This article has been accepted for publication in IEEE Access. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2024.3363869

Date of publication xxxx 00, 0000, date of current version xxxx 00, 0000.

Digital Object Identifier 10.1109/ACCESS.2017.DOI

Challenges and Opportunities in Green Hydrogen Adoption for Decarbonizing Hard-to-Abate Industries: A Comprehensive Review

M. JAYACHANDRAN[1*], RANJITH KUMAR GATLA[2], AYMEN FLAH[3,4,8] AHMAD H. MILYANI[5], HISHAM M. MILYANI[6], VOJTECH BLAZEK[7], LUKAS PROKOP[7], HABIB KRAIEM[9],

[1]Department of Electrical and Electronics Engineering, Puducherry Technological University, Puducherry
[2]Department of Electrical and Electronics Engineering, Institute of Aeronautical Engineering, Hyderabad
[3]Processes, Energy, Environment, and Electrical Systems, National Engineering School of Gabes, University of Gabes, Gabes 6029, Tunisia
[4]MEU Research Unit, Middle East University, Amman, Jordan
[5]Department of Electrical and Computer Engineering, King Abdulaziz University, Jeddah 21589, Saudi Arabia
[6]Department of Business Administration, The Applied College, King Abdulaziz University, Jeddah 21589, Saudi Arabia
[7]ENET Centre, VSB-Technical University of Ostrava, Czech Republic
[8]College of Engineering, University of Business and Technology (UBT), Jeddah 21448, Saudi Arabia
[9]Department of Electrical Engineering, College of Engineering, Northern Border University, Arar, Saudi Arabia

"This work was supported by the following project TN02000025 National Centre for Energy II."

ABSTRACT The decarbonization of hard-to-abate industries is crucial for keeping global warming to below 2^oC. Green or renewable hydrogen, synthesized through water electrolysis, has emerged as a sustainable alternative for fossil fuels in energy-intensive sectors such as aluminum, cement, chemicals, steel, and transportation. However, the scalability of green hydrogen production faces challenges including infrastructure gaps, energy losses, excessive power consumption, and high costs throughout the value chain. Therefore, this study analyzes the challenges within the green hydrogen value chain, focusing on the development of nascent technologies. Presenting a comprehensive synthesis of contemporary knowledge, this study assesses the potential impacts of green hydrogen on hard-to-abate sectors, emphasizing the expansion of clean energy infrastructure. Through an exploration of emerging renewable hydrogen technologies, the study investigates aspects such as economic feasibility, sustainability assessments, and the achievement of carbon neutrality. Additionally, considerations extend to the potential for large-scale renewable electricity storage and the realization of net-zero goals. The findings of this study suggest that emerging technologies have the potential to significantly increase green hydrogen production, offering affordable solutions for decarbonization. The study affirms that global-scale green hydrogen production could satisfy up to 24% of global energy needs by 2050, resulting in the abatement of 60 gigatons of greenhouse gas (GHG) emissions - equivalent to 6% of total cumulative CO_2 emission reductions. To comprehensively evaluate the impact of the hydrogen economy on ecosystem decarbonization, this article analyzes the feasibility of three business models that emphasize choices for green hydrogen production and delivery. Finally, the study proposes potential directions for future research on hydrogen valleys, aiming to foster interconnected hydrogen ecosystems.

INDEX TERMS Green or Renewable hydrogen, Renewable electricity storage, Decarbonization, Hard-to-abate industries, Carbon neutrality

I. INTRODUCTION

A. BACKGROUND

Green hydrogen has emerged as a promising solution in the global effort to achieve climate neutrality and meet the ambitious target of limiting global warming to 1.5°C, particularly in the industrial, shipping, and aviation sectors [1]. Produced through water electrolysis using renewable electricity, green hydrogen has the potential to significantly reduce greenhouse gas emissions and mitigate the adverse impacts of climate change [2], [3]. However, there are several challenges that must be addressed to realize the full potential of a green hydrogen economy, including the high cost of renewable electricity, elevated production costs, limited value chain infrastructure, and the need for international standards [4]. Technological advancements in green hydrogen are crucial for decarbonizing the hardest and most expensive industry sectors and meeting the growing demand for renewable power. Moreover, the integration of green hydrogen in the transportation sector can provide significant sustainability benefits, complementing the use of electric vehicles and supporting the development of charging infrastructure. Concurrently, the building sector faces the imperative of transitioning to 100% renewable heating sources [5], [6]. It is worth noting that efficient farming practices play a vital role in mitigating agricultural emissions, particularly in the most challenging agricultural sector [7].

In a prospective climate-neutral economy, hydrogen has the potential to serve as a versatile energy carrier and fuel for hard-to-abate sectors, a chemical feedstock for industrial processes, a heat source for the building sector, and a medium for inter-seasonal energy storage in the power sector [8], [9]. In achieving a 100% renewable future, renewable hydrogen can facilitate emission-free operations in industries, heating, and transportation. Furthermore, hydrogen has reemerged as a promising solution to address the intermittency challenge of renewable energy sources [10], [11].

B. LITERATURE SURVEY AND CONTRIBUTIONS

Hydrogen plays a pivotal role in various applications, including methanol and ammonia production, oil refining, metal processing, fuel cell vehicles, and synthetic natural gas production [12]. Renewable hydrogen technologies, such as Power-to-power, Power-to-gas, Power-to-fuel, and Power-to-feedstock, hold promise in enabling the production of hydrogen, methane, methanol, and ammonia, which are crucial components of a low-carbon future [13]–[15]. The integration of hydrogen into different energy sectors, encompassing production, storage, and re-electrification, is an area of investigation [16]. Notably, hydrogen production from renewable electricity is characterized by negligible negative environmental impacts and presents opportunities to achieve ambitious net-zero emission targets [17], [18]. The cost of producing green hydrogen, which encompasses electricity and electrolytes/catalysts for water electrolysis, is estimated to be approximately ten dollars per kilogram, with conversion efficiency ranging from 60-80% [19].

Hydrogen storage, transport, and delivery require significant space, with the option of storing hydrogen in liquid form to minimize space requirements while maintaining it below its freezing point at -253°C. Despite this, hydrogen remains economically prohibitive due to factors such as lack of infrastructure and associated costs [20]. The development of affordable decarbonization solutions is crucial for achieving a sustainable and green energy transition in the long term. This can be facilitated through advancements in technologies, government policies, and strategic investments to enhance the competitiveness of renewable hydrogen production compared to carbon-based alternatives [21]. The storage and delivery of hydrogen are crucial components for advancing hydrogen and fuel cell technologies, which are applicable in various domains such as stationary power, portable power, and mobility applications [22], [23]. The establishment of adequate infrastructure is essential to facilitate widespread consumer adoption of hydrogen as an energy carrier. This infrastructure typically involves liquefaction plants, pipelines, storage tanks, trucks, compressors, and dispensers at refueling stations, which collectively enable the delivery of hydrogen fuel to the point of consumption [24].

In comparison to rechargeable batteries, hydrogen regenerative fuel cells offer distinct advantages such as remote energy storage, independence of discharge voltage from stored energy levels (State of Charge or SoC), and tunable recharge/discharge rates for mission-specific applications [25]. Adopting green hydrogen as a fuel source in fuel-cell electric vehicles (FCEVs) can lead to doubled mileage or efficiency compared to hydrogen-based internal combustion engines [26]. Recent technological and economic advancements in heavy-duty transportation and heavy industries suggest that hydrogen-powered FCEVs may become an ideal choice for future transportation [27]. Ammonia has also emerged as a potential eco-friendly alternative fuel with the ability to enable a carbon-free economy, particularly in the transportation industry [28]. While the utilization of mature and early-adoption technologies can significantly reduce emissions, ongoing research innovations and industrial scale-up efforts may lead to further price reductions in electric vehicles (EVs) and electrolyzers [29].

Table 1 provides a comprehensive overview of various fuel properties, including hydrogen, highlighting its unique characteristics. While hydrogen offers numerous advantages over fossil fuels in terms of its environmental impact and versatility, it is important to acknowledge that hydrogen also presents inherent safety risks. These risks stem from its high flammability range, low ignition energy, low viscosity, and low density. These inherent characteristics of hydrogen can potentially lead to explosions. As a result, the storage and delivery of hydrogen pose significant challenges from a safety perspective. [30], [31]. Green hydrogen has the potential to significantly reduce carbon emissions, but there are several challenges that need to be addressed for its widespread commercialization. These challenges include sustainable production, cost-effectiveness, infrastructure development, global market expansion, and recognition as a comprehensive solution for transitioning to a hydrogen-based energy system [38].

There is a lack of comprehensive reviews addressing the knowledge gaps related to green hydrogen ecosystems. Therefore, this review aims to provide a comprehensive perspective on the sustainability and feasibility of renewable hydrogen production to delivery on the green hydrogen

TABLE 1. Comparison of properties of hydrogen with other fossil fuels [32]–[37]

Property	Diesel	Biodiesel	Gasoline	Compressed Natural Gas (CNG)	Liquefied Natural Gas (LNG)	Propane (LPG)	Ethanol	Methanol	Hydrogen
Energy content	35.8 MJ/L	38-42.6 MJ/kg	34.2 MJ/L	53.6 MJ/kg	55.5 MJ/kg	46.4 MJ/kg	26.8 MJ/L	19.9 MJ/L	141.8 MJ/kg
Lower heating value (MJ/kg))	42-45	37-39	43-48	47-53	50-56	46-50	23-29	19-20	120-142
Heat of evaporation (kJ/kg))	290-320	270-290	400-450	750-850	380-450	350-400	840-900	950-1100	440-460
Flammability range (in air)	0.6-4.0%	1.0-6.0%	1.4-7.6%	5-15%	5-15%	1.5-10.1%	3.3-19%	4-75%	6-36%
Ignition energy (J)	0.8-1.6	0.7-0.9	0.25-0.3	0.17-0.25	0.25-0.35	0.2-0.25	0.2-0.3	0.3-0.5	0.017-0.05
Viscosity (cSt)	2-6	3.5-6.0	0.4-0.8	0.02-0.2	0.05-0.2	0.4-1.0	1.0-1.2	0.5-1.0	0.007
Density (kg/m^3)	830-860	860-900	700-800	0.67-0.9	420-470	540-580	789	792	0.089-0.090
Carbon content	264 g/L	0-79 g/MJ	235 g/L	30-90 g/MJ	25 g/MJ	73 g/MJ	35 g/MJ	107 g/MJ	0 g/kg
Sulphur content	<15 ppm	0-20 ppm	0-10 ppm	<1 ppm	<1 ppm	<1 ppm	0-17 ppm	0-5 ppm	0.1 ppm
Nitrogen content	<15 ppm	<10 ppm	0-8 ppm	<1 ppm	<1 ppm	<1 ppm	0-62 ppm	<1 ppm	0.1 ppm

(Source:https://afdc.energy.gov/fuels/properties)

network, while considering the nascent stages of modern technological advancements. The review article discusses the hurdles, opportunities, and advancements related to interconnected hydrogen ecosystems, including green hydrogen production, storage, transport, distribution, and end-use levels. Overcoming challenges for the large-scale adoption of green hydrogen involves addressing critical aspects. Cost-competitive production is a key hurdle, requiring the scaling up of processes like electrolysis and photo-electrolysis while improving efficiency for hard-to-abate industries. Catalysts in hydrogen production and fuel cells need continuous innovation for cost-effectiveness and mitigation of poisoning issues. Transportation, distribution, and safety optimization are crucial, involving infrastructure adaptation and material compatibility. Lowering component costs, balancing hydrogen and carbonaceous fuels, and addressing storage challenges are essential for a robust supply chain. Economic viability, supportive policies, and regulatory frameworks are vital for widespread adoption, helping reduce carbon-intensive practices and promote a low-carbon economy.

C. ORGANIZATION

The structure of the study is organized as follows: Section II outlines the review methodology, explaining the systematic approach employed to gather and analyze information on green hydrogen technologies. Section III provides a technical overview of green hydrogen production, highlighting significant hurdles in cost reduction and scaling up in water electrolyzers. Section IV examines the technological issues related to hydrogen storage and highlights the challenges that have hindered the development of a hydrogen economy pathway. Section V investigates the existing hindrances to hydrogen transportation and delivery, with a focus on modern technical solutions. Section VI analyzes the commercialization aspects of green hydrogen for end-use applications. Section VII addresses unresolved scientific issues for future developments in establishing interconnected hydrogen ecosystems, followed by concluding observations. Figure 1 shows the research flowchart of this investigation.

II. REVIEW METHODOLOGY

The methodology employed in this review involved a systematic approach to gather and analyze information on green hydrogen technologies. A thorough literature review encompassed articles, research papers, and publications from reputable sources, covering various aspects of green hydrogen production, storage, transportation, distribution, and end-use applications. Additionally, a patent analysis from 2014 to 2022 was conducted to identify trends in electrolyzer and fuel cell technologies related to water electrolysis. A publication analysis tracked research trends in fuel cells and hydrogen production from 1996 to 2023. This methodological approach ensures a comprehensive exploration of challenges, advancements, and opportunities in the green hydrogen domain.

Using patent information, a study is conducted to analyze the trends and patterns of electrolyzer and fuel cell technologies related to water electrolysis from 2014 to 2022, as shown in Figure 2. The results show the summary of patent filings by the top 20 jurisdictions for international water electrolysis patent families. China has emerged as the global leader in patent filings for water electrolysis, followed by the United States, Europe, and Japan. However, when it comes to fuel cell technology, the United States takes the lead, followed by Europe, Japan, and China. These findings provide valuable insights into the geographical distribution of innovation and research activities in these technologies, as well as the dominance of certain jurisdictions in different aspects of electrolyzer and fuel cell advancements. Figure 3 illustrates the number of publications in the field of fuel cells and hydrogen production sectors from 1996 to 2023, focusing on Proton-exchange membrane fuel cells (PEMFC), Solid oxide fuel cells (SOFC), Alkaline fuel cells (AFC), Alkaline electrolysis (AEL), Proton exchange membrane electrolysis (PEMEL), and Solid Oxide electrolysis (SOEL). The publication trend reveals a significant increase in the number of publications related to PEM technology, indicating rapid advancements in this field.

However, there is a scarcity of recent strategic research

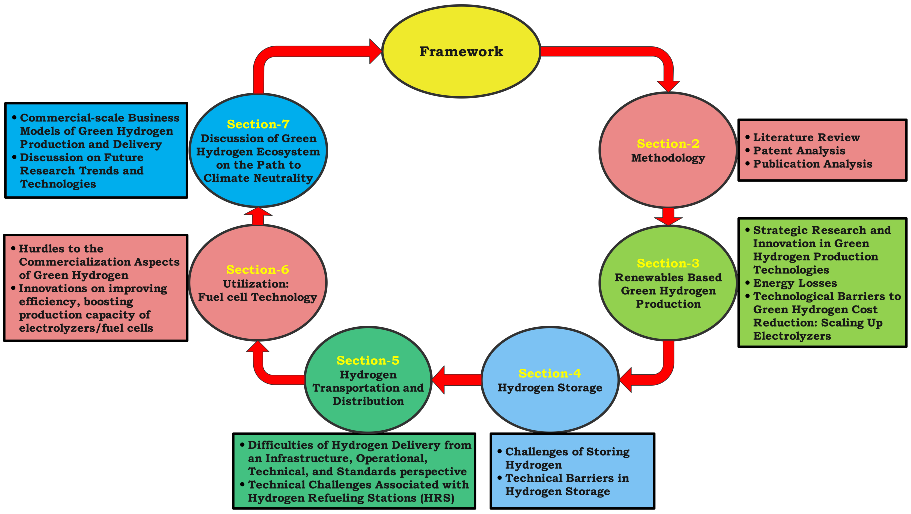

FIGURE 1. Framework of this study

assessments in the literature on the commercialization of green hydrogen. Therefore, this study aims to provide a comprehensive literature review on systematic research related to sustainable hydrogen, with a focus on accelerating the expansion of clean energy infrastructure towards carbon neutrality. The primary objective of this study is to identify knowledge gaps pertaining to the implications of green hydrogen on hard-to-abate sectors in achieving climate neutrality. Additionally, the study addresses the challenges and opportunities associated with commercial-scale green hydrogen production and delivery and suggests potential business models.

III. RENEWABLES BASED GREEN HYDROGEN PRODUCTION

The production of hydrogen through water electrolysis powered by renewable energy sources is currently expensive, but there is a growing need for increased efficiency and cost competitiveness in renewable hydrogen production routes. This requires significant development in electrolyzer technologies, including those supported by thermal dissociation of water through photocatalysis, concentrated solar, and biomass/biogas processes [39]. Water electrolysis is a well-established technology for hydrogen production and has been implemented at the megawatt (MW) scale in various industries worldwide. Different types of electrolysis technologies, such as Alkaline electrolysis (AEL), Anion exchange membrane electrolysis (AEMEL), Proton exchange membrane electrolysis (PEMEL), Proton conducting ceramic electrolysis (PCCEL), and Solid oxide electrolysis (SOEL), are being actively researched and developed to improve their performance and cost-effectiveness in hydrogen production.

A. STRATEGIC RESEARCH AND INNOVATION IN GREEN HYDROGEN PRODUCTION TECHNOLOGIES

The research and development of green hydrogen technologies are focused on various aspects, including reducing capital and operational costs, scaling up to larger sizes (up to 100 kW), achieving high power usage of 40 kWh/kg, developing new catalysts, minimizing environmental impact, and extending the lifetime of the technologies, as summarized in Table 2. These technological advancements contribute to the establishment of a sustainable and low-carbon energy system for the future [40], [41].

Among the promising technologies, Anion Exchange Membrane (AEM) electrolysis combines the advantages of Proton Exchange Membrane Electrolysis (PEMEL) in terms of efficient production of high-purity hydrogen, and traditional Alkaline Electrolysis (AEL) in terms of cost-effectiveness, making it a potential candidate for renewable energy storage and fuel cell vehicle applications. Solid Oxide Electrolysis (SOEL) technology eliminates the need for expensive and corrosive liquid electrolytes, making it suitable for various applications such as renewable energy storage, industrial hydrogen production, and energy-efficient transportation [65]. Highly efficient Proton Conducting Ceramic Electrolysis (PCCEL) technology finds applications in industrial hydrogen production, energy storage, grid stabilization, and fuel cell vehicles [66]. Photoelectrochemical (PEC) technology is a promising area of research with potential applications in renewable energy storage and sustainable fuel for fuel cell vehicles [67]. Biological (dark fermentation) hydrogen production aims to develop a sustainable and cost-effective technology that can provide a reliable source of clean hydrogen for a wide range of applications, including transportation and industrial processes [68]. Bioelectrochemical (BEC) hydrogen production has several advantages over

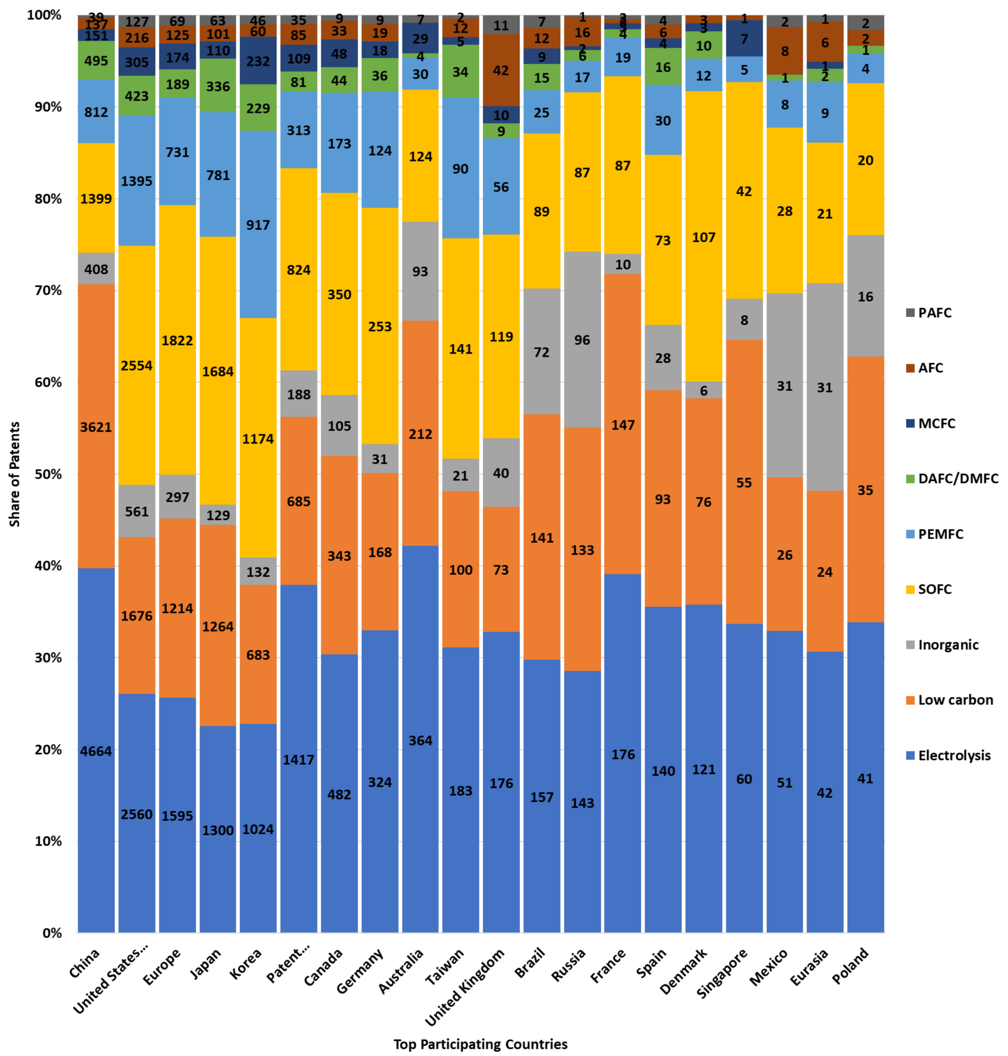

FIGURE 2. The total number of patents filed from 2014 to 2022 for hydrogen production and fuel cells based on water electrolysis.

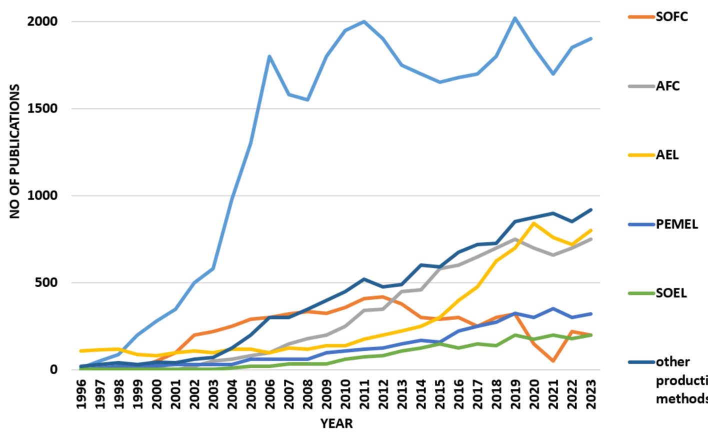

FIGURE 3. The total number of publications from 1996 to 2023 related to Fuel cell and water electrolysis technology.

TABLE 2. Various pathways for hydrogen production and associated development research actions [42]–[64]

Technology	Description	Benefits	Limitations	Development Research Action
PEMEL [42]–[44]	PEM systems are preferred where high dynamic operation is required, due to the short start-up time and wide load flexibility range.	PEMEL's high current density and compact design, and quick response enable it to withstand high pressures. This method has higher energy efficiency (80–90%) and a greater hydrogen generation rate with high purity of gases (99.99%). For decoupled water splitting, a membrane-free flow electrolyzer has been designed.	The overall cost of PEM electrolyzer accounts for the costs of rare metals such as platinum-coated titanium material for bipolar plates at the stack level, iridium on the anode side, platinum on the cathode side at the cell level and system level.	The dearth of scarce metals can hinder accelerated PEM electrolyzer deployment and renewable hydrogen consumption. To prevent this, Iridium, Ruthenium, and other precious Platinum group metal-free catalysts must be invented with a current density of $3A/cm^2$ to support 30-75 GW of the electrolyzer capacity.
AEL [45]	AEL is a mature, affordable, and commercialized technology. The energy efficiency is 70-80%.	In comparison to a PEMEL, AEL has a longer lifespan and lower annual maintenance costs. A high-performance alkaline capillary-fed water electrolysis cell leads to bubble-free operation at electrodes.	The downsides of this technology are low current densities, impure gases, limited operating pressure (3-30 bar), and low dynamic operation. The formation of carbonates on the electrode affects the performance of the electrolyzer.	More compact stack design with 3D electrodes, a high current density of $1A/cm^2$, cell voltage biased at 1.51V, ruthenium-free metals for the cathode, 98% energy efficiency, and energy consumption of 40.4 kWh/kg makes the development of affordable renewable hydrogen.
SOEL [46], [47]	SOEL is the promising solution for energy generation and storage of synthetic fuels due to its maximum conversion efficiency (90–100%), non-noble electrocatalysts, and withstanding high pressures.	Compared to AEL and PEMEL, SOEL has small stack capacities of less than 10kW. The current density in solid oxide electrolysis cells with bimodal-structured nanocomposite oxygen electrodes surpasses $3A/cm^2$.	The main issue with high-temperature. SOEL is material stability and durability, despite its great efficiency.	A pressurized stack must be designed with a current density of $1.5A/cm^2$, the reversible capacity of 40%, and the efficiency of greater than 50% using advanced manufacturing technology.
AEMEL [48]–[51]	AEMEL uses the benefits of PEMEL and AEL systems to produce hydrogen at a potentially affordable and sustainable way.	Reduced usage of IrOx and Pt/C catalysts, KOH-based electrolytes with lesser than 1%mol, the high-current density of 1.5A/cm^2, novel membranes, and waste minimization aids in the production of inexpensive sustainable fuel.	Although several benefits of AEMEL technology, the challenges are the mechanical and chemical stability of the membrane, unstable operation, and short lifetime.	Develop inexpensive porous transport layers (PTLs), reduce gas permeability in membranes and ohmic losses, employ perfluorinated sulfonic acid (PFSA) membranes, and improve membrane durability for AEM electrolyzers.
PCCEL [52]	PCCEL is a high-temperature (500-1000^oC) electrolysis system that uses a proton-conducting ceramic electrolytes to produce hydrogen gas from water.	Protonic ceramic electrochemical cells use solid oxide proton conductors to convert energy between hydrogen and electricity in a self-sustaining and reversible manner.	PCCEL has several challenges that need to be addressed, such as the high operating temperature, durability of the ceramic electrolyte, and the cost of the materials.	A triple conducting oxide of the perovskite-based electrode has been developed for the production of electricity and water electrolysis. Planar/tubular cells in enhanced materials need to be designed for scaling up to kW in PCCEL technology.
Photoelectro chemical systems (PEC) [53]–[56]	PEC is inspired by photosynthesis in plants and uses solar energy to split water.	Graphene oxide with oxygen functionalization is a good electrocatalyst for producing hydrogen peroxide. A hydrogel-protected photocathode exhibits stability over 100 hours, with 70% of its initial photocurrent, and reduces the degradation rate to prevent semiconductor photocorrosion and improve the lifetime of photoelectrochemical devices.	One significant issue is the development of efficient and stable photoelectrode materials capable of producing enough electron-hole pairs while also withstanding the harsh electrolyte conditions. Another issue is the development of suitable electrolytes capable of transporting charge effectively and enabling the desired electrochemical processes.	Although $TiO2$ is the most studied material for PEC technology, its absorption is confined to UV due to its large band gap. The development of PEC water splitting requires contemporary research efforts in nanotechnologies, photovoltaics, and computational materials to improve efficiency.
Biological production [57]–[60]	Biological hydrogen production refers to the use of microorganisms, such as bacteria and algae, to produce H_2 through biological processes. Biohydrogen production can be achieved through two main pathways: dark fermentation and photofermentation.	Although the production cost is around 2-3 USD/kg, biological hydrogen production processes should enhance biohydrogen yield and rate. A 100 m^3 bio-reactor should be built to attain a high hydrogen production rate of more than 15 $kgH_2/m^3/day$ of reactor volume employing technical solutions such as inoculum conditioning and feedstock pre-treatment.	Several challenges need to be addressed to make biohydrogen production of a viable commercial technology, such as low efficiency and low hydrogen yields, high costs, and difficulty in controlling the microbial community. Biophotolysis, dark fermentation, and photo fermentation technologies have low hydrogen yield, are inefficient and require huge reactors.	Some of the key areas of research and development including microbial strain development, efficient bioreactor design, feedstock optimization, integration with other renewable energy systems, and process control and monitoring.
Bioelectro chemical (BEC) [61], [62]	BEC is a process that use microorganisms including wastewater, agricultural waste, and industrial waste to generate hydrogen through the use of an electrochemical cell.	In contrast to conventional fuel cells, BEC systems do not rely on expensive precious metals as catalysts. Biohydrogenesis is a method for producing sustainable and efficient hydrogen gas from various organic compounds as substrates under anaerobic conditions.	Some of the main limitations of BEC process including limited microbial diversity, environmental sensitivity, and reactor design.	The R&D actions in BEC process are focused on improving efficiency, scalability, and cost-effectiveness of the process and also explores its potential applications in waste treatment, renewable energy, and hydrogen production.
Direct Solar [63], [64]	Utilizing photocatalysts is crucial for effective and efficient charge carrier separation. Direct solar thermolysis and photolysis are promising methods for using solar energy to drive chemical reactions.	Intermittent solar irradiation, low energy conversion efficiency typically less than 10%, and high cost of photovoltaic cells are some of the main drawbacks of solar-driven hydrogen production.	Thermolysis-based hydrogen production technology suffers from high capital costs, low conversion efficiency (20-45%), Elements toxicity, and corrosion issues. The hydrogen generation process in photolysis has poor efficiency (0.06%) and a production cost of approximately 8–10 USD/kg.	Innovative architectural designs, composite materials, and collector/ reactor system designs need to be employed to scale up low-temperature thermochemical, photolysis, and photocatalytic water-splitting technologies.

other methods, such as utilizing a wide range of feedstocks, including organic wastes and wastewater [69]. Solar-driven hydrogen production has the potential to be a sustainable and renewable method for hydrogen production, particularly in regions with high levels of solar irradiation [70].

B. ENERGY LOSSES

In the production of green hydrogen, electrolysis, fermentation, and steam reforming are commonly used processes. However, electrolysis, which is an electrolytic method, faces several challenges. These include significant energy losses of 30-35% at each stage of the value chain, low overall efficiency ranging from 60-80%, the need for additional onsite compressors, and a relatively short lifespan of fewer than 5 years. Furthermore, during the conversion of hydrogen derivatives such as ammonia, energy losses of 13-25% may occur. Additionally, around 10-12% of hydrogen can be lost during transportation, and utilization of hydrogen in fuel cells may result in an additional energy loss of 40-50% [71]. On the other hand, the fermentation technique for hydrogen production also has challenges, including poor hydrogen generation yields, difficulties in scaling up microbial electrolysis cell systems while maintaining production rates, and overall efficiency limitations of around 40% [72]. Moreover, steam reforming, which is another common process, faces challenges such as high complexity, low overall efficiency, and the need for reformer adaptation of various composite materials [73]. These challenges need to be addressed in order to improve the efficiency and sustainability of green hydrogen production processes and to enable their widespread adoption as a clean energy source [74].

Research in the field of water electrolysis should focus on various aspects to enhance the commercial viability of the technology. This includes designing large area and high-pressure stacks, developing monitoring and control methods for electrolyzers, exploring reversible hydrogenation, improving the balance of plant designs, integrating MW scale electrolyzers into renewable generation and industrial production plants, utilizing by-products, and exploring the production of ammonia, methanol, and synthetic petrochemicals using renewable hydrogen [56], [78], [79]. Furthermore, continuous improvements are needed in electrolyzer technology, including enhancing efficiency through improved surface catalysis and enhanced solar absorption, durability and lifetime through protective surface coatings and rugged materials, cost reduction through reduced scarce materials, reversible electrolysis, co-electrolysis, connectivity of renewables in the overall energy systems, water management, and scale of deployment. After being produced at a large scale and a competitive price, green hydrogen may then be further transformed into energy carrier variants including ammonia, methane, methanol, and liquid hydrocarbons [80]–[82].

For specific electrolysis technologies, research efforts are targeted toward various aspects. For AEL, integrating porous transport layers (PTLs) into electrodes and diaphragms can lead to cost savings. Current research includes increasing current densities and operating temperature limits, reducing diaphragm thickness, redesigning catalyst compositions, designing high-specific area electrodes, and developing novel PTL/electrode concepts. For PEMEL, bipolar plates and PTLs play a crucial role in cost reduction. Ongoing research focuses on reducing membrane thickness and catalyst quantities, eliminating expensive coating on PTLs, redesigning catalyst-coated membranes, developing novel recombination catalyst concepts, and exploring novel PTL/electrode concepts. SOEL research is aimed at achieving the high efficiency and durability of electrodes. This includes improving electrolyte conductivity, equipping both electrodes with matching thermal expansion coefficients, minimizing reactant crossover, and optimizing mechanical and chemical stability. For AEMEL, research efforts are focused on achieving desirable membrane properties and ionomers, including high mechanical and thermal stability, ionic conductivity, reduced polymer degradation, and improved membrane and ionomer conductivity. Critical performance metrics, including long-term targets for each electrolysis technology, have been summarized in a Table 3.

C. TECHNOLOGICAL BARRIERS TO GREEN HYDROGEN COST REDUCTION: SCALING UP ELECTROLYZERS:

Renewable hydrogen production through water electrolysis using solar or wind energy is gaining momentum as a promising solution to replace fossil fuels in various industrial applications such as long-haul aviation, freight shipping, long-distance trucking, oil refining, ammonia production, and steel manufacturing. However, significant challenges remain to achieve commercial viability. The high demand for renewable electricity to power electrolyzers is a major hurdle, with electricity costs accounting for 80% of the overall production cost [83]. The electrolyzer, being the most expensive component, requires cost-effective solutions to drive down the overall cost of green hydrogen production. The membrane electrode unit, which constitutes 60% to 70% of the total cost, presents another challenge due to the use of precious metals [75]. Additionally, achieving the desired purity of hydrogen at an affordable cost is a critical concern, as the conversion process to more stable forms like ammonia can be expensive. Furthermore, challenges in hydrogen transportation and storage, such as the need for liquefaction at $-253^{O}C$, add to the overall cost of green hydrogen production. At the end-user level, fuel cell vehicles, synthetic fuels for aviation, and the cost of hydrogen tanks are more expensive than fossil fuel counterparts [1]. To make green hydrogen production economically viable, it is essential to reduce construction and procurement costs, improve electrolyzer performance and durability, and scale up from MW to GW scale. Long-term targets for green hydrogen production include achieving a cost of less than USD 200/kW, durability exceeding 50,000 hours, and approaching 80% efficiency [75]. Transitioning from the potential to the reality of large-scale green hydrogen production will require addressing these challenges through

TABLE 3. The critical performance metrics including the long-term targets for each of the four electrolysis technologies for the year 2050 [75]–[77]

Parameter	AEL	PEMEL	SOEL	AEMEL
Nominal current density (A/cm^2)	2	4-6	2	2
Voltage range (V)	< 1.7	< 1.7	< 1.48	< 2
Operating temperature (^oC)	90	80	60	80
Cell pressure (bar)	> 70	> 70	> 20	> 70
Load range (%)	5 – 300	5 – 300	5 – 200	5 – 200
H_2 **purity (%)**	99.99	99.99	99.99	99.99
Voltage efficiency (%)	> 70	> 80	> 85	> 75
Electrical efficiency of stack (kWh/kg H_2)	< 42	< 42	< 35	< 42
Electrical efficiency of system (kWh/kg H_2)	< 45	< 45	< 40	< 45
Lifetime (khrs)	100-120	100-120	80	100
Stack unit size (MW)	10	10	0.2	2
Electrode area (cm^2)	> 30000	> 10000	> 500	> 1000
Cold start to nominal load (min)	< 30	< 5	< 300	< 5
Capital costs of stack (USD/kW)	< 100	< 100	< 200	< 100
Capital costs of system (USD/kW)	< 200	< 200	< 300	< 200

interdisciplinary collaboration and innovation in materials science, electrochemistry, and renewable energy systems.

The challenges associated with cost reduction in water electrolysis, as depicted in Figure 4, can potentially be overcome through technological breakthroughs involving novel materials, increased manufacturing capacity, and economies of scale achieved through research [92]. These challenges fall into several categories, including optimizing operation conditions and electrolyzer structure, addressing material scarcity issues, enhancing technological performance and durability, exploring the stackability of electrolyzers with membranes, developing novel approaches for solar-driven water splitting, and managing plant requirements.

The optimal design of stack configuration for each water electrolysis technology, combined with scaling up plant capacity from MW to GW scale, has the potential to reduce costs by up to 50% [93]. This can be achieved by avoiding the use of scarce materials, such as iridium and platinum, in PEM electrolyzers, which would enable cost savings and allow for large-scale deployment of up to 100 GW [93]. Furthermore, decentralized hydrogen production, facilitated by compact electrolyzer modules, off-grid renewable energy sources, and low capital expenditure (CAPEX) investment per unit of electrolyzer capacity with minimal logistic expenses, has emerged as a viable solution [63]. A combination of lower electrolyzer unit capital costs, estimated at USD 130/kW, along with reduced electricity prices of 20 USD/MWh, increased lifetime of 20 years, improved efficiency of 76%, and optimized electrolyzer operation with full load hours of 4200 hours, could potentially alleviate up to 80% of the production costs of green hydrogen. As a result, competitive green hydrogen production costs of less than USD 1/kg could be achieved, making it a cost-effective alternative to fossil fuel-based hydrogen [94].

These findings highlight the potential for reducing the cost of green hydrogen production through advancements in stack design, scaling up of plant capacity, avoidance of scarce materials, decentralized production approaches, and optimization of key operational parameters.

D. FOSTERING INNOVATIONS IN WATER ELECTROLYSIS FOR REDUCING THE COST OF ELECTROLYZERS:

In order to achieve efficient and cost-effective green hydrogen production through electrolysis, various factors related to electrolyzer design and operation must be considered. For instance, the use of thinner membranes, more active catalysts, and reduced raw material requirements can enhance efficiency, but may also impact electrolyzer stack durability, leading to increased capital expenditure (CAPEX) annuity. Strategies such as employing larger stacks, optimizing manufacturing processes, and implementing quality control measures can further improve efficiency and reduce CAPEX. However, challenges such as low water quality, high-pressure operation, and limited maintenance can result in higher operational expenditure (OPEX) and decreased durability. Therefore, finding a balance between enhancing efficiency and minimizing costs remains a key challenge in the field of electrolysis for green hydrogen production. [92].

1) Cell operation conditions and structure:

Electrolyzer cost estimates vary based on the technology used, with alkaline electrolyzers priced at approximately \$700-900 per kW and PEM electrolyzers being more expensive at \$1300-1500 per kW. When operating PEM electrolyzers, it's crucial to maintain temperatures below 80°C to prevent membrane degradation and ensure optimal efficiency. Furthermore, an operating pressure of around 30 bar strikes a balance between efficiency and hydrogen production. Increasing current density in PEM electrolyzers can offer cost-saving benefits by enhancing efficiency and reducing material costs, but it necessitates advanced cooling systems to manage the increased heat generation. Expanding the cell area and stack height can also improve efficiency and reduce the overall cost per kW of electrolysis capacity, though practical limits need to be considered. These factors collectively impact the design, operation, and cost-effectiveness of electrolysis systems, which are pivotal in the development and implementation of hydrogen production technologies. Optimizing cell operation conditions and structure, such as

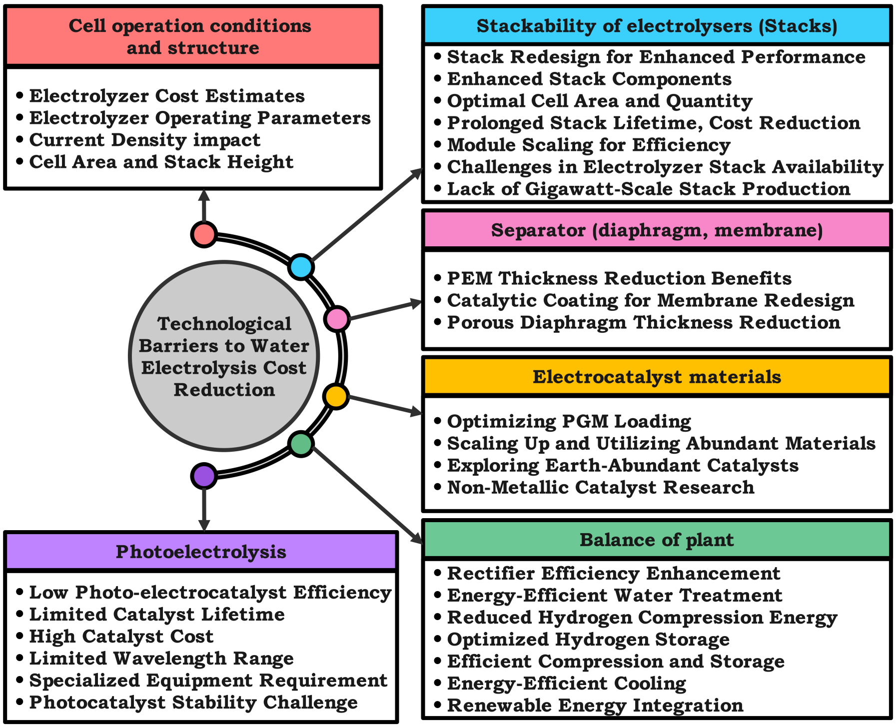

FIGURE 4. The technological obstacles to water electrolysis and explores six groups of sub-technologies for enhancing productivity and reducing overall electrolyzer costs [9],

operating at higher pressures and temperatures, can enhance the efficiency of electrolyzers without compromising membrane performance and durability, resulting in lower costs for green hydrogen production [95].

2) Stackability of electrolyzers (stacks):

For enhancing stack performance, it is essential to redesign stacks for higher current density, efficiency, lifespan, and durability while reducing the reliance on precious materials. This improvement can be achieved by enhancing stack components such as porous transport layers, bipolar plates, electrodes, and membranes, as well as minimizing costly protective coatings. Maximizing the cell area and increasing the cell count within stacks can significantly boost hydrogen production. Moreover, extending stack lifespan and reducing material costs are critical for improving the economic feasibility of hydrogen production via electrolysis. Scaling up module sizes can further enhance production rates and overall efficiency. However, challenges exist, including the current and anticipated scarcity of electrolyzer stacks, as well as the absence of gigawatt-scale stack production in the supply chain, which must be addressed to facilitate the widespread adoption of hydrogen production through electrolysis. Advancements in bipolar plates, electrodes, and porous transport layers can potentially lead to lower capital costs for electrolyzer stacks. Transitioning from manual to automated stack production at gigawatt (GW)-scale manufacturing plants may also result in significant cost savings [92].

3) Separators (diaphragms, membranes):

Modifying the thickness of proton exchange membranes (PEMs) and diaphragms in electrolyzers presents both advantages and challenges. In the case of PEMs, reducing their thickness from 50 to 25 microns can yield a 40% decrease in cell resistance and a 10% increase in current density, improving overall efficiency. However, this comes with potential trade-offs, as thinner polymer/ceramic membranes may face durability and mechanical stability issues. Redesigning membranes or diaphragms with catalytic coatings, such as adding a platinum layer to an anion exchange membrane (AEM), can significantly reduce hydrogen evolution overpotential by 75% and increase cell voltage by 40% at a given current density, enhancing performance. Similarly, decreasing the thickness of porous diaphragms from 1.5 mm to 0.5 mm can reduce energy consumption by 40% and boost hydrogen production rates by 20%. Nonetheless, thinner diaphragms may be more susceptible to fouling or blockage, potentially affecting both performance and durability. Balancing these factors is crucial for optimizing the design and operation of electrolyzer systems. Implementing effective mass transport strategies, such as using thinner membranes like ceramic and polymer electrolyte membranes, can enhance the efficiency of electrolyzers and reduce electricity consumption [96].

4) Electrocatalyst materials:

Current benchmarks for precious group metal (PGM) loading in PEM electrolyzers stand at around 0.5 mg/cm², ensuring stable and efficient performance. Utilizing a porous carbon support with a thin PGM catalyst layer can significantly reduce PGM loading while preserving performance, contributing to cost-efficiency. Scaling up production and exploring alternatives to scarce materials like platinum and iridium are essential to meet growing demand and reduce reliance on limited resources. The exploration of earth-abundant catalysts based on elements like cobalt, nickel, and iron holds promise, but their long-term stability and scalability require further investigation. Additionally, research into non-metallic catalysts, such as carbon-based nanomaterials, metal-organic frameworks, and 2D materials like graphene and molybdenum disulfide, is crucial to develop cost-effective, high-performance catalysts and drive sustainability in hydrogen production technologies. The scarcity of certain materials poses a significant barrier to the cost and scale-up of electrolyzers. Developing alternative materials, such as non-noble metal alloys and ceramics, could provide solutions to mitigate this challenge and enable more cost-effective electrolysis processes [97].

5) Balance of Plant

Enhancing the efficiency of hydrogen production through electrolysis involves a multifaceted approach. This includes improving rectifier efficiency to over 98% to minimize power losses, optimizing water treatment for energy efficiency and reduced water consumption (less than 0.5 kWh/m³ of deionized water circulation), reducing hydrogen compression energy consumption to less than 5 kWh/kg of hydrogen, and optimizing buffer storage to match hydrogen production and demand (targeting at least 24 hours of storage capacity). Additionally, it entails minimizing energy consumption in the compression and storage process (less than 10 kWh/kg of hydrogen), optimizing the cooling system for energy efficiency (targeting less than 1 kWh/kg of hydrogen produced), and designing the electrolyzer system to maximize the utilization of renewable energy sources with a target of at least 50% renewable energy incorporation. To enhance the overall efficiency and sustainability of the hydrogen production system, a comprehensive approach is taken, encompassing various aspects of the Balance of Plant [98].

6) Photoelectrolysis:

The development and implementation of photo-electrocatalytic systems for solar-driven water splitting face several challenges. These include low photo-electrocatalyst efficiency, with reported efficiencies ranging from less than 1% to approximately 15%. Catalyst lifetimes are limited, typically spanning from hundreds to thousands of hours, and the high cost of photocatalysts, which can account for up to 90% of the total system cost, poses a significant challenge. To address these issues, combining photocatalysts with different absorption properties can expand the applicable wavelength range, and specialized equipment, such as photo-reactors and photo-electrochemical cells, is required, adding to the complexity and cost. Furthermore, the stability of photocatalysts is a concern, potentially reducing the efficiency of PV-electrolysis systems over time. Research suggests that stability can be enhanced through structural modification or the use of protective coatings, offering potential solutions to these challenges in the development of solar-driven water splitting technologies. Despite the current challenges of technical maturity and route efficiency, photoelectrolysis offers the potential to integrate electricity and hydrogen production in a single process, which could lead to cost savings, in the long run, [99]. Electrolyzers could be more cost-competitive with photoelectrolysis when compared to fossil-based energy sources.

In order to achieve more affordable pricing of electrolyzers, continued research on anode and cathode catalysts is crucial, as these catalysts significantly contribute to the cost of the stack by increasing surface area (over 50 m^2/g) and utilization (over 80%). Further research on anodic and cathodic catalysts for both acidic and alkaline electrolyzers, which are used in on-site hydrogen stations for water electrolysis, can enable cost-effective refueling [100]. The development of precious metal-free catalysts, particularly those that do not contain iridium and titanium, with comparable activity to electrodes at lower temperatures and improved durability is of great importance [101]. Targeted research advancements should focus on reducing interface resistances and mechanical degradation of catalyst layers, minimizing contamination issues related to sulfur dioxide (SO_2) dissolution from the stack, addressing thermal instability caused by electrode and electrolyte mismatch, and scaling up stack units [102]. Additional improvements are needed to mitigate issues such as nickel hydride (NiH) formation on the cathode, critical degradation of catalysts, control of the oxidation state of catalysts on the anode, and membrane poisoning/deactivation by precious elements. Innovations in the design of recombination catalysts and enhancing the kinetics of oxygen and hydrogen evolution with nickel-based alloys are necessary for maintaining long-term stability [103].

In summary, Figure 4 comprehensively addresses the technological challenges and sub-technologies pertinent to advancing water electrolysis for hydrogen production. The six categories cover diverse aspects, ranging from cell operation conditions and stackability to separators, electrocatalyst materials, the balance of the plant, and photoelectrolysis. These considerations span efficiency optimization, material usage, cost reduction, and sustainability enhancements. The outlined challenges and potential solutions underscore the intricate landscape of water electrolysis, highlighting key areas demanding attention for the progression and cost-effectiveness of hydrogen production technologies.

This article has been accepted for publication in IEEE Access. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2024.3363869

IV. HYDROGEN STORAGE

Hydrogen is a promising method for storing renewable power and mitigating greenhouse gas emissions, with hydrogen-powered vehicles being a prominent application. However, the main challenge in realizing a hydrogen economy is the development of cost-effective, compact, conformable, and safe hydrogen storage systems. Distinct standards for hydrogen storage and fuel cell vehicles are necessary for stationary and mobility solutions. The hydrogen storage system must meet stringent criteria, including safety, lightweight design, compactness, cost-effectiveness, durability, long-term performance, and efficient refueling capabilities [104].

A. CHALLENGES OF STORING HYDROGEN

Hydrogen storage is a critical aspect of the hydrogen economy, with compression, cooling, or hybrid methods being the primary approaches employed. However, several significant barriers hinder the effective storage of hydrogen. These challenges encompass energy-intensive compression processes, stringent temperature and pressure requirements for solid hydrogen storage, complex design considerations, social and legal concerns, safety issues, high costs, and limited durability of materials (metals, fiber, polymers, etc.), as well as the need for purification processes before end-use. Additionally, bulk storage at geological formations such as abandoned mines or salt caverns poses logistical challenges, and the reliance on imports for fuel cell stacks, components, and hydrogen storage materials further complicates the storage landscape [105]. The multifaceted challenges associated with hydrogen storage are highlighted in Figure 5.

Dormancy issues involve high-pressure requirements, heavy containers, super insulation for cryo-compressed storage, boil-off rates, and energy-intensive liquefaction. Safety considerations revolve around hydrogen's explosive potential, necessitating safe integration with propulsion and refueling systems, effective insulation, and addressing concerns with LH2 storage, including boil-off losses and embrittlement. Hazards encompass potential rupture of high-pressure storage containers due to high temperatures, risks associated with larger tanks, steel embrittlement, and challenges in on-board gas hydrogen storage. Charging and discharging rates vary, requiring thermal management, faster refueling systems, and diverse responses. Material selection must account for permeation, capacity, operating temperatures, reversibility, and the development of new materials. System weight and volume entail heavy storage, thicker walls at high pressures, lightweight solutions, increased storage capacity, and balance of plant considerations. Energy efficiency differs with system types and can degrade over time. Durability concerns focus on material embrittlement, cracking, and degradation. Uniform adoption of standards and regulations is critical, including fuel quality standards and pressure relief device codes. System costs, including expensive vehicular hydrogen storage, highlight the need for cost-effective storage technologies, recyclable materials, and sustainability. Fuel costs and the challenge of storing large hydrogen quantities at ambient conditions emphasize the importance of efficiency. Fuel quality challenges address impurities like sulfur compounds, requiring regulatory frameworks to mitigate safety risks [9], [16], [84]–[91], [104], [105].

B. TECHNICAL BARRIERS IN HYDROGEN STORAGE

Hydrogen, a versatile energy carrier, can be stored in various forms such as solid, liquid, and gaseous, each with unique advantages and challenges. Gaseous hydrogen is often compressed to high pressures, typically up to 700 bars, and stored in different types of tanks including Type I (metal), Type II (metallic vessel hoop-wrapped with carbon fiber), Type III (metallic liner fully wrapped with carbon fiber), Type IV (polymeric liner fully wrapped with carbon fiber), and Type V (all composite vessel without liner) to achieve high volumetric density. Cryocompressed hydrogen storage, achieved by cooling hydrogen to cryogenic temperatures, also offers high volumetric and gravimetric efficiency [106], [107].

Liquefaction, which involves compressing hydrogen to high pressures and cooling it to cryogenic temperatures (-253^oC), is another storage option, but it incurs energy losses due to the high power consumption of the liquefaction process, estimated to be around 20-40% of the fuel energy. Storage of liquid hydrogen at cryogenic temperatures and near-ambient pressure (0.6 MPa) requires proper tank insulation to prevent the leakage of evaporated gas. Additionally, there are challenges associated with the long-term storage and potential hydrogen loss during the liquefaction process. However, it is considered to be the most efficient storage method currently available [83].

Hydrides, including metal, chemical, and complex hydrides, offer high gravimetric hydrogen storage capacity in the solid form [108]. Despite their overall energy efficiency, ammonia synthesis and breaking processes require significant energy input. Ammonia cracking is necessary as fuel cells typically require pure hydrogen, and research efforts have addressed the technical and economic challenges in this stage. The reliability of the renewable ammonia supply chain, including safe production, storage, and transportation, has also been investigated [109]–[111]. Liquid ammonia, stored in cryogenic tanks refrigerated to -33°C, is another viable option for hydrogen storage at modest pressures due to its higher energy density per volume compared to liquid hydrogen. Liquid organic hydrogen carriers (LOHCs) are potential candidates for long-term storage and long-distance transportation of hydrogen, as they can store hydrogen at ambient pressure by saturating and desaturating hydrogen in the hydrogenation and dehydrogenation processes, respectively. Additionally, storage in suitable geological formations such as salt caverns or abandoned mines, known as suburb storage, can be a cost-effective option for compressed gaseous hydrogen storage [112].

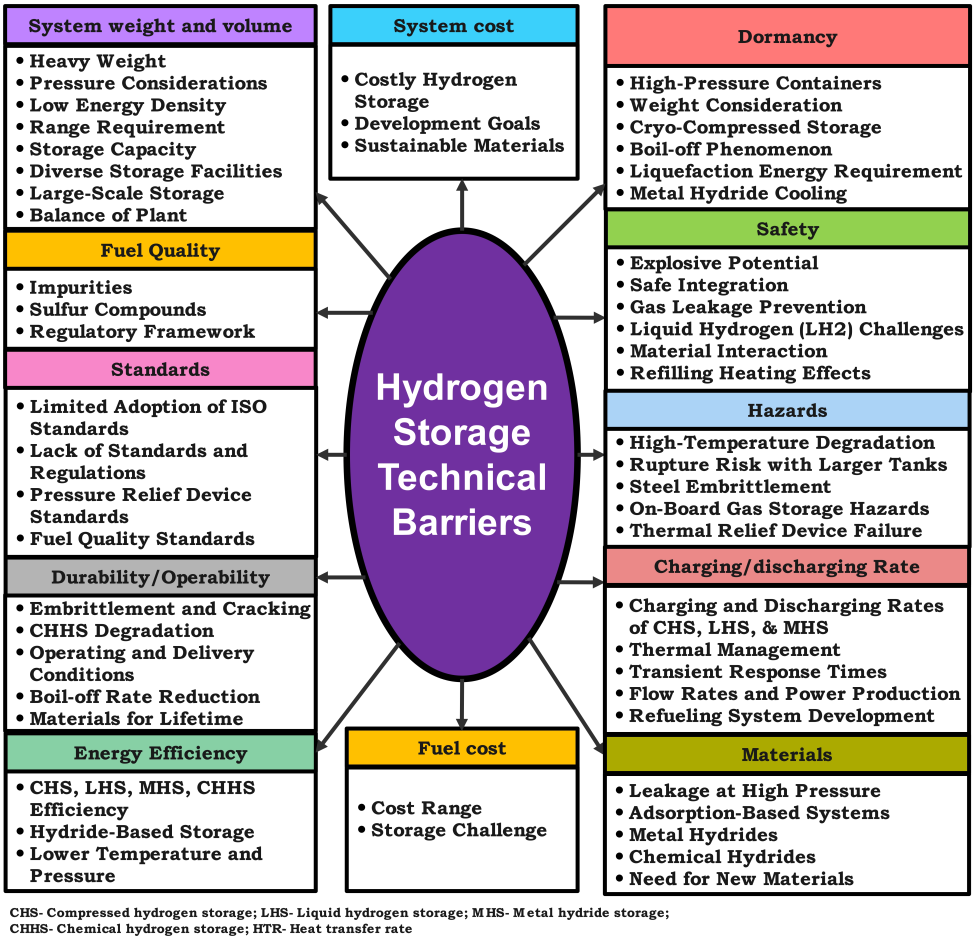

FIGURE 5. The technological issues associated with hydrogen storage [9], [16], [84]–[91], [104], [105]

1) Hydrogen liquefaction:

Superinsulated cryogenic tanks are utilized for the delivery of liquid hydrogen, despite boil-off losses during storage. These tanks have a high volume-to-surface ratio and are designed to store cryogenic liquid hydrogen for industrial applications, with temperatures as low as 200K and elevated pressures as high as 500 bars. To limit boil-off losses during transport, integrated refrigeration and storage systems are employed. Advanced cooling materials and cryogenic containers for hydrogen liquefaction are being developed to improve energy efficiency and lower costs. It is anticipated that compressed and liquefied hydrogen for long-distance liquid renewable transportation systems will become economically sustainable in the future [83].

2) Liquid organic hydrogen carriers:

The effective storage and release of hydrogen as an energy carrier is a critical requirement for its utilization. Hydrogen-rich aromatic and alicyclic components have been investigated for their ability to absorb and release hydrogen energy through the hydrogenation process. The feasibility of distributing hydrogen from liquid organic hydrogen carrier storage technologies to hydrogen refueling stations has garnered significant research interest. Efforts to enhance roundtrip efficiency and reduce costs in this context have focused on the development of novel metal-based catalysts, reduction of expensive raw materials, improved reactor technologies, and optimization of high-capacity CO_2 hydrogenation/formic acid dehydrogenation facilities [113]. Furthermore, in backup power applications, metal-organic framework adsorbents combined with fuel cells and electrolyzers have been shown to be price competitive with modern energy storage technologies [114].

3) Chemical hydrogen storage:

The utilization of hydrogen as a fuel has gained attention due to its ability to be harvested, compressed, stored, and used during periods of energy scarcity. Ammonia is currently being considered as a potential alternative to carbon-

This article has been accepted for publication in IEEE Access. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2024.3363869

based fuels, offering a means of delivering renewable energy worldwide [109]. In this context, the development of new catalysts for reforming and cracking processes has been explored as a replacement for conventional Haber-Bosch-based ammonia production plants. Electrochemical lithium-mediated nitrogen reduction reactions have shown promising results, achieving higher ammonia output rates of 150 nmol $s^{-1}cm^{-2}$ and nearly 100% current-to-ammonia efficiency [115].

4) Underground H_2 storage facility:

Underground gas storage facilities are widely used for the extensive seasonal storage of hydrogen, where enormous amounts of hydrogen are preserved in salt or porous caverns. The use of microporous metal-organic absorbers, which are targeted to achieve a capital cost of $30 per kg, has been explored as a potential solution for providing buffering functions in such storage systems [116].

5) Compression, purification, and separation:

The refueling of high-pressure storage tanks and managing start-stop loads in hydrogen refueling stations (HRS) can be achieved through various methods, including chemical, thermal, hydride, electrochemical, and turbo compression techniques. In particular, the development of platinum group metal (PGM)-free catalysts for proton exchange membranes in electrochemical and thermochemical purification/separation processes is of utmost importance in achieving high hydrogen purity levels of 99.99% [117].

High-pressure hydrogen storage is widely used in hydrogen delivery, onboard hydrogen storage (such as Type III or Type IV tanks), and hydrogen storage at refueling stations due to its economic and technological advantages. Low-temperature liquid hydrogen storage is highly desirable for long-distance and large-volume hydrogen storage, delivery, and refueling stations, as it offers high hydrogen storage density. For smaller-scale and short-distance hydrogen storage and transportation with easy and safe operation, metal hydride storage is a promising option. Future research in hydrogen storage should prioritize nanoporous materials or metal-organic frameworks with high gravimetric capacity, graphene and composite materials for hydrogen storage, high-pressure and lightweight hydrogen storage cylinders for automotive applications, characterization of metal hydrides, and complex hydrides for thermal management applications [105], [118]–[123].

In summary, Figure 5 provides a comprehensive overview of the multifaceted challenges associated with hydrogen storage. These include dormancy, safety, hazards, charging rates, materials, fuel costs, energy efficiency, durability, standards, fuel quality, and system weight/volume. High-pressure containers, cryo-compressed storage, liquefaction energy requirements, and safety concerns contribute to the complexity of the storage landscape. Hazards such as rupture risks and steel embrittlement, varying charging rates, and material compatibility further add to the intricacies. Additionally, standards, fuel quality, and system weight/volume considerations present challenges in the hydrogen storage domain. Addressing these issues necessitates comprehensive research and innovative solutions across various hydrogen storage technologies to promote the development of effective, safe, and standardized systems, crucial for realizing a hydrogen-powered future.

V. HYDROGEN TRANSPORTATION AND DISTRIBUTION

Pipelines have been widely recognized as the most cost-effective mode of transportation for large quantities of hydrogen, ranging from 10-100 kilotonnes annually, over distances up to 1500 km [124]. However, for transportation of hydrogen up to 4000 kg over longer distances to fueling stations, liquid hydrogen in trucks has been identified as the most economical option [125], [126]. Despite its cost-effectiveness, the transportation of liquid hydrogen in ships incurs significant energy losses due to liquefaction, which contributes to its high expense [127]. Comparatively, the transportation costs of ammonia and compressed gaseous hydrogen are similar. Among the various processes involved in the hydrogen industry, ammonia synthesis and reformation are considered the most expensive. Ammonia may become a preferred option for long-haul oversea shipping [128]. Hydrogen pipelines and tank storage are identified as the most expensive components in the compressed gaseous hydrogen value chain. Pressurized tube trailers (200-500 bar) are found to be ideal for transporting modest quantities of compressed hydrogen over short distances [129]. However, to enable the widespread use of hydrogen as a global energy carrier, revolutionary advancements are needed in hydrogen transportation and distribution, considering its low volumetric density and high energy content [130]. One potential solution for hydrogen production involves utilizing completely exposed palladium metal cluster catalysts to convert nitrogen heterocycles into hydrogen. This catalytic reaction, which does not require any observers, enhances reactivity and atomic efficiency in the transportation and utilization of hydrogen [131].

A. DIFFICULTIES OF HYDROGEN DELIVERY FROM AN INFRASTRUCTURE, OPERATIONAL, TECHNICAL, AND STANDARDS PERSPECTIVE

The transportation of hydrogen is primarily carried out through gaseous tube trailers, pipelines, and liquefied hydrogen tankers, which are widely used modes for delivering hydrogen to different destinations. However, the current hydrogen transmission pipeline infrastructure, which spans only about 5000 km, is inadequate to meet the projected future demand for hydrogen. Although liquefied hydrogen is more efficient for transportation compared to high-pressure tube trailers, there is a lack of infrastructure for the distribution of hydrogen to end-user locations, such as hydrogen refueling stations, which are limited in number (only 470), and precise control of hydrogen flow at refueling stations poses challenges. Quick transfers of compressed hydrogen can result in evaporation, leading to significant losses, thermal instability, and inefficient usage of hydrogen. Additionally, the conversion of existing natural gas pipelines to hydrogen transportation presents difficulties. It is imperative to expand the current infrastructure to accommodate the growing demand for green hydrogen-based synthetic fuels.

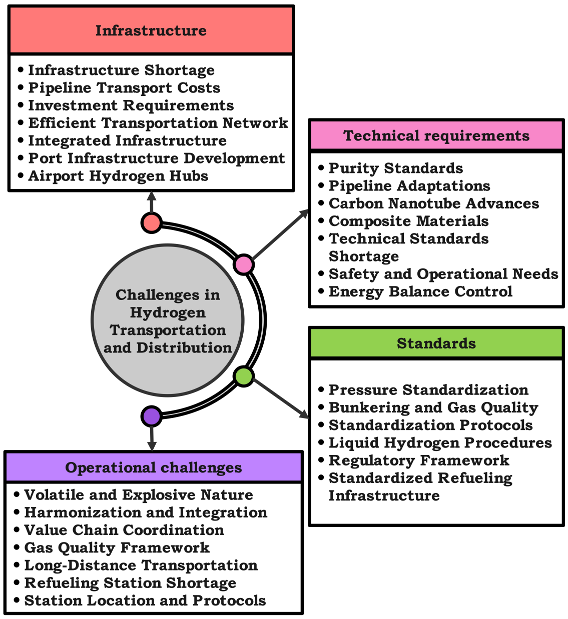

FIGURE 6. The difficulties of hydrogen delivery from an infrastructure, operational, technical, and standards perspective [9], [16], [84]–[91]

The key challenges associated with hydrogen transportation are summarized in Figure 6. These challenges encompass aspects such as cost, energy efficiency, hydrogen purity, boil-off, hydrogen leakage, safety, and environmental concerns [132], [133].

a) Infrastructure: The establishment of a robust hydrogen infrastructure faces several challenges, including a notable shortage of hydrogen delivery infrastructure, the need for substantial investments in new pipelines, and the development of hydrogen refueling stations. Hydrogen pipeline transport costs can vary widely, ranging from approximately \$1 to \$10 per kilogram of hydrogen, contingent on factors like transportation distance, pipeline diameter, and pressure. To address these challenges and create an efficient transportation network for hydrogen, significant investments, potentially reaching \$200 billion by 2050, may be required for the development of a comprehensive hydrogen pipeline network. This network aims to provide reliable and efficient hydrogen transportation, including integrated concepts that utilize coastal and offshore renewable power sources for various applications, port infrastructure development to support the transition of waterway vessels and coastal shipping to hydrogen propulsion, and the creation of airport hydrogen hubs to cater to local non-aviation consumers and liquid hydrogen (LH_2) fueling stations. These initiatives are crucial for advancing the adoption and utilization of hydrogen as an energy carrier in various sectors [134].

b) Technical requirements: Meeting the technical requirements for safe and efficient hydrogen utilization and infrastructure development is essential. These include stringent purity standards, demanding at least 99.999% purity with less than 10 ppm impurities during hydrogen transportation. Adaptations in sensors, compressors, and valves are necessary to handle high pressure, low hydrogen viscosity, and prevent leaks. Advances in carbon nanotubes can significantly improve hydrogen flow rates and longevity, while advancements in composite materials are crucial for constructing lighter and safer vessel tanks. The shortage of technical standards impedes the development of hydrogen-ready grids and the repurposing of existing gas grids. It's essential to establish safety, operational, and maintenance requirements for hydrogen infrastructure, along with developing energy balance control mechanisms for hydrogen systems at the Transmission System Operators (TSOs) and Distribution System Operators (DSOs) levels. Addressing these technical needs is paramount for the successful deployment and integration of hydrogen as an energy carrier [135], [136].

c) Standards: The standardization of hydrogen transportation and safety is paramount to ensure the widespread and safe adoption of hydrogen as an energy carrier. This includes establishing standardized safety and pressure limits for hydrogen transportation, which typically operates within a range of 80 to 345 bar. Addressing the lack of standards in bunkering compressed hydrogen for maritime use, hydrogen gas quality for pipelines, vessel tank pressure, tank topology, and the use of ammonia as ship fuel is critical. Developing standardized protocols and procedures for handling and transporting compressed hydrogen is necessary to ensure safety, quality control, and compatibility with existing infrastructure. For liquid hydrogen, standard operating procedures for handling, including filling nozzles and volume debits, and transportation through tunnels should be required. Additionally, the creation of a regulatory framework for the safe onward distribution of hydrogen and the implementation of standardized hydrogen refueling infrastructure for all mobility applications are essential steps in achieving a safe and reliable hydrogen ecosystem [137].

d) Operational challenges: Hydrogen transportation and operational challenges are significant hurdles in the widespread adoption of hydrogen as an energy carrier. These challenges stem from hydrogen's volatile and explosive nature, with a wide explosive limit range, necessitating stringent safety measures. The lack of harmonization and integration for pipelines and transport further complicates safe and efficient hydrogen transportation. Coordination across the value chain is essential to control gas quality and quantity and maintain hydrogen purity. The absence of a framework for handling hydrogen gas quality at the Transmission System Operator (TSO) level is a major obstacle in hydrogen adoption. Long-distance hydrogen transportation faces challenges related to cost reduction, enhanced energy efficiency, hydrogen purity preservation, and the prevention of hydrogen leakage risks. Additionally, the inadequate availability of hydrogen refueling stations is a key challenge, which can be addressed by identifying optimal refueling station locations, developing standardized installation protocols, and ensuring user accessibility to hydrogen fuel. Overcoming these challenges is vital for a successful transition to hydrogen as a clean energy source [138].

Fiber-reinforced polymer (FRP) pipes are increasingly being employed for the transportation of hydrogen gas. However, the utilization of polymer materials in vehicle fuel systems presents significant challenges due to pressure gradients and heat transients that arise during fuel consumption and refilling operations. Polymers and polymer composites have been utilized for sealing and bearing applications in liquid hydrogen environments, addressing the unique requirements of hydrogen transportation [139].

B. TECHNICAL CHALLENGES ASSOCIATED WITH HYDROGEN REFUELING STATIONS (HRS):

High-capacity hydrogen refueling stations face technical challenges, including the need for innovative interfacing technological components to improve efficiency and reduce CAPEX and OPEX. These challenges can be addressed through the development of flexible operation strategies to accommodate variable renewable energy sources (RES), enabling low inlet pressure, and implementing heavy-duty nozzles, flexibles, and chillers. Additionally, efforts should be made to reduce the overall footprint of HRS and deploy high-throughput HRS with multi-ton/day capacity. Standardization and industrialization of reliable and safe heavy-duty HRS equipment are also critical for the advancement of hydrogen infrastructure [83]. Among various options for hydrogen transport and storage, the use of hydrogenated liquid organic hydrogen compounds is considered cost-effective. However, challenges exist in maintaining extremely low temperatures around -253^oC, which requires significant energy input for storage. Further demonstration of bulk hydrogen storage is needed in various settings, including urban areas, warehouses, refueling stations, and standalone systems, to advance the adoption of this technology [112].

In summary, Figure 6 provides a comprehensive overview of the difficulties associated with hydrogen delivery, spanning infrastructure, operational, technical, and standards perspectives. The challenges include an inadequate hydrogen delivery infrastructure, high costs of hydrogen pipeline transport, the necessity for substantial investments, and the imperative development of a comprehensive hydrogen pipeline network. Technical challenges encompass stringent purity standards, adaptations in sensors and valves, and the shortage of technical standards for hydrogen-ready grids. Standardization issues, such as pressure limits and bunkering procedures, add complexity to hydrogen transportation. Operational challenges arise from hydrogen's explosive nature, the lack of harmonization across the value chain, and inadequate availability of hydrogen refueling stations. Overcoming these challenges is crucial for the successful deployment and integration of hydrogen as an energy carrier. Addressing technical challenges in hydrogen refueling stations, including interfacing technological components, operational flexibility, and footprint reduction, is vital for advancing hydrogen infrastructure. Additionally, the utilization of hydrogenated liquid organic compounds for cost-effective transport faces challenges related to energy input for extremely low-temperature storage. To foster the widespread adoption of hydrogen technologies, it is imperative to invest in infrastructure development, standardization, and innovative solutions that enhance the efficiency, safety, and reliability of hydrogen transportation and distribution systems.

VI. GREEN HYDROGEN UTILIZATION: FUEL CELL TECHNOLOGY

Fuel cells have diverse applications, such as large-scale power plants, data center backup power, and light-duty and heavy-duty vehicles. Proton-exchange membrane fuel cells that utilize thin membranes (810 µm thick) operate at low pressures of around 36 bar. To further improve the reliability and affordability of PEMFCs, the development of new materials and catalysts is crucial. Solid oxide fuel cells with reversible operation capability can potentially extend the operating hours and maintain system temperature stability. To successfully commercialize fuel cells, electrocatalysts for oxygen reduction reactions must meet stringent performance criteria, including high durability, fault-tolerance, and scalability for high-volume production with consistent quality [140]–[143].

A. HURDLES TO THE COMMERCIALIZATION ASPECTS OF GREEN HYDROGEN

Although hydrogen fuel cells offer promising advantages over battery systems for sustainable transportation, the widespread commercialization of green hydrogen for various end-use applications is hindered by several challenges. These challenges include concerns related to fuel cell efficiency, durability, size, robustness, state of health, current densities, power, methods for monitoring system performance, thermal and water management, volume and cost control, purification, and humidification [144]–[146]. Major challenges associated with green hydrogen utilization at the end-use level are observed in transportation, industrial, heat generation, and power sectors as well as in fuel cell applications, as depicted in Figure 7 [144]–[146].

One key hurdle is the cost of hydrogen fuel cell systems for electric vehicles, which currently stands at approximately \$100-200 USD per kilowatt (kW), making fuel cell electric vehicles (FCEVs) 2-3 times more expensive to produce than internal combustion engine (ICE) vehicles. However, it's essential to consider the long-term cost savings and environmental benefits. Advancements in technology are necessary to reduce these costs. Another challenge is the limited

This article has been accepted for publication in IEEE Access. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2024.3363869

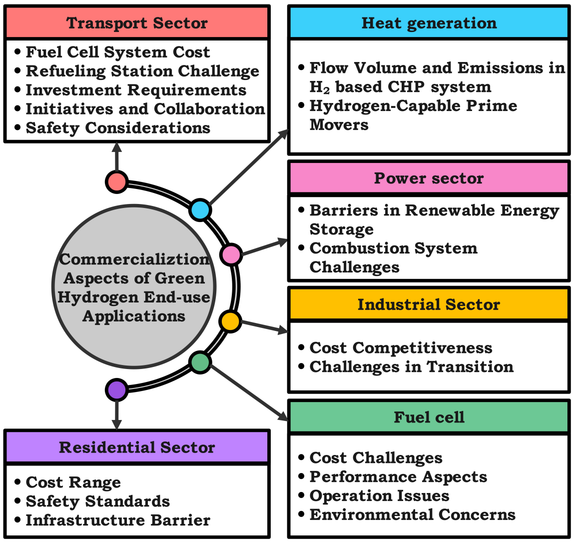

FIGURE 7. The key hurdles to the commercialization aspects of green hydrogen [5], [9], [16], [84]–[91]

availability of hydrogen refueling stations (HRS), with each HRS costing around \$1-5 million, compared to the lower costs of battery electric vehicle charging stations. Significant investment is required to establish HRS, and partnerships, pilot projects, and technological advancements are crucial to promote greater adoption of green hydrogen and ensure cost competitiveness. Initiatives, government policies, incentives, and collaboration between automakers and energy companies are also needed to address the challenges of FCEVs. Additionally, addressing safety considerations is essential to ensure the safe use of hydrogen in mobility and co-generation applications, particularly at airports. Overcoming these challenges will be vital in the successful commercialization of green hydrogen in the transport sector [147].

Combined heat and power (CHP) applications, specific challenges arise in hydrogen utilization level, including higher flow volume due to hydrogen's lower energy density, faster flame speed, and increased NOx emissions from higher flame temperatures. These challenges can be mitigated through appropriate infrastructure, equipment, and emission control technologies. Additionally, for widespread adoption of hydrogen-based CHP systems, it's crucial to develop hydrogen-capable prime movers and a robust hydrogen infrastructure, making it essential for all CHP prime movers to be designed to be 100% hydrogen-capable, thus paving the way for a sustainable and efficient hydrogen-based energy system [148].

For hydrogen to serve as a competitive long-term renewable energy storage solution, the levelized cost of hydrogen fuel cells, which currently ranges from \$0.12-0.68 per kWh, must become more cost-competitive with lithium-ion-based storage, which costs between \$0.05-0.40 per kWh. Co-firing hydrogen at gas-fired power plants faces technical barriers related to fuel cell efficiency, technology cost, production, infrastructure, safety, and combustion system development. In addition, the development of combustion systems for natural gas and hydrogen mixtures up to 100% H_2 requires addressing challenges concerning combustion stability, emissions control, fuel delivery, materials compatibility, and system performance, underscoring the multifaceted nature of hydrogen integration and its economic feasibility [149], [150].

The cost of green hydrogen production from electrolysis is currently around \$3.5-7 per kilogram, while natural gas costs about \$1.5-2 per kilogram. Replacing steam-methane reforming with renewable hydrogen production processes for industrial demand faces technical barriers, including electrolysis efficiency, scaling up hydrogen production, storage, transportation, regulatory frameworks, partnerships, system integration, infrastructure investment, and cost-competitiveness in production, storage, and transportation of green hydrogen [21].

Cost challenges in the adoption of hydrogen fuel cells are notable, with current costs ranging from \$40 to \$400 per kilowatt (kW) depending on the application. To promote widespread use, it's essential to address cost reductions, enhance system component production, and improve assembly methods. Moreover, enhancing performance aspects of fuel cells, including reliability, cold start capabilities, durability, efficiency, control, power, and size & weight considerations, is vital, particularly for increasing power density. Operation considerations, such as installation, testing, system integration, and maintenance, are necessary to ensure the safe and reliable operation of fuel cell systems. Additionally, assessing the potential benefits and drawbacks of hydrogen fuel cells should account for their environmental effects, emissions, hydrogen safety, energy security, and energy independence. These factors play a crucial role in the broader adoption and success of hydrogen fuel cell technologies [16].

Small-scale electrolysis systems for residential use come with a cost range of $2,000$ to $7,000$ per kilowatt (kW), which varies depending on the system's size and capacity. However, challenges exist in terms of safety standards; current codes and standards for hydrogen storage and handling require improvement and updating to address the unique properties of hydrogen. Moreover, the lack of hydrogen infrastructure serves as a significant barrier to the widespread adoption of hydrogen in residential settings. To overcome this challenge, new infrastructure investments will be necessary to support the deployment of small-scale electrolysis systems and hydrogen storage tanks in residential areas, facilitating the integration of hydrogen as an energy source in homes [151].

High initial costs can be a barrier, as the upfront investment required for fuel cells and electrolyzers can be daunting for businesses. Infrastructure development, including production, storage, and distribution, demands substantial investment and planning, slowing down the adoption process. The development and implementation of regulatory frameworks and standards is crucial but often complex and time-consuming. Green hydrogen technologies face competition from well-established alternatives, hindering their market penetration. Ensuring economic viability in comparison to cheaper, established alternatives is a persistent challenge. Scalability, intermittency of renewable energy sources, public perception, research and development, supply chain complexity, and efficient storage and transportation methods all contribute to the multifaceted challenges of integrating green hydrogen into various applications and industries. Overcoming these challenges is vital for realizing the potential of green hydrogen in decarbonizing the energy sector [152].

B. INNOVATIONS ON IMPROVING EFFICIENCY, BOOSTING PRODUCTION CAPACITY OF ELECTROLYZERS/FUEL CELLS

The inadequate interaction between electrodes and electrolytes in ceramic fuel cells often leads to performance degradation. To address this issue, the surface of high-temperature annealed electrolytes can be treated with simple acids to improve stability and efficacy in decoupled electrochemical water splitting processes [153], [154]. Similarly, the unsatisfactory performance of anion exchange ionomers and membranes poses barriers in anion exchange membrane fuel cells. However, the utilization of fluorenyl aryl piperidinium-based membranes and ionomers have shown high performance in alkaline fuel cells [155]. Thermomechanical instability remains a challenge in the commercialization of solid oxide fuel cells. One potential solution is the use of composite electrodes comprising cobalt-based perovskite and negative-thermal-expansion materials, which have exhibited high activity and stability when paired with the electrolyte [156]. Another approach involves using perovskite nickelate electrolytes with high initial ionic and electronic conductivity, low activation energy, and performance comparable to the best-performing electrolytes in SOFCs at the same temperature range [157].

Proton ceramic fuel cells have shown promise in using hydrogen and hydrocarbon fuels directly to generate power with high potential efficiency for commercial applications. PCFCs have demonstrated good performance and durability in long-term testing with various fuel types without the need for composition or architecture changes, showing resistance to issues such as coking, sulfur poisoning, and temperature fluctuations [158]. Next-generation proton-exchange membrane fuel cell technology based on nanomaterials is expected to improve membrane electrode assembly, heat management, and power density [159]. Recent research has shown that water content in hydrocarbon polymer membranes in PEMFCs can be controlled by "nano cracks" that act as nanoscale valves, preventing water desorption and maintaining ion conductivity during dehumidification. Such hydrocarbon fuel-cell membranes with surface nano crack coatings exhibit reduced bulk resistance and improved ionic selectivity, leading to superior electrochemical reaction performance [160].

One of the major challenges in fuel cell development is the production of electrodes with high and durable electrocatalytic activity in a cost-effective and time-efficient manner. Metal nanoparticles on electrode architectures have shown excellent performance in both fuel cells and electrolyzers, and emerging nanomaterials offer the potential to integrate fuel cells and electrolyzers into a single device [161].

C. COMMERCIAL-SCALE BUSINESS MODELS OF GREEN HYDROGEN PRODUCTION AND DELIVERY

Understanding the commercial-scale business models associated with its production and delivery is critical for evaluating its viability as an alternative energy source. This section analyzes feasibility and sustainability of three distinct business models for green hydrogen production and delivery, namely onsite production, off-site production, and decentralized generation with district distribution.

For large-scale green hydrogen generation, "Onsite production" is a commercially viable solution where the electrolyzer is installed at the end-user site and powered by solar or wind energy systems. This approach eliminates the need for transportation infrastructure and associated costs. However, challenges include limited production capacity and finding the optimal balance between desired volumes and generation capability. The medium to long-term solution involves "Off-site production" and distribution of green hydrogen. In this model, large-scale electrolyzers are installed near renewable energy sources, and hydrogen is transported to end-users via pipelines or trucks. This approach allows for wider consumer distribution and potentially lower production costs due to economies of scale. The short-term solution for green hydrogen production is the "Decentralized generation and district distribution". In this hybrid model, electrolyzers are located close to end-user consumption points and connected to the local electrical network, operating on renewable energy. Benefits include lower production costs due to economies of scale and shorter development time for the hydrogen grid. However, challenges exist in garnering consensus to increase local volume consumption [94], [162].

This assessment will take into consideration critical factors such as capital investment, operational costs, revenue generation, regulatory frameworks, and market demand. The capital investment required for green hydrogen production and delivery can vary significantly depending on the project scale, the technology used, and infrastructure requirements. For instance, a large-scale green hydrogen production plant using AEL is estimated to have a capital cost ranging from \$500 to \$1400 per kg of hydrogen, PEMEL around \$1100 to \$1800 per kg of hydrogen, and SOEL \$2800 to \$5600 per kg of hydrogen. Operational costs are also subject to variation due to factors such as energy prices, labor rates, and maintenance requirements. For example, operational costs for PEMEL can range from \$2 to \$6 per kg of hydrogen, while for AEL, it can range from \$1 to \$3 per kg of hydrogen [163], [164]. The findings of this study will provide valuable insights into the viability and feasibility of these business models, helping inform decision-making processes for the adoption and implementation of green hydrogen technologies in the transition towards a sustainable and low-carbon energy future.

In summary, Figure 7 provides a comprehensive overview of the hurdles obstructing the commercialization aspects of green hydrogen utilization, particularly in fuel cell technology. These challenges span various sectors, including transportation, heat generation, power generation, industrial applications, fuel cell development, and residential usage. Issues such as the cost of fuel cell systems, limited hydrogen refueling stations, and safety considerations hinder the widespread adoption of green hydrogen in the transport sector. In heat generation, challenges arise in handling higher flow volumes and emissions in hydrogen-based combined heat and power systems. The power sector faces barriers related to renewable energy storage and combustion system development. The industrial sector encounters challenges in achieving cost competitiveness and managing the transition. Fuel cell technologies confront issues regarding cost, performance aspects, operational challenges, and environmental concerns. Additionally, the residential sector faces obstacles in terms of cost range, safety standards, and infrastructure barriers. Overcoming these multifaceted challenges is essential for realizing the full potential of green hydrogen in various applications and industries, necessitating technological advancements, collaborative initiatives, and supportive regulatory frameworks.

VII. DISCUSSION OF GREEN HYDROGEN ECOSYSTEM ON THE PATH TO CLIMATE NEUTRALITY

The green hydrogen value chain encompasses several critical research areas, including electrolysis technologies, renewable energy integration, storage and transportation, fuel cells and applications, materials and catalysts, techno-economic analysis, lifecycle analysis and sustainability, policy and regulation, safety and standards, and education and outreach. Table 4 provides an overview of global R&D activities in the green hydrogen value chain and identifies key development research initiatives needed to bridge technology gaps. Notably, cost-effective electrolyzers and renewable electricity are crucial for competitive green hydrogen production, while advancements in fuel cell technology, catalysts, membranes, system components, and stack assembly are essential for cost-competitive fuel cells in various sectors such as transportation, logistics, heating, cooling, and power generation sectors [170]. The storage of hydrogen necessitates the development of carbon composite and hydride cylinders using indigenous materials. Furthermore, hydrogen distribution infrastructure must be expanded with the installation of pipelines and dispensing stations. A comprehensive ecosystem for hydrogen production, storage, and distribution needs to be established, catering to both stationary and transport applications. In addition to technological advancements, supportive policies, regulations, infrastructure, and political backing are pivotal for a successful transition to a clean hydrogen economy [74]. Achieving a sustainable, decarbonized, and integrated energy system requires robust scientific research and innovation efforts, encompassing areas such as repurposing natural gas infrastructure, novel production methods, improved electrolyzers, safety and material considerations, environmental impact, and cost-effectiveness of clean hydrogen solutions.

A comprehensive analysis of the requirements, technological constraints, and economics of hydrogen utilization in hard-to-abate sectors has been conducted, with a focus on the entire hydrogen value chain. To accelerate the deployment of hydrogen and build interconnected hydrogen ecosystems, several scientific priorities and challenges are identified for future research.

A. DEVELOPMENT OF ELECTROLYZERS:

Future research in electrolyzer technology should prioritize scaling up PEMEL and AEL, improving the thermal connectivity of SOEL, developing spin-polarized catalysts for energy-efficient AEMEL, exploring PGM-free catalysts and electrodes, synthesizing high-purity hydrogen from methanol and water, integrating electrolyzers into steel plants for energy management, addressing safety issues in electrolysis processes, developing intermetallic catalysts with carbon nanotubes, advancing electrode/cell design and membrane separation technologies, understanding performance/durability mechanisms, evaluating environmental impact and circularity of electrolyzers, and exploring the possibility of impure/seawater electrolysis and direct air electrolysis [171]–[175].

B. DEVELOPMENT OF HYDROGEN STORAGE AND DISTRIBUTION:

Future research should focus on developing new concepts for large-scale above and underground hydrogen buffer storage to enable continuous industrial process output, characterizing and selecting polymer materials for cryogenic storage systems, exploring advanced materials for hydrogen storage, developing dedicated liquid hydrogen tanks for aircraft applications, and adopting a pluralistic approach for logistical infrastructure to transport the hydrogen from potential renewable areas to demand centers [176], [177].

C. PROCESSES ADAPTATION IN THE INDUSTRY:

Future research directions in the industrial sector should include advancements in co-electrolysis processes, integration of electrolyzers and hydrogen storage tanks, development of hydrogen burners for boilers, modification of melting and smelting processes, conversion of combustion engines from fossil fuels to efficient internal combustion engines for heavy-duty commercial hydrogen vehicles, hosting demonstrations of hydrogen turbines, and design of dedicated turbines for aircraft [178].

D. ALTERNATIVE HYDROGEN PRODUCTION:

Research on other routes of sustainable hydrogen production for large-scale distributed plants, such as thermochem-

TABLE 4. Summary of key stakeholders and R&D activities happening globally in the green hydrogen value chain [165]–[169]

Country	Government	Consortia	Research	Research Activity
Canada	Natural Sciences and Engineering Research Council of Canada. Natural Resources Canada. Innovation, Science and Economic Development Canada.	Hydrogen Business Council of Canada. Canadian Hydrogen Fuel Cell Association.	University of British Columbia. CanmetENERGY. Ontario Tech University. McGill University. National Research Council .	Steam methane reforming with carbon capture and storage and electrolysis using renewable energy sources, Grid-scale energy storage, feedstock for the production of clean ammonia, High-pressure or cryogenic storage, Fuel cell electric vehicles, Hydrogen-powered buses, Fuel cell vehicle systems.Stationary, portable, and backup power. Developing new materials for fuel cells, improving the performance and durability of fuel cells
China	Ministry of Science and Technology. Ministry of Industry and Information Technology. National Development and Reform Committee. NEC – National Energy Commission.	China Society of Automotive Engineers. China Hydrogen Alliance.	Energy Research Institute. Chinese Academy of Sciences . Chinese Academy of Engineering. Tianjin University. Zhejiang University. Tsinghua University.	Hydrogen fuel cell vehicle components such as fuel cells, hydrogen storage systems, and hydrogen refueling systems. Steam methane reforming with carbon capture and storage, electrolysis, and biomass gasification, solid-state hydrogen storage materials, hydrogen storage in underground salt caverns, and hydrogen storage in liquid organic hydrogen carriers, fuel cell electric vehicles, fuel-cell buses, and fuel-cell backup power systems.
France	Agency for Ecological Transition. National Research Agency.	France Hydrogène. Europe: Fuel Cells and Hydrogen Joint Undertaking.	Alternative Energies and Atomic Energy Commission. Centre Nationale de Recherche Scientifique.	Electrolysis using renewable energy sources, biomass gasification, and methane pyrolysis. Solid-state hydrogen storage materials, hydrogen storage in metal hydrides, and hydrogen storage in underground salt caverns, Fuel cell technologies for stationary power and transportation applications, Safe and efficient transportation and distribution of hydrogen
Germany	Ministry of Education and Research. Ministry of Economic Affairs and Climate Action.	National Organisation for Hydrogen and Fuel Cell Technology . Fuel Cells and Hydrogen Joint Undertaking.	Helmholtz Association. Fraunhofer Institute.	Electrolysis, fossil fuel conversion, biomass and waste conversion, photochemical and photocatalytic, biological production, thermal water splitting, compression and liquefaction, chemical carriers, gas blending, transport, electricity generation, and industrial processes.
India	Department of Science and Technology. Department of Scientific and Industrial Research. Ministry of New and Renewable Energy.	Indian Hydrogen Alliance.	Academy of Scientific and Innovation Research. National Institute of Technology. Council of Scientific & Industrial Research.	Electrolyser design, Storage & transport systems (pipelines, tanks), FCEV components, systems/stacks, re-fuelling stations, developing new materials and technologies for fuel cells, improving the performance and durability of fuel cells, and developing fuel cell-based power systems for off-grid applications.
Japan	Japan Oil, Gas and Metals National Corporation. New Energy and Industrial Technology Development Organisation. Japan Science and Technology Agency. Ministry of Economy, Trade and Industry.	Clean Fuel Ammonia Association. Japan Hydrogen Association. Advanced Hydrogen Energy Chain Association for Technology Development. CO2-free Hydrogen Energy Supply-chain Technology Research Association.	University of Tokyo. Kyushu University. Kyoto University. National Institute of Advanced Industrial Science and Technology	Water electrolyzer, liquefied hydrogen carriers and methylcyclohexane, fuel ammonia, synthetic methane, ammonia fuel cells, ammonia cracking technologies, ammonia-based power generation systems, fuel cell vehicles, hydrogen liquefaction technologies, hydrogen-based power generation systems,
Singapore	Development Board/Energy Market Authority Ministry of Trade and Industry/Economic.	Singapore Energy Centre. Centre for Hydrogen Innovations.	Nanyang Technological University. Agency for Science, Technology and Research.	Water electrolysis, steam methane reforming, biomass gasification, new catalysts and materials, solid-state hydrogen storage materials and hydrogen carriers, proton exchange membrane fuel cells, and solid oxide fuel cells.
Republic of Korea	National Research Council of Science and Technology. Ministry of Trade Industry and Energy.	H2KOREA HyNet Consortium	Korea Institute of Energy Research . Korea Advanced Institute of Science and Technology.	Development of hydrogen-powered trains and ships, and the promotion of hydrogen as a fuel for aviation, solid oxide fuel cells, hydrogen refueling stations, and hydrogen production technologies,
US	Department of Energy: Office of Fossil Energy and Carbon Management. Office of Nuclear Energy. Office of Science. Office of Clean Energy Demonstrations. Office of Energy Efficiency & Renewable Energy.	H2@Scale Fuel cell and Hydrogen Energy Association. 21st Century Truck Partnership.	DOE Hydrogen and Fuel Cell Technologies. Office research consortia. Department of Energy. National laboratories.	Low and high-temperature electrolysis, thermochemical, photoelectrochemical, and solar water splitting, biological approaches, gasification, pyrolysis, reforming, cofiring and modular systems, fuel cells and combustions, high-pressure tanks, cryogenic vessels/ trucks, tube trailers, and reversible fuel cells.
UK	UK Research and Innovation. Department for Business, Energy and Industrial Strategy. Engineering and Physical Sciences Research Council.	UK Hydrogen and Fuel Cell Association .	Imperial College London. UK Research and Innovation Engineering and Physical Sciences Council.	Electrolysis, steam methane reforming, autothermal reforming, biomass gasification, pyrolysis, photoelectrochemical, high-temperature water splitting.

ical splitting, biomass & biowaste, electro-hydrogenesis, water thermolysis, photocatalysis, and photoelectrocatalysis, should be explored [179]. Additionally, substances such as aluminum, zinc, and silicon that chemically react with water for hydrogen production should be investigated [39], [59], [139], [180], [181]. Promising methods, such as photo-reforming of biodegradable oxygenates and PV/photo-electrocatalytic cell integration technology, should be further researched to enhance solar-to-hydrogen efficiency and device lifespan [182]–[184]. Furthermore, liquid electricity, such as eMethanol (electricity-to-methanol), could be explored as a green fuel for heavy-duty transport [185].

E. DEVELOPMENT OF FUEL CELL:

In the realm of hydrogen technology, advancing fuel cell technology is pivotal. Research must prioritize critical materials and stack technologies for electrolysis and fuel cells, with a focus on enhancing stack designs and materials to improve overall system performance and cost-effectiveness. Innovative fuel cell concepts tailored to heavy-duty vehicles are needed to address unique challenges in this sector, such as power output and durability. Enhancing the durability and availability of fuel cell components, alongside the development of advanced hydrogen purification technologies, is essential for long-term viability. [142], [186], [187]. Research must also explore regenerative fuel cells for maritime applications and address integration challenges in Power-to-X systems such as onboard fuel cell storage and powertrain integration, dedicated solid-oxide (SO) and proton exchange membrane (PEM) fuel cell systems for aviation propulsion, thin film reversible solid-oxide fuel cells as energy storage systems. Additionally, the utilization of ammonia as a fuel source for solid-oxide fuel cells holds promise for various applications [14], [80], [188]–[191]. These research priorities and challenges are instrumental in accelerating the deployment of hydrogen technologies, particularly in hard-to-abate sectors [192].

VIII. CONCLUSION

In the dynamic landscape of the green hydrogen economy, achieving a Levelized Cost of Hydrogen (LCOH) production of \$1/kg at GW-scale requires targeted efforts. Emphasizing improvements in energy conversion efficiency, reducing CAPEX/OPEX, and enhancing the durability of electrolyzer systems are pivotal. Collaborative initiatives in research, technology, and business model innovation are key elements for shaping a sustainable energy future.

Government support is crucial for the entire hydrogen production value chain, particularly in hard-to-abate sectors where a harmonious blend of technology advancements and market incentives is vital. Despite notable progress, persistent economic scale challenges for crucial components demand immediate attention. Overcoming these challenges is essential for technology readiness, successful green hydrogen commercialization, and substantial contributions to carbon neutrality.

Proposing future research directions, several key areas demand exploration. Key directions include exploring large-scale, sustainable energy conversion processes using novel materials, prioritizing high-density solid-state materials for hydrogen storage, developing highly efficient power converters, establishing regulatory frameworks, and innovatively exploring sector coupling through hydrogen. This comprehensive approach aims to propel hydrogen and fuel cell technologies into mainstream use, fostering a sustainable and low-carbon future across diverse industries.

ACKNOWLEDGEMENT

The authors extend their appreciation to the Deputyship for Research & Innovation, Ministry of Education in Saudi Arabia, for funding this research work through the project number NBU-FFR-2023-0058. The authors gratefully thank the Prince Faisal bin Khalid bin Sultan Re- search Chair in Renewable Energy Studies and Applications (PFCRE) at Northern Border University for their support and assistance.

REFERENCES

[1] S. van Renssen, "The hydrogen solution?" Nature Climate Change, vol. 10, no. 9, pp. 799–801, 2020.
[2] N. Mac Dowell, N. Sunny, N. Brandon, H. Herzog, A. Y. Ku, W. Maas, A. Ramirez, D. M. Reiner, G. N. Sant, and N. Shah, "The hydrogen economy: A pragmatic path forward," Joule, vol. 5, no. 10, pp. 2524–2529, 2021.
[3] F. Wang, J. D. Harindintwali, Z. Yuan, M. Wang, F. Wang, S. Li, Z. Yin, L. Huang, Y. Fu, L. Li et al., "Technologies and perspectives for achieving carbon neutrality," The Innovation, vol. 2, no. 4, p. 100180, 2021.
[4] B. C. Tashie-Lewis and S. G. Nnabuife, "Hydrogen production, distribution, storage and power conversion in a hydrogen economy-a technology review," Chemical Engineering Journal Advances, vol. 8, p. 100172, 2021.
[5] H. Montazerinejad and U. Eicker, "Recent development of heat and power generation using renewable fuels: A comprehensive review," Renewable and Sustainable Energy Reviews, vol. 165, p. 112578, 2022.
[6] M. Jayachandran, C. Kalaiarasy, and C. Kalaivani, "Implementation issues with large-scale renewable energy sources and electric vehicle charging stations on the smart grid," in Smart Grids for Renewable Energy Systems, Electric Vehicles and Energy Storage Systems. CRC Press, 2022, pp. 45–58.
[7] G. Luderer, M. Pehl, A. Arvesen, T. Gibon, B. L. Bodirsky, H. S. de Boer, O. Fricko, M. Hejazi, F. Humpenöder, G. Iyer et al., "Environmental co-benefits and adverse side-effects of alternative power sector decarbonization strategies," Nature communications, vol. 10, no. 1, pp. 1–13, 2019.
[8] A. M. Oliveira, R. R. Beswick, and Y. Yan, "A green hydrogen economy for a renewable energy society," Current Opinion in Chemical Engineering, vol. 33, p. 100701, 2021.
[9] C. B. Agaton, K. I. T. Batac, and E. M. Reyes Jr, "Prospects and challenges for green hydrogen production and utilization in the philippines," International Journal of Hydrogen Energy, 2022.
[10] M. Jayachandran, C. R. Reddy, S. Padmanaban, and A. Milyani, "Operational planning steps in smart electric power delivery system," Scientific Reports, vol. 11, no. 1, p. 17250, 2021.
[11] M. Jayachandran, K. P. Rao, R. K. Gatla, C. Kalaivani, C. Kalaiarasy, and C. Logasabarirajan, "Operational concerns and solutions in smart electricity distribution systems," Utilities Policy, vol. 74, p. 101329, 2022.
[12] C. Mansilla, C. Bourasseau, C. Cany, B. Guinot, A. Le Duigou, and P. Lucchese, "Hydrogen applications: Overview of the key economic issues and perspectives," Hydrogen Supply Chains, pp. 271–292, 2018.
[13] V. Maestre, A. Ortiz, and I. Ortiz, "Challenges and prospects of renewable hydrogen-based strategies for full decarbonization of stationary power applications," Renewable and Sustainable Energy Reviews, vol. 152, p. 111628, 2021.

[14] I. Sorrenti, T. B. H. Rasmussen, S. You, and Q. Wu, "The role of power-to-x in hybrid renewable energy systems: A comprehensive review," Renewable and Sustainable Energy Reviews, p. 112380, 2022.
[15] M. Ozturk and I. Dincer, "A comprehensive review on power-to-gas with hydrogen options for cleaner applications," International Journal of Hydrogen Energy, vol. 46, no. 62, pp. 31 511–31 522, 2021.
[16] M. Yue, H. Lambert, E. Pahon, R. Roche, S. Jemei, and D. Hissel, "Hydrogen energy systems: A critical review of technologies, applications, trends and challenges," Renewable and Sustainable Energy Reviews, vol. 146, p. 111180, 2021.
[17] M. Hermesmann and T. Müller, "Green, turquoise, blue, or grey? environmentally friendly hydrogen production in transforming energy systems," Progress in Energy and Combustion Science, vol. 90, p. 100996, 2022.
[18] M. Jayachandran, R. K. Gatla, K. P. Rao, G. S. Rao, S. Mohammed, A. H. Milyani, A. A. Azhari, C. Kalaiarasy, and S. Geetha, "Challenges in achieving sustainable development goal 7: Affordable and clean energy in light of nascent technologies," Sustainable Energy Technologies and Assessments, vol. 53, p. 102692, 2022.
[19] S. S. Kumar and V. Himabindu, "Hydrogen production by pem water electrolysis–a review," Materials Science for Energy Technologies, vol. 2, no. 3, pp. 442–454, 2019.
[20] O. Bachmann, "Large scale low-cost green hydrogen production using thermal energy storage and polymer electrolyte membrane electrolysis systems," IET Renewable Power Generation, 2022.
[21] S. G. Nnabuife, J. Ugbeh-Johnson, N. E. Okeke, and C. Ogbonnaya, "Present and projected developments in hydrogen production: A technological review∗," Carbon Capture Science & Technology, vol. 3, p. 100042, 2022.
[22] P. Ferreira-Aparicio and A. M. Chaparro, Portable Hydrogen Energy Systems: Fuel Cells and Storage Fundamentals and Applications. Academic Press, 2018.
[23] B. Widera, "Renewable hydrogen implementations for combined energy storage, transportation and stationary applications," Thermal Science and Engineering Progress, vol. 16, p. 100460, 2020.
[24] R. Moradi and K. M. Groth, "Hydrogen storage and delivery: Review of the state of the art technologies and risk and reliability analysis," International Journal of Hydrogen Energy, vol. 44, no. 23, pp. 12 254–12 269, 2019.
[25] B. Sundén, Hydrogen, batteries and fuel cells. Academic Press, 2019.
[26] G. J. Offer, D. Howey, M. Contestabile, R. Clague, and N. Brandon, "Comparative analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system," Energy policy, vol. 38, no. 1, pp. 24–29, 2010.
[27] V. Oldenbroek, S. Wijtzes, K. Blok, and A. J. van Wijk, "Fuel cell electric vehicles and hydrogen balancing 100 percent renewable and integrated national transportation and energy systems," Energy Conversion and Management: X, vol. 9, p. 100077, 2021.
[28] C. Kurien and M. Mittal, "Review on the production and utilization of green ammonia as an alternate fuel in dual-fuel compression ignition engines," Energy Conversion and Management, vol. 251, p. 114990, 2022.
[29] Z. Liu, Z. Deng, G. He, H. Wang, X. Zhang, J. Lin, Y. Qi, and X. Liang, "Challenges and opportunities for carbon neutrality in china," Nature Reviews Earth & Environment, vol. 3, no. 2, pp. 141–155, 2022.
[30] E. Abohamzeh, F. Salehi, M. Sheikholeslami, R. Abbassi, and F. Khan, "Review of hydrogen safety during storage, transmission, and applications processes," Journal of Loss Prevention in the Process Industries, vol. 72, p. 104569, 2021.
[31] A. Kotchourko and T. Jordan, Hydrogen Safety for Energy Applications: Engineering Design, Risk Assessment, and Codes and Standards. Butterworth-Heinemann, 2022.
[32] B. C. Tashie-Lewis and S. G. Nnabuife, "Hydrogen production, distribution, storage and power conversion in a hydrogen economy - a technology review," Chemical Engineering Journal Advances, vol. 8, p. 100172, 2021.
[33] R. Sakthivel, K. Ramesh, R. Purnachandran, and P. Mohamed Shameer, "A review on the properties, performance and emission aspects of the third generation biodiesels," Renewable and Sustainable Energy Reviews, vol. 82, pp. 2970–2992, 2018.
[34] F. Synak, K. Culik, V. Rievaj, and J. Gana, "Liquefied petroleum gas as an alternative fuel," Transportation Research Procedia, vol. 40, pp. 527–534, 2019, tRANSCOM 2019 13th International Scientific Conference on Sustainable, Modern and Safe Transport.
[35] J. Jiao, J. Li, and Y. Bai, "Ethanol as a vehicle fuel in china: A review from the perspectives of raw material resource, vehicle, and infrastructure," Journal of Cleaner Production, vol. 180, pp. 832–845, 2018.
[36] C. Bae and J. Kim, "Alternative fuels for internal combustion engines," Proceedings of the Combustion Institute, vol. 36, no. 3, pp. 3389–3413, 2017.
[37] A. Demirbas, "Importance of biodiesel as transportation fuel," Energy policy, vol. 35, no. 9, pp. 4661–4670, 2007.
[38] A. Trattner, M. Klell, and F. Radner, "Sustainable hydrogen society–vision, findings and development of a hydrogen economy using the example of austria," International Journal of Hydrogen Energy, vol. 47, no. 4, pp. 2059–2079, 2022.
[39] J. De Vrieze, K. Verbeeck, I. Pikaar, J. Boere, A. Van Wijk, K. Rabaey, and W. Verstraete, "The hydrogen gas bio-based economy and the production of renewable building block chemicals, food and energy," New biotechnology, vol. 55, pp. 12–18, 2020.
[40] X. Zhang, X. Gao, Y. Zheng, Y. Xu, E. Chung, and A. R. Sayed, "Low-carbon oriented collaborative planning of electricity-hydrogen-gas-transportation integrated system considering hydrogen vehicles," IEEE Transactions on Network Science and Engineering, 2023.
[41] I. Sorrenti, Y. Zheng, A. Singlitico, and S. You, "Low-carbon and cost-efficient hydrogen optimisation through a grid-connected electrolyser: The case of greenlab skive," Renewable and Sustainable Energy Reviews, vol. 171, p. 113033, 2023.
[42] X. Yan, J. Biemolt, K. Zhao, Y. Zhao, X. Cao, Y. Yang, X. Wu, G. Rothenberg, and N. Yan, "A membrane-free flow electrolyzer operating at high current density using earth-abundant catalysts for water splitting," Nature Communications, vol. 12, no. 1, pp. 1–9, 2021.
[43] M. N. I. Salehmin, T. Husaini, J. Goh, and A. B. Sulong, "High-pressure pem water electrolyser: A review on challenges and mitigation strategies towards green and low-cost hydrogen production," Energy Conversion and Management, vol. 268, p. 115985, 2022.
[44] Y. Zhao, P. V. Kumar, X. Tan, X. Lu, X. Zhu, J. Jiang, J. Pan, S. Xi, H. Y. Yang, Z. Ma et al., "Modulating pt-o-pt atomic clusters with isolated cobalt atoms for enhanced hydrogen evolution catalysis," Nature communications, vol. 13, no. 1, pp. 1–11, 2022.
[45] A. Hodges, A. L. Hoang, G. Tsekouras, K. Wagner, C.-Y. Lee, G. F. Swiegers, and G. G. Wallace, "A high-performance capillary-fed electrolysis cell promises more cost-competitive renewable hydrogen," Nature communications, vol. 13, no. 1, pp. 1–11, 2022.
[46] H. Shimada, T. Yamaguchi, H. Kishimoto, H. Sumi, Y. Yamaguchi, K. Nomura, and Y. Fujishiro, "Nanocomposite electrodes for high current density over 3 a cm- 2 in solid oxide electrolysis cells," Nature communications, vol. 10, no. 1, pp. 1–10, 2019.
[47] L. Ye, M. Zhang, P. Huang, G. Guo, M. Hong, C. Li, J. T. Irvine, and K. Xie, "Enhancing co2 electrolysis through synergistic control of non-stoichiometry and doping to tune cathode surface structures," Nature communications, vol. 8, no. 1, pp. 1–10, 2017.
[48] D. Li, E. J. Park, W. Zhu, Q. Shi, Y. Zhou, H. Tian, Y. Lin, A. Serov, B. Zulevi, E. D. Baca et al., "Highly quaternized polystyrene ionomers for high performance anion exchange membrane water electrolysers," Nature Energy, vol. 5, no. 5, pp. 378–385, 2020.
[49] I. Vincent, E.-C. Lee, and H.-M. Kim, "Comprehensive impedance investigation of low-cost anion exchange membrane electrolysis for large-scale hydrogen production," Scientific Reports, vol. 11, no. 1, pp. 1–12, 2021.
[50] W. H. Lee, Y.-J. Ko, J. H. Kim, C. H. Choi, K. H. Chae, H. Kim, Y. J. Hwang, B. K. Min, P. Strasser, and H.-S. Oh, "High crystallinity design of ir-based catalysts drives catalytic reversibility for water electrolysis and fuel cells," Nature Communications, vol. 12, no. 1, pp. 1–10, 2021.
[51] H. G. Kuppusamy, P. Dhanasekaran, N. Nagaraju, M. Neeshma, B. M. Dass, V. M. Dhavale, S. M. Unni, and S. D. Bhat, "Anion exchange membranes for alkaline polymer electrolyte fuel cells—a concise review," Materials, vol. 15, no. 16, p. 5601, 2022.
[52] H. Ding, W. Wu, C. Jiang, Y. Ding, W. Bian, B. Hu, P. Singh, C. J. Orme, L. Wang, Y. Zhang et al., "Self-sustainable protonic ceramic electrochemical cells using a triple conducting electrode for hydrogen and power production," Nature communications, vol. 11, no. 1, pp. 1–11, 2020.
[53] B.-W. Zhang, T. Zheng, Y.-X. Wang, Y. Du, S.-Q. Chu, Z. Xia, R. Amal, S.-X. Dou, and L. Dai, "Highly efficient and selective electrocatalytic hydrogen peroxide production on co-oc active centers on graphene oxide," Communications Chemistry, vol. 5, no. 1, pp. 1–7, 2022.

[54] J. Tan, B. Kang, K. Kim, D. Kang, H. Lee, S. Ma, G. Jang, H. Lee, and J. Moon, "Hydrogel protection strategy to stabilize water-splitting photoelectrodes," Nature Energy, pp. 1–11, 2022.

[55] Y. Qi, Y. Zhang, L. Yang, Y. Zhao, Y. Zhu, H. Jiang, and C. Li, "Insights into the activity of nickel boride/nickel heterostructures for efficient methanol electrooxidation," Nature communications, vol. 13, no. 1, pp. 1–11, 2022.

[56] B. Zhou, X. Kong, S. Vanka, S. Chu, P. Ghamari, Y. Wang, N. Pant, I. Shih, H. Guo, and Z. Mi, "Gallium nitride nanowire as a linker of molybdenum sulfides and silicon for photoelectrocatalytic water splitting," Nature communications, vol. 9, no. 1, pp. 1–8, 2018.

[57] R. Silva, A. Abreu, A. Salvador, M. Alves, I. C. Neves, and M. Pereira, "Zeolite addition to improve biohydrogen production from dark fermentation of c5/c6-sugars and sargassum sp. biomass," Scientific reports, vol. 11, no. 1, pp. 1–14, 2021.

[58] F. Russo, V. Luongo, M. R. Mattei, and L. Frunzo, "Mathematical modeling of metal recovery from e-waste using a dark-fermentation-leaching process," Scientific reports, vol. 12, no. 1, pp. 1–17, 2022.

[59] W. J. Martinez-Burgos, E. de Souza Candeo, A. B. P. Medeiros, J. C. de Carvalho, V. O. de Andrade Tanobe, C. R. Soccol, and E. B. Sydney, "Hydrogen: Current advances and patented technologies of its renewable production," Journal of Cleaner Production, vol. 286, p. 124970, 2021.

[60] J. C. Wood, J. Grové, E. Marcellin, J. K. Heffernan, S. Hu, Z. Yuan, and B. Virdis, "Strategies to improve viability of a circular carbon bioeconomy-a techno-economic review of microbial electrosynthesis and gas fermentation," Water Research, vol. 201, p. 117306, 2021.

[61] D. Ferraren-De Cagalitan and M. Abundo, "A review of biohydrogen production technology for application towards hydrogen fuel cells," Renewable and Sustainable Energy Reviews, vol. 151, p. 111413, 2021.

[62] C. Santoro, P. Bollella, B. Erable, P. Atanassov, and D. Pant, "Oxygen reduction reaction electrocatalysis in neutral media for bioelectrochemical systems," Nature Catalysis, pp. 1–12, 2022.

[63] S. Guo, X. Li, J. Li, and B. Wei, "Boosting photocatalytic hydrogen production from water by photothermally induced biphase systems," Nature communications, vol. 12, no. 1, pp. 1–10, 2021.

[64] D. W. Wakerley, M. F. Kuehnel, K. L. Orchard, K. H. Ly, T. E. Rosser, and E. Reisner, "Solar-driven reforming of lignocellulose to h2 with a cds/cdox photocatalyst," Nature Energy, vol. 2, no. 4, pp. 1–9, 2017.

[65] P. S. Gaikwad, K. Mondal, Y. K. Shin, A. C. van Duin, and G. Pawar, "Enhancing the faradaic efficiency of solid oxide electrolysis cells: progress and perspective," npj Computational Materials, vol. 9, no. 1, p. 149, 2023.

[66] H. Zheng, F. Han, N. Sata, and R. Costa, "Hydrogen production at intermediate temperatures with proton conducting ceramic cells: Electrocatalytic activity, durability and energy efficiency," Journal of Energy Chemistry, vol. 86, pp. 437–446, 2023.

[67] H. Liang, M. Li, Z. Li, W. Xie, T. Zhang, and Q. Wang, "Photoelectrochemical co2 reduction with copper-based photocathodes," Journal of CO2 Utilization, vol. 79, p. 102639, 2024.

[68] J. F. Soares, F. D. Mayer, and M. A. Mazutti, "Hydrogen production from brewer's spent grain hydrolysate by dark fermentation," International Journal of Hydrogen Energy, vol. 52, pp. 352–363, 2024.

[69] A. Y. Goren, I. Dincer, and A. Khalvati, "Comparative environmental sustainability assessment of biohydrogen production methods," Science of The Total Environment, p. 166613, 2023.

[70] P. Lykas, N. Georgousis, E. Bellos, and C. Tzivanidis, "A comprehensive review of solar-driven multigeneration systems with hydrogen production," International Journal of Hydrogen Energy, vol. 48, no. 2, pp. 437–477, 2023.

[71] Y. Patcharavorachot, N. Chatrattanawet, A. Arpornwichanop, and D. Saebea, "Comparative energy, economic, and environmental analyses of power-to-gas systems integrating soecs in steam-electrolysis and co-electrolysis and methanation," Thermal Science and Engineering Progress, vol. 42, p. 101873, 2023.

[72] B. D. Catumba, M. B. Sales, P. T. Borges, M. N. Ribeiro Filho, A. A. S. Lopes, M. A. de Sousa Rios, A. S. Desai, M. Bilal, and J. C. S. dos Santos, "Sustainability and challenges in hydrogen production: An advanced bibliometric analysis," International Journal of Hydrogen Energy, vol. 48, no. 22, pp. 7975–7992, 2023.

[73] A. Di Nardo, M. Portarapillo, D. Russo, and A. Di Benedetto, "Hydrogen production via steam reforming of different fuels: thermodynamic comparison," International Journal of Hydrogen Energy, vol. 55, pp. 1143–1160, 2024.

[74] E. Bianco and H. Blanco, "Green hydrogen: a guide to policy making," 2020.

[75] I. R. E. Agency, "Green hydrogen cost reduction: Scaling up electrolysers to meet the 1.5° c climate goal," 2020.

[76] S. Shiva Kumar and H. Lim, "An overview of water electrolysis technologies for green hydrogen production," Energy Reports, vol. 8, pp. 13 793–13 813, 2022.

[77] S. G. Nnabuife, J. Ugbeh-Johnson, N. E. Okeke, and C. Ogbonnaya, "Present and projected developments in hydrogen production: A technological review," Carbon Capture Science & Technology, vol. 3, p. 100042, 2022.

[78] N. Meng, J. Shao, H. Li, Y. Wang, X. Fu, C. Liu, Y. Yu, and B. Zhang, "Electrosynthesis of formamide from methanol and ammonia under ambient conditions," Nature Communications, vol. 13, no. 1, pp. 1–8, 2022.

[79] M. Jayachandran and G. Ravi, "Design and optimization of hybrid micro-grid system," Energy Procedia, vol. 117, pp. 95–103, 2017.

[80] G. Glenk and S. Reichelstein, "Reversible power-to-gas systems for energy conversion and storage," Nature communications, vol. 13, no. 1, pp. 1–10, 2022.

[81] W. Li, Z. Yin, Z. Gao, G. Wang, Z. Li, F. Wei, X. Wei, H. Peng, X. Hu, L. Xiao et al., "Bifunctional ionomers for efficient co-electrolysis of co2 and pure water towards ethylene production at industrial-scale current densities," Nature Energy, vol. 7, no. 9, pp. 835–843, 2022.

[82] R.-P. Ye, J. Ding, W. Gong, M. D. Argyle, Q. Zhong, Y. Wang, C. K. Russell, Z. Xu, A. G. Russell, Q. Li et al., "Co2 hydrogenation to high-value products via heterogeneous catalysis," Nature communications, vol. 10, no. 1, pp. 1–15, 2019.

[83] F. Stöckl, W.-P. Schill, and A. Zerrahn, "Optimal supply chains and power sector benefits of green hydrogen," Scientific reports, vol. 11, no. 1, pp. 1–14, 2021.

[84] A. J. Shih, M. C. Monteiro, F. Dattila, D. Pavesi, M. Philips, A. H. da Silva, R. E. Vos, K. Ojha, S. Park, O. van der Heijden et al., "Water electrolysis," Nature Reviews Methods Primers, vol. 2, no. 1, pp. 1–19, 2022.

[85] A. Odenweller, F. Ueckerdt, G. F. Nemet, M. Jensterle, and G. Luderer, "Probabilistic feasibility space of scaling up green hydrogen supply," Nature Energy, vol. 7, no. 9, pp. 854–865, 2022.

[86] J. Gong, "A commentary of green hydrogen in mit technology review 2021," Fundamental Research, vol. 1, no. 6, pp. 848–850, 2021.

[87] H. Renaudineau, A. M. Llor, R. Cortés, C. A. Rojas, C. Restrepo, and S. Kouro, "Photovoltaic green hydrogen challenges and opportunities: A power electronics perspective," IEEE Industrial Electronics Magazine, vol. 16, no. 1, pp. 31–41, 2021.

[88] R. Raman, V. K. Nair, V. Prakash, A. Patwardhan, and P. Nedungadi, "Green-hydrogen research: What have we achieved, and where are we going? bibliometrics analysis," Energy Reports, vol. 8, pp. 9242–9260, 2022.

[89] F. Eljack and M.-K. Kazi, "Prospects and challenges of green hydrogen economy via multi-sector global symbiosis in qatar," Frontiers in Sustainability, vol. 1, p. 612762, 2021.

[90] A. Clerici and S. Furfari, "Challenges for green hydrogen development," in 2021 AEIT International Annual Conference (AEIT). IEEE, 2021, pp. 1–6.

[91] X. Song, D. Liang, J. Song, G. Xu, Z. Deng, and M. Niu, "Problems and technology development trends of hydrogen production from renewable energy power electrolysis-a review," in 2021 IEEE 5th Conference on Energy Internet and Energy System Integration (EI2). IEEE, 2021, pp. 3879–3882.

[92] I. R. E. Agency, "Innovation trends in electrolysers for hydrogen production," 2022.

[93] J. Knöppel, M. Möckl, D. Escalera-López, K. Stojanovski, M. Bierling, T. Böhm, S. Thiele, M. Rzepka, and S. Cherevko, "On the limitations in assessing stability of oxygen evolution catalysts using aqueous model electrochemical cells," Nature communications, vol. 12, no. 1, pp. 1–9, 2021.

[94] S. Song, H. Lin, P. Sherman, X. Yang, C. P. Nielsen, X. Chen, and M. B. McElroy, "Production of hydrogen from offshore wind in china and cost-competitive supply to japan," Nature communications, vol. 12, no. 1, pp. 1–8, 2021.

[95] J. Hughes, J. Clipsham, H. Chavushoglu, S. Rowley-Neale, and C. Banks, "Polymer electrolyte electrolysis: A review of the activity and stability of non-precious metal hydrogen evolution reaction and oxygen evolution reaction catalysts," Renewable and Sustainable Energy Reviews, vol. 139, p. 110709, 2021.

[96] M. Maier, K. Smith, J. Dodwell, G. Hinds, P. Shearing, and D. Brett, "Mass transport in pem water electrolysers: A review," International Journal of Hydrogen Energy, 2021.
[97] S. Saha, B. Rajbongshi, V. Ramani, and A. Verma, "Titanium carbide: An emerging electrocatalyst for fuel cell and electrolyser," International Journal of hydrogen energy, vol. 46, no. 24, pp. 12 801–12 821, 2021.
[98] G. Sakas, A. Ibáñez-Rioja, V. Ruuskanen, A. Kosonen, J. Ahola, and O. Bergmann, "Dynamic energy and mass balance model for an industrial alkaline water electrolyzer plant process," International Journal of Hydrogen Energy, vol. 47, no. 7, pp. 4328–4345, 2022.
[99] S. Harrison and M. Hayne, "Photoelectrolysis using type-ii semiconductor heterojunctions," Scientific Reports, vol. 7, no. 1, pp. 1–11, 2017.
[100] D. Wu, K. Kusada, S. Yoshioka, T. Yamamoto, T. Toriyama, S. Matsumura, Y. Chen, O. Seo, J. Kim, C. Song et al., "Efficient overall water splitting in acid with anisotropic metal nanosheets," Nature communications, vol. 12, no. 1, pp. 1–9, 2021.
[101] S. Pan, H. Li, D. Liu, R. Huang, X. Pan, D. Ren, J. Li, M. Shakouri, Q. Zhang, M. Wang et al., "Efficient and stable noble-metal-free catalyst for acidic water oxidation," Nature Communications, vol. 13, no. 1, pp. 1–10, 2022.
[102] B. Turan, J.-P. Becker, F. Urbain, F. Finger, U. Rau, and S. Haas, "Upscaling of integrated photoelectrochemical water-splitting devices to large areas," Nature communications, vol. 7, no. 1, pp. 1–9, 2016.
[103] L. Fan, P. F. Liu, X. Yan, L. Gu, Z. Z. Yang, H. G. Yang, S. Qiu, and X. Yao, "Atomically isolated nickel species anchored on graphitized carbon for efficient hydrogen evolution electrocatalysis," Nature communications, vol. 7, no. 1, pp. 1–7, 2016.
[104] T. Egeland-Eriksen, A. Hajizadeh, and S. Sartori, "Hydrogen-based systems for integration of renewable energy in power systems: Achievements and perspectives," international journal of hydrogen energy, vol. 46, no. 63, pp. 31 963–31 983, 2021.
[105] A. Ahmed, S. Seth, J. Purewal, A. G. Wong-Foy, M. Veenstra, A. J. Matzger, and D. J. Siegel, "Exceptional hydrogen storage achieved by screening nearly half a million metal-organic frameworks," Nature communications, vol. 10, no. 1, pp. 1–9, 2019.
[106] J. Andersson and S. Grönkvist, "Large-scale storage of hydrogen," International Journal of Hydrogen Energy, vol. 44, no. 23, pp. 11 901–11 919, 2019.
[107] A. M. Elberry, J. Thakur, A. Santasalo-Aarnio, and M. Larmi, "Large-scale compressed hydrogen storage as part of renewable electricity storage systems," International journal of hydrogen energy, vol. 46, no. 29, pp. 15 671–15 690, 2021.
[108] M. Sahlberg, D. Karlsson, C. Zlotea, and U. Jansson, "Superior hydrogen storage in high entropy alloys," Scientific reports, vol. 6, no. 1, pp. 1–6, 2016.
[109] Z. Wan, Y. Tao, J. Shao, Y. Zhang, and H. You, "Ammonia as an effective hydrogen carrier and a clean fuel for solid oxide fuel cells," Energy Conversion and Management, vol. 228, p. 113729, 2021.
[110] M. Hattori, S. Iijima, T. Nakao, H. Hosono, and M. Hara, "Solid solution for catalytic ammonia synthesis from nitrogen and hydrogen gases at 50 c," Nature communications, vol. 11, no. 1, pp. 1–8, 2020.
[111] P. Xie, Y. Yao, Z. Huang, Z. Liu, J. Zhang, T. Li, G. Wang, R. Shahbazian-Yassar, L. Hu, and C. Wang, "Highly efficient decomposition of ammonia using high-entropy alloy catalysts," Nature communications, vol. 10, no. 1, pp. 1–12, 2019.
[112] P. Hu, E. Fogler, Y. Diskin-Posner, M. A. Iron, and D. Milstein, "A novel liquid organic hydrogen carrier system based on catalytic peptide formation and hydrogenation," Nature communications, vol. 6, no. 1, pp. 1–7, 2015.
[113] D. Wei, R. Sang, P. Sponholz, H. Junge, and M. Beller, "Reversible hydrogenation of carbon dioxide to formic acid using a mn-pincer complex in the presence of lysine," Nature Energy, vol. 7, no. 5, pp. 438–447, 2022.
[114] P. Peng, A. Anastasopoulou, K. Brooks, H. Furukawa, M. E. Bowden, J. R. Long, T. Autrey, and H. Breunig, "Cost and potential of metal–organic frameworks for hydrogen back-up power supply," Nature Energy, vol. 7, no. 5, pp. 448–458, 2022.
[115] H.-L. Du, M. Chatti, R. Y. Hodgetts, P. V. Cherepanov, C. K. Nguyen, K. Matuszek, D. R. MacFarlane, and A. N. Simonov, "Electroreduction of nitrogen at almost 100% current-to-ammonia efficiency," Nature, pp. 1–2, 2022.
[116] H. Li, L. Li, R.-B. Lin, G. Ramirez, W. Zhou, R. Krishna, Z. Zhang, S. Xiang, and B. Chen, "Microporous metal–organic framework with dual functionalities for efficient separation of acetylene from light hydrocarbon mixtures," ACS sustainable chemistry & engineering, vol. 7, no. 5, pp. 4897–4902, 2019.
[117] Y. Sun, S. Polani, F. Luo, S. Ott, P. Strasser, and F. Dionigi, "Advancements in cathode catalyst and cathode layer design for proton exchange membrane fuel cells," Nature communications, vol. 12, no. 1, pp. 1–14, 2021.
[118] D. P. Broom, C. Webb, G. S. Fanourgakis, G. E. Froudakis, P. N. Trikalitis, and M. Hirscher, "Concepts for improving hydrogen storage in nanoporous materials," International journal of hydrogen energy, vol. 44, no. 15, pp. 7768–7779, 2019.
[119] A. E. Baumann, D. A. Burns, B. Liu, and V. S. Thoi, "Metal-organic framework functionalization and design strategies for advanced electrochemical energy storage devices," Communications Chemistry, vol. 2, no. 1, pp. 1–14, 2019.
[120] E. S. Cho, A. M. Ruminski, S. Aloni, Y.-S. Liu, J. Guo, and J. J. Urban, "Graphene oxide/metal nanocrystal multilaminates as the atomic limit for safe and selective hydrogen storage," Nature communications, vol. 7, no. 1, pp. 1–8, 2016.
[121] X. Zhang, Y. Sun, G. Xia, and X. Yu, "Light-weight solid-state hydrogen storage materials characterized by neutron scattering," Journal of Alloys and Compounds, vol. 899, p. 163254, 2022.
[122] J. Barale, S. Deledda, E. M. Dematteis, M. H. Sørby, M. Baricco, and B. C. Hauback, "Synthesis and characterization of magnesium-iron-cobalt complex hydrides," Scientific reports, vol. 10, no. 1, pp. 1–11, 2020.
[123] P. Schouwink, M. B. Ley, A. Tissot, H. Hagemann, T. R. Jensen, L. Smrčok, and R. Černỳ, "Structure and properties of complex hydride perovskite materials," Nature communications, vol. 5, no. 1, pp. 1–10, 2014.
[124] A. Witkowski, A. Rusin, M. Majkut, and K. Stolecka, "Comprehensive analysis of hydrogen compression and pipeline transportation from thermodynamics and safety aspects," Energy, vol. 141, pp. 2508–2518, 2017.
[125] Y. Rong, S. Chen, C. Li, X. Chen, L. Xie, J. Chen, and R. Long, "Techno-economic analysis of hydrogen storage and transportation from hydrogen plant to terminal refueling station," International Journal of Hydrogen Energy, 2023.
[126] G. Di Lullo, T. Giwa, A. Okunlola, M. Davis, T. Mehedi, A. Oni, and A. Kumar, "Large-scale long-distance land-based hydrogen transportation systems: A comparative techno-economic and greenhouse gas emission assessment," International Journal of Hydrogen Energy, vol. 47, no. 83, pp. 35 293–35 319, 2022.
[127] Y. Ishimoto, M. Voldsund, P. Nekså, S. Roussanaly, D. Berstad, and S. O. Gardarsdottir, "Large-scale production and transport of hydrogen from norway to europe and japan: Value chain analysis and comparison of liquid hydrogen and ammonia as energy carriers," International Journal of Hydrogen Energy, vol. 45, no. 58, pp. 32 865–32 883, 2020.
[128] C. J. McKinlay, S. R. Turnock, and D. A. Hudson, "Route to zero emission shipping: Hydrogen, ammonia or methanol?" International journal of hydrogen energy, vol. 46, no. 55, pp. 28 282–28 297, 2021.
[129] K. Reddi, A. Elgowainy, N. Rustagi, and E. Gupta, "Techno-economic analysis of conventional and advanced high-pressure tube trailer configurations for compressed hydrogen gas transportation and refueling," International journal of hydrogen energy, vol. 43, no. 9, pp. 4428–4438, 2018.
[130] S. F. Ahmed, M. Mofijur, S. Nuzhat, N. Rafa, A. Musharrat, S. S. Lam, and A. Boretti, "Sustainable hydrogen production: Technological advancements and economic analysis," International Journal of Hydrogen Energy, vol. 47, no. 88, pp. 37 227–37 255, 2022.
[131] C. Dong, Z. Gao, Y. Li, M. Peng, M. Wang, Y. Xu, C. Li, M. Xu, Y. Deng, X. Qin et al., "Fully exposed palladium cluster catalysts enable hydrogen production from nitrogen heterocycles," Nature Catalysis, pp. 1–9, 2022.
[132] "Hydrogen on the rise," Nature Energy, vol. 1, no. 16127, 2016.
[133] X. Yang, C. P. Nielsen, S. Song, and M. B. McElroy, "Breaking the hard-to-abate bottleneck in china's path to carbon neutrality with clean hydrogen," Nature Energy, vol. 7, no. 10, pp. 955–965, 2022.
[134] C. Kim, S. H. Cho, S. M. Cho, Y. Na, S. Kim, and D. K. Kim, "Review of hydrogen infrastructure: the current status and roll-out strategy," International Journal of Hydrogen Energy, vol. 48, no. 5, pp. 1701–1716, 2023.
[135] A. Aghakhani, N. Haque, C. Saccani, M. Pellegrini, and A. Guzzini, "Hydrogen transportation and distribution," in Towards Hydrogen Infrastructure. Elsevier, 2024, pp. 187–224.
[136] M. S. Ali, M. S. H. Khan, R. A. Tuhin, M. A. Kabir, A. K. Azad, and O. Farrok, "Hydrogen energy storage and transportation challenges: A

review of recent advances," Hydrogen Energy Conversion and Management, pp. 255–287, 2024.

[137] S. Kumar, A. Nanan-Surujbally, D. P. Sharma, and D. Pathak, "Hydrogen safety/standards (national and international document standards on hydrogen energy and fuel cell)," in Towards Hydrogen Infrastructure. Elsevier, 2024, pp. 315–346.

[138] K. R. Simonsen, D. S. Hansen, and S. Pedersen, "Challenges in co2 transportation: Trends and perspectives," Renewable and Sustainable Energy Reviews, vol. 191, p. 114149, 2024.

[139] C.-L. Chang, W.-C. Lin, L.-Y. Ting, C.-H. Shih, S.-Y. Chen, T.-F. Huang, H. Tateno, J. Jayakumar, W.-Y. Jao, C.-W. Tai et al., "Main-chain engineering of polymer photocatalysts with hydrophilic non-conjugated segments for visible-light-driven hydrogen evolution," Nature Communications, vol. 13, no. 1, pp. 1–11, 2022.

[140] M. K. Debe, "Electrocatalyst approaches and challenges for automotive fuel cells," Nature, vol. 486, no. 7401, pp. 43–51, 2012.

[141] Z. Feng, J. Huang, S. Jin, G. Wang, and Y. Chen, "Artificial intelligence-based multi-objective optimisation for proton exchange membrane fuel cell: A literature review," Journal of Power Sources, vol. 520, p. 230808, 2022.

[142] S. B. Beale, M. Andersson, C. Boigues-Muñoz, H. L. Frandsen, Z. Lin, S. J. McPhail, M. Ni, B. Sundén, A. Weber, and A. Z. Weber, "Continuum scale modelling and complementary experimentation of solid oxide cells," Progress in energy and combustion science, vol. 85, p. 100902, 2021.

[143] A. Harriman, "Electrochemical catalysts to meet the challenge for sustainable fuel production from renewable energy," Current Opinion in Green and Sustainable Chemistry, vol. 30, p. 100492, 2021.

[144] P. Plötz, "Hydrogen technology is unlikely to play a major role in sustainable road transport," Nature Electronics, vol. 5, no. 1, pp. 8–10, 2022.

[145] S. Rashidi, N. Karimi, B. Sunden, K. C. Kim, A. G. Olabi, and O. Mahian, "Progress and challenges on the thermal management of electrochemical energy conversion and storage technologies: Fuel cells, electrolysers, and supercapacitors," Progress in Energy and Combustion Science, vol. 88, p. 100966, 2022.

[146] H. Q. Nguyen and B. Shabani, "Review of metal hydride hydrogen storage thermal management for use in the fuel cell systems," International Journal of Hydrogen Energy, vol. 46, no. 62, pp. 31 699–31 726, 2021.

[147] M. Tahir, S. Hu, T. Khan, and H. Zhu, "Sustainable hybrid station design framework for electric vehicle charging and hydrogen vehicle refueling based on multiple attributes," Energy Conversion and Management, vol. 300, p. 117922, 2024.

[148] S. Yu, Y. Fan, Z. Shi, J. Li, X. Zhao, T. Zhang, and Z. Chang, "Hydrogen-based combined heat and power systems: A review of technologies and challenges," International Journal of Hydrogen Energy, 2023.

[149] Y.-K. Kim, J.-H. Kim, and S.-H. Yoo, "Public perspective on co-firing hydrogen with natural gas in power plants in south korea," International Journal of Hydrogen Energy, vol. 48, no. 11, pp. 4119–4128, 2023.

[150] Z. Xi, T. Lian, X. Shi, Z. Liu, S. Han, X. Yang, J. Zhang, W. Li, B. Mei, and Y. Li, "Co-firing hydrogen and dimethyl ether in a gas turbine model combustor: Influence of hydrogen content and comparison with methane," International Journal of Hydrogen Energy, vol. 47, no. 90, pp. 38 432–38 444, 2022.

[151] D. Keiner, C. Thoma, D. Bogdanov, and C. Breyer, "Seasonal hydrogen storage for residential on-and off-grid solar photovoltaics prosumer applications: Revolutionary solution or niche market for the energy transition until 2050?" Applied Energy, vol. 340, p. 121009, 2023.

[152] F. Ferrada, F. Babonneau, T. Homem-de Mello, and F. Jalil-Vega, "The role of hydrogen for deep decarbonization of energy systems: A chilean case study," Energy Policy, vol. 177, p. 113536, 2023.

[153] W. Bian, W. Wu, B. Wang, W. Tang, M. Zhou, C. Jin, H. Ding, W. Fan, Y. Dong, J. Li et al., "Revitalizing interface in protonic ceramic cells by acid etch," Nature, vol. 604, no. 7906, pp. 479–485, 2022.

[154] J. Huang and Y. Wang, "Efficient renewable-to-hydrogen conversion via decoupled electrochemical water splitting," Cell Reports Physical Science, vol. 1, no. 8, p. 100138, 2020.

[155] N. Chen, H. H. Wang, S. P. Kim, H. M. Kim, W. H. Lee, C. Hu, J. Y. Bae, E. S. Sim, Y.-C. Chung, J.-H. Jang et al., "Poly (fluorenyl aryl piperidinium) membranes and ionomers for anion exchange membrane fuel cells," Nature communications, vol. 12, no. 1, pp. 1–12, 2021.

[156] Y. Zhang, B. Chen, D. Guan, M. Xu, R. Ran, M. Ni, W. Zhou, R. O'Hayre, and Z. Shao, "Thermal-expansion offset for high-performance fuel cell cathodes," Nature, vol. 591, no. 7849, pp. 246–251, 2021.

[157] Y. Zhou, X. Guan, H. Zhou, K. Ramadoss, S. Adam, H. Liu, S. Lee, J. Shi, M. Tsuchiya, D. D. Fong et al., "Strongly correlated perovskite fuel cells," Nature, vol. 534, no. 7606, pp. 231–234, 2016.

[158] C. Duan, R. J. Kee, H. Zhu, C. Karakaya, Y. Chen, S. Ricote, A. Jarry, E. J. Crumlin, D. Hook, R. Braun et al., "Highly durable, coking and sulfur tolerant, fuel-flexible protonic ceramic fuel cells," Nature, vol. 557, no. 7704, pp. 217–222, 2018.

[159] K. Jiao, J. Xuan, Q. Du, Z. Bao, B. Xie, B. Wang, Y. Zhao, L. Fan, H. Wang, Z. Hou et al., "Designing the next generation of proton-exchange membrane fuel cells," Nature, vol. 595, no. 7867, pp. 361–369, 2021.

[160] C. H. Park, S. Y. Lee, D. S. Hwang, D. W. Shin, D. H. Cho, K. H. Lee, T.-W. Kim, T.-W. Kim, M. Lee, D.-S. Kim et al., "Nanocrack-regulated self-humidifying membranes," Nature, vol. 532, no. 7600, pp. 480–483, 2016.

[161] J.-h. Myung, D. Neagu, D. N. Miller, and J. T. Irvine, "Switching on electrocatalytic activity in solid oxide cells," Nature, vol. 537, no. 7621, pp. 528–531, 2016.

[162] D. Milani, A. Kiani, and R. McNaughton, "Renewable-powered hydrogen economy from australia's perspective," International Journal of Hydrogen Energy, vol. 45, no. 46, pp. 24 125–24 145, 2020.

[163] Y. Li and F. Taghizadeh-Hesary, "The economic feasibility of green hydrogen and fuel cell electric vehicles for road transport in china," Energy Policy, vol. 160, p. 112703, 2022.

[164] P. J. Megia, A. J. Vizcaino, J. A. Calles, and A. Carrero, "Hydrogen production technologies: from fossil fuels toward renewable sources. a mini review," Energy & Fuels, vol. 35, no. 20, pp. 16 403–16 415, 2021.

[165] B. Delaval, T. Rapson, R. Sharma, W. Hugh-Jones, E. McClure, M. Temminghoff, and V. Srinivasan, "Hydrogen rd&d collaboration opportunities: Global report," 2022.

[166] International Energy Agency (IEA), "Global hydrogen review 2022," 2022.

[167] H. H. Cho, V. Strezov, and T. J. Evans, "A review on global warming potential, challenges and opportunities of renewable hydrogen production technologies," Sustainable Materials and Technologies, vol. 35, p. e00567, 2023.

[168] V. Panchenko, Y. Daus, A. Kovalev, I. Yudaev, and Y. Litti, "Prospects for the production of green hydrogen: Review of countries with high potential," International Journal of Hydrogen Energy, vol. 48, no. 12, pp. 4551–4571, 2023.

[169] H. Ishaq, I. Dincer, and C. Crawford, "A review on hydrogen production and utilization: Challenges and opportunities," International Journal of Hydrogen Energy, vol. 47, no. 62, pp. 26 238–26 264, 2022, sI: Progress in Hydrogen Production, Storage and Distribution (Ahmadi).

[170] T. B. Ferriday and P. H. Middleton, "Alkaline fuel cell technology-a review," international journal of hydrogen energy, vol. 46, no. 35, pp. 18 489–18 510, 2021.

[171] S. Zhang, Y. Liu, M. Zhang, Y. Ma, J. Hu, and Y. Qu, "Sustainable production of hydrogen with high purity from methanol and water at low temperatures," 2022.

[172] J. Zhang, L. Zhang, J. Liu, C. Zhong, Y. Tu, P. Li, L. Du, S. Chen, and Z. Cui, "Oh spectator at irmo intermetallic narrowing activity gap between alkaline and acidic hydrogen evolution reaction," Nature communications, vol. 13, no. 1, pp. 1–9, 2022.

[173] F.-Y. Gao, P.-C. Yu, and M.-R. Gao, "Seawater electrolysis technologies for green hydrogen production: challenges and opportunities," Current Opinion in Chemical Engineering, vol. 36, p. 100827, 2022.

[174] G. K. Li, J. Guo, Y. Zhang, A. Zavabeti, K. Chen, Y. Guo, G. Hu, and X. Fan, "Hydrogen production from the air," 2021.

[175] F.-Y. Gao, P.-C. Yu, and M.-R. Gao, "Seawater electrolysis technologies for green hydrogen production: challenges and opportunities," Current Opinion in Chemical Engineering, vol. 36, p. 100827, 2022.

[176] R. R. Barth, K. L. Simmons, and C. W. San Marchi, "Polymers for hydrogen infrastructure and vehicle fuel systems," Sandia National Lab.(SNL-CA), Livermore, CA (United States); Pacific . . . , Tech. Rep., 2013.

[177] A. H. Azadnia, C. McDaid, A. M. Andwari, and S. E. Hosseini, "Green hydrogen supply chain risk analysis: A european hard-to-abate sectors perspective," Renewable and Sustainable Energy Reviews, vol. 182, p. 113371, 2023.

[178] B. Shadidi, G. Najafi, and T. Yusaf, "A review of hydrogen as a fuel in internal combustion engines," Energies, vol. 14, no. 19, 2021.

[179] Z. Wang, R. Roberts, G. Naterer, and K. Gabriel, "Comparison of thermochemical, electrolytic, photoelectrolytic and photochemical solar-to-hydrogen production technologies," International journal of hydrogen energy, vol. 37, no. 21, pp. 16 287–16 301, 2012.

[180] F. Kuttassery, S. Sagawa, S. Mathew, Y. Nabetani, A. Iwase, A. Kudo, H. Tachibana, and H. Inoue, "Water splitting on aluminum porphyrins to form hydrogen and hydrogen peroxide by one photon of visible light," ACS Applied Energy Materials, vol. 2, no. 11, pp. 8045–8051, 2019.

[181] G. Mussabek, S. A. Alekseev, A. I. Manilov, S. Tutashkonko, T. Nychyporuk, Y. Shabdan, G. Amirkhanova, S. V. Litvinenko, V. A. Skryshevsky, and V. Lysenko, "Kinetics of hydrogen generation from oxidation of hydrogenated silicon nanocrystals in aqueous solutions," Nanomaterials, vol. 10, no. 7, 2020.

[182] D. Banerjee, N. Kushwaha, N. P. Shetti, T. M. Aminabhavi, and E. Ahmad, "Green hydrogen production via photo-reforming of bio-renewable resources," Renewable and Sustainable Energy Reviews, vol. 167, p. 112827, 2022.

[183] P. Chatterjee, M. S. K. Ambati, A. K. Chakraborty, S. Chakrabortty, S. Biring, S. Ramakrishna, T. K. S. Wong, A. Kumar, R. Lawaniya, and G. K. Dalapati, "Photovoltaic/photo-electrocatalysis integration for green hydrogen: A review," Energy Conversion and Management, vol. 261, p. 115648, 2022.

[184] M. Rumayor, J. Fernández-González, A. Domínguez-Ramos, and A. Irabien, "Perspectives for a sustainable implementation of super-green hydrogen production by photoelectrochemical technology in hard-to-abate sectors," Cleaner Production Letters, vol. 4, p. 100041, 2023.

[185] F. Schorn, J. L. Breuer, R. C. Samsun, T. Schnorbus, B. Heuser, R. Peters, and D. Stolten, "Methanol as a renewable energy carrier: An assessment of production and transportation costs for selected global locations," Advances in Applied Energy, vol. 3, p. 100050, 2021.

[186] H. Xin, "Catalyst design with machine learning," Nature Energy, pp. 790–791, 2022.

[187] S. Zhai, H. Xie, P. Cui, D. Guan, J. Wang, S. Zhao, B. Chen, Y. Song, Z. Shao, and M. Ni, "A combined ionic lewis acid descriptor and machine-learning approach to prediction of efficient oxygen reduction electrodes for ceramic fuel cells," Nature Energy, pp. 1–10, 2022.

[188] T. M. Gulotta, R. Salomone, F. Lanuzza, G. Saija, G. Mondello, and G. Ioppolo, "Life cycle assessment and life cycle costing of unitized regenerative fuel cell: A systematic review," Environmental Impact Assessment Review, vol. 92, p. 106698, 2022.

[189] G. Shen, J. Liu, H. B. Wu, P. Xu, F. Liu, C. Tongsh, K. Jiao, J. Li, M. Liu, M. Cai et al., "Multi-functional anodes boost the transient power and durability of proton exchange membrane fuel cells," Nature communications, vol. 11, no. 1, pp. 1–10, 2020.

[190] S. S. Rathore, S. Biswas, D. Fini, A. P. Kulkarni, and S. Giddey, "Direct ammonia solid-oxide fuel cells: A review of progress and prospects," International Journal of Hydrogen Energy, vol. 46, no. 71, pp. 35 365–35 384, 2021.

[191] K. Dahal, S. Brynolf, C. Xisto, J. Hansson, M. Grahn, T. Grönstedt, and M. Lehtveer, "Techno-economic review of alternative fuels and propulsion systems for the aviation sector," Renewable and Sustainable Energy Reviews, vol. 151, p. 111564, 2021.

[192] D. Pivetta, C. Dall'Armi, P. Sandrin, M. Bogar, and R. Taccani, "The role of hydrogen as enabler of industrial port area decarbonization," Renewable and Sustainable Energy Reviews, vol. 189, p. 113912, 2024.

JAYACHANDRAN. M has been researching Green Energy since the late 2016s. He has published many articles in journals and conferences on the topic. He has a Bachelor's degree (2006) from Anna University and a doctorate (2021) from Pondicherry University. He has currently worked at Puducherry Technological University, Puducherry, India. He has 10+ years of experience in academia, research, teaching, and academic administration. His current research interests include Green and Sustainable Energy System.

RANJITH KUMAR GATLA is working as an Associate Professor in the EEE Department and Dean of Intellectual Property Management and Commercialization at the Institute of Aeronautical Engineering, Hyderabad, India. He received the M.Tech. degree in power electronics from SRM University, Chennai, India, and the Ph.D. degree in power electronics from Wuhan University of Technology, Wuhan, China, in 2008 and 2019, respectively. Dr. Ranjith Kumar Gatla has 11+ years of experience in academia, research, teaching, and academic administration. His current research interests include the reliability of power electronics systems, grid-connected PV systems, multilevel inverters, and electric vehicle technologies. Dr. Ranjith Kumar Gatla is an IEEE Senior Member. He is a Life-Member of ISTE, Associate Member of IE (I), and Member of IAENG. He published 40+ research papers and 4+ patents. He is a frequent reviewer, editorial board member and TPC member in flagship conferences and refereed journals.

AYMEN FLAH was born in Gabès, Tunisia, in 1983. He received the bachelor's degree in electrical engineering and the M.Tech. degree from the ENIG, Tunisia, in 2007 and 2009, respectively, and the Ph.D. degree from the Department of Electrical Engineering, in 2012. He has academic experience of 11 years. He has published over 40 research articles in reputed journals, and over 40 research papers in international conferences and book chapters. His research interests include electric vehicle, power systems, and renewable energy.

AHMAD H. MILYANI received the B.Sc with distinction and the M.Sc degrees in Electrical and Computer Engineering from Purdue University in 2011 and 2013, respectively, and the Ph.D. degree in Electrical Engineering from the University of Washington in 2019. He is currently an Associate Professor with the Department of Electrical and Computer Engineering, King Abdulaziz University, Jeddah, Saudi Arabia. His research interests include power systems operation and optimization, renewable and sustainable energy, power electronics, electric machines, electric vehicles, and computational intelligence applications.

PLACE
PHOTO
HERE

H isham M. Milyani received the Ph.D. degree from Florida State University in 1983. He is currently an Associate Professor with the College of Applied Studies, King Abdulaziz University, Jeddah, Saudi Arabia. His research interests include economics, management, budgetary process, and public policy.

VOJTECH BLAZEK was born in Czech Republic, in 1991. He received the Ing. degree from the Department of Electrical Engineering, VSB—Technical University of Ostrava, in 2016. He is currently an Internal Doctoral Student and a Junior Researcher with the Research Centre ENET–Energy Units for Utilization of Non- Traditional Energy Sources, VSB—Technical University of Ostrava. His current work includes developing modern and green technologies in off-grid systems with vehicle to home technologies.

LUKAS PROKOP graduated the Ing. degree majoring in electrical power engineering from the Faculty of Electrical Engineering and Communication, Brno University of Technology. He is an Associate Professor at FEI TU Ostrava. Currently, he is engaged in renewable energy sources, modern technologies, and methods in electrical power engineering and electrical measurements. He is a research team member of Czech and international research projects. He serves as the Deputy Head of the ENET Research Centre.

HABIB KRAIEM earned his Ph.D. in Electrical Engineering from the National Engineering School of Gabes, Tunisia, in October 2010. In 2012, he became a faculty member in the Electrical Department at the Higher Institute of Industrial Systems in Gabes, Tunisia. Since 2015, he has been serving in the Department of Electrical Engineering at the College of Engineering, Northern Border University, Saudi Arabia. His research primarily focuses on power electronics, machine drives, automatic control, and the development of renewable energy technologies.