# Addressing Hydrogen Storage Challenges with Regenerative Green Hydrogen-Based Batteries -A mini-review

Emmanuel Kweinor Tetteh*, Samukelo Mngadi, Thashrik Pirthira, Sudesh Rathilal

***Abstract*—**As a sustainable energy carrier, hydrogen presents alternative solutions to pressing global issues aggravated by anthropogenic and industrial activities using carbon-based fuels and greenhouse gas emissions (GHGs). Among the types of hydrogen allied with their production routes and energy sources, the candidature of green hydrogen via water electrolysis-powered renewable energy is advantageous for decarbonizing the environment. However, storage, transportation, and power generation challenges associated with hydrogen production are also inevitable in green hydrogen production. Therefore, this review encompasses various hydrogen production routes and technological solutions addressing production and storage. This domain positioned green hydrogen production and fuel cells as a sustainable way of producing and storing clean energy. Types of fuel cells, components, and operational functions were explored and discussed. The role of electrolytes, electrodes, catalysts, and membranes in enhancing fuel cell efficiency was highlighted. It was elucidated that regenerative hydrogen fuel cells, a promising technology, are economically and environmentally viable for producing and storing green hydrogen.

***Keywords*—**Catalysis, electrolysis, fuel cells, green hydrogen, renewable energy.

## I. INTRODUCTION

Global socioeconomic growth and development, technological advancement, and climate change underpin the demand for clean energy. Notwithstanding, energy demand is projected to increase annually by 1.3% until 2040 [1]. The predominance of fossil fuels contributing to greenhouse gas emissions and carbon footprint poses a significant environmental and human health threat, such as climate change [2, 3]. Despite the global interest and national and international efforts in combating climate change, as outlined in the 2015 Paris Agreement [4, 5]. Transitioning from a carbon-based economy to a green energy economy offers alternative fossil fuel-independent solutions. Some renewable sources include solar, wind, hydro, geothermal, ocean and biomass [3, 6, 7].

Subsequently, the debate on decarbonising economy has made climate mitigation and carbon neutrality a global priority to be achieved by 2050 [4]. However, the use of fossil fuels (coal, natural gas, and oil) is found as the most predominant source of energy [8, 9]. Of interest, carbon-based fuels provide 85% of global energy needs and emit about 36 billion tons of $CO_2$ annually [10, 11]. Fossil fuels currently account for over 90% of these emissions, and it is anticipated to rise with climate change over the next couple of years [12]. Nevertheless, the energy demand (industries, transportation sector etc) on the fossil fuels market pose detrimental threat to human health and the environment ($CO_2$ emission) [13]. Also, emission of greenhouse gases (GHGs) into the atmosphere contributes to acidic rain, stratospheric ozone depletion and climate change [14]. The demand on fossil fuels is anticipated to increase with an increase in $CO_2$ emissions. As shown in Fig 1, between 2020-2040, it is projected the $CO_2$ emissions from Asia will increase by 10.8% followed by Europe (7.4%) and Africa (6.4%). The high estimated $CO_2$ emission in the Asian region is due to its cheap energy cost and rapidity attracting larger industries. Energy saving and efficiency have been key components of minimizing $CO_2$ emissions in the European region [15].

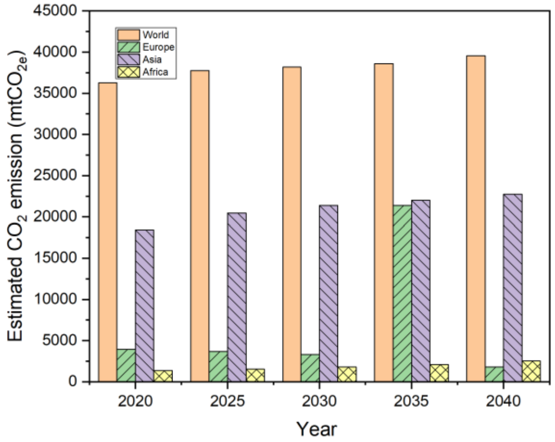

Fig 1 : Energy demand and estimated carbon footprint between 2020 -2024 ; data adapted from Ahmad and Zhang [15]

In the current energy trajectory, green hydrogen is viewed as a promising fuel for sustainable development and energy transition, because it can be generated from natural resources such as water. It is anticipated that the productivity and applicability of green hydrogen will increase in the next decade and meet the global net-zero emission challenge [3, 16]s. Also, hydrogen with low density can be use as energy

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carrier in methanation process coupled with $CO_2$ produce methane ($CH_4$) or methanol ($CH_3OH$) [17]. In addition, iron and steel industries share high market of value of hydrogen and hydrogen -based fuels, which is estimated to increase by 10% in 2050 [7, 18]. Therefore, exploring the potential of producing green hydrogen in Africa comes with essential benefits to support socioeconomic growth and development. As this will result in the improvement of infrastructure weaknesses and disparity in some countries by maximizing renewable resource potential to provide a permanent energy supply [19]. Notwithstanding providing sustainable energy supply together with technological development such as hydrogen can revolutionize the energy sector. This comes with a huge demand for the technological advancement of hydrogen production, transportation, distribution, and storage [20]. So, this study explored the challenges and prospective technology for storing hydrogen. Undeniably, the sustainability of hydrogen production is contingent on coupling renewable energies during the production process, regardless of the technology employed. This presents opportunities to produce hydrogen on a large scale by using readily available energy sources to replace the current fossil fuel-based energy economy.

### *A. Hydrogen as an energy carrier*

Recent environmental pressing issues associated with global energy demand on fossil fuels with carbon footprint and climate change make hydrogen a cleaner alternative energy resource. Hydrogen ($H_2$) emerging as a promising alternative for the transition carbon-based economy to a green economy, is versatile and carbon-free. Table I Presents properties of hydrogen as energy carrier as compared with other energy mix. With a high energy density ranging from 120 to 142 MJ/kg, $H_2$ surpasses other sources such as methane or natural gas (55.5 MJ/kg) by up 2.5 times and exceeds coal (24 MJ/kg), diesel/fuel oil (48 MJ/kg), LPG (46.4 MJ/kg), kerosene (46 MJ/kg) or gasoline (44.4 MJ/kg) by up to 5.9 times [21, 22]. This greater energy density makes $H_2$ capable of tackling critical energy demands driven by fossil fuel consumption. Its adaptability and implementation tend to increase energy efficiency with a stable grid stability of electricity in an electricity-intensive low-carbon country.

TABLE I COMPARING HYDROGEN AS AN ENERGY CARRIER WITH OTHER ENERGY MIX PROPERTIES [22]

| Property | Biodiesel | Natural gas | Hydrogen |
|---|---|---|---|
| Energy content (MJ/kg) | 38-42.6 | 53.6 | 120-142 |
| Lower heating value (MJ/kg) | 37-39 | 47-53 | 120-142 |
| Heat of evaporation (kJ/kg) | 270-290 | 750-850 | 440-460 |
| Flammability range in air (%) | 1-6 | 5-15 | 6-36 |
| Ignition energy (J) | 0.7-0.9 | 0.17-0.25 | 0.017-0.05 |
| Viscosity (cSt) | 3.5-6 | 0.02-0.2 | 0.089-0.09 |
| Density (kg/m3) | 860-900 | 0.67-0.9 | 0 |
| Carbon content (g/MJ) | 79 | 30-90 | 0.1 |
| Sulphur content (ppm) | <20 | <1 | 0.1 |
| Nitrogen content (ppm) | <10 | <1 | 0.1 |

### *B. Carbon-based economy transition with green hydrogen*

Globally, attempts are underway to develop green hydrogen production technologies powered by renewable energy sources [23]. For instance, seawater, wind and solar are readily available in Africa, whereby harnessing energy from these resources are gaining attention. Notwithstanding, making the progressive shift from carbon-based energy to green hydrogen economy requires effective energy policies and implementations [11, 24]. In this context, the number of countries with policies that directly encourage investment in hydrogen technologies is on the rise. For example, Australia, Brazil, Russia, China, India, South Africa, Indonesia, Japan, and other Western developed countries have commercialized hydrogen projects towards zero carbon emissions [25]. This has drawn the attention of many European Union countries to upscale and increase their productivity to assist curb carbon emissions by 2050 [26]. Table II presents some of the ongoing projects related to green hydrogen production. In Russia hydrogen consumption is also gaining momentum with chemical companies (ammonia (58 %) and methanol (12 %) production), oil refineries (27 %), and 3% for other consumable industries such as metallurgy, microelectronic, power generation (as refrigerant), food) [23]

TABLE II GREEN HYDROGEN DEVELOPMENT IN DIFFERENT COUNTRIES ADAPTED FROM [19]

| Project location | Description | Remarks |
|---|---|---|
| Brazil | To develop and consolidate the Brazilian hydrogen market and to boost the country's economic competitiveness on a global scale. Examine existing national rules and regulations to subsidise incorporating hydrogen as an energy vector and fuel in the Brazilian energy matrix | Encourage government authorities to regulate the production, transportation, quality, storage, and use of hydrogen and associated technologies |
| Rusia | Hydrogen Energy and Plasma, Technology Institute in Rusia has 560 W and 1.5 kW H2 green hydrogen power technology | The Russian hydrogen industry has existed for more than 100 years and is one of the biggest in the world.<br>In 2021, hydrogen production of Russia exceeded 5 mln tons |

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| | | |
|---|---|---|
| South Africa (Limpopo) | Anglo American Plarinum developing a pilot plant of 3.5 MW to produce 1 ton /day of green hydrogen to power the fuel cells for running large haul trucks | Renewable technology in the generation of electricity (solar PV) |
| China | To develop 50,000 fuel cell vehicles and produce 100,000–200,000 tonnes/year of green hydrogen (3.3–6.7 TWh) in 2025.<br>Advance demonstration projects in urban districts, storage and transport, and the chemical and metallurgy industries. | Begin preparing learners for careers in the hydrogen industry, engage in global standardisation and cooperation, and encourage research and development in key core technologies. |
| India | To produce five million metric tonnes per year (MMTPA) of green hydrogen by 2030 (Green Hydrogen Policy). | To maximise the capacity of renewable energy resources |

### C. Hydrogen production pathways

The production of hydrogen from renewable energy resources (Fig 2), including coal, natural gas, geothermal, solar, wind , ocean thermal energy conversion, biomass, and water has the potential to replace fossil fuels [27]. This presents a widely available energy source to replace fossil fuels in transportation, industrial, residential, and commercial sectors. Thus, an economy based on hydrogen has a prospect solution to environmental issues, natural resource depletion, and socioeconomic demands of population growth [8, 28]. However, the viability of hydrogen production is related to the environmental impact of the production route and the amount of energy required for the process. The energy required to drive hydrogen production can be obtained from different renewable sources (solar, wind, ocean waves, etc.) [29, 30]. The energy derived from renewable sources (like wind, solar, geothermal, tidal, wave, ocean, hydro, biomass) or nuclear energy can be used in the form of electrical and thermal. Likewise photonic energy from solar radiation biochemical energy is obtained from degradation of organic matter (glucose, carbohydrates, sugars etc) [31-33]. However, biochemical process can be assisted with or without solar radiation in the form of bio-photolysis and dark fermentation. Of interest, hybridised technologies that can use two combined forms of energy (electrical-thermal, electrical-photonic, biochemical -thermal, photonic-biochemical) are gaining attention [34, 35]. Consequently, it is challenging for decision makers to identify promising innovations and advantageous technology [36]. Herein, reforming, gasification, partial oxidation, water electrolysis, and dark fermentation [34-36], are identified among the conventional technologies that use fossil fuels and renewable resources.

Consequentially, electrochemical processes (Fig 2) such as water electrolysis represent the low-cost, clean, sustainable, and most efficient method of generating hydrogen and oxygen via the cathodic hydrogen and anodic oxygen evolution reactions [37]. In water electrolysis, the water molecule serves as the reactant, which dissociates into $H_2$ and $O_2$ by applying expensive electricity that is generally derived from non-renewable sources [37, 38]. This makes it expensive to operate and accounts for only 4% of the world's $H_2$ production. Despite the economic and energy barriers, water electrolysis is gaining research attention [37, 39]. With the widespread energy distribution of electrolysis shown in Fig 2, its combination with renewable energy sources (solar or wind) presents more merits to balance the discrepancy of energy demand and production.

Furthermore, the hydrogen and oxygen produced can be used as energy sources in the industries and transportation sectors. It can also be used as an energy carrier in fuel cell vehicles as well as a feedstock in the chemical and petrochemical industries (ammonia process, syngas, and fuels). Even though hydrogen offers numerous advantages over fossil fuels in terms of its environmental impact and versatility, it's also having inherent safety risks. These risks can potentially lead to explosions and therefore storage and delivery of hydrogen come with challenges.

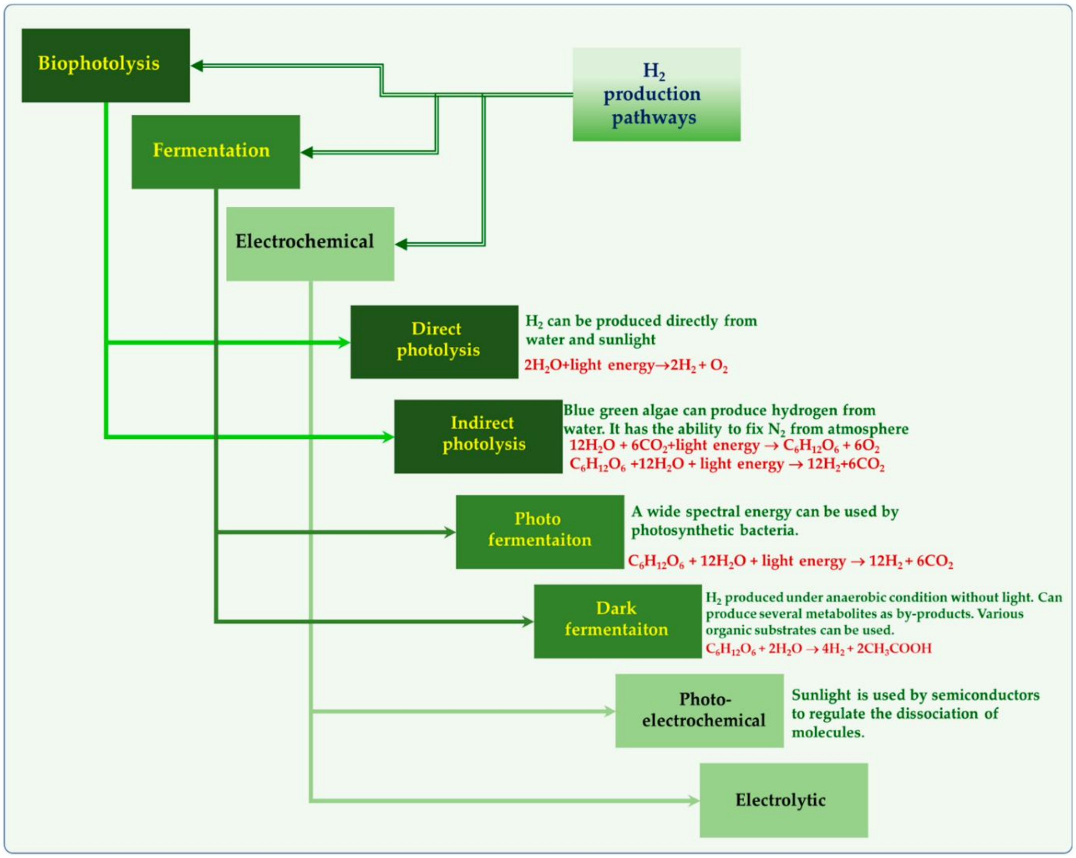

Fig 2 Hydrogen production pathways [27]

*D.Challenges associated with hydrogen as an energy carrier*

The high energy density and versatility of hydrogen as an energy carrier hold great promise for zero-emission applications. Despite the enormous promise of the hydrogen economy, there are still obstacles to be solved, such as the high cost of manufacturing, storage, distribution infrastructure, and safety concerns [39, 40]. Fig 3 shows some of the challenges that need to be addressed to enhance the adoption of hydrogen as a mainstream energy source. In addressing this, a hydrogen educational campaign is required across all industrial sectors to be informed about hydrogen production, storage, safety, and potential viability for decarbonization [16, 17, 41]. In addition, special safety measures need to be considered during the design phase of pipeline networks for transporting hydrogen over longer distances. A safe delivery infrastructure is essential for the successful commercialization of hydrogen to be utilized in various sectors and applications [16].

Conventionally, producing hydrogen via steam-methane reforming with natural gas emits carbon dioxide as a by-product. However, the shifts towards carbon-free hydrogen production such as water electrolysis powered by renewable energy sources (solar, wind) are expensive and most technologies require scalability. Notwithstanding, scaling hydrogen production to meet growing demand requires significant investment, reliable feedstock supply, and resource availability [42]. Whereas, establishing hydrogen infrastructure, including pipelines and refueling stations is very complex and comes with a huge investment. On the other hand, the process of producing, storing, and transporting hydrogen requires considerable energy [17]. Therefore, ensuring energy efficiency across the hydrogen life cycle, storage, and retrofitting existing infrastructure can reduce investment costs.

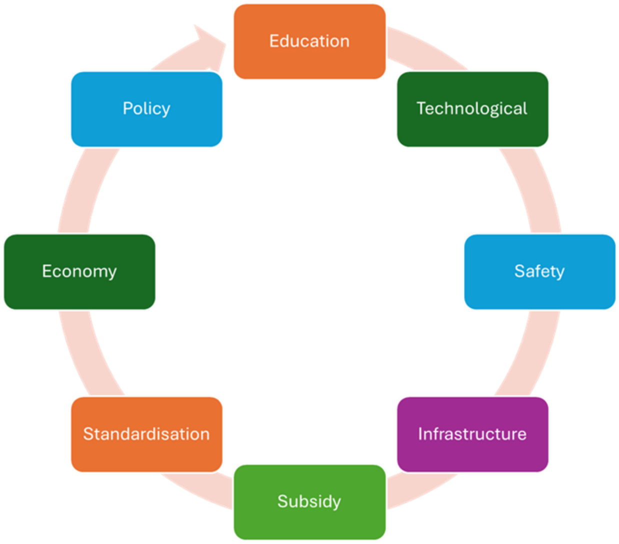

Fig 3 Challenges associated with hydrogen production

## II. HYDROGEN STORAGE TECHNOLOGICAL CHALLENGES AND DIRECTIVES

### A. *Energy storage-based batteries*

The production, storage, and distribution of hydrogen with sustainable and cost-effective technology remains a challenge. Hydrogen with its low density (mass and volume) makes it difficult to store, transport, and utilize as a mainstream energy [6, 16]. To overcome these challenges, effective storage systems are critical to harness hydrogen as an energy solution alternative to fossil fuels. This section explored some of the challenges and technologies underway to address these challenges. Ideally, hydrogen storage follows the principles of energy stored in batteries which are limited in power rating, efficiency, energy density, storage duration, and lifetime [17, 43]. Table III presents the conditions of batteries and hydrogen-based energy storage systems, to meet medium and long-term storage requirements. Table IV shows some advantages and disadvantages of some developed hydrogen storage technologies. Notwithstanding, storage methods such as compressed gas, liquid hydrogen, and solid-state storage have competitive advantages and limitations between storage capacity, safety, and cost trade-offs [16, 42]. As a result, advancing material engineering (graphene, steel, aluminum, alloy, carbon nanotubes) to provide alternative solutions to conventional batteries and storage tanks to be able to withstand the pressure of storing hydrogen is gaining attention **[43].**

TABLE III COMPARING DIFFERENT ENERGY STORAGE BATTERIES [44]

| **Technology** | **Power rating** | **Storage duration** | **Lifetime** | **Efficiency (%)** |
|---|---|---|---|---|
| Li-ion battery | 0.1-100 | 1 min – 8 h | 1000 - 10000 cycles | 85-98 |
| NaS battery | 10-100 | 1 min -8 h | 2500-4400 cycles | 70-90 |
| Hydrogen fuell cells | 0.01-100 | Min - weeks | 5-30 years | 25-45 |
| Flywheels | 0.00 1-1 | Sec- h | 20 000-100 000 cyles | 70-95 |
| Supercapacitors | 0.01-1 | Minsec-Min | 10 000-100 000 cycles | 80-98 |
| Pumped hydrogen storage | 100-1000 | 4 -12 h | 30- 60 years | 70-85 |
| Compressed air energy storage | 10-1000 | 2- 30 h | 20 -40 years | 40- 75 |

TABLE IV COMPARISON OF HYDROGEN STORAGE TECHNOLOGIES [11]

| Hydrogen storage technique | Merits | Demerits |
|---|---|---|
| Compressed gas storage<br>Eg Gas cylinders , tube trailer | -Relatively mature technology<br>-Easily to refuelled<br>-Relatively low capital and operating cost (20 -30 USD/kWh) | -Requires high pressure storage vessels , which can be heavy and bulky<br>-Limited energy density<br>-Compressing process can be energy intensive |
| Liquid hydrogen storage<br>Eg Cryogenic tank | -Can be refuelled easily<br>-It has high energy density than compressed gas<br>-Cost of stored energy is low (15-25 USD/kWh) | -Requires cryogenic temperatures (-253)<br>-Cryogenic storage vessels are relatively expensive to operate<br>-Boil -off loses can occur over time |
| Solid-state storage<br>-Metal hydrides<br>(cost 30 -70 USD/kWh),<br>-Carbon nanotubes (5-25USD/kWh),<br>-Chemical hydrides (40-150USD/kWh) | -Offers high volumetric and gravimetric energy density<br>-No cryogenic temperatures required<br>-Potentially safer than gas or liquid storage | -Emerging technology<br>-Relative low energy density compared to fossil fuels<br>-Upscaling cab be highly expensive |
| Fiber-inforced plastic | - Withstand pressure of 10 000 Psi<br>- Light weight, corrosion -resistant | Limited capacity and expensive |
| Carbon fiber -reinforced plastic | -Withstand pressure of 10 000 Psi<br>-Light weight , high capacity and corrosion-resistant | -Expensive , complex manufacturing process |

### B. *Hydrogen storage-based fuel cells*

Hydrogen to compete in the energy market as an alternative solution to fossil fuels, its production and storage cannot be overlooked. However, the adoption of integrated renewable energy sources (wind, solar) for hydrogen production and storage, makes green hydrogen a competitive energy carrier [31, 45]. Hence, technological advancement, scalability, and supportive policies to drive hydrogen production with cost competitiveness are very important. Notwithstanding, hydrogen fuel cell works with electrochemical principles of generating electricity via the reaction of hydrogen with oxygen to produce water, electricity, and heat. [46, 47] As shown in Table V, hydrogen fuel cell's compositional structure (electrolytes, electrode and catalyst, and membrane) influences their efficiency. Therefore, exploring technical solutions to improve their cost, durability, and overall performance becomes very critical.

TABLE V: SUMMARY OF DIFFERENT TYPES OF FUEL CELLS AND FUNCTIONAL PARAMETERS. [46, 47]

| Type of fuel cell | Energy source | Electrolyte | Operating temperature (℃) | Electrical efficiency (%) |
|---|---|---|---|---|
| Proton exchange membrane fuel cells (PEMFC) | 99.99% $H_2$ | Solid polymer membrane, acidic | 50 -230 | 50 to 65 |
| Solid oxide fuell cells (SOFC) | Hydrogen<br>Methane<br>Natural gas | Solid yttria-stabilised zirconia (YSZ) | 600 to 1200 | 55 to 65 |
| Alkaline fuel cells (AFC) | 99.99 hydrogen | Aqueous potassium hydroxide (KOH) | 50 to 230 | 50 to 65 |
| Phosphoric acid fuel cells (PAFCs) | Hydrogen | Liquid phosphoric acid | 150 to 220 | 35 to 45 |
| Molten carbonated fuell cells (MCFCs) | Hydrogen<br>Methane<br>Natural gas | Liquid alkali carbonates ($Li_2CO_3$/ $Na_2CO_3$/ $K_2CO_3$) | 600 to 800 | 50 to 65 |

## III. ADVANCEMENT OF HYDROGEN STORAGE TECHNOLOGY

### A. Hydrogen regenerative fuel cells (RFCs)

The continued research and innovation on green hydrogen present the integrated fuel cell system with green hydrogen as regenerative green hydrogen-based batteries as a sustainable energy for the future. Here, both electricity and energy stored can be used by reversing the electrochemical reaction, making it to be known as a reversible fuel cells [48]. Notwithstanding the progression of technology from the 19th (1st generation) to the 20th (2nd generation) century [43, 46, 48]. Its scalability and application have proven very promising with significant advantages such as improved energy efficiency and safety than conventional fuels. As shown in Fig 4, the system comprises renewable energy sources (solar, wind), an electrolyzer, a storage device for hydrogen and oxygen, a fuel cell, and a load). The basic parameters of the RFC systems developed in the 19th century and 20th century respectively as 1st and 2nd generation are depicted in Table VI. The functionality of the fuel cell and an electrolyzer in RFCs to produce electricity and split water into hydrogen and oxygen storage, make it very advantageous over other conventional fuel cells [43, 48],

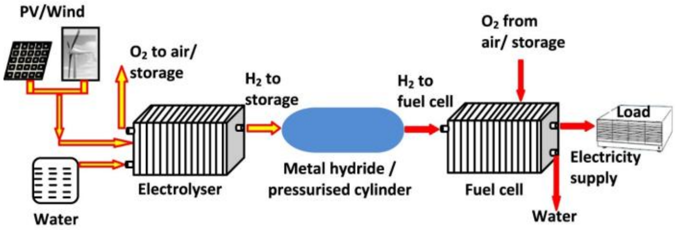

Fig 4 Schematic diagram of regenerative green hydrogen-based fuel cell with hybridized solar and wind energy [43]

TABLE VI BASIC PARAMETERS OF REGENERATIVE HYDROGEN-BASED ENERGY BATTERIES

| Technological conditions | 1st Generation [49] | 2nd Generation [46] |
|---|---|---|
| Year | 1983 | 200 |
| Location | Germany | France |
| Solar input | 43 kWh | 3.6 kWh |
| Battery storage | 303 kWh and 220 VDC | 1.9 kWh and 24 VDC |
| Electrolyser | 26 kWh @ 7 bar | 3.6 kWh @10 bar |
| H2 storage | 27 m3 @ 120bar | 0.4 m3 @ 10 bar |
| O2 storage | 20 m3 @ 70 bar | 0.2 m3 @ 10 bar |
| Fuell cell | 6.5 kW AFC<br>5 PEM<br>2.5 PEM | 4 kW PEM |
| Load | 0.35 kW combined | 5 KW AC load |

### B. Challenges and future outlooks of regenerative fuel cell (RFCs)

The RFCs have potential innovative solutions for hydrogen and energy storage to be converted into electricity and vice versa [43]. However, efficiency, cost, material durability, system complexity, and infrastructure requirements as limitations cannot be overlooked. Therefore, continued research in the areas of material science, techno-economic, and environmental analysis, has the potential of RFCs adaptability in renewable energy integration, grid-scale energy storage, and transportation systems [43, 46, 48]. In addition, green catalysis and electrolytes such as carbon nanotubes graphene, and metal-organic frame (MOFs) as cost-effective alternatives to the use of platinum catalysts, must be given research attention to improve RFCs.

## IV. CONCLUSION

This study explored the potential of addressing hydrogen production and storage challenges as a sustainable energy carrier for the future. It was deduced that hydrogen can be

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produced from different pathways, whereby green hydrogen production routes were environmentally friendly. Among the challenges identified with the green hydrogen economy in meeting the future energy demand, its hydrogen storage was found very crucial. Herein, different types of energy batteries, fuel cells, and hydrogen storage systems were identified with their basic operational parameters and efficiency. Green hydrogen-based regenerative fuel cells (RFCs), which work on the principle of reverse electrochemical reaction are found very promising sustainable energy solutions with zero environmental impact. Additional research is required to address RFC's technological and cost challenges, associated with materials (catalyst and membranes), energy efficiency

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