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Towards Hydrogen Sector Investments for Achieving Sustainable Electricity Generation

Mohamed Khaleel[1*], Ziyodulla Yusupov[1], Muhammet Tahir Guneser[1], Yasser Nassar[2], Hala El-Khozondar[2,3], Abdussalm Ahmed[4], Abdulgader Alsharif[5].

[1]Electrical-Electronics Engineering Department, Faculty of Engineering, Karabuk University, Karabuk 78050, Turkey.

[2]Dept. of Electrical Eng. and Smart Systems, Islamic Univ. of Gaza, Gaza Strip, Palestine.

[3]Department of Materials and London Centre for Nanotechnology, Imperial College London, London, UK.

[4]Mechanical and Industrial Engineering Department, Bani Waleed University, Bani Walid, Libya.

[5]Electrical and Electronic Engineering Department, Faculty of Technical Sciences-Sebha Sebha, Libya.

E-*mail:* yasser_nassar68@ymail.com.

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ABSTRACT

Hydrogen constitutes an integral component within an expansive array of energy technologies poised to facilitate the nation's transition towards achieving a net-zero state. In additional, this endeavor involves harnessing regional resources judiciously, thereby fostering equitable and sustainable growth. The strategic development and utilization of hydrogen technologies necessitate a nuanced approach, encompassing an assessment of diverse technologies spanning various sectors especially power sector. Such a meticulous strategy aims to forge the most efficacious, cost-effective, and sustainable pathways, underpinned by the discerning adoption of these technologies in the market.

The article delves into the intricate relationship between hydrogen and fuel cell technologies, shedding light on their combined impact on the evolving landscape of electricity generation. A particular focus is placed on the integration of variable renewable energy sources, elucidating how hydrogen serves as a key enabler in optimizing the utilization of these fluctuating energy resources. In addition, the article encompasses various methods of hydrogen production, exploring their technological advancements and implications for achieving sustainable electricity generation.

*Corresponding author.

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A particular focus is placed on the integration of variable renewable energy sources, elucidating how hydrogen serves as a key enabler in optimizing the utilization of these fluctuating energy resources. In addition, the article encompasses various methods of hydrogen production, exploring their technological advancements and implications for achieving sustainable electricity generation. Emphasizing the significance of technology development in the hydrogen sector, the paper delves into the potential of hydrogen production methods and their implications for advancing sustainable electricity generation. In essence, the article navigates the trajectory of the hydrogen sector's evolution within the broader context of electricity generation, offering valuable insights into the ongoing developments, challenges, and opportunities. By addressing the critical nexus between hydrogen technologies and the dynamic electricity landscape, the paper aims to contribute to the discourse on the future trajectory of investments in the hydrogen sector for enhanced electricity generation. To Conclude, the United Kingdom has committed GBP 20 billion over a span of 20 years to the development of Carbon Capture, Utilization, and Storage (CCUS) facilities. Additionally, the nation has identified and shortlisted electrolysis projects totalling 408 megawatts (MW) capacity. In Korea, Hanwha Impact has achieved a significant milestone by attaining a 60% hydrogen co-firing share in an 80 MW gas turbine, representing the largest co-firing share recorded thus far in mid-to-large gas turbines. Meanwhile, Anhui Province Energy Group in China has successfully conducted trials involving the co-firing of ammonia at a 300 MW unit. The Group has plans to further extend these trials, aiming to achieve a 50% co-firing level at a 1 GW coal unit. In the United States, notable progress has been made, with a 38% hydrogen co-firing share attained in 2023 at an operational 753 MW combined-cycle power plant.

التوجه للاستثمار في انتاج الهيدروجين لتحقيق الاستدامة في توليد الكهرباء

محمد خليل، زيدالله يوسبوف، محمت طاهر قونسير، ياسر نصار، هالة الخزندار، عبدالسلام أحمد، عبدالقادر الشريف.

ملخص: يعتبر الهيدروجين ضمن مجموعة واسعة من تقنيات الطاقات التي تهدف إلى تحول الدولة الليبية نحو تحقيق صافي انبعاثات صفري، وتعزيز التنمية المستدامة من خلال الاستخدام الأمثل للموارد الطبيعية المحلية. يتطلب استخدام تقنيات الهيدروجين تقنيات متنوعة والتي يجب ان تغطي مختلف القطاعات وخاصة قطاع صناعة الطاقة. وذلك من خلال وضع الإستراتيجيات وصياغة المسارات الأكثر فعالية من حيث التكلفة والاستدامة والمحافظة على البيئة. يناقش البحث العلاقة الهندسية بين تقنيات الهيدروجين وخلايا الوقود، ويسلط الضوء على تأثيرهما المشترك على تطور سوق الطاقة. ويتم التركيز بشكل خاص على تكامل مصادر الطاقة المتجددة، وتوضيحٍ طريقة عمل الهيدروجين كعامل رئيسي في تحسين الاستفادة من موارد الطاقات المتجددة. بالإضافة إلى ذلك، تناول البحث طرقًا مختلفة لإنتاج الهيدروجين، وتسليط الضوء على التقدم التكنولوجي وتأثيره على تحقيق توليد مستدام للطاقة الكهربائية. وتأكيداُ على أهمية تطوير التكنولوجيا في قطاع الهيدروجين، كما تحققت الورقة من إمكانات طرق إنتاج الهيدروجين وآثارها على النهوض بقطاع صناعة الطاقة الكهربائية المحلي. كما يقدم المؤلفون رؤىً قيمة حول التطورات والتحديات والفرص وذلك من خلال معالجة العلاقة بين تقنيات الهيدروجين وآليات توليد الكهرباء. تهدف الورقة إلى المساهمة في التحول المستقبلي للاستثمارات في قطاع الهيدروجين لتعزيز توليد الكهرباء. كما تم مناقشة تجارب بعض الدول الرائدة في مجال التحول الى الصافي الصفري للانبعاثات، وانتاج طاقة الهيدروجين. فعلى سبيل المثال، خصصت

المملكة المتحدة مبلغا وقدره 20 مليار جنيه إسترليني على مدى 20 عاماً لتطوير معدات حجز الكربون واستخدامه وتخزينه. كما قامت بوضع استراتيجيات لزيادة نصيب طاقة الهيدروجين في مزيج الطاقة ليصل الى 408 ميجاوات. في كوريا، حققت شركة Hanwha Impact إنجازاً هاماً من خلال الوصول الى نسبة مشاركة الهيدروجين الى 60% كوقود في توربينات غازية بقدرة 80 ميجاوات، وهو ما يمثل أكبر حصة حرق مشترك تم تسجيلها حتى الآن في توربينات الغاز المتوسطة والكبيرة. وفي الوقت نفسه، أجرت مجموعة الطاقة بمقاطعة آنهوي في الصين بنجاح تجارب تنطوي على الحرق المشترك للأمونيا في وحدة بقدرة 300 ميجاوات. وتخطط المجموعة لتوسيع هذه التجارب بشكل أكبر، بهدف تحقيق مستوى حرق مشترك بنسبة 50% في وحدة فحم بقدرة 1 جيجاوات. وفي الولايات المتحدة، تم الوصول إلى حصة 38% من حرق الهيدروجين المشترك في عام 2023 في محطة طاقة تعمل بالدورة المركبة بقدرة 753 ميجاوات.

1. INTRODUCTION

Hydrogen and energy share a longstanding and intertwined history. The inaugural exhibitions of water electrolysis and fuel cells captivated the imaginations of engineers in the 1800s. Over two centuries ago, hydrogen fueled the initial internal combustion engines [1]. During the 18th and 19th centuries, it served as buoyancy for balloons and airships, while in the 1960s, it played a vital role in propelling humanity to the moon. Hydrogen, as a component in ammonia fertilizer, originating from fossil fuels and, in earlier times, electricity and water—contributed significantly to sustaining a burgeoning global population [2]. Since the mid-20th century, hydrogen has been an integral element in the energy industry, finding widespread usage in oil refining [3].

In fact, the global hydrogen supply to industrial users has evolved into a significant international enterprise. The demand for hydrogen, having expanded more than threefold since 1975, continues its upward trajectory. The demand for pure hydrogen stands at approximately 70 million tonnes per year (MtH2/yr). This hydrogen is predominantly sourced from fossil fuels, with 6% of the world's natural gas and 2% of global coal allocated to hydrogen production. Consequently, hydrogen production contributes to carbon dioxide (CO_2) emissions totaling around 830 million tonnes per year ($MtCO_2$/yr), a figure equivalent to the combined CO_2 emissions of both Indonesia and the United Kingdom. In terms of energy, the total annual global demand for hydrogen is estimated at around 330 million tonnes of oil equivalent (Mtoe), surpassing the primary energy supply of Germany [4].

The prevailing trajectories in energy provision and consumption are unequivocally untenable, manifesting glaring economic, environmental, and social unsustainability. Absent resolute intervention, carbon dioxide (CO_2) emissions stemming from energy activities are poised to more than double by the year 2050, exacerbating apprehensions about the security of fossil energy supplies [5]. It is imperative that a transformative shift in our energy paradigm occurs, steering us away from the current trajectory of sustainability. This necessitates nothing short of an energy revolution, where the pivotal role of low-carbon energy technologies becomes indisputable. Essential components in this transformative journey include enhancing energy efficiency, harnessing renewable energy sources, and implementing carbon capture and storage technologies [6].

The proliferation of announced projects for low-emission hydrogen production is rapidly underway. If all these projects come to fruition, the annual production of low-emission hydrogen could potentially reach 38 Mt by 2030. It is noteworthy, however, that 17 Mt of this projection is associated with projects in their early developmental stages. The anticipated production by 2030, based on the announced projects to date, exceeds the 2022 estimate by 50%. Only a marginal 4% of this production potential has advanced to the stage of securing a final investment decision (FID), marking a twofold increase from the previous year and totaling nearly 2 Mt. Among the total projected production, 27 Mt is attributed to electrolysis and low-emission electricity, while 10 Mt is derived from fossil fuels with carbon capture, utilization, and storage [7]. Figure 1 displays a map illustrating the locations of low-emission hydrogen generating projects that have been officially disclosed. If brought to fruition, the announced projects for low-emission hydrogen production would account for 55% of the level outlined in the NZE Scenario by 2030. To catalyze investment in production projects, decisive policy measures are imperative to generate demand for low-emission hydrogen as illustrated in Figure 2.

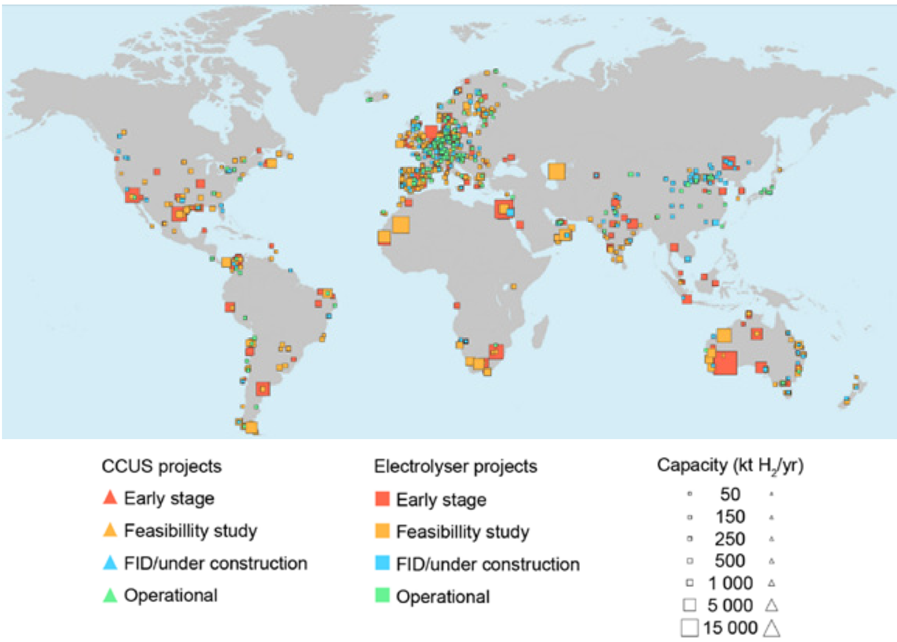


Figure 1. A map illustrating the locations of low-emission hydrogen generating projects.

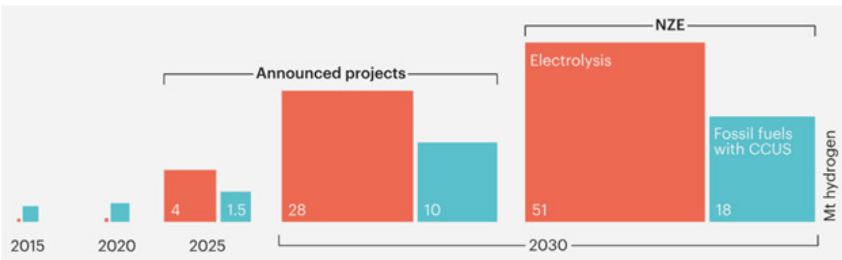
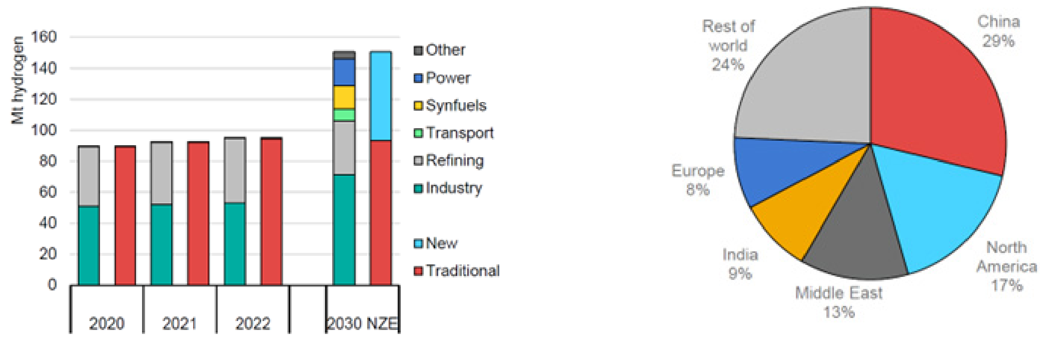


Figure 2. Hydrogen production with limited emissions [8].

In the year 2022, the global utilization of hydrogen amounted to 95 Mt, reflecting an almost 3% upturn compared to our revised estimate for the year 2021. This persistent upward trajectory in hydrogen consumption maintains the trend of growth, which experienced a temporary interruption in 2020 due to the repercussions of the Covid-19 pandemic and the ensuing economic deceleration. Figure 3 displays the utilization of hydrogen by reign in the year 2022. Figure 3. The utilization of hydrogen by sector in the year 2020-2030.

Hydrogen usage has significantly increased in major consumer areas, except for Europe. Hydrogen utilization in Europe experienced a significant setback as a result of reduced engagement, especially in the chemical sector. The decline was a direct result of the substantial increase in natural gas prices caused by the energy crisis sparked by Russia's invasion of Ukraine. The chemical sector experienced a significant impact, with some fertilizer facilities reducing production or completely ceasing operations for extended periods during the year. As a result, the region experienced a decrease in hydrogen consumption of approximately 6%. North America and the Middle East had significant growth, with each region registering an around 7% gain. This growth substantially counteracted the loss observed in Europe. China, despite experiencing a more moderate growth rate of approximately 0.5%, remains the primary global consumer of hydrogen. It accounts for nearly 30% of the total global hydrogen consumption, which is more than twice the consumption of the second-largest user, the United States.



(a) (b)

Figure 3. The utilization of hydrogen by reign and sector: (a) The utilization of hydrogen by sector in the year 2020-2030, and (b) The utilization of hydrogen by reign in the year 2022 [3].

Once hydrogen and fuel cell technologies reach a more advanced stage of development, they possess the potential to significantly contribute to climate change mitigation and bolster energy security objectives across multiple facets of the energy landscape. These sectors include but are not limited to transportation, industry, buildings, and the power sector. Hydrogen, serving as a bridging element, has the capability to interlink disparate energy sectors and traverse energy transmission and distribution (T&D) networks. In this context, it enhances the operational flexibility of forthcoming low-carbon energy systems. Its applications extend to: 1) facilitating the realization of highly low-carbon individual motorized transportation; 2) enabling the seamless integration of substantial proportions of variable renewable energy into the energy infrastructure; 3) playing a vital role in the decarbonization of electrical grid [9]. Figure 4 presents hydrogen production methods using VRE.

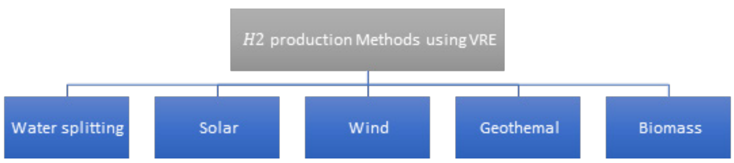


Figure 4. Hydrogen production methods using VRE.

The production process can adopt either a centralized or decentralized model, with options for grid-connected or off-grid configurations, thereby affording scalability, versatility, and consideration for regional specifics. Hydrogen, in this context, presents a myriad of possibilities spanning various sectors, serving as a valuable complement to existing conventional grid and natural gas infrastructure. In contrast to the conventional paradigm of "electrons to electrons" pathways, exemplified by the electric grid feeding into batteries, hydrogen introduces a distinctive advantage by offering storage capabilities and applicability in scenarios where electrification poses challenges. However, a multitude of countries globally are earnestly involved in the exploration and experimentation of these nascent technologies, employing pilot projects and practical trials. The overarching goal is to expedite the incorporation of hydrogen as an environmentally friendly fuel source within the electricity power sectors. The application of hydrogen as an environmentally friendly fuel offers a range of benefits as well as drawbacks. They are some important factors to take into account [10,11]:

Advantages:

- Environmental Advantages: Green hydrogen stands out as a pristine fuel, free from the emission of harmful substances, thereby bolstering environmental well-being and fostering enhanced air quality.
- Renewable and Sustainable: The production of green hydrogen is achievable through renewable energy sources such as solar and wind energy, establishing it as a sustainable alternative to fulfill diverse energy requirements.
- High Energy Conversion Efficiency: Green hydrogen exhibits exceptional efficiency in energy conversion. When employed in fuel cells, it facilitates the generation of electricity with greater efficiency in comparison to conventional fuels.
- Convenient Storage: Green hydrogen lends itself to facile storage through existing natural gas networks, rendering it apt for application across various industries.

Disadvantages:

- Elevated Production Costs: The production of hydrogen is associated with substantial costs, encompassing the expenses incurred in generating solar or wind energy and the intricate process of extracting hydrogen from water.
- Infrastructure Prerequisites: The adoption of hydrogen mandates the establishment of dedicated infrastructure for storage and transportation, demanding considerable investments and continuous developmental endeavors.
- Safety Apprehensions: Green hydrogen poses potential hazards if mishandled or in the event of a leakage. It is imperative to exercise proper handling techniques and adhere to stringent safety protocols.
- Technological Advancements: The effective utilization of green hydrogen hinges on the deployment of sophisticated technologies for storage and application. The development and commercial viability of these technology.

In addition, electrolysers play a pivotal role in the generation of low-emission hydrogen using renewable or nuclear electricity. Figure 5 shows electrolysis methods. While the capacity for electrolysis dedicated to hydrogen production experienced growth in recent years, the momentum decelerated in 2022, with approximately 130 MW of new capacity becoming operational an observed decline of 45% compared to the previous year [12,13].

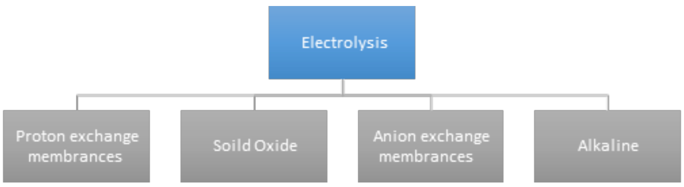


Figure 5. Electrolysis methods.

Nonetheless, there was a noteworthy increase in electrolyser manufacturing capacity, surging by over 25% since the preceding year and reaching nearly 11 GW per annum in 2022. Moreover, the potential realization of all projects currently in the pipeline could result in an installed electrolyser capacity ranging from 170 GW to 365 GW by the year 2030. To clarify, the capacity for electrolysis is expanding, starting from a modest foundation, and necessitates a substantial acceleration to align with the Net Zero Emissions by 2050 (NZE) Scenario. The scenario demands that the installed electrolysis capacity surpasses 550 GW by the year 2030.

According to the authors in reference [14], this study presents a detailed plan focused on promoting hydrogen technologies, developing the necessary infrastructure, and making careful choices regarding energy sources. These efforts aim to facilitate the shift towards a more sustainable and resilient energy system. In addition, life cycle assessment studies have been carried out to evaluate various energy generating systems, including hydrogen. The results are carefully evaluated to make comparisons, confirming that renewables and nuclear energy are the most suitable options for hydrogen production. The global warming potential values for power generation from nuclear and renewable sources are calculated to be 0.027 and 0.043 kg CO_2 eq./kWh, respectively. By comparison, natural gas, oil, and coal have global warming potential values of 0.2, 0.3, and 0.36 kg CO_2 eq./kWh, respectively, highlighting their greater environmental impact as indicated in reference [14].

Hassan [15] examined the integration of green hydrogen in many sectors, including transportation, industry, power generation, and heating, highlighting its ability to reduce carbon emissions in traditionally carbon-intensive areas. Furthermore, it evaluates the tactics and measures employed by organizations such as the European Union, Australia, Japan, the United States, and Canada, with the goal of accelerating the progress and universal acceptance of green hydrogen technology.

The aim of the present study conducted by Kumar et al., [16] is to develop and enhance a Hybrid Renewable Energy System (HRES) specifically designed to fulfill the energy and hydrogen demands of a distant community located in Dungri, Uttarakhand, India. The process entails a comprehensive analysis of energy consumption, the accessibility of local resources, and the lifestyle attributes of the inhabitants. The findings indicate that a techno-economically optimized hybrid renewable energy system (HRES) can be implemented. This system consists of a 90-kW photovoltaic (PV) system, a 25-kW bio-generator, a 30-kW electrolyser, a 15-kW hydrogen storage tank, a 10-kWh storage facility, and a 30-kW converter. The Net Present Value (NPV) is calculated to be Rs. 78.4 lakhs, with a cost of energy (COE) of Rs. 7.61 per kilowatt-hour (kWh) and a cost of hydrogen (COH) of Rs. 330 per kilogram (kg). The yearly electricity generation is anticipated to be 250,641 kilowatt-hours, along with an average annual production of 1,838 kilograms of hydrogen. The hydrogen produced by consuming 80,462 kWh/year of electricity has the capacity to fuel hydrogen-powered buses for a yearly distance of 26,280 km.

This investigation by Zhu [17] endeavors to identify optimal strategies for fostering sustainable and impactful investments in hydrogen energy. Within this context, nine distinct criteria are delineated, encompassing social, managerial, and financial considerations. To assess the significance of these criteria, a methodological approach employing hesitant, interval-valued, intuitionistic fuzzy (IVIF) decision-making trial and evaluation laboratory (DEMATEL) is adopted. Furthermore, impact relation maps are constructed to visually elucidate the causal relationships among these factors. The outcomes underscore that, when juxtaposed with managerial and financial factors, the technical dimension assumes paramount importance in influencing effective decision-making in the realm of hydrogen energy investments. However, Vargas-Ferrer et al., [18] introduced a methodological framework for evaluating the incorporation and advancement of a national power system intertwined with the production and supply chain of electrolytic hydrogen. This framework is rooted in the widely recognized optimization tool for energy system planning, namely, the Open Source Energy Modeling System (OSeMOSYS).

Kakoulaki [19] evaluates the substitution of conventional grey hydrogen with green hydrogen production, achieved via electrolysis powered by renewable energy sources, within the EU27 and the UK at a regional level (NUTS2). This assessment takes into account the prevailing electricity consumption and the demand for hydrogen. The findings bear significance for formulating policies integral to the execution of the EU energy transition, particularly concerning the role of green hydrogen and the consequential implications at the regional level for the deployment of renewable electricity generation capacity.

In the pursuit of sustainable energy solutions, the focus on hydrogen investments emerges as a transformative catalyst, particularly in the realm of electricity generation. This endeavor represents a significant contribution to the ongoing discourse on sustainable energy, offering multifaceted benefits that extend beyond environmental considerations. Additionally, hydrogen, renowned for its high energy density and minimal environmental impact upon combustion, stands as a pivotal candidate for reshaping the landscape of electricity generation. This contribution advocates for a strategic shift towards hydrogen-based investments, emphasizing its potential to revolutionize the sustainability paradigm in the power sector. Moreover, hydrogen investments offer a clear pathway to achieving carbon neutrality in electricity generation. By leveraging green hydrogen production through methods like electrolysis powered by renewable energy, the carbon footprint of power generation can be substantially reduced, aligning with global decarbonization goals. In this context, the intermittency inherent in renewable energy sources poses a challenge to grid stability. Hydrogen investments provide an innovative solution by acting as a storage medium for surplus energy during peak production periods. This stored energy can then be efficiently utilized during low renewable energy output, ensuring a stable and reliable electricity supply.

Section 2 scrutinizes the adoption of hydrogen and fuel cell technologies. Section 3 focuses on the utilization of hydrogen for the seamless integration of variable renewable energy (VRE). Section 4 provides a discussion on global hydrogen production. Section 5 delves into the deployment of hydrogen technologies across various sectors. Section 6 addresses the role of hydrogen in electricity generation, evaluating its efficacy as a clean and efficient energy carrier. Section 7 demonstrates investments in the hydrogen sector. Section 8 encapsulates the conclusion of the article, synthesizing key insights and offering a nuanced perspective on the current state of hydrogen technologies and their implications for sustainable energy practices.

2. HYDROGEN AND FUEL CELL TECHNOLOGIES ADOPTION

To avert the perils of climate change, concerted efforts in curbing greenhouse gas (GHG) emissions must emanate from both the energy supply sector and all segments of energy demand. Achieving an ambitious emission reduction scenario, particularly to confine global warming to a 2°C increase above pre-industrial levels, necessitates profound decarbonization of the power sector. On a global scale, there is an imperative to slash annual emissions by 85% by the year 2050, relative to current levels. This formidable task is chiefly realized in the 2DS (2-Degree Scenario), predominantly through a substantial surge in renewable power, accounting for approximately 63% of generated electricity by 2050. This elevated integration of renewable energy, surpassing the 2DS in specific regions like the European Union, mandates a profound structural transformation in the operational dynamics of power systems [20,21].

Electricity derived from renewable energy sources inherently carries the temporal and spatial characteristics of its underlying resources, namely sunlight, wind, tidal, and wave patterns. These patterns exhibit a lack of synchronization with fluctuations in demand, both in terms of location and timing of supply. Consequently, periods of surplus and deficit in supply emerge, varying across different geographical regions [23,24]. Furthermore, the erratic output resulting from weather variability introduces rapid oscillations in the energy supply. Figure 6, depicts an integrated hydrogen technology connected to an electrical grid infrastructure.

This poses a challenge as the electricity grid necessitates the immediate and continuous equilibrium of supply and demand. To address the temporal and spatial misalignment between variable electricity supply and demand, a range of strategies is available. These include enhancements to grid infrastructure, the incorporation of flexible generation methods, the implementation of demand-side response mechanisms, and the utilization of energy storage solutions. However, the deployment of these options should be contingent upon their respective economic viability [26].

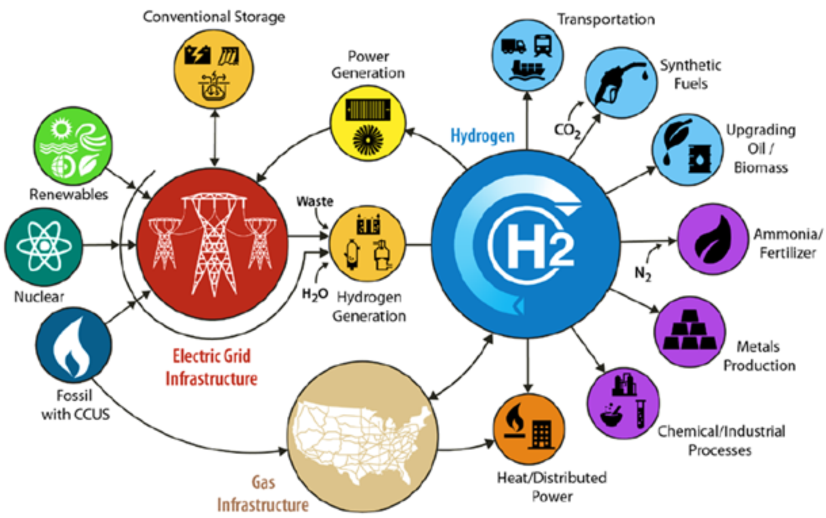


Figure 6. An integrated hydrogen technology connected to an electrical grid infrastructure.

It is important to remind that the storage of hydrogen plays a pivotal role as a facilitating technology for the progression of hydrogen and fuel cell applications, spanning stationary power, portable power, and transportation sectors. While hydrogen boasts the highest energy content per unit mass among all fuels, its inherent limitation in ambient temperature density leads to a relatively low energy per unit volume. Therefore, there is a pressing need for the innovation of sophisticated storage techniques with the potential to achieve enhanced energy density. Illustration depicting the storage of hydrogen in Figure 7. Hence, hydrogen has the ability to be stored physically in either gaseous or liquid forms. Hydrogen typically stays in gaseous form in high-pressure tanks, which have pressure levels between 350 and 700 bar (5,000 to 10,000 psi). On the other hand, liquid hydrogen storage requires the maintenance of extremely low temperatures, as the boiling point of hydrogen at a pressure of one atmosphere reaches a frigid -252.8°C. In addition, hydrogen can be stored on solid surfaces by adsorption or within materials through absorption.

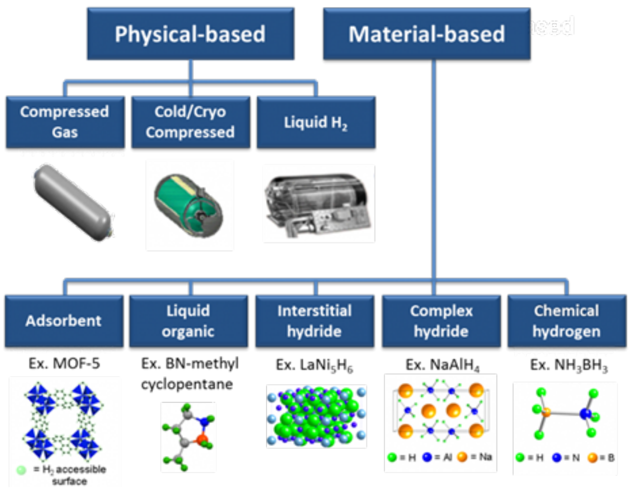


Figure 7. Storage of hydrogen.

The primary distinction resides in the diverse energy vectors employed for supplying the transportation, building, and industrial sectors, notably in the Transmission & Distribution (T&D) grid handling electricity, heat, liquid, and gaseous fuels. The current energy framework heavily relies on fossil fuels, with limited interconnections among various T&D grid, except for co-generation. In a prospective system, hydrogen emerges as a pivotal player, serving to interlink disparate layers of infrastructure within a low-carbon energy framework. The efficiency of hydrogen (H_2) and the fuel cell stack voltage is expressed through the ratio of its output power to the energy flux inherent in the reactants, as calculated in Eq. (1) and Eq. (2).

$$\dot{n}H_2 = \frac{I_{stack} \times n_{cell}}{F \times 2} \quad ....(1)$$

$$\eta_{Fuel\ cell} = \frac{I_{stack} \times V_{stack}}{\Delta h_f \times \dot{n}H_2} \quad ......(2)$$

Where, Δh_f represents the change in free enthalpy during the full combustion of one mole of hydrogen, equating to 285.83 kJ/mol. In this regard, the fuel cell demonstrates its peak efficiency under partial load conditions. Reducing the current density below its maximum power density threshold proves effective in mitigating cell voltage loss, consequently enhancing overall efficiency. Initiatives have been undertaken at the system level to optimize fuel cell operation within its peak efficiency range through strategic control and design. Furthermore, the net efficiency of the fuel cell system is derived from the ratio of generated electricity to the Higher Heating Value (HHV) of the consumed hydrogen, as expressed in the following Eq. (3).

$$\eta_{Fuel\ cell} = \frac{\left(\frac{Output\ energy\ of\ stack\ (kWh)}{Output\ efficiency\ of\ power}\right) - Ancillaryc\ consuption}{Higher\ heating\ value\ \left(\frac{kWh}{kg}\right) \times Consumed\ H_2\,(kg)} \quad ....(3)$$

In fact, hydrogen produced through the electrolysis of water and electricity possesses the capacity for extensive and prolonged storage, with the ability to later undergo reconversion to electricity (power-to-power). However, this process incurs an efficiency cost exceeding 70% of the initial input electricity. The stored hydrogen can be introduced into the natural gas grid, converted into synthetic methane (power-to-gas), or marketed as fuel for Fuel Cell Electric Vehicles (FCEVs) in the transportation sector (power-to-fuel). Consequently, hydrogen presents innovative avenues for integrating renewable electricity into the energy system, partially compensating for the flexibility reduction stemming from diminished reliance on fossil fuels. Battery Electric Vehicles (BEVs) have the advantage of tapping into existing electricity generation and Transmission & Distribution (T&D) infrastructure, capitalizing on the ongoing decarbonization efforts within the power sector [27,28]. Thus, batteries confront a significant trade-off between energy capacity and weight, with concerns revolving around range anxiety and extended recharging times, which are prominent considerations for consumers. However, the production of biofuels raises sustainability questions and raises concerns about displacing food production. This concern is particularly relevant as substantial quantities of biofuels will be indispensable for the decarbonization of extensive domains such as long-haul road freight, aviation, and shipping.

3. UTILIZING HYDROGEN FOR THE INTEGRATION OF VRE

The seamless incorporation of substantial proportions of variable renewable energy (VRE) into the energy infrastructure necessitates a concomitant enhancement of the operational flexibility of the power sector [29]. Figure 8 demonstrates the incorporation of VRE into various applications through the utilization of hydrogen.

This entails either the storage of surplus electricity generated at times or locations where it is not immediately required or its transformation for utilization in another sector of the energy system. By the year 2030, there will be a threefold increase in renewable capacity, primarily propelled by solar photovoltaic and wind, supplemented by the expansion of nuclear and other sources.

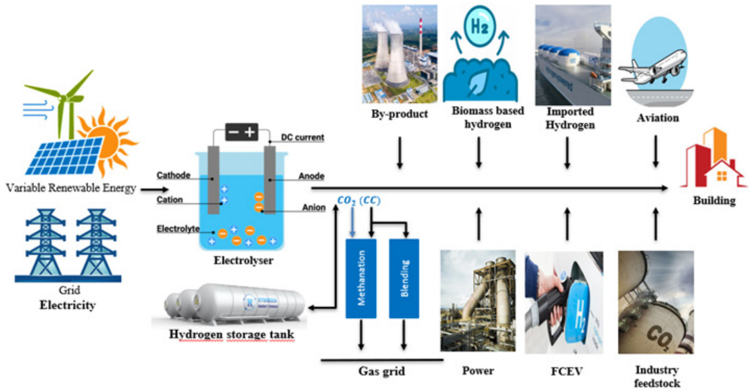


Figure 8. The incorporation of VRE into various applications through the utilization of hydrogen.

However, the surge in renewable capacity will elevate the contribution of low-emission sources to electricity generation from 39% in 2022 to 71% in 2030 and ultimately achieve a complete transition to 100% in 2050 [30-32]. Figure 9, illustrates sources of electricity that produce low emissions.

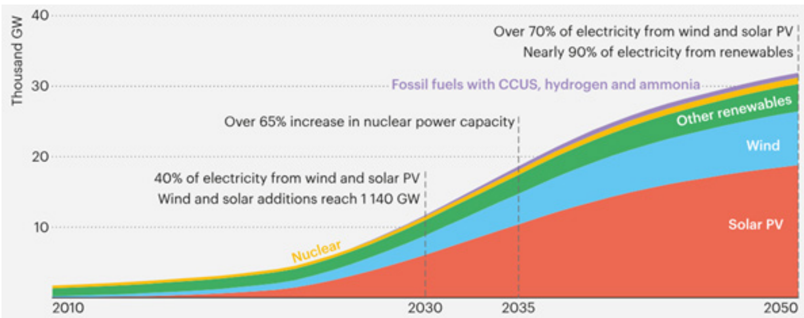


Figure 9. Sources of electricity that produce low emissions [33].

Although systems that depend on hydrogen to absorb excess electricity are not limited only to storing electricity. These energy storage systems that rely on hydrogen have the ability to incorporate surplus VRE electricity into different energy sectors. They can be used as fuel in transportation or as raw material in industrial processes. The classification of these systems can be categorized as follows:

- Power-to-power involves the conversion of electrical power into hydrogen by a process called electrolysis. The hydrogen produced is subsequently stored in an underground cavern or a pressurized tank and can be turned back into energy as needed, using either a fuel cell or a hydrogen gas turbine.
- Power-to-gas: This process involves the conversion of electricity into hydrogen by electrolysis. The hydrogen produced can be either mixed with the natural gas grid to create hydrogen-enriched natural gas (HENG), or undergo a subsequent methanation process to generate synthetic methane. The second approach necessitates an economical source of carbon dioxide for the methanation procedure.
- Power-to-fuel: In this scenario, the process involves the conversion of power into hydrogen, which is then used as a fuel for Fuel Cell Electric Vehicles (FCEVs) in the transportation sector.
- Power-to-feedstock: In this context, the process involves the conversion of electricity into hydrogen, which is then used as a raw material, specifically in sectors like refining.

All pathways involving the integration of VRE through hydrogen entail multiple transformation steps, ultimately resulting in relatively low efficiencies throughout the entire conversion chain,

typically falling within the range of 20% to 30%. Figure 10 demonstrates the ongoing conversion efficiency of different hydrogen-based methods for integrating VRE. It is crucial to conduct comparisons solely within the realm of final energies of identical quality, such as electricity intended for use within the power system or for FCEVs. As the number of incorporated conversion steps increases, the overall efficiency tends to decrease. The trade-off between power-to-power and power-to-gas options revolves around the higher overall efficiency inherent in pure power-to-power applications, as opposed to the potential utilization of existing storage and Transmission & Distribution (T&D) infrastructure for power-to-gas systems.
In the short term, the latter presents a compelling argument, where otherwise-curtailed renewable electricity could seamlessly integrate into the energy system.

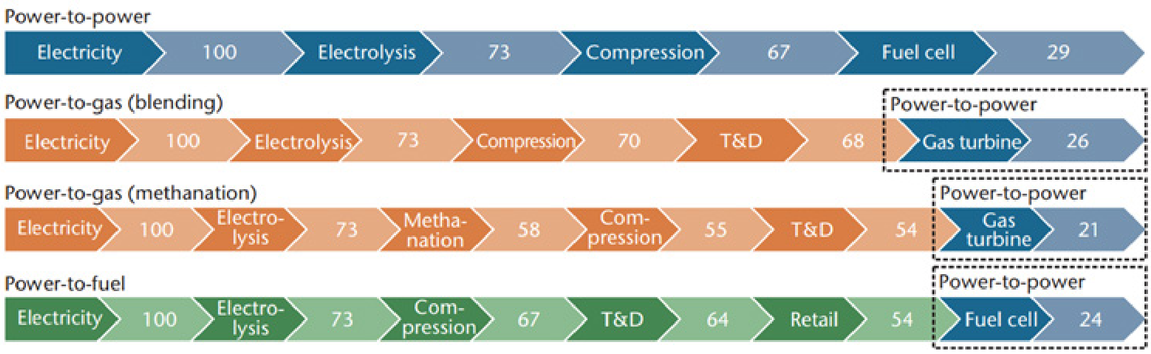


Figure 10. The ongoing conversion efficiency of different hydrogen-based methods for integrating VRE.

This integration can occur through the blending of hydrogen, reaching levels of 5% to 10% in the natural gas mix, or direct transformation into synthetic natural gas via methanation. Despite the absence of compatibility issues with subsequent end-use technologies in the case of power-to-gas, including methanation, the substantial impediment of poor overall efficiency is likely to hinder widespread deployment. Nonetheless, the assimilation of substantial proportions of solar photovoltaic (PV) and wind power sources necessitates energy storage that extends beyond short-duration timescales. This encompasses both long-duration (discharge duration >10 hours and <100 hours) and seasonal (discharge duration >100 hours) energy storage, as illustrated in Figure 11. However, the requisite storage power capacity demonstrates a linear increase, while the needed energy capacity (or discharge duration) experiences exponential growth with the escalation of solar PV and wind energy shares. Furthermore, the implementation of long-duration and seasonal energy storage holds the potential to fortify grid resiliency, particularly in light of the escalating incidence of extreme weather events, such as prolonged droughts, heightened wildfires, and severe snowstorms.
Figure 11 illustrates the energy storage demands for a projected power system that aims to be 95% carbon-free are well defined. a) Hourly net load refers to the difference between electricity demand and the availability of variable renewable energy, which includes wind and solar PV power. This calculation is done over a year, assuming a specific distribution of 28.4% wind energy and 51.5% solar PV energy. b) Daily net load on a given day. c) Cumulative daily net load, providing for appropriate short-duration storage capacity for intraday energy adjustment, estimated over a week. d) The total amount of electricity demand per month, taking into account sufficient storage capacity for both short-term and long-term energy adjustments within the month [34].
The blue and grey zones represent the overall excess of variable renewable energy and the necessary stable generation, respectively, throughout different time periods. The black arrows represent the transmission of energy across different time intervals.

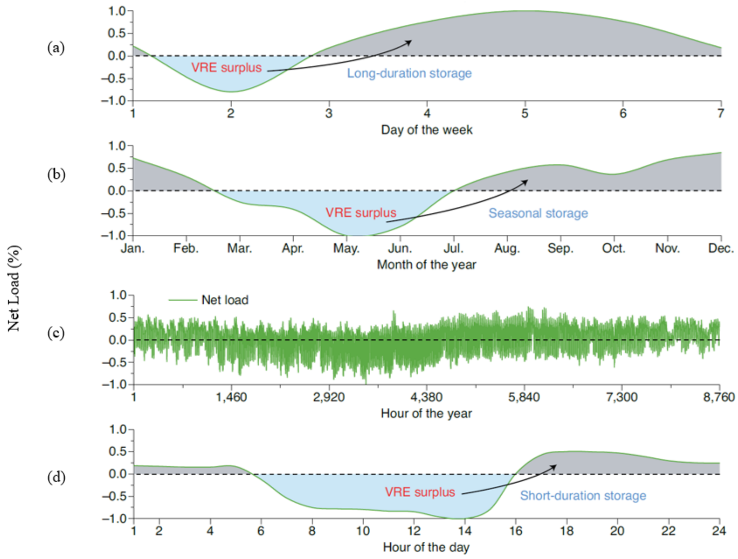


Figure 11. The energy storage for power system. a) Hourly net load. b) Daily net load. c) Cumulative daily net load. d) The total amount of electricity demand per month.

The word "per unit" (p.u.) represents figures that are derived from the highest absolute net load for each specific period. Sepulveda and colleagues have conducted a scenario analysis that takes into account power capacity cost, energy capacity cost, and efficiency factors. Based on their findings, they estimate that long-duration storage technologies would need to have an energy capacity cost of US$10 per kilowatt-hour (kWh) or lower in order to effectively replace nuclear power in the optimal power generation mix, taking into consideration current electricity demand profiles. Conversely, it is considered crucial to reach a specific energy cost goal of US$1 per kWh in order to replace natural gas power plants with carbon capture and sequestration, or by utilizing the combustion of blue hydrogen. Meeting other criteria is required, such as having a relatively low power capacity cost (e.g., US$200 per kilowatt) and a high efficiency threshold (e.g., 60% or more).

4. GLOBAL HYDROGEN PRODUCTION

The procurement of hydrogen involves costs related to logistics and production, which are further influenced by financial and regulatory issues, ultimately impacting the total expenditure [35,36]. The expense of the energy source employed in the manufacturing process, regardless of whether it is obtained from renewable or fossil fuel sources, significantly affects fluctuating expenses and technological competitiveness. Hydrogen had a substantial impact in 2020, potentially satisfying around 8% of the worldwide energy requirement at a production expense of approximately 2.50 $/kg. Projections suggest that the price of hydrogen will decrease to around 1.80 $/kg by 2030, making it capable of meeting approximately 15% of the world's energy needs. By 2030, the International Renewable Energy Agency emphasizes that renewable energy sources can make hydrogen production cost-competitive with fossil fuels. This is due to decreasing costs, economies of scale, and improved performance [37,38]. In 2022, the global production of low-emission hydrogen constituted less than 1% of the entire global hydrogen output. The present iteration of hydrogen production relies predominantly on fossil fuel technology, with around one-sixth of the worldwide hydrogen supply originating as "by-product" hydrogen, primarily within the petrochemical sector. In the same year, the predominant source (70%) of energy used for specialized hydrogen production was derived from natural gas, while coal contributed around 30% of the energy, primarily used in China. China dominated global coal consumption, with a substantial 90% portion, mostly for the purpose of hydrogen production [39,40]. Table 1 provides a concise overview of global hydrogen production by technology under the Net Zero Scenario, covering the period from 2019 to 2030.

Table 1. The Global hydrogen production by technology in the Net Zero Scenario from 2019 to 2030.

	2019	2020	2021	2022	2030
Fossil fuels without CCUS	75.8 Mt H_2	74.4 Mt H_2	77.4 Mt H_2	79.6 Mt H_2	68.0 Mt H_2
Fossil fuels with CCUS	0.4 Mt H_2	0.4 Mt H_2	0.4 Mt H_2	0.5 Mt H_2	22.4 Mt H_2
By-product	14.3 Mt H_2	14.2 Mt H_2	14.4 Mt H_2	14.8 Mt H_2	13.3 Mt H_2
Bioenergy	-	-	-	-	0.2 Mt H_2
Electricity	-	-	0.1 Mt H_2	0.1 Mt H_2	50.8 Mt H_2

In 2022, the production of low-emission hydrogen, despite a 5% increase compared to 2021, constituted less than 1% of the total hydrogen output. The increase in low-emission hydrogen production can be attributed to the addition of 130 MW of electrolysis capacity and the start of operations for a project in China. This project particularly concentrates around the manufacture of hydrogen from coal using Carbon Capture, Utilization, and Storage (CCUS) technology [41-43]. In order to meet the ambitious targets of the Net Zero Emissions (NZE) Scenario, there is an imperative for a swift and substantial expansion of low-emission hydrogen production. The scenario calls for approximately 50 Mt of hydrogen production through electrolysis and an additional 30 Mt generated from fossil fuels with Carbon Capture, Utilization, and Storage (CCUS) by the year 2030. This cumulative contribution surpasses 50% of the total hydrogen production. Achieving this requires the establishment of an installed capacity exceeding 550 GW of electrolysers. Consequently, a rapid upscaling of electrolyser manufacturing capacity is essential, along with the extensive deployment of dedicated renewable capacity for hydrogen production and the fortification of the power grid. To sum up, theoretical computation of the production rate of hydrogen relies on the formulation encapsulated in the subsequent Eq. (4) [44].

$$\text{Production rate of } H_2 = \frac{n_{cell} \times I \times V_m \times 3600}{F \times 2} \quad ....(4)$$

In this context, I represents the current, and V_m denotes the molar volume of hydrogen, equivalent to 0.022414 m3 mol−1. Consequently, the judicious choice of current density becomes pivotal in the pursuit of striking an optimal balance between minimizing the specific electrolyser cost and guaranteeing heightened efficiency [45]. The efficiency of a hydrogen power system involves, on one hand, the stack voltage efficiency of hydrogen devices, as previously addressed, and on the other hand, the overall system efficiency when accounting for the consumption of all auxiliary components [46]. The efficiency of a water electrolysis system can be expressed through the ratio of the High Heating Value (HHV) of the generated fuel to the electricity expended, as demonstrated by Eq. (5) [44]:

$$\eta_{EL} = \frac{\text{Higher Heating Value}\left(\frac{kWh}{kg}\right) - \text{produced } H_2\,(kg)}{\left(\frac{\text{Output energy of stack }(kWh)}{\text{Efficiency of power supply}}\right) + \text{Ancillary losses }(kWh)} \quad ....(5)$$

The determination of the Levelized Cost of Hydrogen (LCOH) hinges on the economic attributes of the production facility, encompassing equipment investment costs, annual fixed operation and maintenance costs, and variable operational costs. Additionally, in order to account for the geographical influence on LCOH, location-specific factors for each cell are incorporated into the investment equations. This incorporation aims to ascertain the levelized cost of the fixed expenditures associated with producing a unit of green hydrogen. Eq. 6 elucidates the formulation for calculating the LCOH in green hydrogen production [44].

$$H = \frac{CAPEX + \sum_{t=1}^{lf} \frac{OPEX_{fixed,t} + OPEX_{var,t} \times E_t}{(1+WACC_t)^t}}{\sum_{t=1}^{lf} \frac{E_t}{(1+WACC_t)^t}} \quad ....(6)$$

In this context, CAPEX represents the initial investment costs,$OPEX_{fixed,t}$ denotes the annual fixed operation and maintenance cost for year t, $OPEX_{var,t}$ accounts for the variable operation and maintenance cost contingent upon the production level, E_t signifies the annual hydrogen production output, $WACC_t$ stands for the weighted average cost of capital in year t, and lt designates the lifetime of the production facility.

Typically, a premium on production remains constant over time, devoid of any adjustments for inflation or discounting effects. This unchanging premium is incorporated into the calculation of the *LCOH* to demonstrate direct impact on the overall reduction of *LCOH*, as described in Eq. (7). Contrastingly, investment support is provided at year 0, rendering it immune to depreciation effects attributable to interest rates. The incorporation of this support into the *LCOH* equation is explained in Eq. (8) [44].

$$LCOH = \frac{CAPEX + \sum_{t=1}^{lf} \frac{OPEX_{fixed,t} + OPEX_{var,t} \times E_t - H_2 \; premium \times E_t}{(1+WACC_t)^t}}{\sum_{t=1}^{lf} \frac{E_t}{(1+WACC_t)^t}} \quad ....(7)$$

$$LCOH = \frac{CAPEX - Investment \; support + \sum_{t=1}^{lf} \frac{OPEX_{fixed,t} + OPEX_{var,t} \times E_t}{(1+WACC_t)^t}}{\sum_{t=1}^{lf} \frac{E_t}{(1+WACC_t)^t}} \quad ....(8)$$

The cost of capital encompasses a spectrum of factors including regulatory risks, political risks, off-taker risks, currency risks, and additional considerations related to land, resources, and technology. Significantly, regulatory and political risks can collectively contribute up to half of the overall weight within the spectrum of risk elements. The present WACC values are derived from the International Renewable Energy Agency's (IRENA) 2022 World Energy Transitions Outlook: 1.5°C Pathway report, with future *WACC* values extrapolated.

This methodology allows for the estimation of a country-specific, risk-adjusted *WACC* for the calculation of the *LCOH* over the operational lifespan of the plant. On the other hand, the assumption underlying this approach is a gradual reduction in *WACC* values over time, attributed to diminishing risks associated with the progressive adoption of hydrogen technologies and increased demand. *WACC* values are anticipated to converge across different countries, given the assumption of a growing financial risk transfer mechanism or an increased reliance on international finance.

This, this assumption aims to align the *WACC* of countries facing high political and regulatory risks with those of more stable regions such as Europe, which is projected to have a *WACC* of 6% by the year 2050.

5. HYDROGEN TECHNOLOGY DEPLOYMENT

The global demand for hydrogen experienced an approximate 3% growth in 2022, yet it continues to be predominantly focused on traditional applications, displaying sluggish penetration into emerging uses. In 2022, global hydrogen demand reached 95 Mt, marking an almost 3% increase from the previous year.

Table 2. The global demand for hydrogen within different sectors in the Net Zero Scenario from 2020 to 2030.

	2019	2020	2021	2022	2023
Refining	40.1 Mt H_2	37.9 Mt H_2	39.9 Mt H_2	1.9 Mt H_2	37.0 Mt H_2
Ammonia	32.3 Mt H_2	30.0 Mt H_2	32.8 Mt H_2	32.9 Mt H_2	34.5 Mt H_2
Methanol	13.3 Mt H_2	13.5 Mt H_2	14.6 Mt H_2	14.9 Mt H_2	17.1 Mt H_2
Iron and steel	4.7 Mt H_2	4.5 Mt H_2	5.0 Mt H_2	5.1 Mt H_2	12.7 Mt H_2
Other	-	-	-	-	50.0 Mt H_2

The demand for hydrogen remains concentrated in conventional applications within the refining and industrial sectors, encompassing chemicals and natural gas-based direct iron reduction (DRI), while its presence in novel applications remains exceedingly limited. Demand from emerging sectors such as transport, high-temperature heat in industry, hydrogen-based DRI, power, and buildings collectively accounts for less than 0.1% of global demand [47,48]. Table 2 demonstrates the global demand for hydrogen within different sectors in the Net Zero Scenario from 2020 to 2030.

Over the past year, various demonstrations showcasing the practical applications of low-emission hydrogen and hydrogen-based fuels have commenced operations, notably in chemicals production, refining, high-temperature heating, and shipping. Accelerating the commercialization of these technologies is imperative for swiftly capturing a substantial portion of demand within these emerging applications. To align with the ambitious targets of the Net Zero Emissions (NZE) Scenario, a significant transformation in demand creation is essential, particularly in the realm of new applications. By 2030, hydrogen demand must undergo a considerable upswing, exceeding 1.5 times its current level to surpass 150 Mt. It is clear that, almost 30% of this heightened demand is projected to emanate from the burgeoning new applications sector [49,50].

Numerous projects dedicated to low-emission hydrogen production are currently in progress, as indicated by our monitoring of announced initiatives. The yearly output of low-emission hydrogen has the potential to exceed 20 Mt by 2030, contingent upon the realization of all the announced projects focused on hydrogen production through water electrolysis and fossil fuels with Carbon Capture, Utilization, and Storage (CCUS). Figure 13 illustrates low-emission hydrogen production categorized by technology route, maturity, and region.

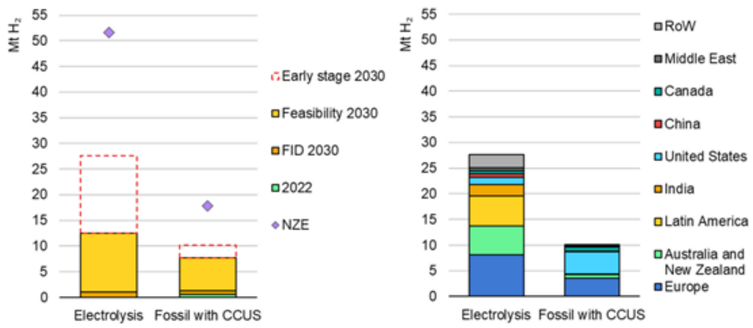


Figure 13. Low-emission hydrogen production categorized by technology route, maturity, and region.

This classification is based on the projects that have been announced and aligns with the Net Zero Emissions by 2050 Scenario, projecting into the year 2030.
Moreover, by the year 2030, half of the anticipated hydrogen production from the announced projects is attributed to endeavors currently undergoing feasibility studies, with an additional over 45% emanating from projects in their nascent stages, as gauged by production levels. Projects either under construction or having secured a final investment decision (FID) constitute a mere 4% of the announced projects in terms of production [51,52]. To Clarify, nearly half of these projects are linked to existing hydrogen applications in refineries and the chemical industry, as illustrated in Figure 14.

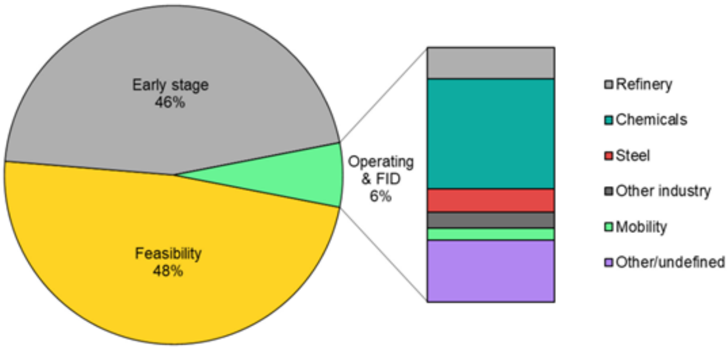


Figure 14. Hydrogen applications in refineries and the chemical industry.

Among the announced hydrogen production initiatives, those centred around electrolysis take precedence, accounting for over 70% of the projected low-emission hydrogen production in 2030. However, a significant portion of these electrolyser projects, amounting to 55%, is still in the early stages of development. Recognizing that the maturation of these projects requires a considerable investment of time, it becomes imperative to focus concerted efforts in the coming years to ensure their operationalization by the year 2030.

6. ELECTRICITY GENERATION

Hydrogen's utilization as a fuel in the power sector is currently negligible, accounting for less than 0.2% of the global electricity generation mix. In this context, the limited presence of hydrogen in this context primarily arises from mixed gases that incorporate hydrogen generated in processes such as steel production, refineries, or petrochemical plants, rather than from pure hydrogen sources. However, the procedure involved the direct electrolysis of authentic seawater without undergoing alkalization or acidification. Additionally, it demonstrated sustained stability surpassing 100 hours at an intensity of 500 milliamperes per square centimeter, comparable to the performance of a standard proton exchange membrane (PEM) electrolyser functioning in ultrapure water [53,54].
In addition to that, contemporary technologies enabling the utilization of pure hydrogen for electricity generation are commercially accessible. Some configurations of fuel cells, internal combustion engines (ICE), and gas turbines have the capability to operate on hydrogen-rich gases or even pure hydrogen. Another prospective avenue for electricity generation involves the utilization of hydrogen in the form of ammonia. Successful trials in Japan and China have demonstrated the co-firing of ammonia in coal-fired power plants. Ammonia also holds promise as a potential fuel for gas turbines. A noteworthy achievement in 2022 involved the successful deployment of a 2 MW gas turbine in Japan, directly utilizing 100% ammonia. Ongoing efforts are now directed towards the development of a 40 MW turbine specifically designed for the use of pure ammonia.

While incorporating hydrogen and ammonia into power generation processes offers a means to curtail CO_2 emissions, the issue of nitrogen oxides (NO_x) emissions poses a notable concern. Contemporary gas turbines are equipped with dry low NO_x technologies to effectively manage NO_x emissions. These technologies permit hydrogen co-firing shares ranging from 30-60% (in volumetric terms), contingent upon burner design and implemented combustion strategies. Research and development initiatives are currently in progress to engineer dry low NO_x gas turbines capable of accommodating the entire hydrogen blending range, up to 100%. In this direction, Addressing NO_x emissions from ammonia involves the utilization of flue gas treatment technologies, such as selective catalytic reduction, which are already established for coal power plants. However, it is crucial to note that ammonia combustion may result in the release of nitrous oxide (NO_x), a potent greenhouse gas. Nevertheless, a 2 MW demonstration project in Japan demonstrated the feasibility of achieving a 99% reduction in overall greenhouse gas emissions (NO_x and N_2O combined) when comparing an ammonia-fired gas turbine to one utilizing natural gas [55,56].

In this context, the projects that have been publicly disclosed involving the utilization of hydrogen and ammonia in the power sector are anticipated to contribute to an installed capacity of 5,800 MW by the year 2030. This represents a substantial 65% increase compared to the corresponding capacity outlined in recent study for 2022, as depicted in Figure 15. Approximately 70% of these projects are associated with the deployment of hydrogen in open-cycle or combined-cycle gas turbines, with 10% allocated to the use of hydrogen in fuel cells and 3% dedicated to the co-firing of ammonia in coal-fired power plants in terms of announced project capacity. Geographically, these projects are predominantly situated in the Asia-Pacific region (39%), followed by Europe (36%), and North America (25%).

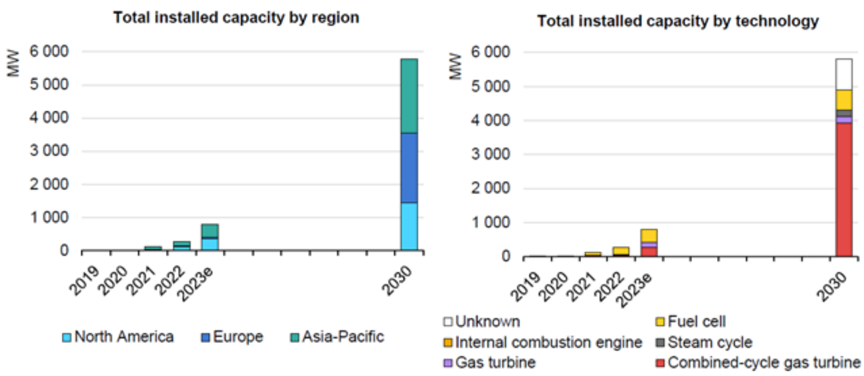


Figure 15. The regional capacity in power generation using hydrogen and ammonia, including historical data and projections from announced projects, for the period of 2019-2030.

The capacity for power generation fueled by hydrogen and ammonia could potentially reach 5,800 MW by the year 2030, as indicated by the announcements of various projects. This projection is primarily driven by the incorporation of hydrogen co-firing in combined-cycle gas turbines. Furthermore, numerous utility companies have declared their intentions to either construct new gas power plants or enhance existing ones to be H2-ready, implying their capability to co-fire a specific proportion of hydrogen. Notably, specific commencement dates for the initiation of co-firing initiatives have not been definitively disclosed in most instances. The anticipated hydrogen share of the announced H-ready capacity is estimated at 3,400 MW. However, it is likely that this figure represents the lower end of the range, considering the available information on projects that have released details regarding hydrogen co-firing capabilities. Additionally, other newly planned gas-fired power plants are expected to have the capacity to co-fire a certain amount of hydrogen, although pertinent information on this aspect is currently unavailable. Likewise, prevailing gas-fired power plants have the capability to accommodate specific proportions of hydrogen, ranging from 10% to 100%, contingent upon the design of the gas turbine. Drawing from the available data on the currently installed gas turbines and their maximum hydrogen blending capacities, the global hydrogen-fired capacity from existing gas turbines could potentially surpass 70 GW. It is essential to note that this figure is likely a conservative estimate, given that comprehensive information was only accessible for 465 GW of the existing gas-fired capacity [57,58].

7. HYDROGEN SECTOR INVESTMENTS

The low-emission hydrogen sector is experiencing an increasing amount of capital due to government policies and the strategic activities of project developers. The calculations suggest that global spending on electrolyser installations in 2022 passed a significant milestone, amounting to USD 0.6 billion. This represents a twofold increase compared to the figure recorded in 2021, taking into account both operational and under-construction projects. Figure 16 illustrates the allocation of investment in electrolyser installations in various locations (on the left) and the projected utilization of these installations (on the right). Furthermore, it demonstrates the imperative of attaining a state of net zero emissions by the year 2050, particularly during the timeframe spanning from 2019 to 2030. In addition, an additional USD 0.5 billion was earmarked in 2022 for ongoing initiatives that aim to manufacture low-emission hydrogen using carbon capture, utilization, and storage (CCUS) technologies. In order to reach the targeted USD 41 billion expenditure on electrolyser installations by 2030, as specified in the Net Zero Emissions by 2050 Scenario (NZE Scenario), it is crucial to maintain a 70% annual growth rate in investments for the remaining years of this decade [59,60].

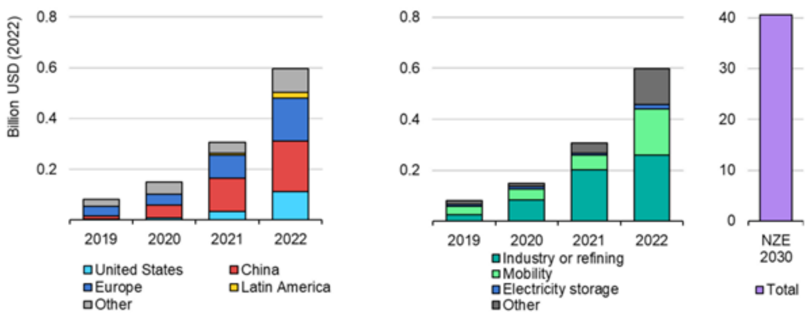


Figure 16. The distribution of investment in electrolyser installations across different regions (on the left) and the expected usage of these installations (on the right), specifically for the period between 2019 and 2030.

Since 2021, the investments in hydrogen generation have been marked by the prevalence of a relatively small number of exceedingly big projects. In 2022, there were multiple final investment decisions (FIDs) that resulted to a significant increase in spending, despite the fact that the operational capacity in 2022 was smaller than the previous year. In the previous year, there was a single large-scale installation with a capacity of 150 MW that started operating. The most noteworthy Foreign Direct Investments (FDIs) comprised of the 2-gigawatt NEOM Green Hydrogen project in Saudi Arabia and the 320-megawatt Green Hydrogen and Green Ammonia project in Oman. Both projects are focused on producing ammonia for international trade, starting in 2026. In June 2023, a 260 MW power plant located at a refinery in Xinjiang, China, commenced operations, setting a new standard for the size of a functioning facility. Furthermore, a coal-to-chemicals factory in China successfully implemented an 80 MW project in June 2023

[62, 63].
The Holland Hydrogen I project, led by Shell in the Netherlands, is set to exceed the capacity of Europe's largest current plant by a factor of ten. With a capacity of 200 MW, it seeks to provide an existing refinery with hydrogen by 2025. Meanwhile, in Sweden, H2 Green Steel is making progress towards obtaining a Final Investment Decision (FID) for an electrolyzer that will have a capacity of over 700 MW, as well as a new steel production facility. Since 2022, this venture has obtained EUR 3.5 billion (equivalent to approximately USD 3.7 billion) in debt and EUR 1.8 billion (equivalent to approximately USD 1.9 billion) in equity. An important project under the European Union's support measures is the creation of the European Hydrogen Bank in March 2023. This funding mechanism is facilitated by the European Commission. The main objective of the organization is to carry out "reverse auctions," where financing from the Innovation Fund is given to the bidders who offer the lowest cost per unit of hydrogen that meets the environmental standards set by the European Union. The initial budget for the first auction is set at EUR 800 million, which is approximately USD 842 million [64,65]. The European Commission is currently investigating the feasibility of earmarking funds to aid potential external hydrogen exporters to the European Union, while also offering assistance to makers of electrolyzers. This suggested allocation will enhance the assistance provided by member states through the Important Projects of Common European Interest (IPCEI) provisions, authorized in 2022.
In Austria, groundbreaking trials commenced in July 2023, marking the initial attempts at co-firing hydrogen in an established 395 MW gas-fired combined heat and power plant. The objective of these trials is to attain a notable 15% hydrogen co-firing share during continuous operation. This pioneering effort underscores Austria's commitment to exploring innovative approaches to incorporate hydrogen into existing gas-fired power infrastructure. Furthermore, in the United Kingdom, the budget announced in March 2023 pledged GBP 20 billion (~USD 25 billion) over a span of 20 years for Carbon Capture, Utilization, and Storage (CCUS)-equipped facilities. As part of the available funding of GBP 240 million (~USD 296 million), 408 MW of electrolysis projects were shortlisted in March 2023. Moreover, Hanwha Impact achieved a groundbreaking milestone in Korea by successfully implementing a 60% hydrogen co-firing share in an 80 MW gas turbine In July 2023. This achievement represents the largest co-firing share to date in mid-to-large gas turbines, signifying significant progress in incorporating hydrogen as a fuel source for power generation [66,67]. In China, the Anhui Province Energy Group has successfully concluded trials involving the co-firing of ammonia at a 300 MW unit within its Wanneng Tongling coal power plant. These trials spanned a period of three months and encompassed co-firing levels ranging from 10% to 35%. The company is strategically planning additional trials, aiming for a more ambitious 50% ammonia co-firing at a larger 1 GW coal unit. This initiative reflects the commitment to exploring innovative approaches to reduce carbon emissions in the power generation sector. In the United States, a significant advancement was demonstrated in 2023, showcasing a remarkable 38% hydrogen co-firing share at an operational 753 MW combined-cycle power plant. This achievement underscores a notable leap forward in integrating hydrogen as a substantial component in the power generation mix within existing infrastructure [68,70]. Locally, many researchers highlighted the impacts of such researches on science, economy, and environment in the Libyan society [71-75].
Environmentally: The electric power industry sector in Libya is considered one of the most environmentally polluting sectors. The contribution of the electric power sector is about 35%, followed by the transportation sector with 18% of all other sectors [76].
Hydrogen energy can be used effectively in these two sectors. The electricity generation system in Libya relies on burning fossil fuels at a large rate of up to 99%, with low generation efficiencies that reach 12% in some power stations, and the estimated carbon dioxide emission factor is about

967.35 kgCO_2/MWh. Therefore, the use of hydrogen will prevent the release of this amount of CO_2 into the atmosphere [77].
Economically: The impact of using hydrogen as an energy source is divided into two parts. The first part is to save crude oil and use it in the petrochemical industries, which will provide more profit than burning it to generate electricity. Studies show that 1 MWh requires burning 291 kg of diesel, and this requires refining an estimated 1141 kg of crude oil [78].
Also, reducing the amount of CO_2 will mitigate the damage to the environmental system, which requires spending a lot of money to rehabilitate the ecosystem and cover the cost of environmental damage, which is estimated at about $75/ton CO_2. [79.80]

8. CONCLUSION

To Sum up, this article has provided a comprehensive exploration of the interplay between hydrogen and fuel cell technologies, casting a spotlight on their collaborative influence on the dynamic landscape of electricity generation. The focal point on the integration of variable renewable energy (VRE) sources has unveiled the pivotal role of hydrogen as a facilitator in optimizing the utilization of these inherently fluctuating energy resources. The discussion has further encompassed diverse methods of hydrogen production, delving into their technological advancements and the profound implications they hold for achieving sustainable electricity generation. In this context, Austria has initiated ground-breaking trials in 2023 to integrate hydrogen and alternative fuels into power generation. The UK allocated GBP 20 billion over 20 years for Carbon Capture, Utilization, and Storage facilities, with 408 MW of electrolysis projects shortlisted. Hanwha Impact in Korea achieved a 60% hydrogen co-firing share in an 80 MW gas turbine, marking the largest co-firing share in mid-to-large gas turbines. Anhui Province Energy Group in China successfully conducted ammonia co-firing trials at a 300 MW unit, planning further trials for a 50% co-firing level at a 1 GW coal unit. The United States achieved a 38% hydrogen co-firing share in 2023 at an operational 753 MW combined-cycle power plant. The article underscores their crucial role in propelling advancements toward sustainable electricity generation. Navigating the trajectory of the hydrogen sector's evolution within the broader context of electricity generation, this article has provided valuable insights into the ongoing developments, challenges, and opportunities. In addressing the critical nexus between hydrogen technologies and the ever-evolving electricity landscape, this paper aspires to contribute meaningfully to the discourse surrounding the future trajectory of investments in the hydrogen sector. The overarching goal is to pave the way for enhanced electricity generation methods that align with the imperatives of sustainability and innovation.

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