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Using Fuel Cell Technology to Power Water Purification Systems: A Sustainable Solution for Clean Drinking Water

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ABSTRACT

The global water crisis, driven by population growth, the changing climate and pollution necessitates innovative solutions to ensure availability of safe drinking water. This study explores the integration of fuel cell technology with water purification systems as a sustainable and efficient solution. Fuel cells, converting chemical l energy to electric energy through electrochemical reactions, offer a clean, adaptable, and efficient power source. The study examines multiple cells classification, such as proton exchange membrane fuel cells (PEMFC) and solid oxide fuel cells (SOFC), and Microbial Hydrogen Powered Cell (MHPC), emphasizing their environmental benefits, energy efficiency, and off-grid capabilities. Fuel cell-based water purification leverages their ability to yield electrical output while enabling processes such as advanced membrane-based water treatment and electrochemical disinfection. Such implementations show efficiency improvements in remote or disaster-prone areas, providing reliable clean water with minimal emissions. Case studies, such as PEMFC-powered desalination plants in Kenya, highlight their transformative potential in addressing water scarcity and improving public health. Despite challenges like high costs, limited infrastructure, and hydrogen production constraints, advancements in technology and supportive policies are enhancing the feasibility of fuel cell-powered systems. This research underscores the role of fuel cell technology in achieving global water security and advancing the UN SDGs (Sustainable Development Goals) for clean water and affordable energy.

Keywords: Fuel Cell, Water Purification, Renewable Energy Integration, Electricity Generation.

1.0 INTRODUCTION

Fuel cells are advanced energy systems that convert chemical energy directly into electricity through electrochemical reactions. [1] In this process, hydrogen or hydrogen-rich fuels react with oxygen from the air, generating both electricity and heat as byproducts. While this is the core principle, variations exist depending on the type of fuel cell and the fuel source used. Unlike conventional combustion-based technologies, fuel cells offer higher efficiency and significantly lower emissions, making them a promising solution for clean and sustainable energy. With applications spanning micro power generation, backup power systems, stationary and distributed energy production, and portable power for transportation, military, and automotive uses, this technology is highly versatile. [2,3]

The concept of the fuel cell was first identified in 1838 by German scientist C. F. Schönbein. Building on this discovery, Welsh scientist Sir William Robert Grove demonstrated the first operational fuel cell in 1839. [4,5] A significant advancement came in 1939 when British engineer F.T. Bacon developed a 5-kilowatt stationary fuel cell. [6,5] Further progress was made in 1955 by W.T. Grubb, a chemist at General Electric, who enhanced the design by using a sulfonated polystyrene ion-exchange membrane as the electrolyte.[7,4] In 1958, GE chemist L. Niedrach contributed by devising a technique to coat the membrane with platinum, enabling it to serve as a catalyst for hydrogen oxidation and oxygen reduction.[8,4]

Figure 1: Illustrates the global challenge of water sanitation. [85]

Water purification is the process of removing harmful chemicals, biological contaminants, suspended particles, and gases from polluted water sources. [9,10] Its purpose is to make water suitable for specific uses. While the primary goal is often to produce safe drinking water, purification methods can also be adapted for applications in medicine, pharmaceuticals, industry, and chemical processing.[11,12] Common purification techniques include physical methods such as filtration, sedimentation, and distillation; biological treatments like slow sand filtration and activated carbon; chemical processes such as flocculation and chlorination; and the use of electromagnetic radiation, including UV light. These processes help eliminate or significantly reduce a variety of contaminants—ranging from suspended solids and microorganisms (like bacteria, viruses, algae, and fungi) to dissolved substances—that water may collect as it interacts with the environment after precipitation. [12] The acceptable parameters for drinking water quality are typically defined by national or global standards, outlining threshold limits for various contaminants according to the water's designated use.

As a fundamental necessity for all living things, water sustains plants, animals and human life alike. In fact, 71% of the earth is covered by water, freshwater occupies only 2.5% of the total water and is mostly stored as glaciers, ice caps, and groundwater. [13,14] Despite that, it is challenging to meet all human, animal and plant demand for freshwater. As the only viable source for drinking, agriculture, industry, and other critical uses, freshwater is indispensable. [15,16] Its availability ensures food security, livestock sustenance, industrial productivity, and the protection of biodiversity and environmental health.

Water scarcity has emerged as one of the most critical global challenges in modern times. It is defined as the condition when annual water availability drops below 1,000 cubic meters per capita.[15,17] Current estimates indicate approximately 2.2 billion people worldwide lack access to clean drinking water, with nearly 4 billion encountering acute water scarcity for at least one month annually.[15] This growing crisis stems from multiple interconnected factors, including rapid population expansion, climate variability, environmental contamination, and unsustainable water management. Projections suggest that by 2025, about 33% of the population in developing nations will confront extreme water deficits. [18,19]

With water resources becoming more heavily disputed in various regions, an increasingly higher proportion of normal flow of water is likely to be consumed, and the risk of shortages in periods of low flow will increase. For this reason, the need for additional storage as a proportion of the total water consumed will increase in the future.

As the global population continues to grow, the demand for freshwater increases. Urbanization exacerbates the problem, as cities often struggle to manage water resources effectively. In many regions, population growth is advancing faster than the infrastructure required to deliver safe water can be developed. Globally, the population increases by approximately 80 million annually. [15,19] Consequently, an additional 64 billion cubic meters of water must be secured each year to meet rising demand. [20,21]

2.Basic Principles of Fuel Cells

The electrochemical reaction between an oxidizing agent, usually oxygen, and a fuel, usually hydrogen, is the fundamental process of a fuel cell. An electrolyte, which keeps electrons apart while allowing ions to flow between the anode and cathode, is present throughout this reactive event. [22,4] Electrons produce electricity as they go across an external circuit. The only by-products of this reaction are water and heat, making it an environmentally friendly process.[22]

The fundamental unit of a fuel cell consists of an electrolyte layer sandwiched between porous anode and cathode electrodes. Unlike batteries, which store energy chemically, fuel cells generate electricity through continuous electrochemical reactions. These reactions occur when gaseous fuels (e.g., hydrogen) are supplied to the anode and an oxidant (e.g., oxygen) to the cathode.[4]

In acid-electrolyte fuel cells, the anodic reaction proceeds as follows. While fuel cells share some components with conventional batteries, they differ critically: batteries deplete their stored chemical reactants upon discharge, whereas fuel cells—functioning as energy converters rather than storage devices—can operate indefinitely with sustained fuel/oxidant input. Practical limitations arise only from material degradation (e.g., corrosion) or component failure.

2.1 Fuel Cells Technologies

A fuel cell operates as an electrochemical system that directly transforms the chemical energy stored in hydrogen or other fuels into electrical power. Various fuel cell technologies exist commercially, differentiated by factors such as their operational temperature thresholds, compatible fuel types, catalytic materials employed, and energy conversion efficiencies.[22] The main commercially available technologies include (Table 1):

Proton Exchange Membrane Fuel Cells (PEMFCs): Proton Exchange Membrane Fuel Cells (PEMFCs) are known for their compact size and high efficiency, making them ideal for use in vehicles and portable energy systems. These cells use a polymer electrolyte membrane and typically achieve efficiencies between 40% and 50%.[4]

Operating at around 80°C, they fall under the category of low-temperature fuel cells, which makes them well-suited for automotive and residential energy needs. Nonetheless, PEMFCs require highly purified fuel and rely on expensive platinum catalysts, contributing to their overall cost. Despite these limitations, PEM technology is capable of delivering sufficient power for both domestic and commercial applications under various environmental conditions. Additionally, hydrogen production through a chemical reaction involving water and sodium (NA) metal in PEM generators results in low emissions and minimal noise. [23,24] These fuel cells are also suitable for medium to heavy-duty vehicle applications. Their advantages include low operating temperatures, solid-state electrolytes, high power density, and robust durability and reliability. The performance of PEMFCs is influenced by their operating conditions, and mathematical modeling can be used to enhance performance predictions. When employed as a mechanical power source, PEMFCs experience dynamic loads that initially reduce voltage below steady-state levels, with gradual voltage recovery potentially causing performance degradation over time. [25,22] A diagram of the PEMFC system is shown below.

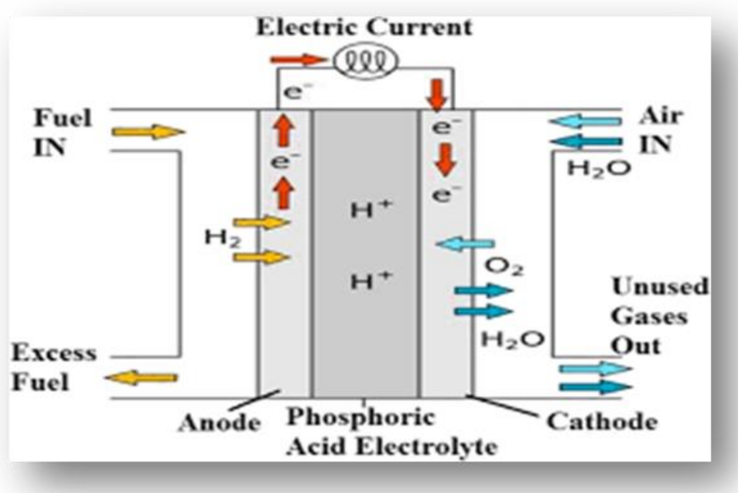

Figure 2: The Proton Exchange Membrane Fuel Cell. [86]

Solid Oxide Fuel Cells (SOFCs): Designed for high-temperature operation, they represent an ideal solution for large-scale power generation, offering high efficiency and fuel flexibility. Solid oxide fuel cells utilize a ceramic-based electrolyte composed of metal oxides (e.g., calcium compounds).[26] These systems achieve approximately 60% energy conversion efficiency while operating at extreme temperatures around 1000°C. [26] Although SOFCs represent the most environmentally benign energy conversion technology, their implementation costs remain significantly higher than conventional alternatives such as gas turbines or combustion engines. The necessity for high-temperature operation constrains their viability for vehicle and household applications (excluding PEMFCs). Nevertheless, their superior energy conversion rates compared to conventional thermal systems position fuel cells as attractive prospects for future energy infrastructure. The technology offers broad applicability across multiple industries. Key operational challenges include prohibitive mass/volume parameters and thermal profiles incompatible with mobile/domestic implementations.[27,28] SOFC architectures necessitate sustained operation at 800-1000°C, thus favoring deployment in stationary megawatt-scale power facilities where the solid electrolytes batteries create opportunities cogeneration applications including space heating, industrial thermal and power applications, or use of a steam turbine in Rankine cycles for more power generation.[29,30] Solid electrolytic fuel cells, need inverters to change the direct current to alternating current, and can be availed in relatively small, modular units. The solid electrolytic fuel cells are particularly attractive for urban application due to their compact size and cleanliness e.g. in Tokyo, there are 25 kw units in operation. [29]

Alkali Fuel Cells (AFC): The Alkali fuel cells use compressed H_2 and O_2 as an energy source and oxidant while the electrolyte generally uses the solution of potassium hydroxide in water. The alkali fuel cell operates at operating at about 70% efficiency and a temperature of operations is between 150 and 200 0C, (about 300 to 400 0F). The generation output is between 300 watts to 5 kilowatts. [4,31] A typical use of the alkali power cells is in Apollo spacecraft to supply both drinking water and Electrical power. The primary drawback is that alkali power cells use pure hydrogen fuel, and a platinum electrode catalyst which are expensive. [32,28] The alkali fuelcell is demonstrated in figure below.

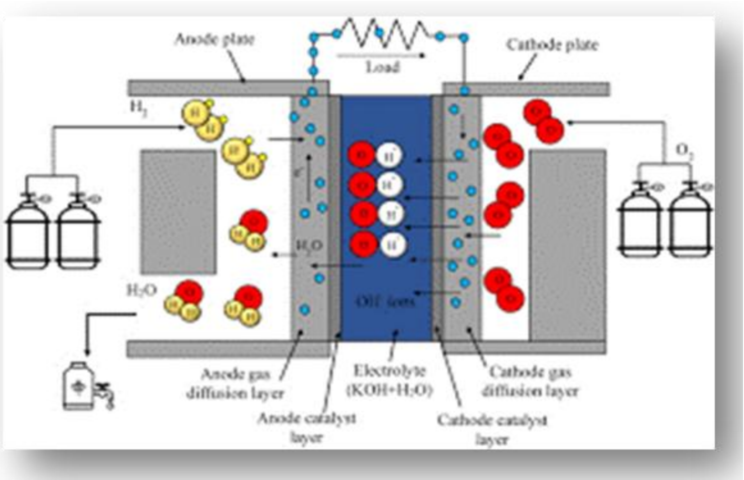

Figure 3: The Alkali Fuel Cell (Source: Clean Energy Institute, 2021. [87])

Table 1: Fuel Cells Technologies. [4,33,22]

<100	60-120	60-120	160-220	600-800	800-1000 Low temperature (500-600) possible
KOH	Perfluoro sulfonic acid (Nafion membrane)	Perfluoro sulfonic acid (Nafion membrane)	H_3PO_4 immobilized in SiC matrix	Li_2CO_3-K_2CO_3 eutectic mixture immobilized in γ-$LiAlO_2$	YSZ (yttria stabilized zirconia)
OH^-	H^+	H^+	H^+	CO_3^{2-}	O^{2-}
$H_2 + 2OH^- \rightarrow 2H_2O + 2e$	$CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6e$	$H_2 \rightarrow 2H^+ + 2e$	$H_2 \rightarrow 2H^+ + 2e-$	$H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e$	$H_2 + O_2^- \rightarrow H_2O + 2e$
$½O_2 + HO + 2e- \rightarrow 2OH-$	$3/2\ O_2 + 6H^+ + 6e- \rightarrow 3H_2O$	$½O_2 + 2H+ + 2e- \rightarrow H_2O$	$½O_2 + 2H+ + 2e- \rightarrow H_2O$	$½O_2 + CO_2 + 2e- \rightarrow CO_3^{2-}$	$½O_2 + 2e- \rightarrow O_2^-$
Anode: Ni Cathode: Ag	Anode: Pt, PtRu Cathode: Pt	Anode: Pt, PtRu Cathode: Pt	Anode: Pt, PtRu Cathode: Pt	Anode: Ni-5Cr Cathode: NiO(Li)	Anode: Ni-YSZ Cathode: lanthanum strontium manganite (LSM)

2.2 Potential in Sustainable Technology

Fuel cells offer several advantages that make them a key player in the shift toward renewable energy systems:

i. Clean Energy Production: Fuel cells generate power using little to no emissions. The primary by-product, water, is non-polluting, which significantly reduces the sustainability implications compared to fossil fuels-based power generation.
ii. Fuel cells are more efficient than conventional combustion engines, converting a greater portion of fuel energy into usable electricity. This improved efficiency results in reduced fuel usage and lower greenhouse gas emissions.
iii. Fuel cells are highly adaptable and can be used in a wide range of applications, from powering vehicles and portable electronics to providing backup power and heating for buildings. Their flexibility makes them suitable for both centralized and decentralized energy systems.
iv. Fuel cells can utilize hydrogen produced from renewable sources such as wind, solar, or biomass. This allows for a sustainable energy loop, where renewable energy generates hydrogen, which fuel cells then convert back into electricity.
v. Fuel cells also contribute to energy storage solutions. Surplus renewable energy can be used to produce hydrogen through electrolysis, which can then be stored and later converted into electricity via fuel cells. This helps to mitigate the variability and intermittency of renewable energy sources

2.3 How Fuel Cell-Based Water Purification Works

Fuel cell-based water purification leverages the principles of electrochemical reactions to produce not just clean energy but also treat and purify water.[34,35] This dual functionality makes it an innovative and sustainable solution for addressing water scarcity and ensuring the availability of clean drinking water.

Key Components and Process

1. Microbial Fuel Cells (MFCs)

- Microbial Activity: Microbial fuel cells utilize microorganisms to oxidize organic matter present in wastewater. As microbes consume the organic compounds, they release electrons and protons as by-products. [36,37]
- Electrodes: The released electrons flow towards the anode, electricity moving through an external circuit to the cathode.
- Electricity Generation: The movement of electrons generates electricity, which can be harnessed to power various processes, including water purification.

2. Electrochemical Reactions

- Oxidation and Reduction: The electric current created by the MFCs is utilized to drive electrochemical reactions. In these reactions, contaminants in the water, including heavy metals and pathogens, are oxidized or reduced, rendering them harmless.[37]
- Disinfection: Electrochemical disinfection is achieved by generating reactive oxygen species (ROS) at the cathode. [38,39] These species, including hydroxyl radicals and Hydrogen peroxide demonstrates high efficacy at breaking down and neutralizing harmful microorganisms.

3. Water Purification System

- Filtration: The purified water is passed through a series of filters to remove any remaining particulates and suspended solids.
- Further Treatment: Additional treatment steps, such as ion exchange or adsorption, may be employed to remove unwanted substances lacking addresses by the primary electrochemical process. [40,41]
- Output: The end result is purified, potable water that meets or exceeds regulatory standards.

- Advantages of Fuel Cell-Based Water Purification
- Sustainability: By using organic waste as a fuel source, microbial fuel cells provide a renewable and sustainable method for both energy generation and water purification.
- Efficiency: The process is highly efficient, as it simultaneously treats wastewater and generates electricity, maximizing resource utilization.
- Environmental Impact: This technology reduces the requirements for chemical disinfectants and minimizes the synthesis of secondary waste, offering an environmentally friendly alternative to conventional water treatment methods. [42,43]

Applications

Fuel cell-based water purification systems are particularly suited for use in:

- Remote and Off-Grid Areas: Where access to traditional power sources is limited or unavailable, These systems are capable of delivering both electricity and clean water.
- Wastewater Treatment Plants: Integration with existing infrastructure to enhance operational effectiveness and environmental sustainability of water treatment processes.
- Disaster Relief
- Hydrogen Fuel Cell Systems
- Explanation of hydrogen fuel cell technology and cell technology and their types (Microbial Fuel Cells, Soil Microbial Fuel Cells, Hybrid Fuel Cells).
- Mechanisms of electricity generation in fuel cells.
- Advantages of using hydrogen fuel cells instead of conventional power energy sources

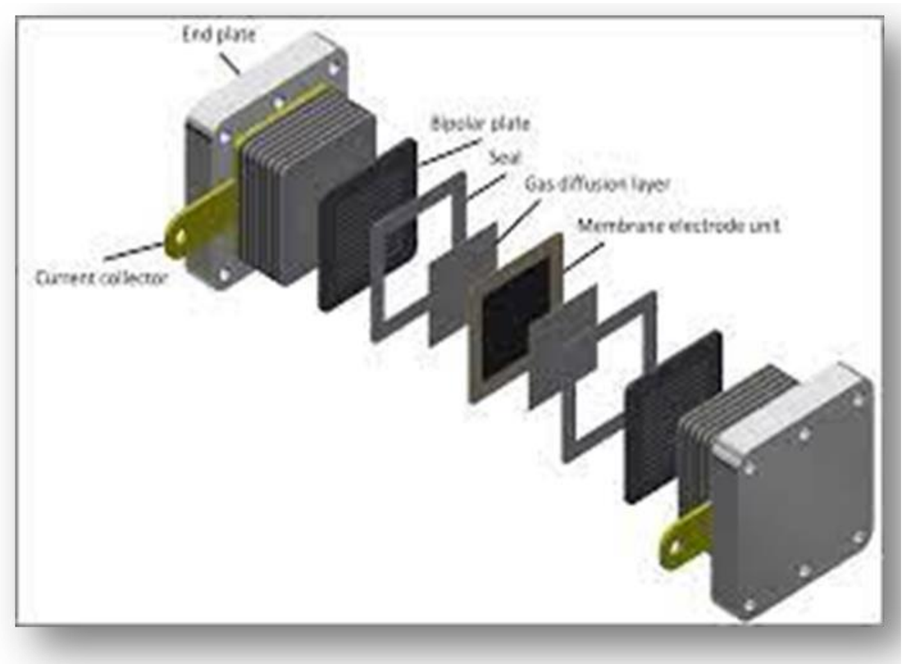

Figure 4: Structure of a hydrogen fuel cell.
(Concept adapted from: DILICO GmbH, 2020. [88])

2.4 Advantages of Hydrogen Fuel Cell Technology in Water Purification

2.4.1 Environmental Benefits

Fuel cells generate electricity without emitting harmful pollutants at the point of use, making them an eco-friendly alternative to diesel generators or coal-powered electricity, which emits greenhouse gases and pollutants. Additionally, the byproduct of the fuel cell reaction is water, which aligns with the goal of clean water provision and minimizes waste generation. When renewable energy is used to produce hydrogen for the fuel cell, the entire process can be virtually carbon-neutral.

2.4.2 Superior Energy Conversion Efficiency

Fuel cells achieve superior energy utilization rates, especially compared to conventional combustion-based power sources. PEM fuel cells, for instance, have efficiencies ranging from 40% to 60% and can exhibits enhanced characteristics when coupled with a secondary energy recovery system, such as Combined Heat and Power (CHP), which captures and utilizes waste heat. [5,22]

2.4.3 Reliability and Off-Grid Capability

Fuel cells can provide consistent power regardless of weather conditions, unlike solar or wind energy. This reliability is particularly beneficial in disaster-prone or remote areas where water purification systems are needed most. Portable, self-contained fuel cell systems can be deployed rapidly, ensuring immediate reliable clean water accessibility in emergencies.

2.5 Effects of Poor Water Purification System

Availability of portable water is not just a basic necessity but a fundamental human right. Yet, for millions living in developing countries and impoverished communities, this essential resource remains a distant dream, overshadowed by the harsh realities of waterborne diseases, environmental degradation, and economic disparities. On average, women and girls in developing countries walk 3.7 miles every day to collect 5 gallons of water and carry it to their homes. [44,17,45]. Even still, the water is often contaminated and can cause diseases. With 783 million people worldwide without access to water, [17,15] water treatment in developing countries is more crucial than ever, yet it isn't easy.

Figure 5: Poor Water (An image from Water Journalists Africa, 2016.[89])

2.5.1 Why is Proper Water Treatment Necessary?

i. When someone drinks contaminated water, there is a risk of diarrhea, vomiting, stomach pain, and, in some cases, death. UNICEF reports that 829,000 people die from diseases attributed to drinking unsafe water every year.[44]
ii. Cooking, washing food, bathing, and brushing teeth also come with the risk of getting ill. Even gathering water from contaminated sources by accessing them directly can expose individuals to dangerous diseases.
iii. Iii. Water treatment is necessary for physical survival, food production, and sustainable socio-economic development. Even crystal-clear water can have dangerous pathogens or chemical contamination.

2.5.2 How Do Developing Countries Get Clean Water

Reducing the spread of waterborne diseases in developing countries requires clean water and sanitation. The ever-growing cost of infrastructure is the largest barrier when addressing clean water problems.

In recent years, efforts to develop efficient, economical, and technologically sound methods of producing clean water in developing countries have increased, with several alternatives to traditional water treatment facilities.

i. Membrane-Based Separation

Membrane filtration represents a newer approach in water treatment technologies. The process through membrane technology involves pushing water through a porous barrier to separate the pollutants. [46,47] Membrane filtration produces microbiological-safe water and doesn't require additional chemicals to operate.

Types of separation membranes vary in size of the pores – some large enough to let viruses pass through and some so small that even salts are removed. [47,46,48] They also vary in application size with some large enough for municipal water treatment facilities and others are in "straw" form for personal use or small buckets. [47,48]

The two membrane separation technologies used most in developing countries are ultrafiltration and reverse osmosis.

Reverse osmosis removes dissolved substances from water, such as minerals and salts, and chemicals, such as arsenic, mercury, or lead. [48] However, a significant amount of water is wasted through reverse osmosis.

Ultra filtration systems are more cost-effective than reverse osmosis and are easier to install and maintain. Ultra filtration systems remove viruses and bacteria from water. [49]

While ultrafiltration is most commonly used, the decision of which system to use depends on the community's needs.

ii. Solar Water Disinfection (SODIS)

Solar Water Disinfection (SODIS) utilizes UV light from the sun and increased water temperature to effectively eliminate germs. [11,50] By raising the water temperature, the disinfection process is expedited, enhancing the germ-killing capabilities of UV light. This combined effect exposes pathogens to both UV radiation and higher temperatures, boosting the efficiency of water purification and reducing the likelihood of waterborne illnesses.[50]

SODIS is only highly effective in killing germs in areas with significant amounts of strong sunlight, and the treatment the procedure may require from 6 hours and 48 hours, depending on the cloud cover.[11] It also functions exclusively with fairly small quantities of water potentially limiting factor.

iii. Ceramic Filtration (CF)

Studies show that high-quality ceramic filters (CF) effectively eliminate bacteria in water and reduce the chances of diarrheal disease by 60% to 70% if used properly. [51,52]

The process of CF includes using a flowerpot-shaped filter with small pores to remove dangerous pathogens, including bacteria, dirt, and debris. CF systems are easy to use and inexpensive because they utilize regionally available materials such as rice husks and clay.[53]

Ceramic filtration systems do come with drawbacks. CF requires frequent replacement due to breaking and is not effective against viruses. [51,54] The frequent maintenance and requirement for replacement components may lead to low compliance by the user.

iv. Chlorination

Chlorination is often used in developing countries because it's an inexpensive and easy-to-use treatment for water contamination. However, the taste of chlorine often keeps people from using the water.

Other disadvantages to chlorination include being ineffective at removing protozoa, and long-term use can lead to health problems, including increasing the chances of developing cancer. [55,56]

v. Biosand Water Filtration (BSF)

Biosand Water Filtration (BSF) is a low-cost, low-technology system designed specifically for household use. Fresh water is poured over the top of the filter of a container filled with layers of sieved and washed sand and gravel, which filters out pathogens from drinking water. [57,58]

BSF increases water's safety by removing most bacteria and parasites. However, it is less effective against viruses, and the system requires the sand to be replaced regularly. The regular maintenance can be a barrier to use.

3. Fuel Cell-Powered Water Purification Systems

Fuel cell-powered water purification systems primarily use reverse osmosis, ultrafiltration, or electrodialysis methods, which require a continuous power supply.[59]

Fuel cells provide a reliable and sustainable power supply enabling these systems in off-grid locations where electrical infrastructure may be limited. Example: Reverse Osmosis (RO) Systems powered by PEMFCs Proton Exchange Membrane Fuel Cells (PEMFCs) are commonly used to power Reverse Osmosis (RO) systems, [60,61] one of the most effective methods for desalinating and purifying water. In an RO system, pressure is applied to force water through a semi-permeable membrane, separating contaminants. [47,48] PEMFCs can meet the high energy demands of RO processes with the advantage of using renewable hydrogen sources. [60,61]

3.1 Reverse Osmosis (RO)

Reverse osmosis has established itself as a foremost effective methods for desalinating and purifying water. [47,48] It operates by applying pressure to force water through a semi-permeable membrane, separating contaminants like salts, microbes, and organic pollutants.[48] The energy-intensive nature of this process makes it a ideal candidate for fuel cell system integration, particularly in regions lacking reliable traditional energy grids.

3.1.1 Fuel Cells as Power Sources for RO Systems

Fuel cells provide a clean, efficient, and reliable energy source, addressing the high energy demands of reverse osmosis processes. The compact form factor and high-performance characteristics of PEMFCs make them especially appropriate for (up to 60%), and ability to utilize renewable hydrogen. [60,61] They emit only water as a byproduct, aligning perfectly with the objectives of sustainable water purification.

3.1.2 Advantages of Integration

i. Environmental Sustainability: Fuel cells eliminate reliance on petroleum-based fuels, dramatically curtailing carbon emissions and other climate-warming pollutants. When powered by green hydrogen, they achieve a near-zero carbon footprint, contributing to global DE carbonization efforts.
ii. Energy Efficiency: PEMFCs and Solid Oxide Fuel Cells (SOFCs) offer high energy conversion rates, allowing reliable continuous and scalable water purification applications. The combined use of waste heat in cogeneration systems can further enhance efficiency, reducing operational costs.
iii. Off-Grid Capabilities: Fuel cell-powered RO systems represent an optimal solution for off-grid and disaster-prone areas where conventional energy infrastructure is unavailable. Mobile systems have already proven effective in disaster relief scenarios. [61,62]

Fuel cell-powered reverse osmosis systems are an emerging sustainable water [solution/technology] purification. Their integration addresses energy demands while aligning with environmental goals. Ongoing research and cost reductions are expected to expand their application in achieving global water security.[62]

Figure 7: ETprotein. Process diagram of a reverse osmosis filter system (reproduced from ETprotein, 2021. [90])

3.2 Ultrafiltration Systems

Ultrafiltration (UF) systems are critical in water purification, utilizing semi-permeable membranes to filter out suspended solids, pathogens, and macromolecules. [63,46] These systems require consistent energy inputs to maintain the pressure needed for filtration. Fuel cells present a sustainable and reliable energy source for powering UF systems, particularly in remote or energy-scarce regions.

3.2.1 Types of Fuel Cells Suitable for UF Systems

i. Polymer Electrolyte Membrane Fuel Cells (PEMFCs)

Compact design, high efficiency (40–60%), and compatibility with hydrogen generated from renewable energy sources.[61] It is Ideal for small-to-medium scale UF systems in off-grid areas.

ii. Microbial Fuel Cells (MFCs)

Generate electricity from wastewater while simultaneously aiding in preliminary treatment, reducing the load on UF membranes. [64,65] It is often used in hybrid systems that integrate UF and MFCs for dual-purpose purification and energy generation.

iii. Solid Oxide Fuel Cells (SOFCs)

High operating temperatures enable the use of multiple fuels, including natural gas and biogas, providing flexibility for large-scale operations. [22,66] It is Suitable for industrial UF systems where continuous operation and high energy demands are prevalent.

3.2.2 Advantages of Fuel Cell Integration in UF Systems

i. Sustainability

Zero greenhouse gas emissions at the point of use, especially when powered by green hydrogen. It reduces reliance on traditional energy sources, aligning with global decarbonization goals.

ii. Energy Efficiency

Fuel cells provide a consistent energy supply, ensuring the stable operation of UF membranes. PEMFCs and MFCs can achieve efficiencies exceeding conventional power sources, further reducing energy costs. [91]

Figure 8: Ultrafiltration System (concept from [46],[63])

3.3 Electro dialysis Method

Electro dialysis (ED) is a widely used water treatment process, especially for desalination and brackish water purification. [67,68] It employs an electric field to drive the migration of ions across ion-selective membranes, effectively separating salts and additional soluble substances in aqueous solutions. [67,68] Given its energy-intensive nature, integrating electro dialysis with fuel cell technology offers a sustainable and efficient solution for clean water production.

3.3.1 Advantages of Fuel Cell Integration in ED Systems

i. Sustainability

- Fuel cells produce clean energy, with water as the primary byproduct, aligning with environmental sustainability goals.
- The integration with renewable hydrogen sources ensures near-zero carbon emissions.

ii. Energy Efficiency

- Fuel cells provide a stable power supply, crucial for maintaining consistent ion movement in ED systems.
- Waste heat from SOFCs can be utilized in pre-treatment stages, enhancing overall system efficiency. [69,70]

iii. Versatility and Adaptability

- Modular fuel cell designs facilitate seamless interoperability with both small-scale and industrial ED systems. [71,69]
- • Mobile fuel cell-ED modules demonstrate exceptional utility for disaster relief and remote applications. [71,62]

Figure 9: Electrodialysis Method.[92]

4. Case History: Kenya PEMFC Powered Desalination Plant

Kenya's Polymer Electrolyte Membrane Fuel Cell (PEMFC)-powered desalination plant represents a groundbreaking approach to addressing water scarcity in coastal regions. Situated in an area where access to clean drinking water is limited, this innovative facility combines advanced desalination technology with sustainable energy solutions to deliver essential services to underserved communities. [72,73]

PEMFC-powered desalination plant in Kenya has provided clean water to over 3,000 residents, significantly reducing waterborne diseases. [74,75] This success demonstrates the viability of fuel cells as a power source for desalination units in low-resource settings. The Kenyan state has designated land for the development of aa desalination plant in Likoni, a coastal town in Mombasa County. [76,77] This move aims to address the chronic water scarcity faced by the local population and support the region's economic growth.

The proposed Likoni desalination plant will have a capacity of 100,000 cubic meters per day, making it a significant addition to the country's water supply infrastructure.[78] The plant will utilize state-of-the-art technology to remove salt and other minerals from seawater, generating potable water compliant with international standards. The government's provision of land for the project demonstrates its commitment to addressing the water needs of the coastal region. The project is expected to create jobs, stimulate local economic growth, and improve public health outcomes. The desalination plant will also help alleviate the pressure on existing water sources, such as rivers and lakes, which are often stressed by climate change, population growth, and agricultural activities. With this project, Kenya now stands alongside fellow African nations like South Africa, Egypt, and Algeria that have invested in desalination technology to address water scarcity challenges. [79,80] Overall, the Likoni desalination plant project is a significant milestone in Kenya's efforts to ensure water security and promote sustainable development in the coastal region.

Figure 10: a photograph by Jean from The Star, shows Kenyan officials at the proposed site for the Likoni plant.[93]

After natural disasters, traditional power infrastructure is often compromised. Fuel cells can be deployed rapidly in such scenarios. In the wake of Hurricane Maria's landfall in Puerto Rico, mobile fuel cell units were utilized to power water filtration systems, providing essential drinking water to affected populations.[81] Natural disasters, such as hurricanes, earthquakes, and floods, can cause significant damage to traditional power infrastructure, leading to power outages and disruptions to essential services. In such scenarios, fuel cells can play a critical role in providing emergency power and supporting disaster relief efforts. One notable example is the deployment of mobile fuel cell units In post-Maria Puerto Rico in 2017. The hurricane caused widespread destruction and power outages, depriving numerous communities of critical infrastructure, particularly safe water systems. [82,83]

To address this need, mobile hydrogen fuel cell systems were implemented to power water filtration systems, providing essential drinking water to affected populations. These fuel cell units were rapidly deployed and provided a reliable source of power, enabling the water filtration systems to operate continuously and provide clean drinking water to those in need.

The use of fuel cell applications in this operational context demonstrated their potential as a rapid response solution for disaster relief and emergency response. Fuel cell systems provide multiple operational benefits in such scenarios, including:

Rapid deployment: Fuel cells can be quickly deployed and set up, providing power within hours or days, compared to traditional power infrastructure which can take weeks or months to restore.[81]

The deployment of fuel cells in ‘‘In post-Maria Puerto RicodemonstratesRico’’ demonstrates their potential as a valuable tool for disaster relief and emergency response, and highlights the importance of considering fuel cells as part of a comprehensive emergency preparedness and response plan.

5. CONCLUSION

Fuel cell-based water purification systems offer a sustainable solution to a top-tier priority global issues: access to clean drinking water. By providing a clean, efficient, and adaptable power source, fuel cells can enhance water purification processes, especially in off-grid or disaster-prone areas. While challenges in cost, infrastructure, and fuel availability remain, ongoing research and innovation will likely make fuel cell-powered purification systems increasingly viable. Leveraging this technology could make a significant impact on global water security and contribute to achieving the UN's 2030 Agenda for Sustainable Development Goals (SDGs) for clean water and affordable energy.

The cost of deploying fuel cell technology remains a challenge, but prices are anticipated to fall with advancements in materials and increased production. Data from the Paris-based energy organization shows the global fuel cell market is projected to grow at a compound annual growth rate (CAGR) of 18.5% by 2030,[84] potentially reducing costs. Moreover, as fuel cells emit minimal greenhouse gases, their environmental impact is significantly lower than fossil fuel-powered alternatives. PEMFC utilization shows quantifiable lifecycle emission reductions, corresponding with IPCC climate pathways.

6. Challenges and Future Prospects

i. Infrastructure and Fuel Accessibility: The viability of fuel cell systems depends on established hydrogen infrastructure, particularly electrolytic production powered by renewables to ensure ecological benefits. Currently, renewable hydrogen accessibility remains constrained in areas lacking sustainable energy grids.

ii. Research and Development Needs: Further research is needed to improve fuel cell efficiency, particularly for PEMFCs and MFCs, which are central to water purification applications. Additionally, advancements in catalyst materials and cost-effective production methods will be crucial to making fuel cells more accessible and affordable.

iii. Access to uncontaminated water is essential for human survival, yet countless communities worldwide still lack this vital resource, yet millions of people worldwide lack access to this basic necessity (e.g. Sub-Sahara regions, south-Asia). Traditional water purification methods often rely on non-renewable energy sources, contributing to greenhouse gas emissions and climate change. Fuel cells-based technology offers a game-changing solution, providing a reliable, efficient, and sustainable way to power water purification systems.

iv. Using fuel cells-based technology to power water purification systems is the best method due to its renewable energy source, high efficiency, reliability, scalability, and zero emissions. Real-world examples demonstrate the effectiveness of this approach in reducing fuel expenditures, atmospheric emissions, and providing clean drinking water to communities worldwide. As the sustainable water provision challenges continues to grow, fuel cells-based technology offers a sustainable and innovative solution to meet this critical need.

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