to mitigate this challenge. In the stationary, portable, and transportation sectors fuel cells are ideal candidates to compete with other renewable technologies because of their high conversion efficiencies, quiet application, modular design, and light weight. However, their large-scale utilization is mitigated by the reduced reliability, durability, and robustness of stacks, even though, the same materials and catalysts are utilized. More effective flow field designs should be developed instead of researching on materials and catalysts to increase stack reliability and dependability. Finally, such technical challenges hinder the public from realizing their full potential towards resource recovery and hence investing less effort in adopting such technology. Overcoming large scale technical challenges of fuel cells will serve as an effective pathway to garner public trust in this emerging technology and further utilize it towards resource recovery.

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