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Hydrogen production from water industries for a circular economy

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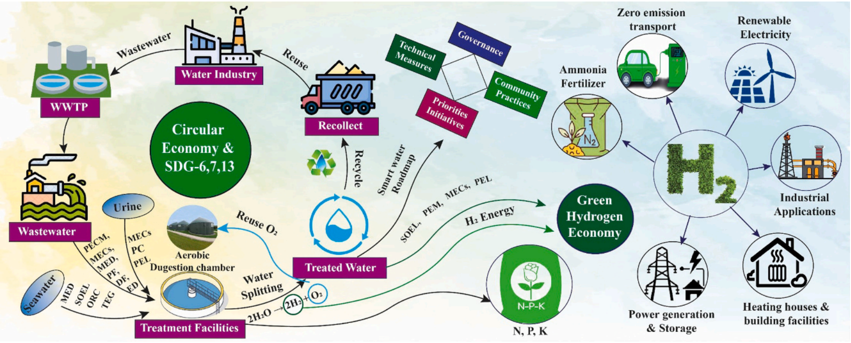
HIGHLIGHTS

- Linking water industries (WI) and circular economy (CRE) perspectives are crucial to green hydrogen production (HP).
- A comprehensive assessment of HP technologies from WI was critically reviewed.
- A detailed bibliometric analysis of HP technologies has been conducted.
- The techno-economic and environmental feasibility study of HP technologies in WI have been carried out.
- The scaling-up challenges of the hydrogen economy (HE) in WI have been assessed.

GRAPHICAL ABSTRACT



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ABSTRACT

The ever-increasing global energy crisis, environmental degradation and climate change issues impacted by excessive consumption of fossil fuels (FFs) are pushing the world to find a suitable and green energy source for ensuring net-zero emissions and attaining the sustainable development goals (SDGs)-6, 7 and 13 through decarbonization of the global energy system (GES). Green hydrogen has been considered one of the most ground-breaking aspects of low-carbon future energy security. Integration of water industries (WI) and circular economy (CRE) perspectives can be crucial to green energy production and sustainable resource management. This study comprehensively and critically assesses the role of WI in hydrogen production (HP) from a CRE perspective. The current scenarios of global energy production, consumption patterns linked with CRE, and the necessity of a worldwide energy transition from FFs to a hydrogen economy (HE) have been discussed constructively. The structures of WI and its function have been proposed for the first time connecting the requisite of CRE. Moreover, a detailed bibliometric assessment of HP technologies has been conducted. In addition, the HP technologies in WI have been described in-depth with their suitability, advantages, and drawbacks. An all-inclusive techno-economic and environmental feasibility study of the HP technologies in WI and the latest case studies have been conducted. Furthermore, the scaling-up challenges of HE in WI have also been assessed. This paper is the first integrated approach to evaluating the HP technology's suitability in WI from a CRE point of view which will provide significant insights to develop a future HE.

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Nomenclature

AEL	Alkaline electrolysis
AEM	Anion exchange membrane electrolysis
AP	Acidification potential
ATR	Autothermal reforming
BA	Bibliometric analysis
BToE	Billion tons of oil equivalent
CCS	Carbon capture and storage
CCUS	Carbon capture, utilization & sequestration
COP	Conference of the Parties
CG	Coal gasification
CRE	Circular economy
DF	Dark fermentation
ED	Electrodialysis
EE	Energy efficiency
EL	Electrolysis
EWE	Economic water environment
ExE	Exergy efficiency
FF	Fossil fuels
GES	Global energy system
GE	Greenhouse effects
GHGs	Greenhouse gases
GWP	Global warming potential
HDS	Hydrodesulfurization
HE	Hydrogen economy
HP	Hydrogen production
HFCEVs	Hydrogen fuel cell electric vehicles
IEA	International energy agency
LCA	Life cycle assessment
LE	Linear economy
MECs	Microbial electrolysis cell
MED	Microbial electrodialysis
NEW	Natural water environment
PC	Photocatalyst
PECM	Photo-electrochemical method
PEL	Photoelectrolysis
PEMs	Proton exchange membrane electrolysis
PF	Photo-fermentation
POx	Partial oxidation
PW	Pure water
R & D	Research and development
RED	Reverse electrodialysis
AD	Anearobic digestion
SA	Sustainability analysis
SCC	Social cost of carbon
SCWG	Super critical water gasification
SOEL	Solid oxide electrolysis
SR	Steam reforming
SMR	Steam methane reforming
SW	Saline/Sea Water
SWE	Social water environment
UWE	Urban water ecosystem
WEL	Water electrolysis
WGS	Water-gas-shift
WI	Water industry
WW	Wastewater
WWTP	Wastewater treatment plant

1. Introduction

Energy is considered one of the most vital resources for socioeconomic progress and securing the quality of life worldwide [1]. According to global energy scenarios, industrial development is an escalated demand for energy consumption in the context of the global energy scenario. By 2050, the amount of energy consumed worldwide is expected to have increased dramatically, from 13.6 billion tons of oil equivalent (BToE) in 2010 to 44.6 BToE, as assumed by Ahmad and Zhang [2]. The present world is going to confront a transition in global energy systems. The development of human civilization in the past century predominantly depended on fossil fuels (FFs). Although fossil energy resources significantly made a rapid techno-economic revolution within a short time, its consequences in terms of the environmental performance of the Earth are alarming [3].

Nowadays, most countries are concerned about producing and executing renewable energy technologies that could provide a clean electricity source. However, utilizing electricity could only meet the energy demand of some end-users, thus making it challenging to complete energy system decarbonization. Green hydrogen could be a suitable alternative to FF resources, which can be produced by water electrolysis (WEL) technology applying an electric current to split water into O_2 and H_2. Consequently, there will be no greenhouse gases (GHGs) emissions in the atmosphere, and the needed electricity can be integrated from renewable energy sources such as solar, wind, biomass and hydrothermal. The high energy density per unit mass, very light weight, and easy electrochemical transformation allow hydrogen to transport energy across diverse geographical regions through pipelines and liquid fuels like NH_3 [4]. Hydrogen can be applied in various sectors, such as industries, transportation systems, heating houses, building facilities, and power. In addition, its long-term storage capacity in tanks or underground reservoirs makes it the only single energy transformation technology to store it throughout the year [5].

The CRE concept has achieved great attention worldwide in the recent decade. The current linear economy (LE) practice of take-make-use-dispose pushed our society's requirement beyond the Earth's capacities. The CRE model seeks to redefine progress, focusing on constructive society-wide advantages. It entails gradually decoupling economic activity from consuming finite resources and designing waste out of the system. Underpinned by a transition to renewable energy sources, the circular model builds economic, natural, and social capital. It is based on three principles: design out waste and pollution, keep products and materials in use and regenerate biological systems. Water industries (WIs) are moving towards a vision of integrated resource recovery due to expanding sustainability and livability aspirations, operational challenges, network constraints, and emerging contextual factors. Opportunities abound to apply CRE principles across water's roles as a resource, nutrient carrier, source of energy, and service. There is value in adopting a CRE approach for integrated water services for water utilities, society, and our natural environment.

Water (SDG 6) is the single most important shared resource across all aspects of our lives. Besides quantity, water quality plays a significant role in satisfying basic human needs. Water quality is threatened by increasing urbanization, climate change, and industrial and agricultural activities [6]. It is observed that globally around 80 % of the wastewater is directly disposed of into the environment [7], and approximately 2 billion people use drinking water sources polluted with feces [8]. The CRE paradigm considers waste as a resource, and specific opportunities exist to manage wastewater sustainably from the CRE perspective. Wastewater is a valuable resource for water, energy, and materials [9,10]. Water can be reclaimed from wastewater for potable or non-potable purposes [11], energy can be recovered [12–14], and nutrients retrieved can be used for agricultural purposes [15]. Thus, it is essential to manage the water, and wastewater resources following reduce, reuse, recycle, reclaim, recover, and restore (6Rs) strategies of CRE.

Table 1

Comparative table of global energy production and consumption [29,36] with copyright permission from International Energy Assosication (IEA), 2021 under the license of CC BY 4.0.

Energy	Global Energy Production/Supply								Total Energy Production	Global Energy Consumption								Total Energy Consumption	Net Energy (Energy Gap)
(TJ)	1990	1995	2000	2005	2010	2015	2019	2021		1990	1995	2000	2005	2010	2015	2019	2021		
Coal	92962604	92345651	96876327	125224095	152992480	160976300	162375732	2787284	883753189	31470482	27648926	22689352	34522696	44257171	46098834	39786218	16010000	246473679	637279510
Natural gas	69597508	75495152	86550367	98640052	114447753	122498778	140784380	6433019	708013990	39543757	42003303	46864239	50049872	56341398	59521976	68404947	145350000	362729492	562663990
Nuclear	22002473	25459860	28280459	30216369	30091065	28063289	30461171	2030196	194574686	14072041	11994848	10392497	10890720	11518680	11395703	12822746	25310000	83087235	111487451
Hydroelectricity	7703880	8908060	9406153	10564092	12414905	14017921	15194639	5387091	78209650	34928037	39144683	45707689	54483184	64391725	72867426	82251570	40260000	393774314	37949650
Wind, solar, etc.	1533085	1784759	2529177	2944819	4616284	8526212	13417236	7176756	35351572	143516	224410	361948	503348	895700	1732437	2318093	39910000	6179452	29172120
Biofuels and waste	36688520	39397760	41490083	44663882	49123321	52822020	56813210	1386455	320998796	31824701	34030361	36680293	38341923	40536083	41945250	43414906	34800000	266773517	286198796
Oil Products	135326568	141138864	153594988	167959369	172740070	181265383	187364800	7152101	1139390042	108656537	116771810	129979163	143682184	149660971	159773622	168375005	184210000	976899292	162490750

One of the essential requirements of WEL technologies to produce hydrogen is the need for highly pure water feeds. The minimum requirement is the American Society for Testing and Materials (ASTM) Type II deionized (DI) water (resistivity >1 MΩ cm). ASTM Type I DI water (>10 MΩ cm) is highly preferred for higher purity (99.99 %) hydrogen. An estimation showed that 21 billion m^3 of fresh, pure water will be required to meet the demand of the future hydrogen economy by 2030. Accessible freshwater makes up <1 % of the planet's water. It is best to avoid burdening freshwater usage, especially in areas where drinking water is difficult to attain. Almost all the remaining 99 %, or about 1.4 billion km^3, is seawater, which can be purified through desalination processes before being used as an electrolysis feedstock by ED or RO techniques to produce hydrogen.

Various fragmented research has been focused on hydrogen production strategies from wastewater [16–24]. However, WI can be a great source of green hydrogen energy and simultaneous resource recovery. Establishing a CRE-based, self-energy-generating WI can be a plausible solution for the future energy crisis and sustainable resources management. This study comprehensively and critically assessed the role of WI in hydrogen production from a CRE perspective. The current scenarios of global energy production, consumption patterns linked with CRE, and the necessity of a global energy transition from FFs to a hydrogen economy have been discussed constructively. The structures of WI and its function have been proposed for the first time linking the requisite of CRE.

Moreover, a detailed bibliometric assessment of hydrogen production technologies has been conducted. In addition, the hydrogen production technologies in WI have been described in-depth. A detailed techno-economic and environmental feasibility study of the hydrogen production technologies in WI, along with the latest case studies, has been carried out. Furthermore, the scaling-up challenges of the hydrogen economy in WI have been assessed critically. This paper is the first integrated approach to assessing the hydrogen production technology's suitability in WI for a CRE perspective.

2. Global demand for green hydrogen energy, a transition towards global energy sustainability

2.1. Recent scenarios of global energy production and consumption

Energy scenarios can address the uncertainties surrounding the socio-technical evolution of energy sectors. Depending on the scenario, inputs from experts and stakeholders may be qualitative or quantitative. At the regional and governmental levels, there are numerous energy scenarios, such as the ASEAN Energy Outlook (SE Asia), EIA Annual Energy Outlook (USA), China Renewable Energy Outlook, and the Deep Decarbonization Pathways Project (various countries) [25]. In our viewpoint, we emphasize global scenarios with the most extensive world implications. Industrial development is an escalated demand for energy consumption in the context of the global energy scenario. By 2050, the amount of energy consumed worldwide is expected to have increased dramatically, from 13.6 billion tons of oil equivalent (BToE) in 2010 to 44.6 BToE, as discussed by Ahmad and Zhang [2]. Global coal demand climbed from 3.6 BToE in 2010 to 12.9 BToE in 2050 because of the burgeoning influence of China within international energy markets.

Additionally, the demand for coal energy increased globally from 26.5 % in 2010 to 28.9 % in 2050, while the demand for gas and electricity declined as a percentage of overall demand [26]. The annual average growth in the world's energy demand is 1.5 %. Around 80 % of all primary energy is derived from fossil fuels (FFs), from which 90 % of the world's FFs resources are exploited by 10 % of the population. Reducing reliance on FFs, which account for most of the world's energy demands, is desperately required today. The formation of FFs by nature takes >3 million years, even though the rate of depletion of FFs is currently 100,000 times greater than their formation rate [27]. Fig. S1 provides the energy sources diagram to grasp the energy resource and reserve dynamics. There are 826 billion tons of coal reserves at the current production rate, which will be exhausted in 122 years. The projected 42-year supply of the world's conventional crude oil reserves is 1258 billion barrels. According to an estimate, natural gas was reserved for 60 years.

Moreover, nuclear power meets roughly 11.5 % of the world's energy needs with >390,000 MWe of installed capacity and 17,000 reactor years of experience. Although conventional energy sources, such as coal, petroleum, and natural gas reserves, are expected to diminish drastically, energy consumption appears to keep rising. Renewable energy is being prioritized in anticipation of this collapse as a substitute and stable source of energy generation. The world desperately needs to get ready for a time without FFs. For all nations, the use of sustainable energy has become vital. As illustrated in Table 1, the net energy found in 2021 is 162,490,750 terajoule, representing a 77 % rise in global energy consumption from 2000 to 2040 [2,28]. Optimizing energy performance and limiting global energy consumption would considerably reduce the growth in energy demand and the energy gap identified. In a nutshell, there will be a continued demand for FFs worldwide in the upcoming decades. Numerous energy sources, conventional or non-conventional and renewables, are required to address this rising demand.

2.2. Linking circular economy (CRE) with a global energy system (GES)

Energy is the primary source of economic growth worldwide and the cornerstone of human progress and wealth. Unfortunately, the global energy crisis and the dependency on FFs are becoming more and more concerning due to rapid population expansion, economic advancements, and technological progress. The International Energy Agency (IEA) estimates that oil is the world's primary energy source, with global consumption of 31.2 %, followed by coal consumption at 27.2 % and natural gas consumption at 24.7 %. The world's energy usage in 2021 was 83.1 % from all FFs, while the remaining 12.6 % is renewable [29,30]. The world's energy system needs to transform to decarbonize our planet

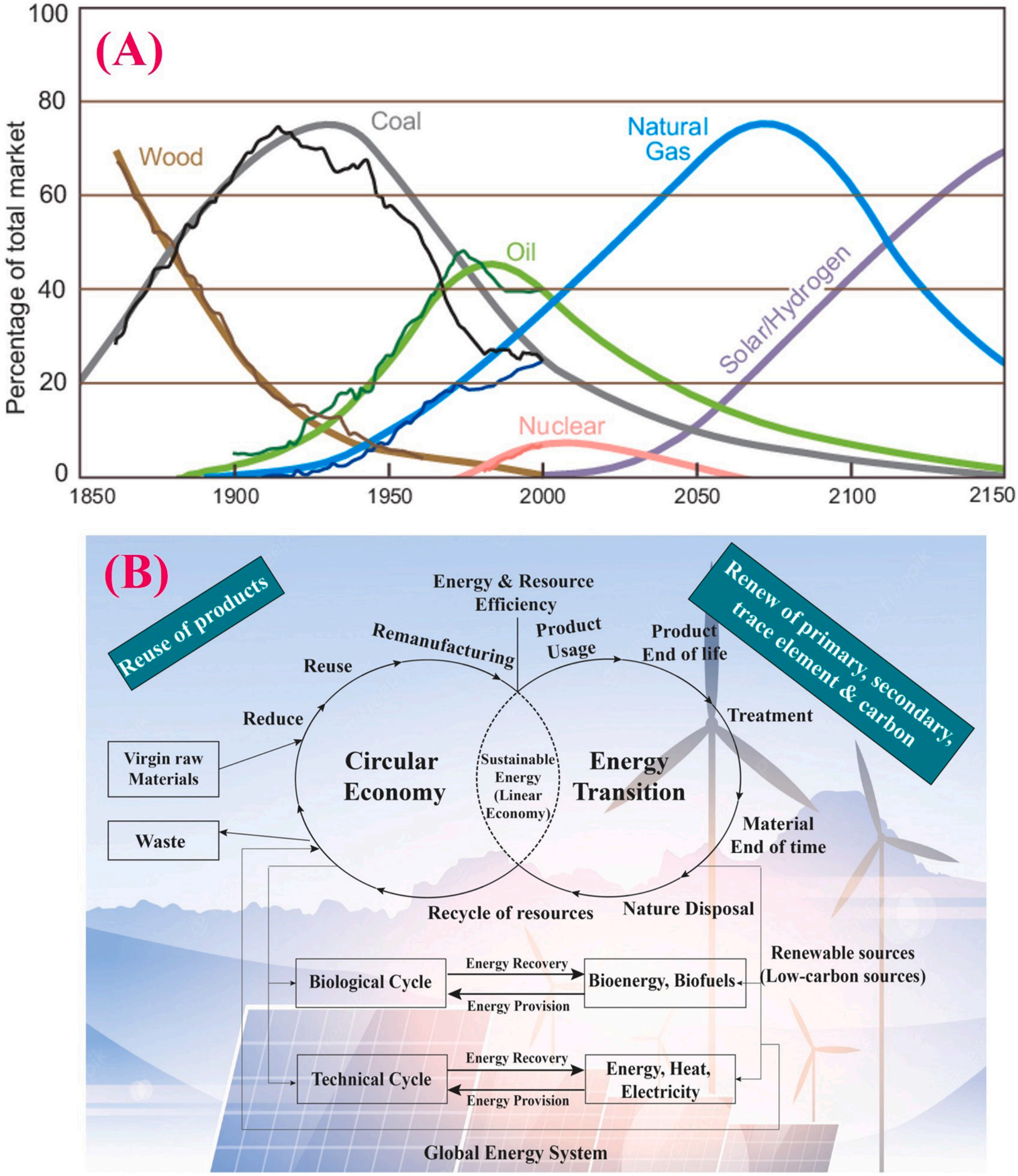

Fig. 1. (A) Global energy system transition wave [29], (B) Linking CRE with a GES [36]. This figure was modified with the copyright permission of International Energy Assosication (IEA), 2021 under the license of CC BY 4.0.

and forecast the degradation of its finite resources. FFs should be transitioned out in favor of renewable energy sources. Fig. 1A shows that the global energy system is slowly transitioning to renewable energy from FFs use.

The CRE is a framework that tries to maximize the use of resources, keep goods and resources in circulation and reduce waste by designing them to be recycled. It serves as an essential foundation in the shift to clean energy. For the transition of the GES, CRE might be a preferable option [31]. Since it is the primary force behind the GES, renewable energy currently accounts for most of the CRE's activities. To reach a scenario of net zero global emissions by 2050 and keep temperature increases to below 1.5 °C by the end of this century, it will be necessary to extract resources six (6) times higher than currently we have. Several industrialized economies intending to decarbonize by 2050 and China committed to 2060, over 70 % of the global GDP is currently covered by a net-zero target [32–34]. CRE will be essential to achieving this goal in a cyclical material energy flow. Fig. 1B represents the relationship between GES and the idea of product reuse, representing CRE, remanufacturing, and refurbishment, which needs fewer resources and energy.

The CRE concept, which is currently quite popular, extends the usage of renewable energy sources. Reducing the use of the product with efficient production and consumption process, altering the end-product that is not usable for recycling in products and production processes, and waste to get a sustainable economy is the ultimate approach of CRE [35].

In pursuit, the CRE and energy transition framework and their relationship (industrial symbiosis) provide clear ideas to achieve the objective of sustainable production and consumption of goods and energy. It is crucial to rethink the value chain and alter the GES by restructuring industrial systems to use renewable energy instead of carbon-based energy.

2.3. *Why is the transition of global energy necessary?*

The current world is going to confront a transition in GES. The development of human civilization in the past century predominantly depended on FFs. Although fossil energy resources significantly made a rapid techno-economic revolution within a short time, its consequences in terms of the environmental performance of the Earth are alarming [3]. The energy consumption patterns vary globally mainly due to the population and per capita energy utilization. An estimate showed that approximately 7800 million people in 2020, with a yearly growth rate of 1 %, will fall into highly industrialized clusters of the world [37]. In contrast, segments of Asia and Africa have the highest growth rates of population, accounting for 2.5 %. Geographical variations also influence the per capita energy consumption; for example, developed nations utilize ten (10) times the world average while developing countries use

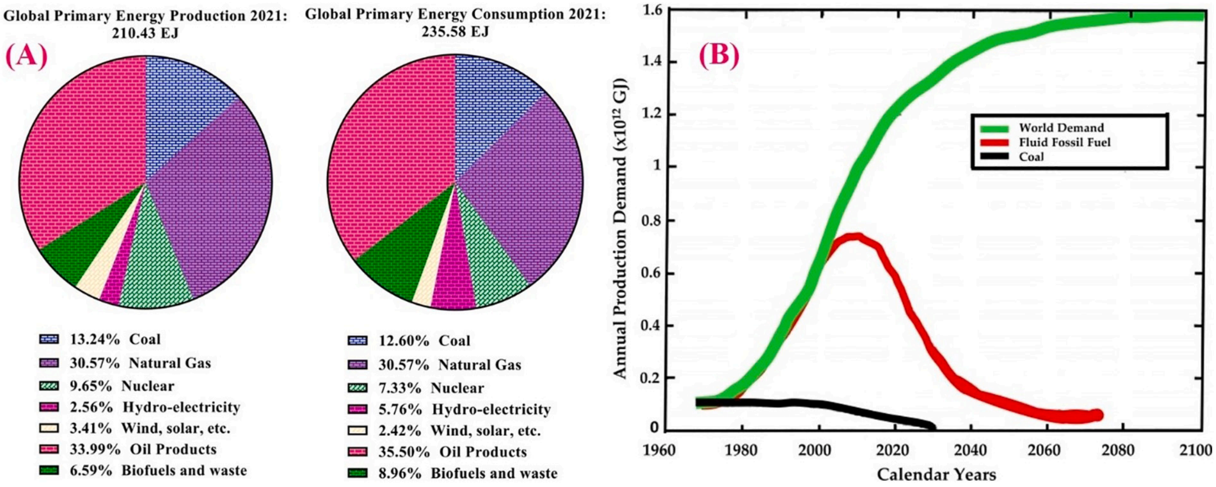

Fig. 2. (A) Comparison of global primary energy production and consumption [44] (copyright: International Energy Assosication (IEA), 2019 under the license of CC BY 4.0), (B) Forecasted world production of fossil fuel [45] (Copyright from 2022 MDPI).

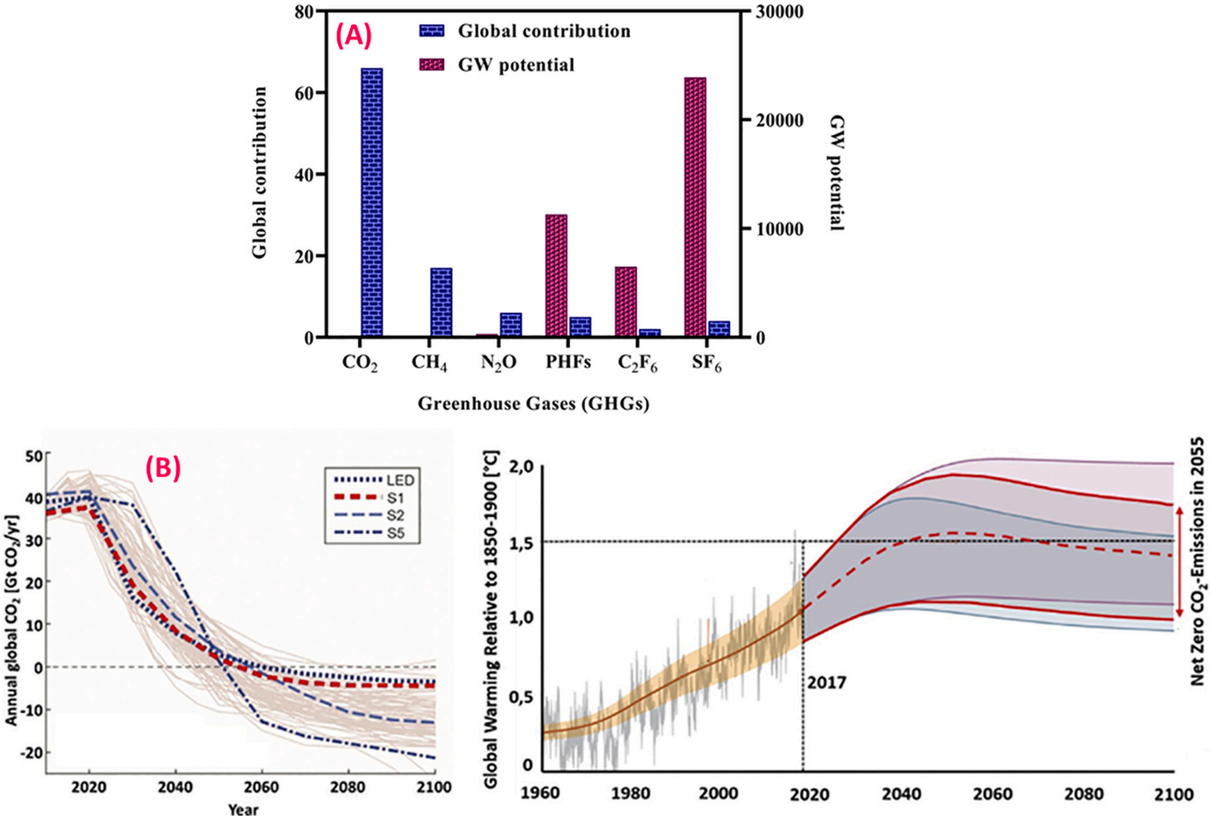

Fig. 3. (A) Climate-relevant GHGs and their global share [46] (B) Global warming scenarios according to IPCC [47–49] (copyright: International Energy Assosication (IEA), 2019 under the license of CC BY 4.0).

<10 % of the world's energy [38]. The net energy consumption reached 235.58 EJ in 2021. FFs, i.e., oil products, natural gas and coal, accounted for 83.62, 64.62 and 29.69 EJ, respectively (see Fig. 2A). As the world's population grew, global energy demand increased significantly. Till now, FFs primarily supplies this growing demand. The predominant share of fossil energy resources seemed stable and constant over the years to fulfil the global energy demand. The primary energy dispersal worldwide demonstrated an analogous portrait of FFs domination. The initial energy transforms into its ultimate form in which the energy can be utilized, known as final energy, which is electricity accounted for 19 %. The conversion efficacy from the primary to the last point is 67 %, so we lost 33.33 % of direct energy [39]. However, the energy requirement will continue to rise for two reasons: (i) the continuous increase in world population and (ii) the increasing demand for energy by developing nations to improve their quality of life. Currently, 65 % of the world's energy supplies are fulfilled by liquid FFs because of their easy access and convenient use. Nonetheless, it is assumed that the production of FFs will soon peak at its apex and subsequently start to decrease [40–43]. Fig. 2B presents the forecast of liquid FFs production rates and global demand. It assumes that the liquid FFs production globally will constantly increase for the next fifteen (15) years and then tend to decline afterwards. Coal manufacture is projected to remain constant for the following decade and then begin to decline.

Moreover, environmental degradation and deterioration of human health are the worst consequences of FFs-based energy consumption. The energy production sector is the most important to any country for its economic development but is simultaneously responsible for the greenhouse effect (GE) and climate change. It was reported that 80 % of carbon dioxide (CO_2) emissions worldwide are caused by the energy sector [50]. It notes that 35 billion tons of CO_2 are recently emitted annually, nearly 13 kg CO_2/capita/day. The concentration of atmospheric CO_2 sharply increased since 2016; it was above the value of 400 ppm [51–53]. The natural GE keeps the Earth's surface temperature at 15 °C instead of −18 °C. It was observed that nearly two-thirds of the GE is triggered by water vapor, while one-third by CO_2 and methane (CH_4). These gases are said to be connected by a natural cycle. The artificial GE is caused by the emissions of GHGs. According to the Intergovernmental Panel on Climate Change (IPCC), the continuous increase in GHGs by man-made activities is conscientious of global warming (GW). The climate-related greenhouse gases and their potential to cause global warming have been presented in Fig. 3A.

The IPCC's scenarios to combat global warming (GW) have been illustrated in Fig. 3B. Based on these plans, it can be assumed that the average temperature of the Earth should be kept within 2–6 °C by 2100 while minimizing to 2 °C would be the most cost-effective and environmentally feasible option [54]. The projected impacts of GW are damaging, including sea level rise, climate-induced refugees, shortages of foods and water supplies and rapid extinction of plant and animal species. Increasing extent of floods, droughts, fire, and heavy rain will keep on rising, and for some time, already triggering severe destruction to many coastal regions of the world [47]. To accomplish this 2 °C goal, a quick and radical fall in CO_2 emissions is essential, achieving a net-zero CO_2 emission by the year 2050 (Fig. 3B). According to the Conference of the Parties (COP) 21 climate conference, the global average temperature should be maintained well below 2 °C by the edge of this century. The treaty was approved by 195 countries, whereas measures to succeed in the target are not well planned. In essence, considering the environmental pollution and GW issues as well as future energy security, a twofold revolutionary energy transition is immediately necessary. The earliest movement can be a revolution of energy: the steady and intensive transition from FF-based primary energy to sustainable and renewable energy sources such as solar, wind, geothermal, biomass and water. The subsequent phase would be the development of a sustainable hydrogen economy based on the extensive usage of hydrogen as a green secondary energy carrier.

2.4. Green hydrogen: a milestone of sustainable energy

Hydrogen can be considered a revolutionary energy carrier that can undoubtedly have a significant and persuasive influence on the global energy transition. It leads to a massive cut of GHGs in the upcoming decades. An estimation showed that a 60 % decline in GHGs in the previous phase of the energy transition was mainly contributed by renewable energies, green hydrogen, and the development of green electrification [55]. However, combined attempts of governments, industries and financiers are essential prerequisites for decarbonizing future energy systems. Moreover, sufficient investment is necessary to establish a global hydrogen value chain and a sustainable hydrogen economy (HE) [56,57].

2.4.1. Physical characteristics of hydrogen

Henry Cavendish discovered the hydrogen atom by employing water decomposition techniques in 1766. However, Antoine Lavoisier named this gas hydrogen (H) widely available in the Universe, and 93 % of current molecules have H in their atomic structures. Hydrogen is a diatomic molecule (H_2) [58]. It has an atomic weight and number of 1.00797 and 1, respectively, and is the first element in the periodic table with an electronic configuration of $1s^1$. H_2 is one of the lightest elements on Earth, with a density of 0.08967 kg/m^3, 14.4-fold less than that of air. It has an ionic and van der Waals's radius of 0.208 and 0.12 nm, respectively. At standard atmospheric pressure (1 atm) and temperature (25 °C), H_2 has no color, odor or taste and is insoluble in water [58].

Hydrogen has flammable characteristics, and the highest diffusion capacity for its low density compared to air and has a liquid state at −253 °C. The physical attributes of hydrogen molecules are presented in Fig. S2. Hydrogen has different unique properties, making it more appealing than other fuels. The combustion process of hydrogen releases a tremendous amount of energy, such as a high-level calorific value [59–61] (Fig. S3). Hydrogen has the highest amount of energy per unit mass compared to all other fuels. It was noted that 1 g of hydrogen provides an equal amount of energy as 2.8 g of gasoline. This novel low molecular mass fuel occupied a volume in its liquid state 700 times lesser than what it would settle in its gaseous phase [59,60].

The hydrogen flame poses an exceptionally high-level thermal gradient with a greater energy density (38 kWh/kg) when compared with gasoline (14 kWh/kg). The energy requirement to detonate an air-hydrogen mixture is 0.04 MJ, while it was 0.25 MJ for hydrocarbons.

Table 2
Ignition and detonation characteristics of hydrogen, data were obtained from [58,63] with copyright permission from 2008 Elsevier.

Properties	H_2
Density at STP (kg/m^3)	0.084
Vaporization heat (J/g)	445.6
Lower heating value (kJ/g)	119.93
High heating value (kJ/g)	141.8
Thermal conductivity at std. condition (mW/cm/K)	1.897
Diffusion co-efficient in the air at std. condition (cm^2 s)	0.61
Flammability limits in the air (vol%)	4.0–75
Detonability limits in the air (vo l%)	18.3–59
Limiting oxygen index (vol%)	5.0
Stoichiometry composition in the air (vol%)	29.53
The minimum energy of ignition in the air (Mj)	0.02
Auto ignition temperature (K)	858
The flame temperature in air (K)	2318
Maximum burning velocity in the air at std. condition (m/s)	3.46
Detonation velocity in the air at std. condition (km/s)	1.48–2.15
The energy of explosion mass related g TNT (g)	24.0
The energy of explosion volume related g TNT (m^3) (STP)	2.02

Thus, hydrogen is highly flammable in the air, and under some conditions, impulsive combustion can happen [62]. The ignition and detonation characteristics of hydrogen are given in Table 2.

2.4.2. Chemical characteristics of hydrogen

From a chemistry viewpoint, the H atom is highly reactive; thus, it is hard to locate independent elemental forms in a natural environment. Hydrogen is comparatively less reactive without any activation sources at room temperature, whereas extremely high temperatures can dissociate H_2 into its atomic state. To capture hydrogen from natural compounds, energy expenses are essential. Thus, hydrogen can be considered a medium of energy carrier which ultimately stores and transmits energy from the initial energy sources. Hydrogen is a powerful reducing agent that can react with oxides of metals and chlorides, thus allowing to leave available metals and non-metallic elements like N, Na, P and K to generate the corresponding hydrides [64,65]. The H atom reacts with organic materials to produce a complex mixture of different products. For example, ethane and butane can be found in the reactions of hydrogen and ethene. A large quantity of heat can be generated from the violent reactions of hydrogen and oxidants, halogens, and unsaturated hydrocarbons. The combustion and electrochemical processes generate energy via reactions between hydrogen and oxygen, where water vapor is formed as a by-product. These prolonged reactions can be sped up using various catalysts such as platinum or simple electrical sparking. The hydrogen diffusion process is faster than other fuel gases, with a diffusion coefficient of 61 m^2/s. This property is the most significant issue related to the safety of hydrogen used as fuel [65,66].

2.4.3. Types of hydrogen fuels

The production of molecular hydrogen needs energy. Based on the sources of energy and production methodologies, H_2 can be categorized into grey, blue, and green hydrogen (see Fig. S4). Hydrogen can be generated from FFs, which is linked to the emission of GHGs. At the same time, water electrolysis techniques produce hydrogen by splitting water into hydrogen and oxygen, where GHGs are absent [67]. Coal and natural gas-based hydrogen is called grey hydrogen. It was estimated that approximately 95 % of the total hydrogen produced worldwide till now is grey hydrogen. There are two primary production techniques of grey hydrogen, i.e., steam methane reforming (SMR) and coal gasification, and both processes emit CO_2 into the atmosphere. Thus, grey hydrogen should not be considered a low-carbon fuel [68,69]. Blue hydrogen is almost like grey hydrogen. However, blue hydrogen can be considered low-carbon fuel because the stimulated CO_2 emission can be reduced by using carbon capture and storage techniques (CCS). Production of blue hydrogen fuel is expensive since CCS techniques require capital and maintenance costs [67]. Renewable, clean energy sources are used to produce green hydrogen hence considered zero-emission hydrogen because its production process does not emit GHGs in the environment. However, water splitting by electrolysis is expensive due to the supplementation of clean electricity, but it ensures environmental

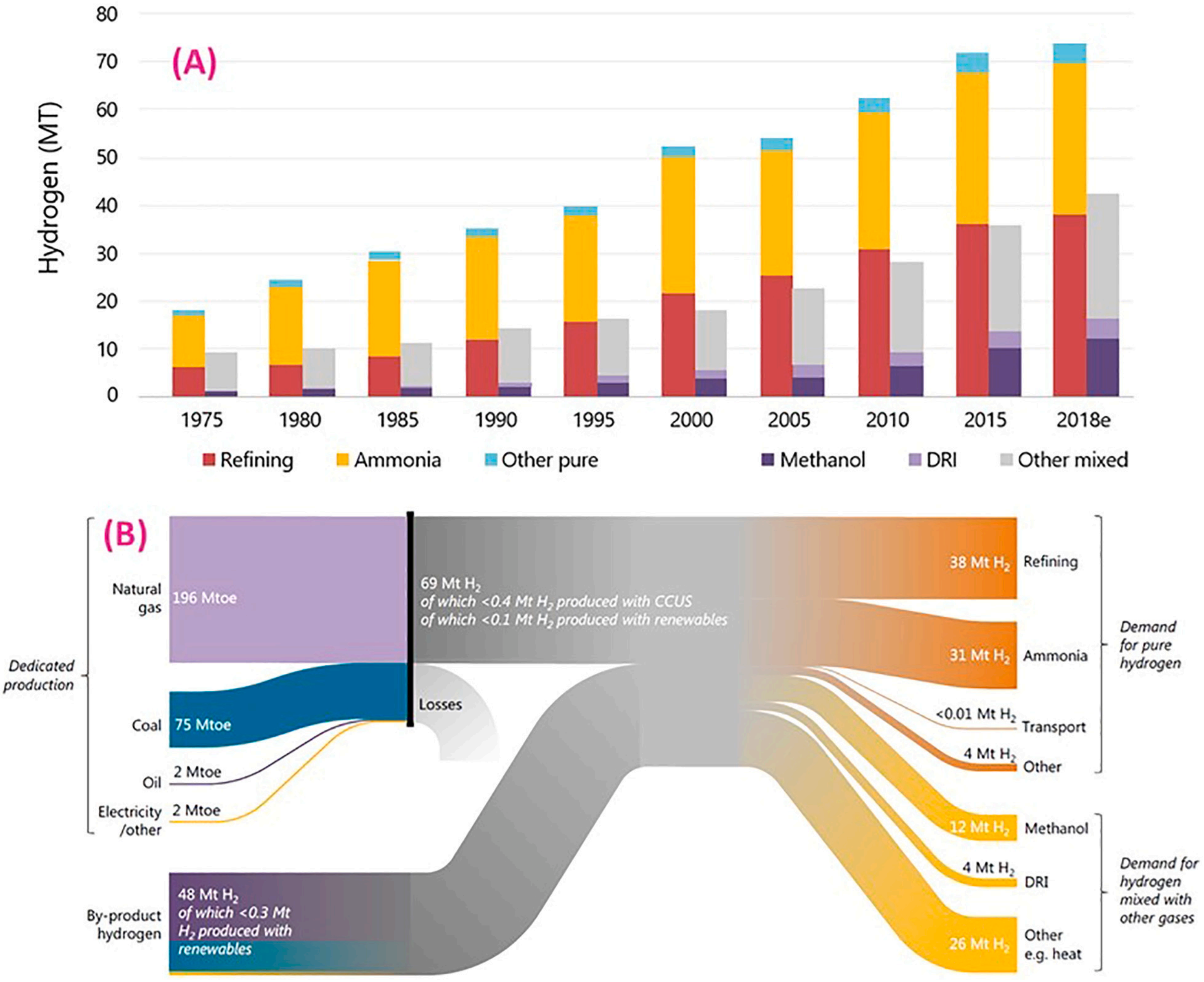

Fig. 4. (A) Global hydrogen demand from 1975 to 2018, (B) Today's world hydrogen value chains [45,46] (copyright permission from International Energy Assosication (IEA), 2019 under the license of CC BY 4.0).

sustainability and, future energy security, a green HE [70].

2.4.4. Prospects, future outlooks, and hydrogen use strategies

Hydrogen can be considered a prospective energy paradigm shifter, which can play a significant role in the upcoming low-carbon energy economies maintaining green power facilities in transportation, electrification, industrial services, buildings, and heating. Since the mid-20th century, hydrogen has been an essential part of energy industries, where it was intensively used in oil refining. Industrial hydrogen use is considered one of the most intensive sectors for business. The demand for hydrogen fuel increased three (3) times from 1975 to 2018 (Fig. 4A). Pure hydrogen demand is 70 MT per year. The term "pure" indicates the use of hydrogen in any specific application with only little amount of contamination and additives. Hydrogen's leading applications are refining oil and ammonia production for fertilizers. An additional 45 MT is used as a mixture of different gases for feedstock or fuel, especially for methanol and steel manufacturing. One-third of hydrogen demand today is indirectly linked to mobility sectors; in refineries, methanol is exploited as in-vehicle fuel (Fig. 4B). The maximum amount of this is supplied from FFs (60 %), where 6 % comes from natural gas, 2 % from coal and a minor fraction comes from water splitting known as electrolysis process. An estimation proved that the current production processes of hydrogen are damaging the environmental balance, triggering Global warming potential (GWP) by emitting 830 MT CO_2/year.

In terms of energy, the total worldwide hydrogen demand is equivalent to 330 MT of oil, greater than the primary energy sources of Germany. However, only 0.7 % of total hydrogen comes from renewables in conjunction with carbon capture, utilization, and sequestration (CCUS) facilities. The discussion above directed us to a hydrogen-based resilient, and sustainably secured future energy by two potential pathways: (i) current applications of hydrogen should be provided with green alternative and cleaner production technologies ensuring zero-emission and using diverse renewable sources of energy, and (ii) hydrogen could be used in diverse new alternative applications, for example, transportation, industries, power generation, buildings, and heating. Hydrogen can be used in its pure condition or transformed into H_2-based fuels such as synthetic methane, liquid fuels, ammonia, and methanol.

Hydrogen fuel is facing unprecedented momentum at the current time. Although, the inquisitiveness about hydrogen's potential as a widespread, low-carbon energy carrier is not a brand-new issue. In recent decades, scientists worldwide devoted their research to emission-free hydrogen production (HP) technologies, transporting directions, and storage facilities of hydrogen fuel to provide the latest energy services.

Nowadays, the scopes and opportunities of hydrogen utilization are being discussed worldwide with geo-political interests, and there are immensely innovative and technological, political, and policy-oriented competitive races beginning among nations on how hydrogen can be brought to their energy market as a safe, green, and sustainable alternative to FFs for long term energy security. The number of policies that supported direct financing of hydrogen production technologies is increasing globally, together with the expanded utilization sectors they targeted. There were 50 different objectives, directives, and policy enticements to support the financing of hydrogen scalation by 2019 worldwide (Fig. 5A). These policies were based on the future use of hydrogen covering six (6) crucial areas and transportation sectors are so far the largest one. The group of twenty (G20), the European Union and 11 others issued policies. The national roadmap for hydrogen energy was made by nine nations worldwide. In the last year, several governments created significant hydrogen-allied statements (Table S1). In the previous several years, research, development, and demonstration (RD&D) on hydrogen energy research increased significantly, while it continues lower than the apex of 2008 (Fig. 5B).

Hydrogen has substantial applications in areas that renewables could not reach without a bridge and hydrogen has the potential to meet these gaps for decarbonizing the energy sectors as it has intrinsic flexibility both as a chemical and an emission-free energy carrier. Oliveira et al. [71] projected that the global demand for hydrogen could reach 3.3 GT/year by 2050 compared to 70 MT per year used today. They proposed a

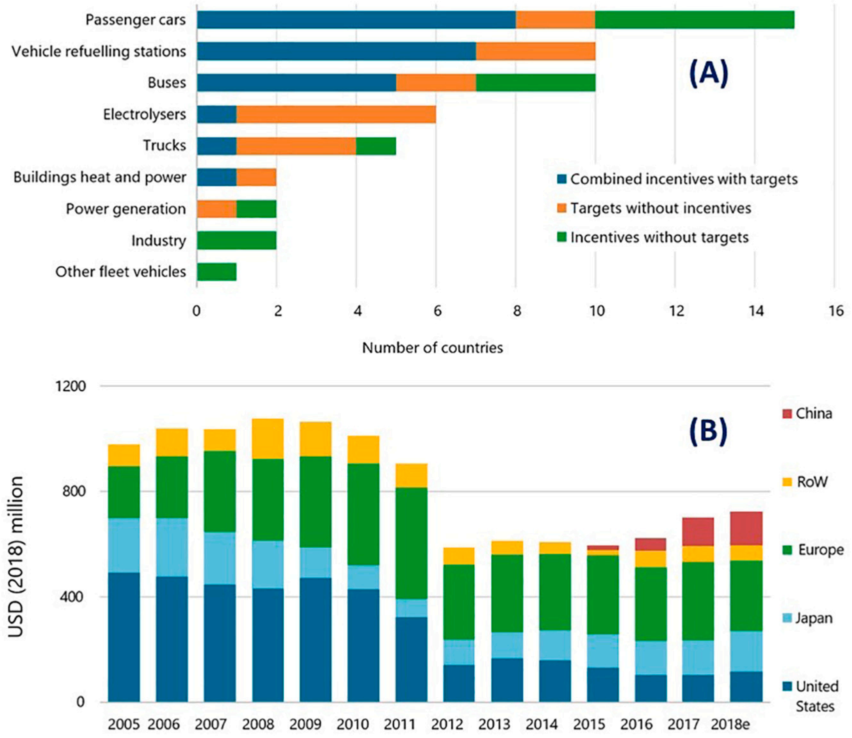

Fig. 5. (A) Policies financing for hydrogen application by target sectors; (B) Government RD&D funding for hydrogen production [29] (copyright: International Energy Assosication (IEA), 2019, under the license of CC BY 4.0).

Table 3

The properties of most common fuels [10,29,36]. Copyright permission from 2021 Elsevier.

Fuels	H_2 quantity	storage (°C)/P	Flammability limits (in the air)	Explosion Limits (in the air)	The gravimetric energy density (MJKg^{-1})	The volumetric energy density (GJ m^{-3})
Hydrogen (H_2)	100 %	20/250	4–74 %	18.3–59 %	120.21	2.15
Methanol (CH_3OH)	12.5 %	20/1	6–36 %	5.5–44 %	19.7	15.58
Methane (CH_4)	25 %	20/250	5.3–15 %	5.7–14 %	50	9.77
Ammonia (NH_3)	17.6 %	20/10	–	16–25 %	18.65	11.38

novel "green HE combining renewable energy society" and framed hydrogen as an important catalyst along with a robust hydrogen market value in a 100 % renewable future. In this review, we have proposed four-stage hydrogen applications for complete decarbonization integration with renewable energy sources. These applications are as follows:

a. Current and potential industrial applications of hydrogen.
b. Potential uses of hydrogen in transportation systems.
c. Application of hydrogen for heating houses and building facilities.
d. Application of hydrogen in power sectors.

Industrial sectors can be considered as one of the dominant hydrogen exploiting sectors. Oil refining (33 %), production of ammonia (27 %), generation of methanol and steel manufacturing (3 %) by direct reduction of iron (DRI) ore are the top four single uses of hydrogen in industries. Oil refining industries use >60 % of hydrogen today from natural gas. Over a short period, the demand for ammonia and methanol production will be increased. To avoid these emissions from FFs use, technologies are accessible. In many cases, alternatives have already been used where supportive policies and economies have existed. An overview of the present and probable future industrial uses of hydrogen has been outlined in Table S2.

Hydrogen has long-term potential in several areas, along with the current industrial applications. Hydrogen has been considered a prospective transportation fuel. This fuel can offer low-carbon options to FFs, supplementing other substitutes like electricity and sophisticated biofuels. Hydrogen fuel cell electric vehicles (HFCEVs) could reduce local and regional air pollution problems. HFCEVs have zero exhaust pipe emissions, contrary to battery electric vehicles (BEVs) [72]. The conversion of hydrogen to hydrogen-based fuels such as synthetic methane, methanol, ammonia, and liquid fuels has significant transportation uses. The production of synthetic liquid fuels from hydrogen is called "power-to-liquid". The potentials of hydrogen-based fuels in different transport sectors have been presented in Table S3. It was accounted that the buildings sector uses 30 % of global final energy such as hot water generation, space heating and cooking. Conventional solid biomass burning in developing countries and relevant energy demand was 2200 Mtoe in 2017. Approximately 50 % of these energy sources come from FFs, including natural gas accounts to be 620 Mteo. Nonetheless, ~28 % of global energy-related CO_2 emissions result from building energy usage [73]. Although the replacement of heat requirements with low-carbon substitutes and lessening heat requirements by improving buildings is challenging. The opportunities for green hydrogen deployment in the heating and building sectors are illustrated in Table S4. Hydrogen portrays an insignificant role in the power industries today: it constitutes only 0.2 % of electricity production in the steel industry, petrochemical plants, and refineries. However, these scenarios could be changed soon [74]. Ammonia co-firing could diminish the carbon requirement in present traditional coal power plants. Hydrogen-triggered gas turbines and blended-cycle gas turbines could give springiness to electricity schemes with expanding segments of varying renewables. Hydrogen can become a long-standing storage alternative to offset cyclical differences in electricity requirement or production from renewables in the form of compressed gas, ammonia, or synthetic methane (Table S5).

2.4.4.1. *Green ammonia, hydrogen peroxide and methanol as an alternative format of hydrogen supporting, HE*

2.4.4.1.1. Green ammonia. Ammonia (NH_3) has a hydrogen amount of 17.6 wt (%) with no carbon content. NH_3 can quickly decompose into a gas mixture of 75 % hydrogen and 25 % oxygen, offering high output and clean hydrogen production with zero carbon emission. On the contrary, carbon-based fuels such as methanol (CH_3OH) and methane (CH_4) would certainly generate CO_2 within the process of power generation or hydrogen production. NH_3 has a boiling point of −33 °C at STP, permitting it to be accumulated in a liquid form easily compared to hydrogen. At a moderate pressure, such as 10 bar, NH_3 gas can be compressed to its liquid form [75,76–78]. It was reported that NH_3 is one of the most produced chemicals worldwide, with an annual production of 180 MT. Ammonia production and storage infrastructures have already been well established and distributed globally [79]. The volumetric energy density (11.38 GJ m^3) of NH_3 makes it an ideal candidate for clean fuel compared to conventional fuels, as illustrated in Table 3.

Ammonia as a fuel is safe as other fuels and has similar safety risks such as hydrogen, gasoline, liquefied petroleum gas (LPG), compressed natural gas (CNG) and methanol [80]. The intense odor of ammonia turns advantages as this pungent stench is quickly detectable by the human nose at a concentration below 20 mg/L in air, permitting preventive measures to be taken readily [81]. In addition, NH_3 is nonflammable, having a narrow explosion limit (16–25 % in the air) [82]. The world has experienced a 100-year growth of safety issues regarding the production and handling of NH_3.

Thus, health and environmental hazards related to ammonia are minimal and manageable, which would not be a hurdle to the development of an ammonia energy economy. The existing infrastructures worldwide will enable a fast shift of ammonia into energy applications [83,84]. Large-scale amenities of ammonia storage are practicable and mature, such as a Qatar fertilizer company that has built two large tanks capable of storing 50,000 T of ammonia where natural gas was available. The USA has 10,000 ammonia storage locations, principally

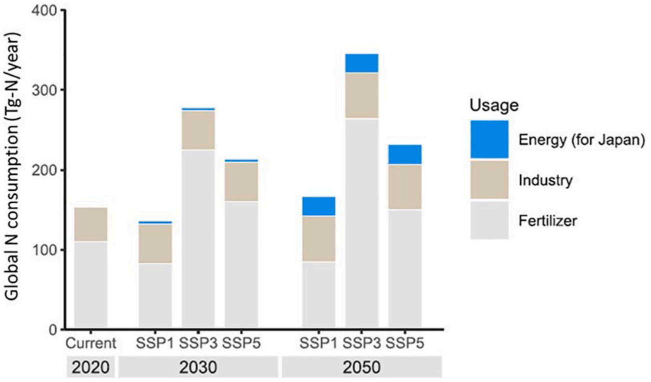

Fig. 6. Current and future scenarios of reactive nitrogen use in ammonia fuel (energy). This figure was obtained from Mogollon et al. [85] with copyright permission from 2022 IOP SCIENCE.

located in Iowa, where a total storage capability of 800,000 T of ammonia is accessible [36]. The quantity of Japanese NH_3 fuel exploitation in 2050 will reach approximately 1/5th of the recent global annual usage of nitrogen in chemical fertilizers. In contrast with Japanese domestic N utilization, the annual N intake in 2015 was 0.5 Tg-N for fertilizer and 0.6 Tg-N for industrial usage. At 20 % co-firing in 2030, NH_3 energy use will significantly surpass these requirements. In the future, in the shared socio-economic pathways-1 scenario (SSP1), which uses the least amount of chemical fertilizers [85], Japan's NH_3 use alone will account for 25 % of the global use of chemical nitrogen fertilizers and about 15 % of the total reactive nitrogen use, including industrial applications (Fig. 6). This situation shows the potentials of energy usage of NH_3 worldwide. Reactive nitrogen usage will be increased soon for energy purposes. Thus, from the above discussion, we can conclude that the application of the " ammonia economy" can be revolutionary support for HE.

2.4.4.1.2. Green hydrogen peroxide as an energy fuel. One amazingly attractive alternative fuel to H_2 that has reaped some attention in the previous decade is hydrogen peroxide (H_2O_2). H_2O_2 is familiar as an oxidant and is utilized in numerous chemical and industrial processes that make use of this characteristic [86–91]. H_2O_2 has even been used as the oxidant in other types of fuel cells where it has been shown to perform even nicer compared to O_2 in some cases [92–95]. However, H_2O_2 is quite unique when applied to fuel cells because it can be both *oxidised* and *reduced*, with each process occurring at a different electrochemical potential (NHE = normal hydrogen electrode).

$$\textbf{Anode} : H_2O_2 \rightarrow O_2 + 2H^+ + 2e^- + 0 : 68\text{VvsNHE} \quad (1)$$

$$\textbf{Cathode} : H_2O_2 + 2H^+ + 2e^- \rightarrow 2H_2O + 1 : 76\text{VvsNHE} \quad (2)$$

$$\textbf{Overall} : 2H_2O_2 \rightarrow O_2 + 2H_2O\ 1 : 09\text{V} \quad (3)$$

This launches the prospect of utilizing H_2O_2 as the fuel and the oxidant in the same fuel cell with the highest theoretical potential of 1.09 V, which is reasonably close to other fuel cells such as those using methanol (CH_3OH)/air (1.21 V) and H_2/air (1.23 V). The major benefits that an H_2O_2 fuel cell has over H_2 is that H_2O_2 can appear in an aqueous solution at room temperature, thus needing no pressurisation or additional storage media.

2.4.4.1.3. Green methanol as an energy fuel. Methanol (CH_3OH) is one of the greatest contenders for the long-term, extensive alternative to petroleum-based fuels [96]. Among renewable substitute energy types, there are many reimbursements for the growth of alternate fuels such as alcohol fuels instead of conventional non-renewable oil resources; for instance, (1) it can mitigate national safekeeping and economic apprehensions over fuel supplies;(2) it can decrease the atmospheric emissions; and (3) it can preserve the sustainable development of the resources [96]. Among gasoline and diesel replacement fuels, CH_3OH fuel has been one of the most favorable fuels for internal combustion (IC) engines [97,98].

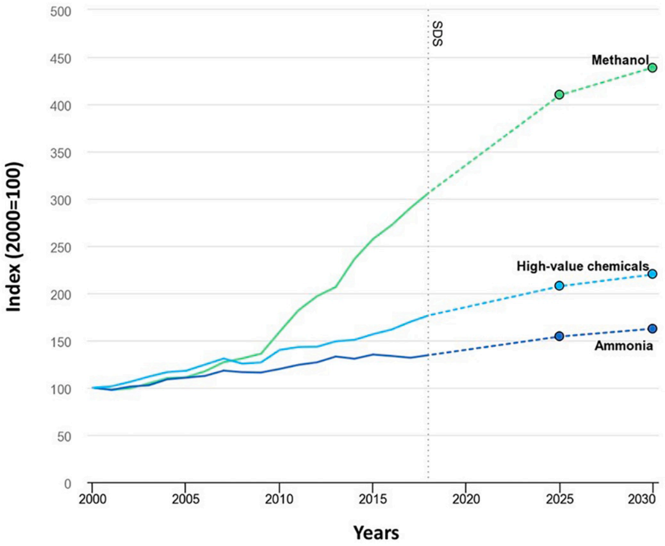

Fig. 7. SDS index of some common fuels. (Copyright: International Energy Assosication (IEA), 2022, under the license of CC BY 4.0).

Methanol, also known as methyl or wood alcohol, is a colourless organic liquid at room temperature that is both flammable and toxic if ingested. Methanol not only affects human health but also affects the environment. Nonetheless, methanol is already present within the human body in small quantities from eating fruits and vegetables. According to the FDA, as much as 500 mg per day of methanol is safe in an adult's diet. In the body, methanol is metabolized in the liver, converted first to formaldehyde, and then to formate [98]. Moreover, compared to other fuels, such as high-value chemicals (HVCs) and ammonia, methanol has a highly sustainable development scenario (SDS) index with increasing time [99]. The SDS index of methanol will be increased from 307 in 2018 to 439 in 2050 (Fig. 7). Methanol must be handled properly to ensure that it does not negatively impact to the environment and human health. Methanol exposure can be avoided and managed safely through the proper design of fuel containers and fuelling systems. No matter how much methanol we use daily, it is important for everyone to know the hazards and safety precautions involved with handling methanol [96].

3. Water industry (WI) and circular economy (CRE)

3.1. WI and its functions

The water industry (WI) provides various socio-economic facilities by supplying potable water and wastewater services in the economy's industrial, domestic, and business-related sectors [100]. These services include water engineering and operations, construction of water and wastewater treatment plants, supply equipment facilities, and specialized chemicals and reagents, to name but a few. The WI is also devoted to serving other industries, such as food and beverage.

The WI sector varies throughout the world based on a variety of activities that a particular WI deal with, such as geographical location and size, quantity and attitude of the customer services, level of commitment to private sectors, nature of market competition, the magnitude of regulation needed and the administrative bodies which determine the monitoring and implementation requirements of specific activities [101]. Overall, a WI has to collect, store, transport, treat, distribute, recycle, and supply bulk water to retailers. Moreover, sewerage and wastewater collection, treatment, and distribution are some regular tasks of WI. In addition, WI also deals with land and resources management, establishing national standards, and water-relevant policy development. The key activities of WI have been illustrated in Fig. 8A.

3.2. The urban water ecosystem (UWE)

The UWE consists of natural, social, and economic aspects of water which is considered one of the most significant components of the urban water environment. Davies and Wright [102] stated that spatiotemporal dispersal of the City's water reflects unique renewable, ecological, and economic functions. However, the UWE is indeed the artificially modified version of the natural water ecosystem, comprised of three major water environments, i.e., a natural water environment (NWE), a social water environment (SWE) and an economic water environment (EWE) (Fig. 8B). All these water environments have been developed based on the NWE underlying by an effective EWE and the overall vision of the settings as mentioned above is a sustainable social-secured water environment [77]. An urban NWE influences the recharging process of water

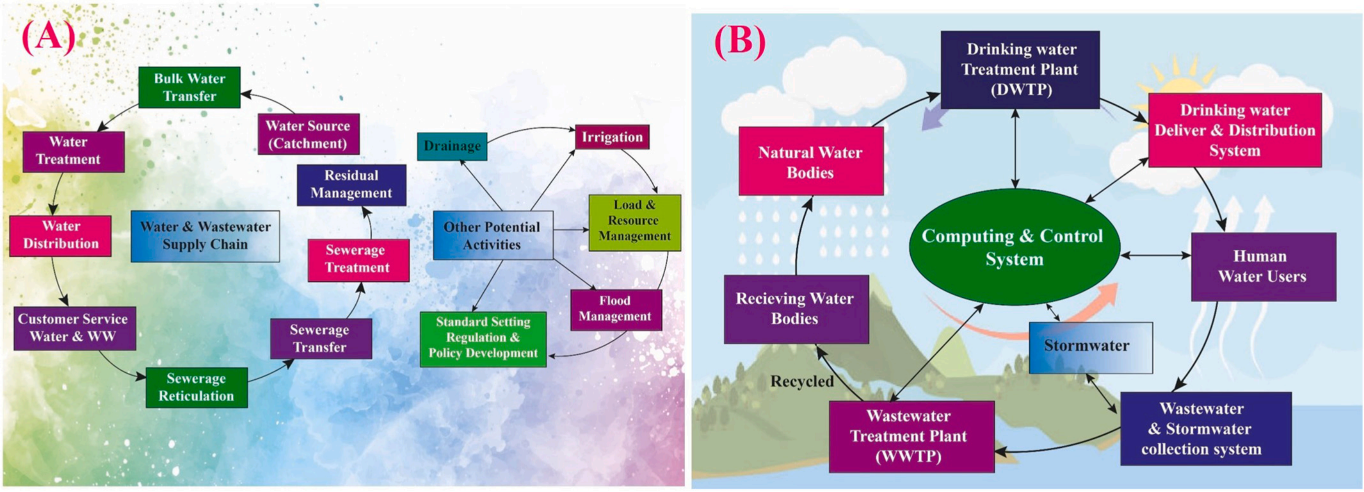

Fig. 8. (A) Key activities of WI, (B) Urban water cycle. Some of the portions of this figure were modified and obtained from [110] with copyright permission from Elsevier 2009 and 2020, respectively.

between surface water, groundwater, and the atmosphere. The precipitation, transpiration, evaporation, and infiltration processes are involved in the recharge system [103,104]. Precipitation plays a crucial role in restoring water systems, which go through the river's networks and groundwater and affect penetrability, slope, soil structures and rainfall intensity. Sustainable deployment of water reserves includes water and wastewater treatment, preservation, and development on which the water economy will be dependent. The objectives of long-term water resources deployment are to ensure adequate water supply for socio-economic and ecological services and provide safety of water quality [105]. The application of water flows from an ecological system in the direction of an economic approach is known as a water recycling economy which can incorporate the economy, environment, and society for sustainable water resources management into the pipelines and ditches. An urban SWE indicates the sustainable improvement of the urban water environmental system for the safety of natural and EWE. An SWE can be developed with logical urban water design which involves several significant factors such as a nice water ecosystem, linking with outside spaces and internal landscape and ecology.

3.3. Why do water industries need CRE?

The approaches and functions of the CRE concept have been evaluated based on the idea of CRE and its connectivity with socio-economic

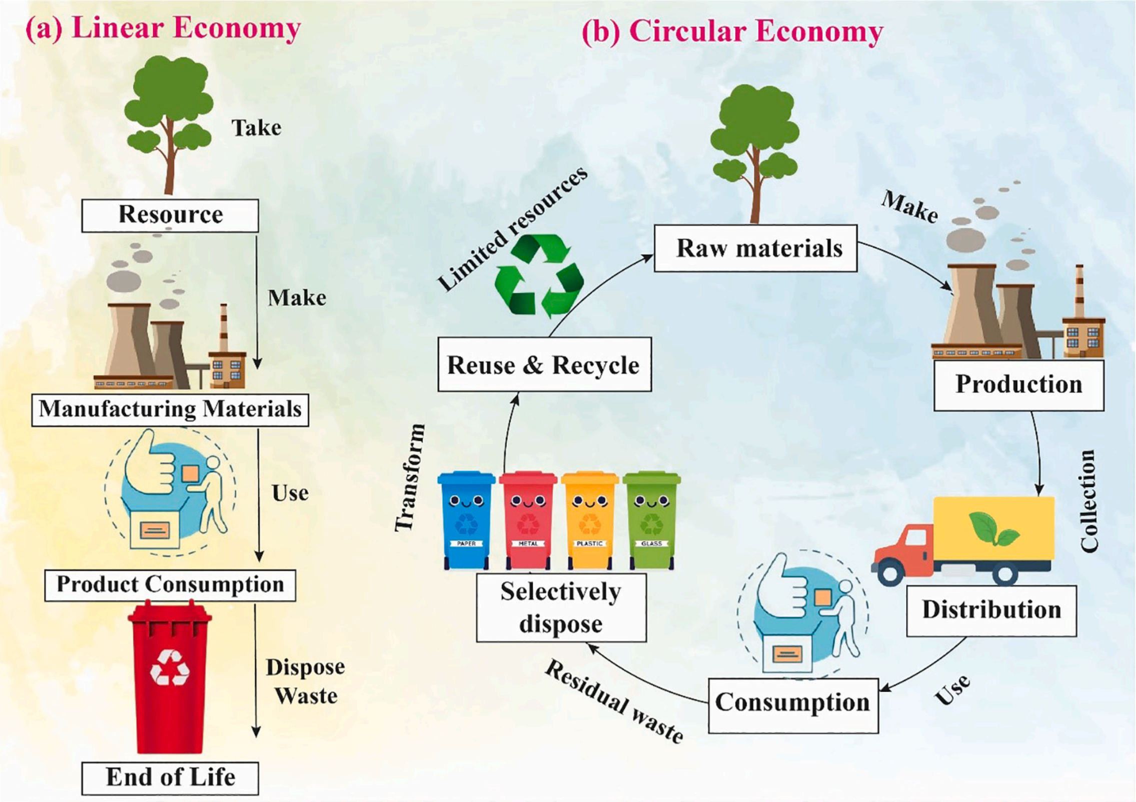

Fig. 9. A flow diagram of linear and circular economy. A portion of this figure was modified from [189] with copyright Permission from 2022 Elsevier.

Table 4
Key findings of CRE and WI-related studies.

Key findings	
Studies focusing economical viewpoint of CRE and WI	Studies
This study applied CRE principles to achieve economic circularity based on economic indicators in water and wastewater sectors.	[110]
To improve the soil fertility and water retention capacity, this study developed soil additives from waste fibres in a CRE framework.	[111]
This paper methodically reviewed the properties of water treatment sludge, their reuse and recycling potential. Moreover, a holistic view of socio-economic and environmental advantages, the obstacles of applying sustainable resource management from water treatment sludge in a CRE perspectives was discussed.	[112]
This study highlighted the plausible steps towards circular water footprint for sustainable water resource management.	[113]
Bio-circularity of leftover sludge in wastewater treatment was investigated.	[114]
Economic aids for utilizing recovered wastewater for agricultural uses have been studied in Braunschweig, Germany.	[115]
Positive feedback was recorded for wastewater treatment in terms of agricultural crop production, and generation of electricity compared to traditional approaches to treatment by cost-benefit evaluation.	[116]
Treated wastewater was used for cooling the power plant, generating economic value. A closed loop water resources system using the CRE principle reduced the transportation cost of recovered wastewater also.	[117]
This study focused on how financial ventures can secure wastewater recycling while maintaining maximum environmental benefits using perceptions from CRE.	[118]
The linear economy was discouraged in this study while working with financial and environmental issues of Jordan's central effluent treatment plan. CRE principles were highly emphasized to implement in WI.	[119]
A new tool named "Circonomics index" was developed to monitor the circularity practices in wastewater treatment plants stressing the role of technology was crucial for the CRE system.	[120]
These studies recommended that the economic attributes of CRE were mainly dependent on the cost of life cycle assessment (LCA).	[121,122]
Studies focusing environmental viewpoint of CRE and WI	
This study reported the interchange of energy, water, and material resources from industries to an eco-park based on the industrial ecology concept which concurred with CRE; waste from an industry can be resources for others.	[123]
Reported sustainable use of water in multiple systems by applying CRE approaches such as agriculture, industrial park, and domestic uses. The author noted the successful implementation CRE with so many case studies in China.	[124]
The circularity of water and wastewater usage was reported in different industries such as power, desalination, salt production and construction plants for a better environment.	[125]
A symbiotic circular industrial association was recorded with the highest environmental sustainability among sewage treatment plants, plant production industries, pig industries and breeding industries missionized for a multi-objectives fulfilment.	[126]
Pyrolysis techniques were used to prepare activated carbon from sludge acquired from WI, aiming for zero waste discharge in industrial clusters.	[127]
Environmental benefits were recorded using a life cycle assessment. The fly ash residues and sludge from the bioenergy wastewater treatment plant (WWTP), respectively were utilized to produce fertilizers.	[128]
A building-based production of electricity by solar energy was reported. Sustainable water and wastewater resources management were performed by reducing, reusing, and recycling where consumers were considered producers called prosumers.	[129]
Sustainable water resources management was at a building scale to achieve CRE concept.	[130]
CRE in the water system and sanitation sectors was implemented at a national scale where the present challenges and prospects were described from Finland's perspective.	[131]
This study focused on the circularity of hydrologic cycle to achieve urban and regional circular water resource management.	[132]
To assess whether CRE framework is followed or not and the suitability of the existing policy's effectiveness, a regional-level study was performed in the EU.	[133]
In this study, CRE indicators were developed to measure the reusability potential of waste produced from pulp and paper industries to stringent observation and implementation of CRE strategies.	[134]
This study provided criteria for the wine industries regarding water expending and wastewater generation which created cognizance of winery personnel in the direction of proper wastewater management.	[135]
The application of CRE approaches to reduce environmental impacts from water, energy, and food sectors. LCA was also performed to understand the interconnections between these sectors.	[136]
This study focused CRE application in water resource management in India. Emphasis was given on 6Rs (reduce, reuse, recycle, reclaim, recover, restore) for waste management and sustainable development.	[137]
Studies focusing technological viewpoint of CRE and WI	
The prospects and possible applications of environmental biotechnology in wastewater management and resource recovery were discussed in this paper based on CRE concept.	[138]
An overview of biological techniques to separate precious elements from wastewater was highlighted, and potential challenges and avenues were also discussed in a CRE framework.	[139]
A review of the current prospect of energy and resources recovery from anaerobic wastewater treatment (WWT) facilities integrating the concept of biorefinery and CRE.	[140]
An overview of sustainable sludge management for resource recovery from WWTP and relevant technologies with their challenges were discussed in this paper.	[141]
Recovery of precious resources from waste streams of sulphate-containing wastewater was proposed.	[142]
The microbial fuel cell (MFC) was considered the most feasible energy recovery option from wastewater for the circularity of resources. This study asserted that MFC will be the sustainable security of energy if future research can be continued.	[143]
Self-sufficient WWTP has been proposed in this study integrating co-digestion of anaerobic treatment and production of photovoltaic energy by applying the principle of CRE.	[144]
Nutrient recovery from wastewater, especially phosphorus (P) is considered most significant because of the continuous decrease of P from natural environmental and eutrophication problems caused by P. A spatial analysis of the production and consumption of P was carried out globally in this study and recycling of this nutrient was highly emphasized in wastewater.	[145]
An overview of P recovery and recycling using different techniques from its non-reactive forms to reactive forms based on wastewater and sludge.	[146]
This study focused development of adsorbents from WWTP's sludge to recover P by adsorption technologies.	[147]
This study considered the role of vivianite (a P-binding chemical) in the recovery of P from WWTP.	[148]
P removal and recovery were recorded by an adsorption-desorption process using phosphate binding protein, which was considered significant for the CRE of P.	[119]
This study focused on combined techniques to recover Nitrogen (N) and P which revealed precious insights and co-benefits in CRE.	[149]
The fertilizer's values of N and P depend on the waste type. This study tries to mix up different wastes to enhance fertilizer values, and suggested sewage sludge had the highest potential for CRE perspective.	[120]
This study focused on bio-sludge derived from pulp and paper industries to investigate the quality of N in terms of fertilizer and revealed the positive value of N in CRE pathways.	[118]
This paper suggested a plausible roadmap providing decision support techniques for different organizations doing nutrients (N and P) research and business in WWTP and AD to accomplish optimal nutrient recovery for a CRE.	[119]
This study used CREP perspective to produce fertilizer containing N and P from discarded water of AD process by chemical precipitation (CP) method.	[150]

(*continued on next page*)

Table 4 (*continued*)

Key findings	
Studies focusing economical viewpoint of CRE and WI	Studies
This paper reported AD process for the recovery of nutrients and removal of organic pollutants from the source-separated black water of a decentralized treatment plant using various filtration techniques.	[151]
An anaerobic membrane bioreactor (AMBR) was designed to recover energy and water for the treatment of dairy products; however, this idea was close to the sphere of resources and nutrients near the supply of waste production. Roset et al. [125] suggested this type of treatment system had health threats that need to be dealt with through centralized treatment processes.	[152,153]
Bioplastics recycle potential was evaluated from wastewater and sludge using polyhydroxyalkanoate. A technical feasibility study was also performed.	[154]
Several studies reported phytoremediation techniques with photo-bioreactor and cultivation of biomass to get benefits from CRE principle, the products are bioenergy, fertilizers, bioplastics, and water from wastewater. However, the health risks associated with the produced food and feed from biomass cultivation and its treatment by AD are prioritized by Markou et al. (2018).	[155–159]
This study focused to promote the wastewater biorefinery concept of dealing with wastewater from different industries for producing clean water and separating valuable resources. The authors integrated the idea of cleaner production, industrial ecology and CRE concepts towards environmental sustainability.	[160]
This paper described the converting techniques of WWTPs to biorefineries, implying novel technologies and alternatives to retrieve precious materials by CA group of Italy, which was a positive step in relation to CRE.	[161]
This study concentrated on transforming traditional wastewater treatment settings into the recovery of water resources emphasizing the anaerobic treatment technologies to accomplish the objectives of CRE and sustainable development.	[162]
This study prepared adsorbents for the recovery of precious metals from wastewater by pyrolysis process using AD's process-activated sludge.	[163]
Adsorption of source-separated urine by granular activated carbon (GAC) was performed by coconut shell to produce urea and fertilizers production is planned based on CRE principles.	[164]
A mini overview summarized the impacts of CWs on the recycling of water for agro-production, services related to the ecosystem, and carbon and nutrient recovery. The shifting of CWs from waste to new a paradigm providing CRE and sustainability is highly appreciated by Masi et al. (2018).	[165,166]
A novel design was proposed combining CWs and living walls in an urban region to alleviate climate change, water shortage and flood defence following CRE perspective.	[167]
An overview of membrane technologies for the treatment and recovery of industrial waste was stated in this paper.	[168]
In leather tanning industries chemical treatment of pickling solution was applied for the recovery of raw materials.	[169]
This paper studies the remediation of organic halogenated compounds from industrial wastewater targeting recycling in the CRE context.	[170]
This study focused on wastewater treatment by microbial biofilm development considering CRE principles.	[171]
Detailed methodology and advantages of volatile fatty acid (VFA) production from wastewater sludge within the context of CRE were provided.	[143]
Gallium recovery based on CRE principles was achieved in this study from wastewater of wafer production industries.	[172]
This study reported the CRE implementation for softening process of drinking water from a water treatment plant (WTP).	[173]
This study integrated information and communication technology (ICT) to bring sustainability in WI by reducing water loss and effective management of water resources for a CRE.	[174]
Studies focusing social viewpoint of CRE and WI	
The CRE principles were applied in this study to connect human actions and water-associated laws and policies for better solutions to water resources problems.	[175]
The proper water and wastewater management plans make smart cities integrate good governance and legal issues prioritizing the circular use of water resources.	[176]
This study emphasized the implications of policy and strategies to reduce water use and make sure no water is wasted by applying an organized governance framework in a CRE in Indonesia.	[177]
This study reported the unorganized reuse of wastewater in Chile where appropriate policies are not available. The authors emphasized formulating policies for resource recovery from wastewater in the background of CRE.	[178]
This study revealed the negative impacts of reuse wastewater due to antibiotic residue contamination on plant growth, plant uptake and ultimately effects on human health.	[179]
CRE viewpoint was applied for assessing effectiveness of EU policy frameworks to ensure sustainability of water and land.	[180]
This study developed a concept of water smart CRE engaging policy instruments and social stakeholders to reduce water and energy loss, increase water efficiency and productivity, reuse treated water/wastewater and reduce pressure on aquatic ecosystems.	[181]
This study offered a unique CRE framework for identifying strategies and issues applicable to basic supply chain of food and water sectors in Gulf Cooperation Council (GCC).	[182]
This study investigated the interactions of water-energy-nutrient nexus in a CRE framework which ultimately helps to develop bio-based business models and creating value-added agrifood products.	[183]
This paper represented the agricultural water management considering different environmental legislative, water management guidelines and CRE practices in Brazil, Germany, Japan, Mexico, Morocco, Portugal, and Taiwan.	[184]
Studies focusing multiple aspects of CRE and WI	
Economic, environmental, social, and technical	[185 – 190]
Environmental and technical	[191 – 197]
Economic and technical	[198 – 200]
Economic, environmental, and technical	[201 – 209]
Economic, environmental, and social	[210 – 213]
Environmental and social	[214 –217]
Economic and environmental	[218 – 225]
Social and strategic	[153,226]

and socio-environmental innovation [106]. The implementation strategies and assessment criteria of CRE in different sectors are still not uniform and effective. A compendious implementation guideline of CRE in the different organizations has been proposed by BS8001:2017 based on the six (6) pillars of CRE but the monitoring plans are not well managed [107]. The lack of unanimity and inappropriate actions to justify the applications of CRE hinders the progress of sector oriented CRE frameworks which could be advantageous to promote CRE in large-scale applications of various sectors [108]. Based on the shortcomings of the linear economy and water resources discrepancy, CRE has gained huge attraction to the scientific community and WI. Although, intensive research has been noted in terms of wastewater 6Rs strategies in fragmented approaches. The role of CRE to integrate these plans necessitate a multi-faceted perception. According to the scientific literature, CRE does not concentrate on water industries at a large-scale, also the applications, scopes, opportunities, limitations, and challenges of CRE implementation in water industries are still unexplored [109]. Thus, identification and the potential implications of CRE in water industries are essential for sustainable water resources management and resource recovery.

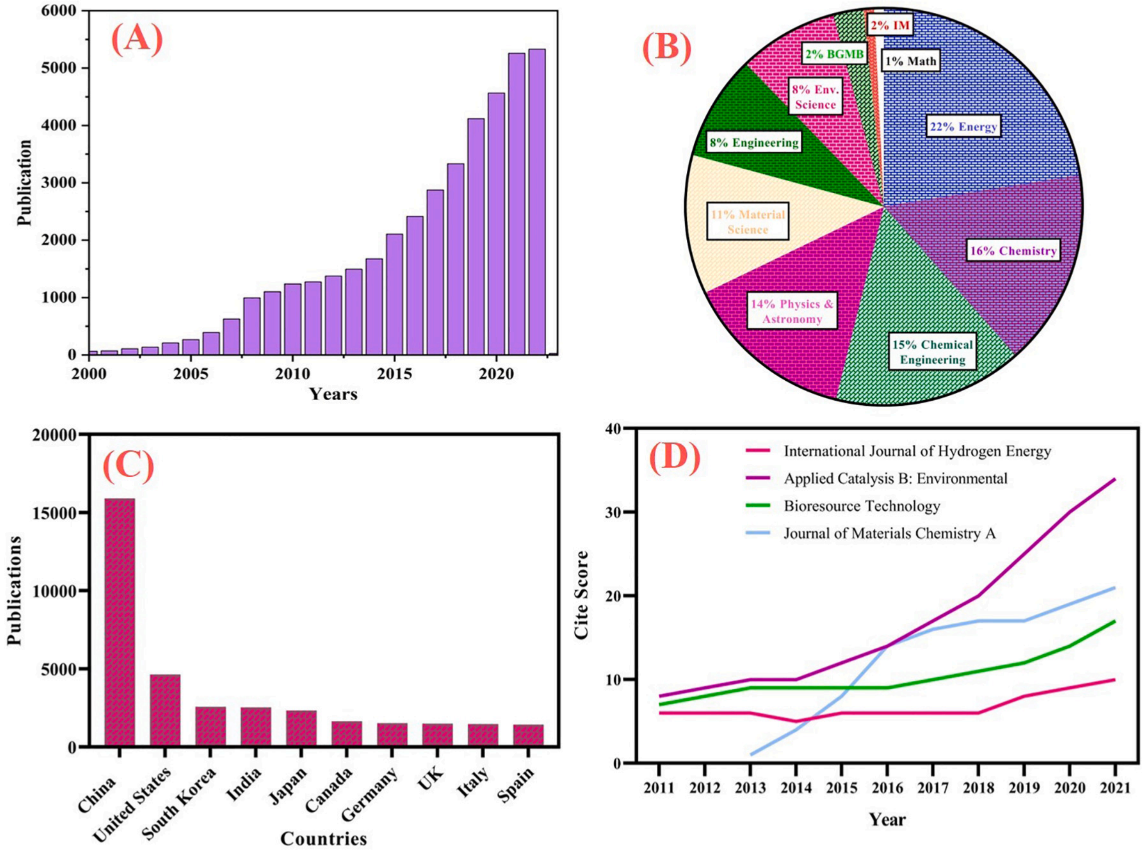

Fig. 10. HP publications. A) Evolution of the number of publications over the years (2000–2023) B) Publications over the subject areas C) Global distribution of the publications (top 10 countries) D) Citations score on the publications.

3.4. CRE in urban WI

The WI helps to circulate water within different components such as surface water, urban water and groundwater and these types of circulation influence the quality and quantity of water. The behavioral and good management practices of water by humans are considered the predominant issues for sustainable water resources management. Consequently, CRE pathways can be the only single way to long-term urban water resources management. The linear and circular distribution of water and wastewater resources as presented in Fig. 9. The CRE viewpoint is strongly suggested for water preservation, wastewater reduction, reuse, recycling, reclamation, recovery, and restoration.

3.5. CRE and WI-related studies

One hundred and fourteen (114) selective papers contented the purposes of CRE, and WI have been retrieved from scopus databases (2010–2023) and studied in-depth. The CRE and WI-related studies and their key findings have been summarized in Table 4. These studies can be grouped broadly into social, economical, environmental, and technological point of views. However, several combined categories also identified such as social and strategic, economic and environmental, environmental and social, economic, environmental, and social, economic, environmental, and technical, economic and technical, environmental and technical, and multiple aspects of CRE and WI.

4. Scientometric analysis of HP in a CRE framework

4.1. Publication evolution of HP research areas

Bibliometric analysis (BA) is now a crucial component of today's research evaluation. Furthermore, academicians and researchers are becoming more accustomed to them because of the expansion of online databases containing citation data and the introduction of improved analytical software. Compared to more conventional kinds of review, BA has many advantages. The findings of the BA highlight the top research fields, keywords, affiliations, journals, authors, and nations [227,228]. Each aspect of the HP research results was analyzed to highlight the hotspots, statistics, and research advancements in this area. The relevant data for the trend of publications between 2000 and 2023 was acquired using the scopus database. A total of 39,683 publications (37,406 original articles and 2277 reviews) from the literature search explored HP over the last 23 years. It was found that there were very few papers published in this field of study during the first eight years under investigation. Since then, publications have gradually fluctuated in quantity and quality throughout the past few years. The exponential growth in research on HP over the past five years, as shown in Fig. 10. is primarily attributed to the expanding demand for renewable energy, which is currently connected to a cutting-edge topic and required for a CRE by current environmental needs [229,230]. Table 5 provides the information generated through the scopus database, i.e., top 10 research areas, journals, affiliations, and authors. The International Journal of Hydrogen Energy, Applied Catalysis B Environmental, and Chemical Engineering Journal were the dominant research journals.

4.2. Most used keywords for HP and wastewater (WW) in the field of CRE

One of the most critical parts of a BA is identifying the fundamental keywords in a research field. Analyzing keyword co-occurrences might help discover research potential and strengths [231]. In this BA, to visualize the keywords, we utilized the VOSviewer software. Fig. 11

Table 5

BA of top 10 publications regarding research areas, affiliations, journals, and authors based on the number of publications over the last 23 years.

Attributes	Documents
Scopus (2000–2023)	39,683
Articles	37,406
Reviews	2277

Ranking	Research Areas	Number	Percentage (%)
1st	Energy	20161	50.81
2nd	Chemistry	14350	36.16
3rd	Chemical Engineering	13862	34.93
4th	Physics and Astronomy	12531	31.58
5th	Materials Science	10180	25.65
6th	Engineering	7679	19.35
7th	Environmental Science	7290	18.37
8th	Biochemistry, Genetics, and Molecular Biology (BGMB)	2215	5.58
9th	Immunology and Microbiology (IM)	775	1.95
10th	Mathematics	698	1.76

Ranking	Journals	Number	Percentage (%)
1st	International Journal of Hydrogen Energy	8186	20.63
2nd	Applied Catalysis B Environmental	1071	2.70
3rd	Chemical Engineering Journal	811	2.04
4th	Bioresource Technology	789	1.99
5th	Journal of Materials Chemistry A	769	1.94
6th	Applied Surface Science	642	1.62
7th	Journal of Power Sources	571	1.44
8th	ACS Applied Materials and Interfaces	529	1.33
9th	Fuel	501	1.26
10th	Energy Conversion and Management	493	1.24

Ranking	Affiliations (Country)	Number	Percentage (%)
1st	Ministry of Education China	2181	5.50
2nd	Chinese Academy of Sciences	2077	5.23
3rd	University of Chinese Academy of Sciences	680	1.71
4th	Xi'an Jiaotong University	592	1.49
5th	Harbin Institute of Technology	553	1.39
6th	Tsinghua University	545	1.37
7th	University of Science and Technology of China	504	1.27
8th	Ontario Tech University	497	1.25
9th	CNRS Centre National de la Recherche Scientifique	475	1.20
10th	Tianjin University	455	1.15

Ranking	Authors	Number	Percentage (%)
1st	Dincer, I.	404	1.02
2nd	Guo, L.	198	0.50
3rd	Jin, Z.	144	0.36
4th	Naterer, G.F.	116	0.29
5th	Rahimpour, M.R.	112	0.28
6th	Rosen, M.A.	111	0.28
7th	Williams, P.T.	92	0.23
8th	Ren, N.Q.	90	0.23
9th	Kumar, G.	90	0.23
10th	Zhang, Q.	87	0.22

presents the bibliometric keyword analysis of HP and WW used by authors during the previous 23 years. Out of the 27, 355 keywords, 1049 were analyzed, but only 60 met the threshold; these keywords are grouped into 4 clusters. Cluster 1 “red” comprises 413 keywords, and it concerns WW. Cluster 2 “green” consists of 357 keywords regarding HP and its production technology. Cluster 3 “blue,” consists of 187 keywords, and its main topic is water treatment. Cluster 4 “yellow” consists of 92 keywords reserved for fermentation. Contrarily, Fig. 12 represents research on HP in the CRE, which has recently attracted attention. As a result, recent research efforts have concentrated on simplifying the procedure to produce hydrogen in a more affordable, environmentally friendly, and effective manner [31,232]. The interdisciplinary nature of the research topic is illustrated by a network visualization keyword study (Fig. 12) that aggregated the top 72 keywords into 5 clusters. The intensity of the color used for each cluster of keywords in the density map, which denotes the significant areas of contention in the subject of study, was another aspect to consider [233]. Consequently, the most frequent keywords found were “hydrogen production”, “wastewater treatment”, “Biohydrogen”, “electrolysis”, “fermentation”, and “circular economy”.

4.3. Recent advancements in hydrogen production technologies

Hydrogen is a fuel that can be generated using a wide range of methods from various feedstocks. The processes for generating hydrogen can be categorized into two groups depending on the types of feedstocks: hydrogen generation from FFs and renewable sources [234,235].

4.3.1. H_2 from FFs

Fuel processing technologies require methane, ammonia, coal, and sulfur to convert them into hydrogen. The most prevalent technique of producing hydrogen currently used in industry is methane processing in fuel. We provide additional methods for producing hydrogen from FFs following a through literature review.

4.3.1.1. Hydrocarbon reforming. Hydrogen is produced from hydrocarbon fuels using four main methods: steam reforming (SR), partial oxidation (PO_X), and autothermal reforming (ATR) and Water-Gas-Shift (WGS). Table S6 summarizes each of these processes' advantages, challenges, and technical efficiency.

1. Steam methane reforming (SMR)

SMR is currently the most popular technique for producing hydrogen, and almost half of the hydrogen in the world comes from this source. Due to the endothermic nature of the process, heat should be added to start the reaction. Typically, it is done at high temperatures of around 800 °C with precious metals or nickel-based compounds acting as catalysts [236]. The reforming mechanism goes through methane and water vapor reactions to produce syngas with primarily H_2 and CO, which are then converted to CO_2. CO_2 is finally taken out of the gas to improve the purity of hydrogen gas. The following chemical reactions occur in the SMR process:

$$CH_4 + H_2O \rightarrow CO + 3H_2 \tag{4}$$

$$CO + H_2O \rightarrow CO_2 + H_2 \tag{5}$$

There are numerous factors affecting SMR technology, i.e., the standard of feedstocks, the selection of fuel and catalyst, the kind of reactor, and so on [237]. Economically speaking, SMR is more affordable and appropriate for mass manufacturing of H_2.

2. Partial Oxidation (PO_X)

Another commercially used method of producing hydrogen from natural gas is PO_X. It occurs when the amount of oxygen given into the reformer is less than what is required for complete oxidation, converting oxygenated hydrocarbon into syngas with high operating temperatures (>900 °C and often >1200 °C) to make H_2 and CO. The fuel or reactant burns entirely during total oxidation, which lowers the hydrogen output [205,207]. The system no longer needs external heat sources because the reaction is exothermic and generates heat through the oxidation (combustion) of methane, as shown in the following reaction:

$$CH_4 + \frac{1}{2}O_2 \rightarrow CO + 2H_2 \tag{6}$$

Purified oxygen is required for the partial oxidation process; hence the cost of purchasing oxygen must be included in the production costs.

3. Autothermal reforming (ATR)

ATR technology brings together the benefits of SMR and PO_X procedures. Linking the components of two processes in a sequence enables the synthesis of hydrogen. The partial oxidation of natural gas produces the heat needed for ATR (700 to 1000 °C), and steam reforming is accomplished using the exotherm of the oxidation process [238]. This chain of reactions will proceed continually when the system achieves overall thermal equilibrium through exothermic and endothermic processes. ATR technology is currently not widely available commercially due to financial reasons [239].

4. Water-Gas-Shift (WGS)

WGS reaction is a powerful tool for efficiently producing hydrogen from carbonaceous sources. The hydrogen produced by the SMR process contains a large amount of CO, typically 5 % or more. Typically, a feed containing steam and CO is transferred into a WGS reactor to raise the hydrogen content while lowering the CO level. As a substitute, methane can be utilized as a supply of CO through the partial catalytic oxidation process. To make highly pure (>99.999 %) hydrogen, a membrane or pressure swing adsorption can be employed [209,211] with WGS.

4.3.1.2. Coal gasification (CG). Coal has the most significant FFs reserves, offering a practical method for producing hydrogen. Primarily, CG is used to convert coal to hydrogen. The fundamental mechanisms of CG are as follows: after being dried and crushed, coal is delivered into a gasifier where it repeatedly combines with oxygen and steam at high temperatures (1600 to 1900 °C) to create a gas mixture that contains H_2, CO, and CO_2 [240] stated in the following equations:

$$C + O_2 \rightarrow CO_2 \tag{7}$$

$$C + H_2O \rightarrow CO_2 + H_2 \tag{8}$$

Researchers have tried incorporating CCS technology to control the detrimental environmental impact that CO_2 emission causes. Kovacs et al. [241] evaluated the GHGs emissions from CG with and without CCS, and the findings revealed that adopting CCS could reduce GHGs emissions by 81.72 %.

4.3.1.3. Hydrocarbon pyrolysis (HCP). Pyrolysis is another hydrogen-producing technology where the hydrocarbon is decomposed into hydrogen and carbon. No emissions (e.g., CO or CO_2) are generated in this process due to the absence of air and water during the following reaction:

$$CH_4 \rightarrow C + 2H \tag{9}$$

Pyrolysis may play a significant role for decreasing CO and CO_2 emissions and its ability to be operated in a way that recovers a considerable portion of the solid carbon that is easily stored [242,243].

4.3.1.4. Desulfurization (DS). The method of purifying natural gas to remove sulfur from fuels like methanol, propane, gasoline, and logistic fuels like jet-A, diesel, JP8, etc., are currently used to produce hydrogen. Alkylation and hydrodesulfurization (HDS) are two mechanisms for removing sulfur. HDS is used in most large-scale commercial applications; as a result, significant catalysts and process optimization have occurred. In this procedure, HDS catalysts either entirely or partially hydrogenate the molecules that contain sulfur, releasing the sulfur as H_2S. The sulfur-containing molecule's boiling point rises due to this technology's increased molecular weight. As a result, sulfur can be removed using distillation techniques. An advantage of HDS is that this method does not require high-pressure hydrogen [209].

4.3.1.5. Plasma reforming (PR). In plasma reforming, a plasma often produced with electricity or heat supplies the energy and free radicals needed for the reforming reaction [211]. Injecting water or steam with the fuel causes the formation of H, OH, and O radicals together with electrons, facilitating both oxidative and reductive reactions [206]. Plasma reforming technologies have been created to enable PO_X, ATR, and SR. This technology has been utilized with or without catalysts to break hydrocarbon streams before they enter conventional reforming reactors. The most effective method seemed to be a non-thermal gliding

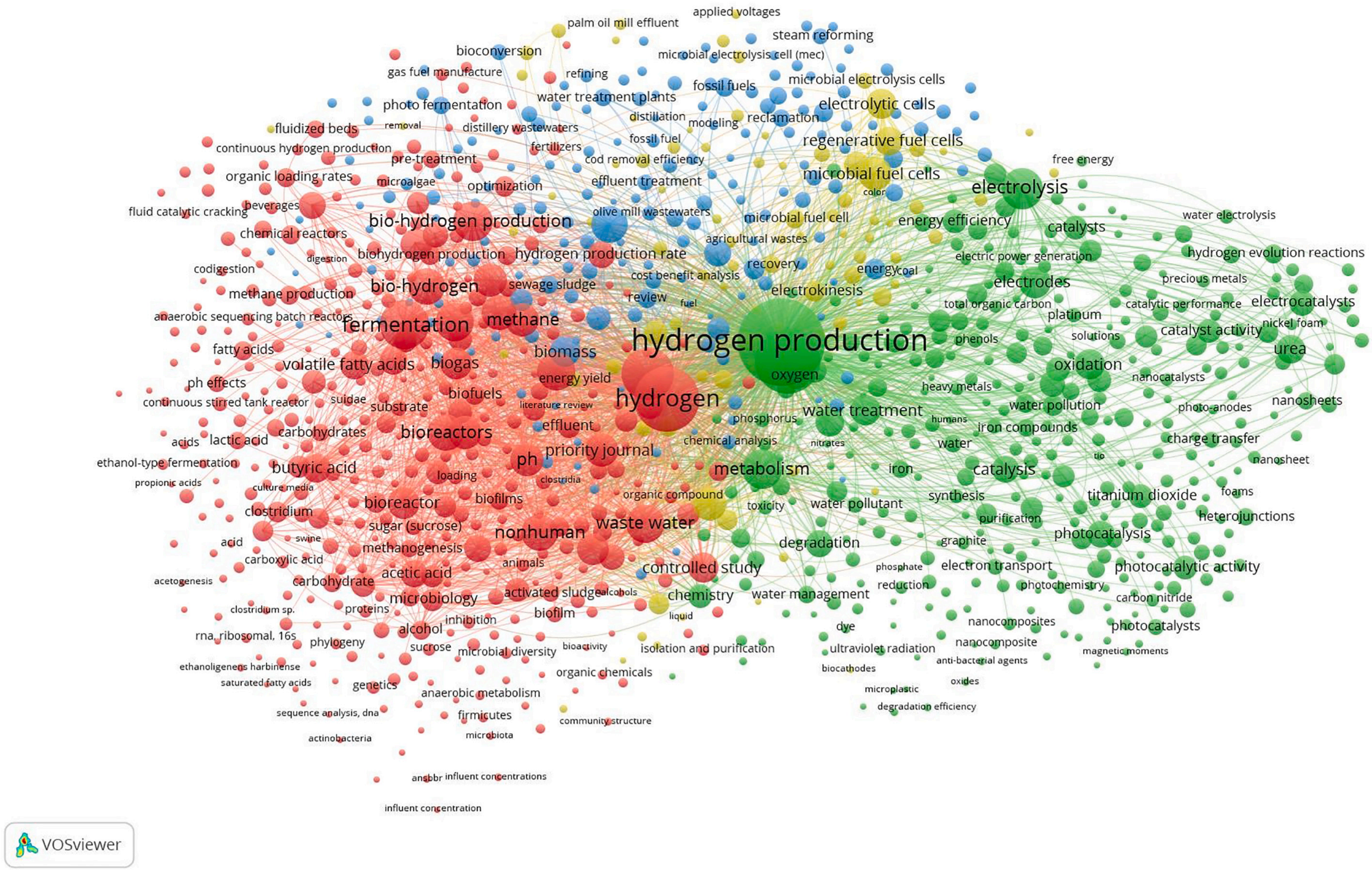

Fig. 11. BA of the keywords related to HP and WW.

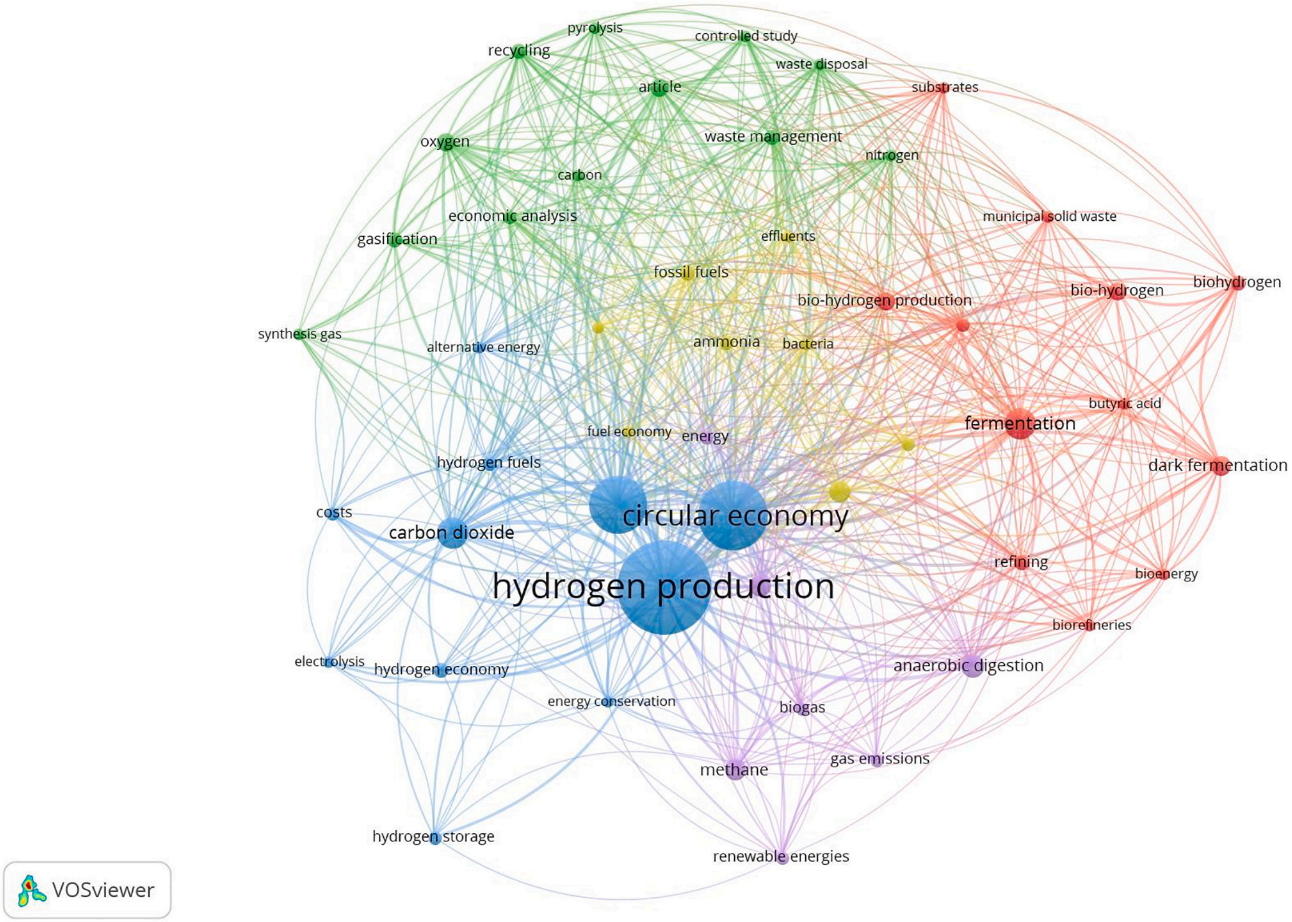

Fig. 12. Significant keywords analysis in hydrogen and CRE research during 2000–2023.

arc plasma.

4.3.1.6. Aqueous phase reforming (APR). APR is being developed to convert oxygenated hydrocarbons or carbohydrates into hydrogen [209]. These reactors frequently run at temperatures between 220 and 270 °C and pressure up to 25 to 30 MPa. APR takes place at low temperatures, allowing WGS to boost the hydrogen yield while reducing CO. However, the catalyst was not stable during long-term tests (200 days on stream) [244]. Microreactor technology, which tends to be rather large and has moderate space-time yields, enhances APR.

4.3.1.7. Ammonia reforming (AR). AR primarily intends to use fuel cells to create hydrogen through the ammonia cracking process. Ammonia decomposition (cracking) reaction is endothermic, simply the reverse of the synthesis reaction [245]. The following reaction occurs at temperatures around 800–900 °C and pressures 250 atm, unlike ammonia synthesis, respectively.

$$Nh_2 \rightarrow \frac{1}{2} + \frac{3}{2} h_2 \tag{10}$$

4.3.2. H_2 production from renewable sources

Using renewable energy sources to produce hydrogen can ensure future energy security. Consequently, various renewable sources, including hydrolysis, water splitting, and biomass, are used to generate green hydrogen are briefly discussed in Section 5.

This study compares, analyses, and assesses several techniques of producing hydrogen based on their primary sources of electrical, thermal, and photonic energy and their typical production costs. Table 6 summarizes these average values and indicates that photonic-based H_2 generation is the most environmentally friendly option, closely followed by hybrid production techniques. Both choices, meanwhile, exhibit low efficiency and high production costs. Despite having the highest energy efficiency, electrical energy also has a high manufacturing cost.

Today's most practical and economical method for manufacturing hydrogen on a large scale from renewable energy sources also poses the most significant environmental risks. Biomass gasification presents an alternate solution due to its reasonable price and lack of additional carbon emissions. However, its effectiveness must be increased, and the impurity issue must be solved. There are numerous benefits to microbial hydrogen production. But since this technology is still in the lab, it cannot be quickly and widely used. This issue can be resolved using electrolysis powered by biomass, wind, solar, and nuclear energy. With the trend of power structure change, it will have more potential. The most practical application now is water electrolysis, and this technology is transitioning from alkaline electrolysis (AEL) to the more adaptable proton exchange membrane electrolysis (PEM). Nuclear energy offers more cost-effective electrolysis and thermolysis compared to other energy sources. Given that nuclear energy is expected to eventually dominate the generation of hydrogen, it is essential to analyze its technological development and safety.

4.4. H_2 production patent analysis

Patent analysis has long been acknowledged as a vital tool for technology monitoring because it may illustrate present innovation and past evolution in a particular technical sector. The analysis of technical trends, the identification of significant technologies, the investigation of emerging technologies, and the projection of technological advancement are all typical applications of analysis [204]. The application of patent analysis to the field of hydrogen energy has been observed over time. The annual evolution of hydrogen generating technology is depicted in Fig. S5A. An average yearly growth rate of 4.21 % is seen in the patent activity field. The scopus database shows 13,341 patent applications for hydrogen production technologies, and 23,246 patents were discovered in wastewater hydrogen production. The five years with the maximum patent activity were 2021 (1358), 2020 (1314), 2019 (1238), 2018 (1237), 2016, 2014, and 2010 (1211). Japan dominates most of the patent-holding nations and regions in the field. With 2829 patent filings for inventions related to hydrogen production, Japan has taken the lead in these areas over the past 20 years. Three other Asian nations, namely China (1869), South Korea (709), and India (288), are included in the top 10 nations or regions list. Collaboration on international patents may contribute to the growth of a technological area. Japan and the United States have the most shared patents (793) out of all the countries [246]. The top 10 most active patent assignees in hydrogen production methods are shown in Fig. S5B. According to the data, all ten assignees are Japanese corporations, underscoring Japan's dominance in the field's development. The Asian firm from China, Shanghai Hejide Dynamic Hydrogen Machine Co. Ltd., which has 63 patent applications and is ranked 12th in the industry, is the non-Japanese company with the highest number of patent applications. Additionally, Intelligent Energy Inc., a US-based business, has filed 31 patents and is ranked 24th in the industry as the non-Asian company with the most patents deposited between 2000 and 2023 [247]. The patent analysis findings add to the knowledge volume by demonstrating the trends in various areas of HP technologies.

4.5. *Summary of significant findings of the BA*

This BA reviewed the production of hydrogen energy from water and wastewater. From 2000 until 2023, a total of 39,683 publications (37,406 articles and 2277 reviews) were recorded. The bibliometric analysis found a tendency towards producing hydrogen from renewable sources to ease the burden on utilizing FFs and eventually establish a CRE. The most used keywords were associated with the possibility of integrating hydrogen and wastewater in terms of CRE. In this study, the overall hydrogen production methods based on electrical, thermal, photonic, and hybrid energy sources are evaluated and compared in terms of their production cost and technological aspects. Water, biomass, and FFs are the material resources used in these techniques. Compared with the overall production method, the most environmentally friendly HP offers photonic energy, and the highest efficiency offers thermal energy. The current inquiry has shown that the field's patent activities are expanding consistently at a pace of 4.21 % per year, with the first decade of the study period recording the highest growth. Over the past two decades, the R&D hotspot has been divided into three major categories: (1) fuel cells and electrical HP methods, (2) end products from HP, and (3) hydrogen generation by methane and methanol steam reforming. With a technical maturity rate of 66 % compared to 57 % for renewable-based technologies, FFs-based HP technologies are the most advanced. With 67 % and 33 % of all patent applications submitted over the last five years, renewable-based innovations have received much more attention than FFs-based ones. WEL is now the most viable application, along with wind or solar energy. Additionally, initiatives are being undertaken to develop electrocatalysts, lower production costs, and safeguard electrodes.

Table 6
Overall comparisons of hydrogen production methods based on primary energy sources [206,213].

Primary energy	HP methods	Energy efficiency (%)	Average production cost ($/kg)
Electrical	Electrolysis Plasma arc decomposition	6.15	8.26
Thermal	Thermolysis Thermochemical Water Splitting Thermochemical conversion of Biomass Gasification Reforming	5.04	7.69
Photonic	PV Electrolysis Photo-catalysis Photo-Electrochemical method	0.71	6.23
Hybrid	High-temperature electrolysis Hybrid thermochemical cycle Bio-photolysis Photo-fermentation Artificial Photosynthesis Photo-electrolysis	2.13	7.08

5. Hydrogen production technologies in WI

HP can be divided into four major methods: (i) biological, (ii) electrical, (iii) photonic, and (iv) thermal. These major methods ca be further branched into different minor methods. Researchers characterized hydrogen production technologies from WI in different ways [203,207,213]. However, in this study hydrogen production technologies can be broadly categorized into three types based on the feed sources i.e., pure water, wastewater, and saline water/others.

5.1. *HP from pure/decontaminated water by electrolysis technologies*

Water electrolysis (WEL) is considered one of the most significant hydrogen production technologies due to the integration of renewable energy sources such as solar, wind, and biomass as DC power to produce high-purity hydrogen (H_2) while generating only oxygen (O_2) as a by-product. This technology is the safest one in terms of environmental sustainability, yet a mere 4 % of total hydrogen comes from WEL nowadays considering the economic viability of this technology [248,249]. WEL technique simply dissociates the water into H_2 and O_2 influenced by electricity. WEL technologies can be grouped into seven categories [250–255] as follows based on the membrane types, electrolytes, operational circumstances, and ionic agents although in all cases operating principles are unique.

a. Proton exchange membrane (PEM) electrolysis
b. Alkaline water electrolysis (AEL)
c. Anion exchange membrane electrolysis (AEM)
d. Solid oxide electrolysis (SOEL)
e. Acid-alkaline amphoteric electrolysis (AAEL)
f. Microbial electrolysis cells (MECs)
g. Photoelectrochemical electrolysis (PECM)

5.1.1. *Proton exchange membrane electrolysis (PEM)*

PEM is the most widely used WEL technology that produces electricity in fuel cells and hydrogen in electrolyzers. PEMs separate the anode and cathode. Nafion™-based membranes have high ionic conductivity, excellent mechanical stability, and durability at low temperatures and higher levels of relative humidity making PEM the most popular WEL technology for hydrogen production [256–260]. PEM electrolyzers have significant current density and high voltage to produce ultra-pure (99.99 %) hydrogen [261] whereas the high price of catalysts and expensive membranes make their applications limited. The schematic illustration of a PEM electrolyzer is given in Fig. 13A.

5.1.2. *Alkaline water electrolysis (AEL)*

The typical components of an AEL electrolyzer are electrodes, a

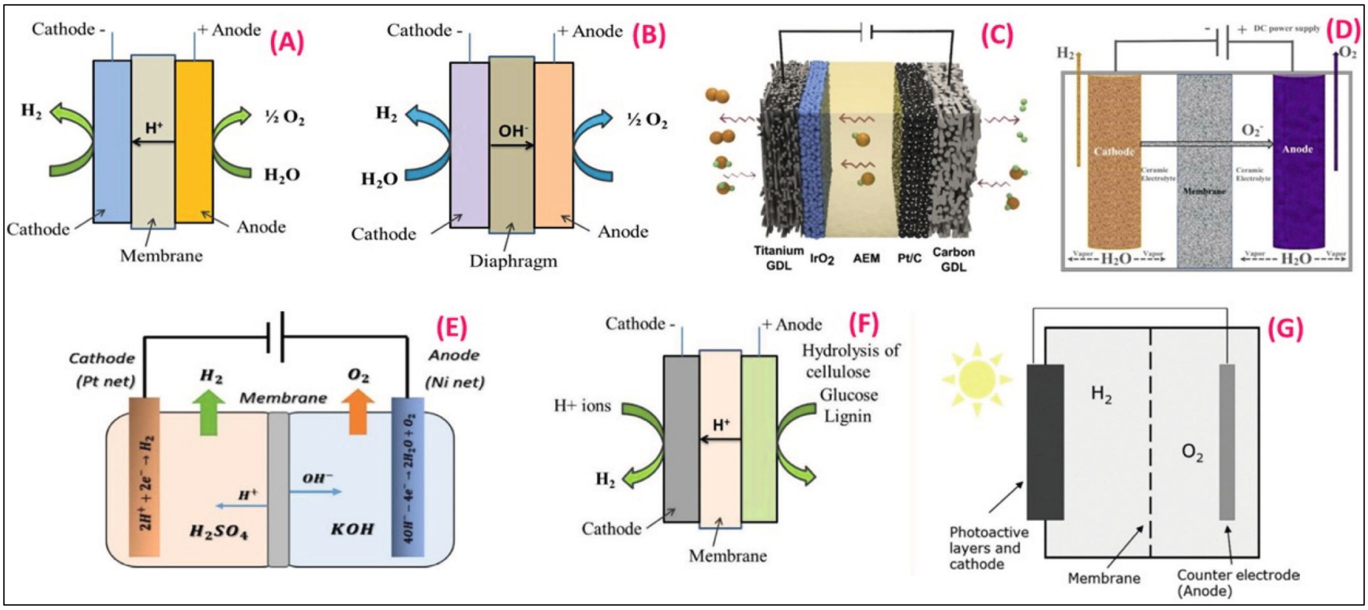

Fig. 13. Hydrogen production technologies from pure water: (A) PEM; (B) AEL; (C) AEM; (D) SOEL; (E) AAEL; (F) MECs; (G) PECM [247,254,255,258–261]. A portion of this figure was modified with the copyright permission from 2019 Elsevier and 2021 MDPI.

microporous separator, and an aqueous alkaline electrolyte with a concentration of around 30 % KOH or NaOH. Nickel with a catalytic coating, such as platinum, is the most typical cathode material in AEL electrolyzers. Metals covered with metal oxides, such as nickel or copper, are utilized as the anode. Water is introduced into an alkaline cell's cathode, breaking it down into H^+ and OH^-. A gas-liquid separation unit outside the electrolyzer is then used to separate the hydrogen from the water [262]. AEL is considered a well-established hydrogen production technology worldwide which was first explored by Troostwijk and Diemann in 1789 [263–266]. AEL can be operated at lower temperatures such as 30–80 °C with an aqueous solution (KOH/NaOH) as the electrolytes, the concentration of the electrolytes can be varied up to 20–30 % [267–269]. The schematic view of an AEL cell is illustrated in Fig. 13B. Nonetheless, AEL technology suffers from low current density and pressure, consequently less energy efficiency.

5.1.3. *Anion exchange membrane electrolysis (AEM)*

Hybridization of PEM and AEL technologies make AEM, which has benefits of both technologies. AEM cell consists of an anion exchange membrane (AEM) made-up with hydrocarbon materials and two transitional metals i.e., iridium (Ir) and platinum (Pt) catalyst-based electrodes [270,271]. AEM needs moderate alkaline electrolytes compared to AEL or simply deionized water can be served the same purposes. Moreover, economic catalysts and stack materials can be incorporated into the AEM electrolyzer [272]. However, AEM suffers from low ionic conductivity, energy efficiency, membrane stability and large ohmic resistance failure and huge quantities of catalyst's input [231]. Development and integration of solid polymer AEM is the current challenge for AEM which requires efforts on catalysts design and fabrication [244,273]. The schematic of an AEM electrolysis cell is presented in Fig. 13C.

5.1.4. *Solid oxide electrolysis (SOEL)*

SOEL technology is well recognized for its extremely high efficiency to convert electrical energy to chemical energy and generates ultra-pure hydrogen [274]. However, this technology is yet under extensive research and development stage after its inception in 1980 by Donitz and Erdle [247]. SOEL works at elevated temperatures ranging from 500 to 1000 °C and integration of ceramic membranes makes SOEL compact and hence has increased response time compared to PEM electrolysis. SOEL technology has dual function, i.e., fuel cell and electrolyzer, with also significant ionic conductivity [275] because of solid-oxide electrolyzer. However, SOEL has several drawbacks, e.g., immature technology, energy intensive, high expenditure, minimal durability, and continuous requirement of high temperature [276,277]. A schematic of SOEL is given in Fig. 13D.

5.1.5. *Acid-alkaline amphoteric electrolysis (AAEL)*

AAEL technology is considered extremely potential for generating hydrogen but needs high-cost functional polymers to construct membranes materials. The operating conditions for AAEL technique vary from 20 to 60 °C temperature, 1.98–2.2 V and 200–800 A cm^{-2} with sulfuric acid (H_2SO_4) and potassium hydroxide (KOH) electrolytes. AAEL electrolysis can be considered a highly efficient process even up to 100 % with some added advantages including reduced overpotential and energy consumption and approximately four times hydrogen production compared to AEL [278]. Nonetheless, AAEL setup requires a bipolar ion-exchange membrane for concurrent application of acidic and alkaline electrolytes in the process [279]. A schematic of AAEL has been given in Fig. 13E.

5.1.6. *Microbial electrolysis cells (MECs)*

MECs technology is the suitable hydrogen producing technology for a wide range of feed sources i.e., pure water, organic matter, or wastewater, which turns electrical energy into chemical energy. MECs electrolysis is quite like microbial fuel cell (MFCs) while operational mechanisms occur in a reverse direction [280]. MECs can produce hydrogen with low external voltage although it requires high inner resistance, complex cell design, high membrane stability, and operating expenditure. MECs are in its initial stages of commercialization [281]. The schematic representation of MECs has been illustrated in Fig. 13F.

5.1.7. *Photoelectrochemical electrolysis (PECM)*

PECM system (Fig. 13G), which transforms solar energy to direct hydrogen applying an easy setup, has received substantial attention in recent years. PECM dissociates water into H_2 and O_2 by capturing photon energy in a semiconductor stuff linked with electrocatalysts [282–284]. PECM is in its early stage of development with a very minimal hydrogen production efficiency (<10 %). Collaboration and cooperation are needed in integrating the scientific community and

Table 7
Summary of the advantages and drawbacks of the current HP technologies from decontaminate/pure water [247,254,255,285–288].

WEL technologies	Advantages	Drawbacks
PEM	Ultra-pure hydrogen (>99.99 %) Excellent current density High efficiency of power Dynamic operation Establish technology	Catalysts have high cost Medium durability Expensive membrane materials Expensive stack materials
AEL	Well developed technology Economically viable Durable electrolyzer Can be operate at low temperature Cheap electrocatalysts	Corrosive electrolytes Low current density Energy efficiency is low Hydrogen purity is low Low operating pressure
AEM	Low catalysts cost Cheap stack materials	Less ionic conductivity Initial stage of development Low energy efficiency Membrane stability is poor Catalysts loading are high
SOEL	Ultra-pure hydrogen Excellent ionic conductivity Excellent reaction efficiency Have dual functions	Energy intensive Economically not suitable High operating temperature Initial development stage
AAEL	Energy consumption is less Overpotential is less High hydrogen productivity	Enhance membrane resistance Bipolar ion-exchange membranes are needed Need both acid and alkaline electrolytes
MECs	Low voltage Can be used organic materials	Complex process design Lower productivity of hydrogen Yet in lab-scale Capital cost is high
PECM	Simple setup Direct solar to hydrogen	Lower energy conversion Lower hydrogen production Early stage of development

industries to increase the efficiency of PECM. Table 7 summarizes the advantages and drawbacks of the HP technologies from pure water.

5.2. HP technologies in WW

HP from WW encompasses a narrower scientific field. The HP technologies from wastewater have been summarized in Table 8 and the advantages and drawbacks of HP technologies in WW are summarized in Table 9. WW is considered a promising source of hydrogen for several reasons, including abundancy and ease of access considering today's domestic and industrial development and WW generation [178]. The major HP technologies in wastewater are described briefly as follows:

5.2.1. Bio-photolysis

In the process of bio-photolysis, some light-sensitive microorganisms serve as biological converters in a photobioreactor designed explicitly for this purpose. The most suited microorganisms are microalgae since they can be cultivated and have the potential to produce hydrogen in closed environments, allowing for hydrogen capture [289]. Cultured microalgal strains display high hydrogen yield. With the aid of photo-activated enzymes, the following reactions often generate hydrogen:

$$6H_2O + 6CO_2 \rightarrow C_6H_{12}O_6 + 6O_2 \quad (11)$$

$$C_6H_{12}O_6 + 6H_2O \rightarrow 6CO_2 + 12H_2 \quad (12)$$

5.2.2. Photo fermentation (PF)

In "photo fermentation", hydrogen is produced by breaking organic materials into hydrogen and carbon dioxide through microorganisms via this reaction:

$$CH_2O + H_2O \rightarrow 2H_2 + CO_2 \quad (13)$$

To maintain smooth hydrogen generation, it is essential to precisely regulate the culture environment for bacteria and the lighting conditions [290]. According to one source, the ideal temperature for a bioreactor is between 30 and 36 °C, while the ideal light wavelengths are between 400 and 1000 nm. Additional prerequisites include a strictly anaerobic atmosphere and a pH range of 6.8–7.5 [291,292].

5.2.3. Dark fermentation (DF)

Dark fermentation generates hydrogen under anaerobic conditions by breaking down complex organic materials into small molecules. A light source is not necessary for this operation. It can use several carbon sources, including biomass wastes [293]. Large organic molecules are initially broken down into soluble carbohydrates and other compounds, further hydrolyzed into more minor compounds like monosaccharides. In the end, they would be broken down into little molecules like organic acids and alcohols, producing H_2 and CO. As a result of the procedure, organic compounds, including acetic acid and butyric acid, may be produced [263,294 – 297].

5.2.4. Photocatalysis (PC)

Photocatalysis is the process in which one or both electrodes are exposed to heterogeneous photocatalysts. The electrolysis cell should also be supported by electrical energy to accomplish photocatalysis. Consequently, photocatalysis is a process that transforms electrical and photonic energy into chemical energy (hydrogen) [206]. The photo electrolytic hydrogen synthesis process starts with the creation of an electron-hole pair with the aid of a photon, followed by the flow of electrons from the anode to the cathode, which creates an electric current, the breakdown of water into hydrogen ions, and gaseous oxygen, the reduction of hydrogen ions at the cathode to produce hydrogen in the form of a gas, the separation of the product gases, processing, and storage [211].

5.2.5. Reverse electrodialysis (RED)

Another potential technology based on the salinity gradient characteristics of high and low saline water is RED. Seawater and sewage treated water were studied for hydrogen production [196,217]. A microbial reverse-electrodialysis cell (MRE) was constructed by Watson et al. [217] to produce hydrogen and to remove contaminants from wastewater such as COD. Song et al. [298] revealed hydrogen production of 0.61 $m^3 H_2/m^3/d$ with 81 % COD removal efficiency and 41 % coulombic efficiency with MREC. Comparative cost analysis of RED

Table 8
Overview of HP technologies in WI.

Technologies	Energy type	Type of wastewater	Stage of development
DF	Biochemical	Starch processing wastewater [306] Waste activated sludge [307] Beverage wastewater [308] Swine wastewater [309] Lactate wastewater [310] Winery wastewater [311] Distillery wastewater [312] Food processing wastewater [313] Paper mill wastewater [314]	Pilot-scale
PF	Biochemical	Food processing wastes [315] Distillery wastewater [316] Synthetic wastewater [317] Bread wastes [318] Synthetic gelatinaceous wastewater [319] Formaldehyde containing wastewater [320]	Pilot-scale
PC	Photonic	Pharmaceutical wastewater [321–323] Brewery industry wastewater [324] Dye treatment [225–327] Synthetic cadmium wastewater [328] Synthetic wastewater [301] Photo-reforming of wastewater [285] Synthetic wastewater [329] Sulphide wastewater [330] Synthetic wastewater [331] Formaldehyde containing wastewater [332] Wastewater from nuclear power plant [305]	Lab-scale
PECM	Photonic	Galvanizing industry [333] Oilfield wastewaters [334] Aromatic organics [335] Synthetic wastewater [336] Synthetic wastewater [337] Olive mill wastewater [338] Animal manure wastewater [339] Synthetic wastewater [340] Sugar industry wastewater [341] Pharmaceutical wastewater [342] Synthetic wastewater [343]	Lab-scale
MECs	Biological, Electrical	Primary sludge [344] Sugar industry [345] Azo dye decolorization [346] Urban wastewater [347,348] Synthetic wastewater [349] Landfill leachate wastewater [350] Municipal and industrial wastewater [201] Corn starch processing wastewater [274] Synthetic wastewater [351] Swine wastewater [352] Dye wastewater [319]	Pilot-scale
EL	Electrical	Aniline wastewaters [313] Urea [353] Ammonia, urea, and hydrazine [174]	Lab-scale
ED	Electrical	Mine tailings wastes, treated wastewater [354]	Lab-scale
RED	Concentration Gradient	Saline waters [217] Alkali and acidic waters [355]	R&D
MED	Electrical, Biological	Sulfate reduction [356] Synthetic wastewater [357]	R&D
SCGW	Hydrothermal	Phenol containing wastewaters [358] Food wastes [276] Wastewater sludge [277] Oil containing wastewater [359] Oilfield wastewater [360] Phenolic wastewater [361] Dairy wastewater [362]	Lab-scale

showed that simultaneous hydrogen and electricity generation could be possible with a high cost ($180/kg H_2 production) [299]. Simultaneous hydrogen production and struvite ($MgNH_4PO_4^{-2}.6H_2O$) precipitation was reported by a novel microbial reverse-electrodialysis electrolysis struvite-precipitation cell (MRESC) [300]. A multi-stage RED stack was applied for hydrogen production and enhance the energy efficiency [301]. The results showed that the maximum net output power, total hydrogen production, and total energy-conversion efficiency were 2.06 W, 881.88 mL h^{-1}, and 7.74 %, respectively. An air-gap diffusion distillation (AGDD)-RED model shown that hydrogen production and energy efficiency were achieved to be 3.7 L h^{-1} and 0.84 %, respectively [302]. However, hydrogen production by RED technology is still in its initial phase. Extensive research works should be carried out to reduce the membrane and heating cost, increasing the H_2 production rate [272].

5.2.6. *Supercritical water gasification (SCWG)*

Each fluid carries a specific critical temperature and pressure, and

Table 9
Advantages and drawbacks of HP technologies in WW [206,213].

Technologies	Advantages	Disadvantages
DF	Robust process Studied widely for high organic loads Low cost of materials Clean and sustainable	The process is limited by the activity of microorganisms Challenges for anaerobic treatment also applies to dark fermentation
PF	The high substrate to hydrogen ratio may be obtained using purple non-sulfur bacteria Disinfection of wastewaters	Hydrogenase enzyme has a high sensitivity for oxygen Low light conversion efficiency Metabolic and genetic engineering is required
PC	Numerous new photocatalyst material studies Durable and efficient photocatalysts available	Low light-to-hydrogen efficiency Hazardous chemicals may be required to produce advanced photocatalysts
PECM	Numerous new photocatalyst material studies Durable and efficient photocatalysts available	Low light-to-hydrogen efficiency Hazardous chemicals may be required to produce advanced photocatalysts
MECs	Low operation temperature Clean and sustainable Pilot-scale studies available	Expensive materials for electrolysis
EL	Treatment of wastewaters that contain ammonia, urea, or hydrazine is possible COD and nitrogen removal are possible with differentially controlling	Still in the R&D phase for wastewater The narrow range of application studies available
ED	Self-generating potentials of hydrogen Simultaneous resources recovery and hydrogen production can be possible Established technique for wastewater treatment	Limited research on hydrogen production Low efficiency Low purity hydrogen
RED	Production of energy and hydrogen by only concentration gradient between two solutions	High cost Energy intensive Only works on saline water
MED	COD removal with hydrogen production is possible	Still in the R&D phase Needs detailed analysis of the system
SCWG	A better alternative to biomass drying	High energy requirement Challenges in scaling up Needs higher temperatures for H_2 production Impurities are present in H_2

the fluid cannot be liquefied past the critical point, to be named a supercritical fluid. For water, supercritical conditions can be achieved at 22.12 MPa and 372.12 °C, and it acts as a strong oxidant above 600 °C. SCWG is a highly efficient method to decompose organics into CO_2 and H_2O in a short time [303]. Reactions inside a supercritical water gasification reactor can be generalized as:

$$CH_xOy + (2-y)\, H_2O \rightarrow CO_2 + (2-y+x/2)\, H_2 \tag{14}$$

$$CHxOy + (1-y)\, H_2O \rightarrow CO + (1-y+x/2)\, H_2 \tag{15}$$

Ibrahim and Akilli [304] studied supercritical water gasification SCWG for wastewater sludge. Energy conversation efficiency was reported to be 55 %, and H_2 rich syngas was obtained above 500 °C. A syngas with a 55.75 % H_2 molar ratio was obtained, and the gas yield was 19.86 mol/kg. Feng and Yang [305] utilized SCWG to decompose Analgin pharmaceutical WW. The hydrogen fraction of the produced gas increased with rising temperature. However, gasification efficiency was below 50 % for most of the experiments. Gasification efficiency reached around 85 % at 530 °C and gas yield was around 32–50 mol/kg in petrochemical WW.

6. HP technologies from seawater (SW) and urine

Oceans and inland seas contain 93 % of the earth's water. Most of the remaining 7 % of water is frozen in the arctic. The two most pressing issues in the globe are the lack of fresh water and the lack of energy due to the continued development of the global population, as well as increased industrial and agricultural needs. These severe matters of energy generation and the availability of fresh water can be resolved by utilizing our ample solar energy and the large amount of seawater available worldwide [363–369]. Since electrolyzers require ultrapure water, hydrogen production technique has a significant drawback. In light of this, before salt water can flow to the fragile membranes, it must first be desalinated, followed by thorough cleaning and filtering. Significant research has been done to manage hydrogen production from seawater. Water electrolysis is one way to generate hydrogen during the desalination process. Other methods include thermal desalination, which uses techniques like multi-effect thermal vapor compression, multi-effect distillation (MED), and multi-stage flash (MSF), and membrane desalination (MD), which uses techniques like reverse osmosis, electrodialysis, and others. Chlorine, oxygen, and hydrogen evolved during the electrolytic process at the anode and cathode, respectively. Table 10 shows the existing technologies for HP in literature from SW and urine. Since the evolved chlorine cannot be released into the environment, a solution to this issue must be discovered. Marques et al. [342] offered tactics for dealing with the evolved chlorine by suggesting to "study the re-conversion of chlorine to oxygen," as seawater seems to be the eventual source of hydrogen. By establishing a hydraulic head between the open sea and a sink reservoir, Salehmin et al. [370] proposed a technique for producing hydrogen from seawater. Solar collectors increase natural evaporation to build the head, and hydrolysis is used to have power that can be used to make hydrogen. They added that the hydrogen gas might be used as fuel. Water is produced as a byproduct, providing both water and energy. Experimental findings from the direct electrolysis of seawater were given by [371–373]. They suggested electrodes that facilitate oxygen evolution from brine solution as a follow-up to their fundamental electrolysis investigation. A new solar-powered model incorporating a thermoelectric generator (TEG) for cooling and producing hydrogen was created [374–376]. The objective was to evaluate the performance of this system in terms of energy, exergy, and exergoeconomics to demonstrate the inclusion of TEG increased energy productivity, HP and overall cost. Using low-grade energy sources, including solar, geothermal, and waste energy, are just one advantage MED units have over other thermal desalination systems, which is, therefore, a practical method for heat recovery. Using a genetic algorithm, Xu [346] examined the exergy, and exergoeconomic performance of a system made up of a proton exchange membrane (PEM), a thermoelectric generator (TEG), and a parabolic trough solar collector (PTSC). The findings demonstrated that using TEG in place of a condenser increases energy efficiency and lowers the unit's cost. The system's energy efficiency in its optimal form was 12.8 %. In an effort to create primary fuel that is high in hydrogen, Behzadi et al.

Table 10
HP technologies form SW and urine.

Feed sources	HP technologies	Energy Efficiency, EE (%)	Exergy efficiency, ExE (%)	H_2 production rate	Electricity generation rate	Freshwater production rate (kg/h)	Cost (total products unit exergy cost)	References
SW	SOEL modified with Biog & Rankine cycle (RC)	36.4	17.1	12.3 kg/h	1393 KW	9880	16.6 USD/GJ	[353]
SW	PEM modified with Organic RC	27.9	–	9.432 kg/h	–	3852	–	[338]
SW	PEM	–	31.6	11.2 kg/h	3636 kw	–	5.24 USD/GJ	[333]
SW	PEM modified with thermoelectric generator (TEG)	–	43.1	147,960 kg/h	98.2 MW	–	8.26 USD/GJ	[342]
SW	PEM & MED	–	14	3,927,000	26.3 MW	–	0.84 USD/GJ	[338]
SW	PEM & TEG	–	13.5	56.16 kg/h	48.5 KW	85,140	18.4 USD/h	[331]
SW	MED-PEM & ORC	63.6	40	1260 kg/h	1102 KW	3384	–	[328]
SW	ORC & PEM	78	25.5	0.8495 kg/h	–	–	–	[342]
SW	PEM & TEG	–	22.49	70.92 kg/h	–	–	–	[340]
Human urine (HU)	Urea adsorption and catalytic reduction	–	–	430 kg/d	–	–	–	[350]
HU	MECs	–	–	0.152 m^3 H_2/d	–	–	–	[328]
HU and cow urine	Catalysis by aluminum nanoparticles (ALNPs)	–	–	740 mL/20 min	–	–	–	[349]
Synthetic urine (SU)	PC	–	–	–	–	–	–	[249]
SU	PEL	–	–	–	–	–	–	[234]
SU	PC	–	–	66.71 μmol/h	–	–	–	[279]
SU	Photo-thermo-catalysis (CPTC)	–	–	23.18 mmol g^{-1} h^{-1}	–	–	–	[282]

[344] integrated PVT panels and PEME with a Solid Oxide Fuel Cell (SOFC) system. The proposed system was compared to the standard system using a tri-objective optimization based on efficiency, economics, and environmental performance. The output power and CO emissions of the model were found to be 8.7 % and 12.9 % greater, respectively, than those of a traditional system.

To discuss alternative feed sources, urine, a common waste, contains between 90 and 96 % water. Although there have been attempts to produce energy from urine (using microbial fuel cells), producing pure hydrogen from urine using any method has received less attention [377]. Photo-thermo-catalysis (CPTC) techniques were applied to generate hydrogen from Synthetic urine (SU) with a production rate of 23.18 mmol g^{-1} h^{-1} [378]. PC techniques produced hydrogen from SU using TiO_2/WO_3 nanosheets [379]. The production rate for this investigation was 66.71 μmol/h. Singla et al. [346] studied molecular hydrogen production from SU by PEL techniques. Emphasis was given to reducing COD as well with various experimental conditions such as pH, contact time, current density, C/N ratio, to name but a few. Urea adsorption coupled with the catalytic reduction techniques was performed to produce hydrogen using HU as a feed source. Hwang et al. [350] studied hydrogen production from HU using MECs with a production rate of 0.152 m^3 H_2/d. Catalysis by aluminum nanoparticles (ALNPs) was employed to produce hydrogen from HU and cow urine. The HP rate was found to be sensitive to the pH of the feed sources [349].

7. Techno-economic and environmental feasibility study of HP technologies in WI from a CRE perspective

This section evaluates the likelihood that producing hydrogen from Pure Water (PW), wastewater (WW), and saline water (SW) will be financially profitable. Analyzing the hydrogen economic market, identifying strengths, limitations, possibilities, and threats, and identifying hurdles to commercialization are the three areas of focus for the techno-economic potential for H_2 production. The techno-economic analysis platform offers more in-depth assessments that cover productivity, the cost of hydrogen, and prospective receiver costs, among other things. The analysis results will serve as a foundation and framework for further developing different feed sources based H_2 generation.

7.1. Sustainability analysis (SA)

Energy, efficiency, environment, and society comprise the four (4) pillars of sustainability analysis (SA). In this section, particular attention is placed on environmental and social SA, as energy and efficiency are automatically considered when performing economic SA. To ensure that everyone has access to affordable, dependable, sustainable, and sophisticated energy, there has a sustainable development goal (SDG) no. 7-which is referred to as “affordable and clean energy”-that includes hydrogen production from wastewater. This section outlines the key SA pillars and demonstrates the connection between SDG-7 and the green hydrogen production depicted in Fig. S6.

7.1.1. Economic factors

7.1.1.1. Cost parameters. The capital cost and operational cost are the factors affecting the economics of the H_2 process. Production logistics (such as the facility’s size, storage, transportation expenses, intended use, etc.) and the kind of energy source utilized to convert electricity to hydrogen are a few variables that affect the cost of HP. As the effectiveness of electrolyzers increases, costs also continue to decline. Electricity, labour, water, culture, feedstock costs, etc., are included in the operating costs, whereas the capital cost is the one-time investment that provides for reactor cost, land cost, etc. While construction costs, management fees, contractor fees, and contingencies make up the indirect capital costs, equipment, pipelines, controls, and electricity make up the direct costs. The costs associated with producing H_2 from various feed sources are shown in Fig. S7. About USD 300 million in capital expenditures are responsible for the H_2 process economic effects. For the manufacture of H_2, the operating costs that include the cost of labor, raw materials, and power [202] are:

- Electricity cost - It is expected that \$0.0478 per kWh of industrial electricity is used for the 3 % of the reactor’s output that is used for power [380]. Direct bio-photolysis costs about 2.4 million USD in electricity, whereas indirect bio photolysis, PF, and DF cost about 2.5 million USD.
- Water cost - 65 millimoles of water per day are needed for biological H_2 generation when 90 % of conversion efficiency is considered. For

bio-photolysis and DF, the cost of water is approximately \$0.03 million.

- Labor cost – Indirect bio-photolysis costs 65.10 million dollars, direct bio photolysis costs 50,469.30 million dollars, PF costs 23.03 million dollars, and DF costs 17.83 million dollars. Labor costs are approximated at 10 % of maintenance workers per acre.

Hydrogen is produced at a generally low-cost using FFs and diverse renewable energy sources. The cost of obtaining water for a hydrogen facility can vary, and in some cases, water shortages may make some projects logistically problematic and add to expenditures. Through 2050, predictions foresee stable costs for hydrogen generation using FFs and CCS and declining prices for renewable hydrogen production using EL.

7.1.1.2. Cost analysis. Comparing the varied production costs of hydrogen energy under various conditions is the goal of the cost analysis. The three most significant costs involved in producing hydrogen energy are capital, fixed operational, and variable operating costs. To ensure that the data are comparable, gathering all the data throughout a specific year is imperative.

- Capital cost – Initial capital cost × (present chemical engineering plant cost indexes / initial chemical engineering plant cost indexes)
- Operational cost – initial operating cost × (present consumer price index / initial consumer price index)

  It is crucial to note that these data come from various plants with varying capacities; consequently, the data should be converted to the same plant capacity for a more accurate comparison.
- Cost of plant with new capacity = (cost of plant with initial capacity) × ratio of new plant capacity to known capacity
- Equivalent annual cost = capital cost × capital recovery factor × fixed operating cost × variable operating cost.
- Levelized Cost of H_2 (LOCH) - A simple method of evaluating costs of several options provided by levelized costs. Diverse production technologies concentrate on the costs imposed by the producer during the plant's lifespan. It includes all essential expenses incurred by the manufacturer, such as financing, operational, and capital costs.

7.1.1.3. Cost comparison. The cost of HP is challenging to calculate as it largely depends on the feedstock pricing, the availability of current infrastructure, and the level of technological product development. Since the price depends on the development of the processes, comparing the costs of H_2 generation with the input source of PW, WW and SW treatment is complex. The literature survey findings of the typical HP costs (per kg of hydrogen) are shown in Fig. 14A and Table 11. Among the selected methods, the HP cost for PW is taken from Dincer and Acar [205], the production cost from WW is compiled from [212]. According to the catalysts type and reactor structure in many ways, it has been shown that the cost of producing hydrogen varies greatly. State-of-the-art production techniques are used in some cases. However, several of these are small-scale laboratory experiments. There are difficulties in turning a lab-scale study into a full-scale application. However, no data from the literature could be discovered because MED is still in the R&D stage. Aydin et al. [212] also evaluated the expenses of hydrogen production for reverse electrodialysis. However, the outcomes make this approach unsuitable for commercial application. The maximum production cost per kilogram of hydrogen is provided by photoelectrochemical systems, according to Table 11. However, this method is still in the early stages of research and development, and one of its main benefits is that it can be used locally. As a result, it is anticipated that as PEM system technology advances, the production costs associated with PEM operation will drop.

7.1.2. Environmental impact comparison

The environmental impact of a particular HP technique is assessed using the GWP and acidification potential (AP) with the investigation of biological, electrical, photonic, and thermal hydrogen production processes. A life cycle assessment (LCA) should be conducted to comprehend and evaluate a process emission fully. Examining the environmental effects of a procedure or product from resource extraction through disposal can be done using the practical technique known as LCA. Leiden University Center of Environmental Science has released a definition of LCA methods that comply with ISO requirements [212,213]. CO_2 emissions are measured by GWP (kg CO_2 eq.), while the change in acidity is measured by AP (g SO_2 eq.), which denotes SO_2 discharge into the atmosphere and water. The GWP and AP values of the various approaches for producing hydrogen gathered for this study from multiple sources are given in Table 11. The results have been standardized to compare the various hydrogen production processes. Fig. 14B displays the GWP and AP values for the environmental effects of different hydrogen production techniques. The methods for producing hydrogen using EL are thought to be the most benign to the environment with low GWP.

7.1.3. Social factors

The social cost of carbon (SCC) is the term used to describe the marginal external cost of a unit of CO_2 emissions. An integrated assessment approach is used to estimate SCC values. This approach uses an initial socio-economic scenario, a model that establishes the link between emissions and temperature change, and a function that connects this temperature change to economic losses. The first stage in the SCC estimate is to specify the reference socio-economic scenarios, which can be identified by their population, emissions, and the rate of technological development. As a next step, a marginal unit of CO_2 emissions is added or subtracted, slightly altering the baseline scenarios. Social welfare is estimated for each baseline and minimally perturbed scenario, which depends on consumption and the selection of discount factors. SCC is determined by comparing the normalized predicted welfare differences between the baseline and perturbed scenarios. Based on the findings presented in the study by Dincer and Acar [205], the SCC of different hydrogen production methods is computed. The SCC of each hydrogen production process is calculated using an average of \$160 per ton of CO_2 emissions. The SCC results of the chosen hydrogen generation techniques are shown in Fig. 14C. The outcomes indicate that hydrogen production based on photonic energy and a hybrid thermochemical cycle is the most advantageous method.

7.1.4. Technological factors

To develop a reliable, cost-effective, zero-emission, and robust seasonal hydrogen storage, it is necessary to cohabit with a small-scale day-night electrical storage. By requiring the employment of additional renewables during its manufacturing, hydrogen can also assist renewables in identifying market potential [202]. It is believed that energy and exergy efficiency help to evaluate energy conversion systems and enhance technical factors' performance. The ratio of productive output to input is used to calculate efficiency. A method for producing hydrogen can be calculated to have an energy efficiency (EE) of:

$$\eta = \frac{mLHW_{H_2}}{E_{in}} \tag{16}$$

LHV is the lower heating value of hydrogen (121 MJ/kg), m is the mass flow rate of the produced hydrogen, and Ein is the rate of energy input to the process. Exergy efficiency (ExE), on the other hand, determines how well a system performs under reversible circumstances. It can also be defined as the proportion of the system's usable work output to its reversible work production for systems that require work. The following equation is used for exergy efficiency:

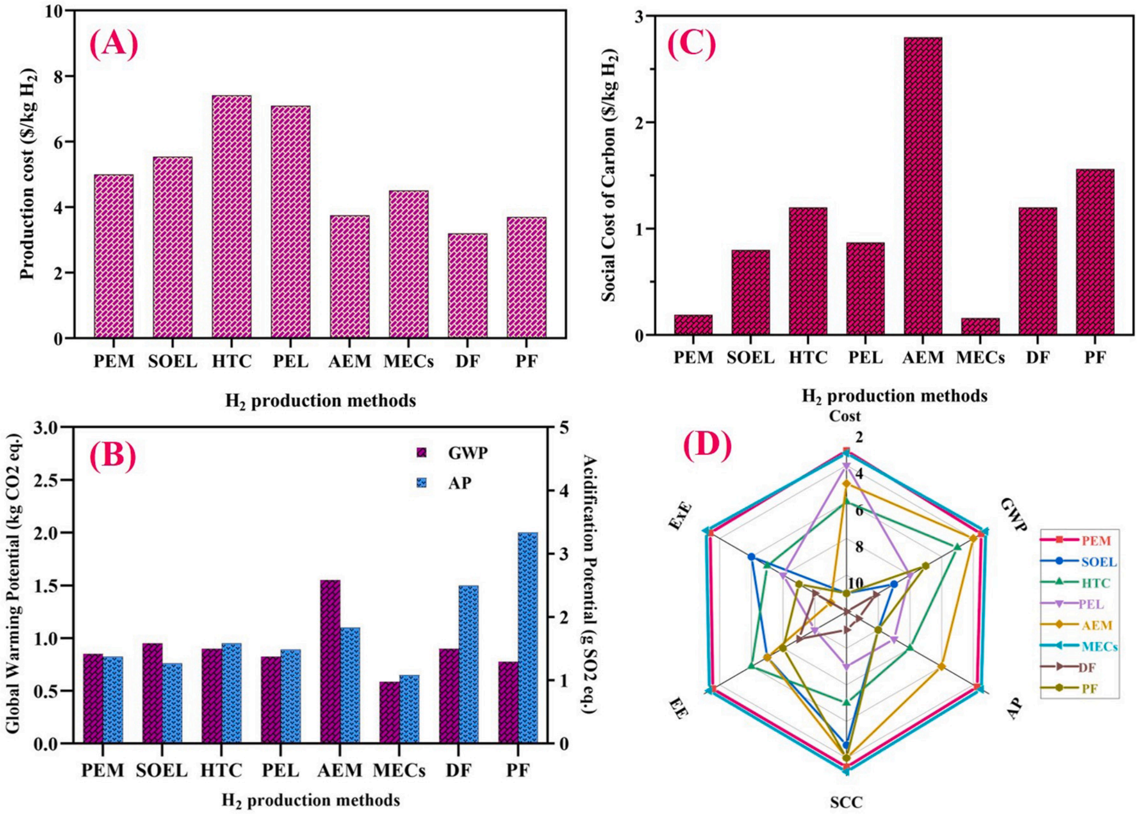

Fig. 14. A) H_2 production cost of selected methods (per kg of H_2), B) GWP and AP of average selected HP methods (per kg of H_2), C) SCC of average selected HP methods (per kg of H_2), D) Comparative assessment of HP methods with WW treatment (per kg of H_2).

Table 11
Ranking of different HP technologies in WI.

feed-sources	Ranking	HP technologies	Cost ($/kg H_2)	Energy efficiency (%)	Exergy efficiency (%)	GWP (Kg CO_2 eq.)	AP (g SO_2 eq.)	SCC	References
Pure Water (PW)	1	Proton Exchange Membrane Electrolysis (PEMs)	5	80	18.9	0.7	0.65	0.19	[60]
	2	High-temperature electrolysis (HTEL) / Solid Oxide Electrolysis (SOEL)	5.54	>90	2.6	0.9	0.52	0.8	[248]
	3	Hybrid thermochemical cycles (HTC)	7.41	77	4.8	0.8	0.9	1.2	[235]
	4	Photoelectrolysis (PEL)	7.09	70	0.34	0.65	0.78	0.87	[394]
	5	Anion Exchange Membrane Electrolysis (AEM)	3.75	55	2.9	2.1	1.2	2.8	[208]
	6	Thermolysis (TL)	6.12	50	4	0.85	1.4	1.25	[395]
	7	Alkaline Electrolysis (AEL)	10	50	1.8	0.85	0.74	1.25	[204]
	8	Photocatalysis (PC)	5.19	46	0.1	0.76	2.5	1.05	[396–397]
	9	Photoelectrochemical method (PECM)	3.24	18	0.15	0.79	1.3	1.15	[65]
	10	Water Splitting Electrolysis	7.34	53	2.5	3.33	0.98	3.5	[361]
	11	PV electrolysis (PVEL)	4.5	16	0.7	0.9	1.7	1.5	[365]
Wastewater (WW)	1	Microbial Electrolysis Cell (MECs)	4.51	78	75	0.17	0.3	0.16	[253]
	2	Dark fermentation (DF)	3.2	10.75	10.81	0.8	2	1.2	[255]
	3	Photo-fermentation (PF)	3.7	25.6	24.08	0.55	3	1.56	[206]
	4	Photocatalyst (PC)	4.98	5.74	4.54	0.51	2	0.9	[211]
	5	Photoelectrochemical method (PECM)	8.43	7	4.5	0.53	1.3	0.57	[211]
	6	Electrolysis (EL)	7.59	0.8	0.23	2.1	0.8	4.5	[207]
	7	Supercritical water Gasification (SCG)	5.66	53.3	48	10.5	12	5.6	[279]
	8	Reverse Electrodialysis (RED)	180	N/A	N/A	N/A	N/A	N/A	[271]
	9	Microbial Electrodialysis (MED)	N/A	N/A	N/A	N/A	N/A	N/A	[329]

$$\Psi = \frac{mex_{H_2}^{ch}}{Ex_{in}} \tag{17}$$

Table 11 provides the energy and exergy efficiencies for the examined hydrogen-generating technologies. Since reverse electrodialysis, microbial electrodialysis, and electrolysis are currently in the research and development stage concerning wastewater treatment, EE and ExE values for these processes are omitted.

7.1.5. Overall ranking of HP technologies in WI

The economic, environmental, social, and technological evaluation outcomes are standardized in this section to evaluate each method effectively. The best scenario represents lower costs, zero emissions, SCC, and higher efficiencies. On the other hand, higher cost, greater emission (high GWP, AP and SCC value), and lower efficiencies represent unsatisfactory performance. The hypothetical ideal case refers to zero-cost and emissions, which means zero SCC. The production cost, GWP, AP, SCC is ranking between 1 and 10, where 10 means poor performance and 1 indicates the ideal case (zero-cost and zero-emissions). The energy and exergy efficiency of this ideal case is 100 %. In terms of EE and ExE, the closest performance to the ideal case is reached by PEMs and MECs for PW and WW, respectively. However, they give considerably low AP compared to other selected methods. SCC rankings of PEMs and MECs are also low. Table 11 represents the average values of normalized GWP, AP, SCC, cost, energy, and exergy rankings of each energy source are used to compare the economic, technical, social, and environmental effects of different hydrogen generation processes depending on their feed sources. The overall comparison of selected HP methods is exhibited in Fig. 14D. The average rankings reveal that water splitting based EL technologies exhibit the highest energy efficiency and the lowest production costs and emissions. The objective of a successful transition to a HE is efficient and affordable hydrogen generation with minimal impact on the environment and society. PEMs and MECs might be the best choice to produce hydrogen from PW and WW to achieve this goal.

7.2. Water requirement for HP in WI

One of the significant requirements of water electrolysis is the need for highly pure water feeds. The minimum requirement is the American Society for Testing and Materials (ASTM) Type II deionized (DI) water (resistivity >1 MΩ cm). ASTM Type I DI water (>10 MΩ cm) is highly preferred for higher purity (99.99 %) hydrogen [381]. The technology used to manufacture hydrogen and how the production facility chooses to manage the necessary water streams will determine how much water is needed. According to the stoichiometric ratios, producing hydrogen through the electrolysis process theoretically takes 9 L of water per kg of hydrogen. But most commercial electrolysis systems today claim to need between 10 and 11 L of deionized water for every kg of hydrogen produced. However, the actual water requirement for different hydrogen production technologies is quite high (Table 12). To produce 1 kg of pure hydrogen, require 60–95 L of good quality raw water, including evaporative cooling by water splitting technique. Whereas biomass gasification, coal gasification, biogas reforming and SMR required 60, 70, 20–45 and 18–44 L of pure water, respectively, to produce 1 kg of hydrogen [4,382]. Before further proceeding to develop a HE by 2030, the feasibility of water requirement is considered crucial. Researchers expressed their concern about future water requirements for a sustainable HE, explaining that providing fresh water for HE will be much more expensive or demanding [71,383]. It was estimated that 21 billion m^3 of pure fresh water would be required to meet the meet ambitious demand for HE by 2030 [354]. Accessible freshwater makes up just <1 % of the planet's water. It is best to avoid burdening freshwater usage, especially in areas where drinking water is difficult to attain. Almost all the remaining 99 %, or about 1.4 billion km^3, is SW, which can be purified through desalination processes before being used as an electrolysis feedstock by electrodialysis or reverse osmosis techniques. Special consideration should also focus on wastewater to hydrogen production. It was estimated that 359 billion m^3 of wastewater is produced each year [384], simultaneous treatment, resource recovery and hydrogen production could be a feasible option to clean green hydrogen production for a better HE without burdening the fresh water.

Table 12
Water requirements of HP technologies in WI [4,354,355].

HP pathways	Stoichiometric demand (L/kg H_2)	Total demand (L/kg H_2), assuming good quality raw water import and evaporative cooling.
Natural Gas reforming (grey H_2)	4.5	15–40
Natural Gas reforming with carbon capture (blue H_2)	4.5	18–44
Biogas reforming (can be classified as green H_2)	4.5	20–45
Coal gasification (black H_2)	Dependent on C:H ratio in coal and coal moisture content	70
Biomass gasification (can be classified as green H_2)	Dependent on C:H ratio in coal and coal moisture content	60
Water electrolysis (green H_2)	9	60–95

7.3. SWOT (strengths, weaknesses, opportunities, and threats) analysis

This analysis evaluates the hydrogen market's strengths, weaknesses, opportunities, and threats in a particular area or industry. This technique can draw attention to the strengths of the study materials: utilization of resources to environmental conservation, and technical strength to SD, weakness: places where need support and assistance i.e., lack of government support, to reduce cost, opportunities: take advantage of new business opportunities, increase cooperation to potential development, and threats: components that prevent the items from moving forward about economic, technical, and social threat [202]. The goal of the SWOT analysis is to assist stakeholders and decision-makers in having a better understanding of the state of the global hydrogen market and in making better decisions to increase market efficacy (Table 13). The SWOT analysis suggested the efficient and environmentally friendly technology for HP (PEMs for PW, SW, and MECs for WW, and HU). However, weakness is the requirement of ultrapure water for HP, the transition from carbon-intensive to low-carbon HP, and the excessive costs for green HP which offering an opportunity of providing a new revenue models of energy recycling in CRE. The biggest threat found was the requirement for international standards and regulations on the growth of worldwide H_2 market, and the lack of cutting-edge technologies for HP from WW, SW and urine.

7.4. Commercialization barriers

The development and effective commercialization of the HE is obstructed by several obstacles (techno-economic barriers).

7.4.1. Technical barriers

There are some challenges to the commercialization of HP, including lower production efficiency and manufacturing cost compared to other technologies [385]. With the gradual advancement of technology, H_2 production by fermentation is still expanding from the primary stage. The higher cost necessary for inoculums' pre-treatments and increased energy usage impact the commercialization of the DF process. Another significant technical challenge is the H_2 yield limitation in DF, which is 4 mol H_2/mol glucose. The production method is a well-known obstacle

Table 13
Comparison of strengths, weaknesses, opportunities, and threats of the hydrogen market [202,398,399].

Strengths	Weakness	Opportunities	Threats
More diversity in resource utilization	Unavailability of an efficient hydrogen infrastructure	New business opportunity	Economic
- Multiple sources and various production methods - Extract value from waste since it is possible to produce it from debris and as a by-product - Reduce dependence on fossil fuels and increase energy diversity - Enables communities to manage their energy supply - It has the potential to integrate intermittent renewable energies into the energy system - It can be used as a feedstock in other industries	- Incomplete H_2 infrastructure - Limited access and availability - Lack of an efficient distribution and storage system to overcome hydrogen explosiveness - Lack of recycling plans	- The emergence of the hydrogen market - Export hydrogen and create value from that. - Emergence and engagement of more companies in the energy sector - Job creations	- Lack of potential suppliers and demanders - Lack of potential investors - Inadequate commercialization plans - Competitions with other renewables, such as hydro power - The strong position of fossil fuel producers, the difficulty in competing with the current fossil fuel market
Environment conservation	Introduction risks	Increase Cooperation	Technical
- Environmentally friendly and reduce the amount of GHG emissions - Less noise pollution compared to other energy production methods	- Public acceptance since it is a new product - Lack of practical tools for the first introduction of hydrogen energy for transportation - The development of support services such as insurance is still very immature - The integration of hydrogen into the energy system is not tested on an industrial scale - System complexity	- Deepened cooperation with local authorities and allied with local politicians of business owners - Collaboration opportunities among line ministries, departments, and other system actors	- Limited practical experience in both producers and consumers - Insufficient storage required/more cost efficient alternatives are available
A key to sustainable development	High costs	Development Potential	Social
- Great development potential - The possibility of production in rural and remote areas - Stimulate research and development - Increase employment - Consistent energy supply and energy security - Sustainable transportable energy source - Have numerous applications in the stationery and transportation market	- High production costs, especially on small scales - High initial installation costs - Procurement costs - High adaptation costs - High energy price - Lack of focused development works from significant companies to develop the equipment and reduce costs - The need to change the current distribution system in residential buildings	- Sustainable development - Innovations and technological development - Effective utilization of hydrogen via fuel cell technology - Stimulate R&D - Hydrogen and fuel cells technology enables investment in sustainable energy infrastructure	- Public acceptance is unclear - Weak support to shift to hydrogen energy - Incomplete legislation
Technical Strengths	System Integration	Environmental benefits	
- High potential for energy storage - Integration with smart grid - Can handle power fluctuations - High efficiency of fuel cell vehicles - Relatively low sensitivity to the impurities in the fuel - The possibility of utilizing current fuel transportation infrastructure - Reduce the dependence on long-distance pipelines	- Lack of comprehensive policies, regulations, codes, and standards - Lack of awareness of capabilities and potential benefits of hydrogen - Resistance from other energy actors in the country - Weak supply network - Safety issues - Unavailability of clear marketing policies and strategies - Unclear plans about combing electricity and hydrogen energy	- Emission-free mobility - Reduction of negative environmental externalities	
	Lack of support from the government	Improve energy security	
	- Insufficient cooperation between political authorities and enterprises	- Energy diversifications	

to biological H_2 generation, but researchers can get around it by developing competitive HP [386]. The processing of the raw materials and their pre-treatments are the main problems in the thermochemical conversion of H_2 generation. Organic contaminants in the resulting syngas pose a significant obstacle to commercial gasification and severe operational challenges [342]. Aside from this, the other considerable problems include environmental impacts, maintaining the gasifier's internal temperature, and tar removal at a reasonable cost. The technological and financial obstacles to the commercialization of H_2 thermochemical and biological conversion technologies are shown in Table 14. The intricacy of the substrate or an absence of microbes with the capacity to hydrolyze the substrate causes these barriers. Analyzing the technological challenges associated with the conversion of trash to H_2 production will lower the overall cost of the H_2 output.

7.4.2. Economic barriers

Since the photobiological process bio-H_2 generation rate is minimal, it cannot be recommended for use on a broad scale. The DF process is also quite expensive, and most research has been conducted only at the laboratory scale. The two biggest economic problems are developing

Table 14
Technical and economic barriers to HP technology.

HP methods	Technical barriers	Economical barriers	Overcoming strategies	References
SCG	-Require particle size reduction, the optimum sludge concentration, ash removal, pump testing, operability, reliability testing, and so on.	-Cost and yield of the algal biomass determine the feasibility. -High harvesting costs	-Research must be optimized for the boost in fuel production. -If a CO_2 producer pays for an algae conversion plant, the cost of hydrogen decreases.	[223]
WEL	-The main obstacle to the widespread use of this technology is the integration of the energy system and business operations.	-The Levelized cost of hydrogen is 40 %–57 % more expensive when electricity is included.	-To reduce expenses, different geographic locations and sophisticated operation tactics might be considered. -Be aware of the electricity's carbon footprint to obtain the lowest possible CO_2 emissions.	[87]
MEL	-Scale-up of membrane-less electrolyzer prototypes		-The low initial investment is required for electrolyzers connected to sporadic renewable energy sources. -Developing inexpensive and readily available electrocatalysts will be crucial to lower the CAPEX of membrane-less electrolyzers.	[238]
DF	-Since pretreatment methods can be adjusted to varied feedstock, they present a significant obstacle before fermentation. -The fabrication and use of practical bioreactors and the thermodynamic restrictions on hydrogen production by microbial fermentation. -The design, construction, and operation required an appropriate bioreactor	-Costly procedure -Feedstock has a high price tag attached to it. -The primary factor affecting biohydrogen cost is substrate cost.	-The technological and financial obstacles are removed by advanced investigations conducted on a big scale. -Enhancing the energy recovery from the substrate by DF integration with other energy-generating systems. -The fermentation that combines dark and light fermentation reduces feedback inhibition.	[400] [223] [358]
PF	-A significant barrier is created by the inhibitory substances used in the pretreatment. -The substrate inhibits either of the processes.	-Increased yield at a higher energy cost	-The significant advancement in the biohydrogen process can be offset by metabolic engineering. -Finding the chromosomal genes in microalgae for increased H_2 synthesis involved examining the effects of nutrient constraint and substrate use. -The development of photobioreactors must be done with the utmost care.	[87]

low-cost photobioreactors and enhancing photosynthetic reactions throughout the bio-photolysis process. Higher operating and installation costs, which reduce hydrogen yield, are the main financial obstacles. The production of H_2 is improved by the secondary methods integrated into the primary processes. Secondary procedures such as methanogenesis, photobiological techniques, MECs and microbial fuel cells (MFCs) are combined with the DF to manufacture hydrogen efficiently. Integrated dark and photo fermentative H_2 production cost estimates ranged from 2.5 to 2.8 USD per kg [213]. Dark fermentative H_2 generation has a limited economic potential compared to natural gas reforming because of its higher cost [387]. The most significant obstacles in thermochemical conversion processes are the existence of Pressure Swing Absorption (PSA) and the price of the catalyst, both of which raise the cost of HP. Although H_2 purification raises the overall cost of the process, it lowers the cost of biomass and improves efficiency, reducing the H_2 production cost [388]. Since the electrolyzer needs more electricity and the production cost rises to around 5 % of the total share in big-scale production, the water electrolysis process is an economically viable choice for small-scale HP. Due to the high cost of producing renewable liquids (methanol, ethanol, and glycerol), liquid reforming technologies are not feasible [314].

7.4.3. Hydrogen safety concerns need to be addressed in WI for a CRE

The properties of H_2, with its high energy content per mass, make it an excellent alternative fuel, while there are several safety issues that need to be addressed to ensure a sustainable HE. Compared to other fuel sources such as methane (5.3–15 vol% flammability, 0.280 mJ ignition energy) and gasoline (1.0–7.6 vol% flammability, 0.25 mJ ignition energy), to name but a few, hydrogen has a wide flammability range (44.0–75 vol%) and a low ignition energy (0.018 mJ) [389]. A leak in pipes or a storage container could cause an explosion or fire. To establish the future HE, a high level of safety issues should be achieved by resolving a variety of factors that could impede its expansion as follows:

1. Hydrogen has low density and viscosity. Moreover, it has a higher diffusion rate through some materials than other gases, which increases the possibility of leaks and loss of containment. Studies reported that, in terms of volumetric leakage, hydrogen could escape from a system around three times quicker than natural gas [390]. Consequently, proper handling is crucial at every stage of the value chain, including production, storage, transmission and application.
2. One of the main issues with hydrogen is storage. Leakage and ventilation are the primary sources of storage-related risks because they can cause mixing H_2 with air and burn. A significant technological advance is required to store hydrogen in liquid form at a minimal temperature, which is quite challenging [389].
3. To be transported, hydrogen should be in the safest condition possible. A proposed pipeline framework is often used to move hydrogen over long distances in vast quantities [391], mainly due to its operational safety. Additionally, lubricants used in typical compression applications may cause unwanted spillages for fuel cell operation. There is a demand for pipeline compression methods that are more reliable, affordable, and effective.
4. Nonetheless, several hydrogen-specific damaging mechanisms must be mentioned. Metals and other substances can become brittle, losing their integrity and ability to store hydrogen. The use of aluminum or stainless steel is typically proposed for most procedures to reduce embrittlement [391]. Process safety engineers should use the intrinsically safer designs, and the best materials should be used for each application.
5. Another risk to consider is decarburization, which happens when metals like steel are heated to temperatures up to 700 °C or more. The metal is broken due to the carbon's reaction with oxygen and hydrogen to form methane [392]. This creates another health safety hazard.
6. Therefore, process safety is essential to creating new energy sources and the route to net zero emissions. Process safety engineers should work to lessen the likelihood of these kinds of accidents [393].

7.4.3.1. Hydrogen safety solutions with detection technologies. Scientists have developed several detection technologies to detect hydrogen gas leakages for early prevention of occupational and environmental health safety of hydrogen. These are summarized as follows:

1. Catalytic Bead Sensor: It can identify flammable substances below their lower explosive limit (100 %), including hydrogen. They respond quickly and have long-term stability. They are primarily used for continuous air quality monitoring across a large areas [392].
2. Flame detectors: Since hydrogen explosion primarily emit energy in the ultraviolet (UV) radiation band, UV and infrared (IR) sensors are frequently coupled in one device for quickly detecting H_2 flames. Another method for detecting hydrogen flames is multi-infrared (MIR). MIR devices utilize a mix of IR sensor filters and software processing to detect the low-level radiation from H_2 flames [393].
3. Ultrasonic gas leak detection: Even small leaks can be detected quickly by using ultrasonic gas detectors, which act as early warning zone monitors because they detect the sound of leaking gas rather than accumulating gas clouds, which allows them to react faster than conventional gas detectors [393].
4. Electrochemical (EC) sensor: When requiring selective measurements of hydrogen at mg/L concentration level, EC sensors can be an excellent option. They have features like quick response time, superior precision, high level of consistency, and long service duration. For the detection of point leaks and the monitoring of individual airflow, this technology is helpful [390].

7.5. Governance of H_2 production economy

Dincer and Acar [205] introduced the so-called "18S method" to those elements and facets of hydrogen advancement whose evaluation should direct public and commercial stakeholders in analyzing, understanding, and putting into practice actions and strategies to enable a successful transition to the HE. A level playing field is necessary to support scalling-up. Government-facilitated laws will accelerate industry investments, which will probably lead to scalability. According to our findings, there are six (6) ways that governments can promote fair competition:

1. Governments significantly influence setting national objectives, as shown by hydrogen standards developed globally [National Strategies].
2. Governments are in a favorable position to deal with potential prospects for local investment as unbiased brokers of industry participants and stakeholders [Coordination].
3. Governments can help to remove current barriers to investment in the hydrogen economy by making it easier to get approval for new refuelling stations and enforcing internationally standardized rules to eliminate trade-related risks [Regulation].
4. Governments can work with industry to coordinate quality needs like increased demands and security [Standardization].
5. Governments can either repurpose current services or invest in new infrastructure (e.g., natural gas networks) [Infrastructure].
6. Governments may also decide to employ incentives like grants or tax exemptions to encourage the early adoption of hydrogen technology [Incentives].

8. The latest case studies of green HP in WI

In the present study, a total of 1933 hydrogen production and WI case studies from 1975 to 2022 [29] have been retrieved and analyzed to find a clear picture of the latest hydrogen production technologies, country, and continent-wise distribution of hydrogen projects, types of energy required to generate hydrogen, end uses of produced hydrogen and the capacity of an individual project. These case studies have different maturity levels such as some of them are in the early stage of conceptualization, feasibility testing, and under construction, and some of them are in the final operational phases. Out of the 1933 cases, stresses were given to the 193 operational case studies related to water electrolysis and HP, as illustrated in Table 15 European countries were the dominant hydrogen producers having 62.69 % of active projects, whereas African countries seemed to be far behind all continents with only 0.51 % of active projects. The order of active HP cases is Europe (62.69 %) > Asia (22.79 %) > North America (7.25 %) > Australia and Oceania (4.14 %) > South America (2.59) > Africa (0.51 %). However, Germany had the highest number of active HP case studies recorded to be 50. On the contrary, Malaysia, Thailand, United Arab Emirates, Iran, Turkey, and Lebanon have only 1 active project individually. Most active case studies employed PEM electrolysis accounting to be 46.63 % followed by AEL which is reported to be 34.19 %. Interestingly, only 2.10 % of active cases used the SOEL technique for water electrolysis and HP. It was observed that most of the hydrogen-producing projects from WI emphasized using renewable energy sources such as solar PV, onshore wind, hydropower, and nuclear. These operational case studies recorded an array of the end use of hydrogen such as transportation, power, grid injection, industries, domestic heat, refining, and ammonia production, to name but a few.

9. The challenges of a future hydrogen economy in WI

There is no doubt that considerable changes must be made to the current energy system to meet the global carbon neutrality goals. The world can transition to a society with zero carbon emissions from hydrogen. Hydrogen is a sustainable, responsible fuel because of environmental protection, scientific developments, and support from the private and public sectors. However, there are still numerous obstacles and limitations that currently limit the potential of hydrogen as a fuel source to serve as a significant alternative to FFs now, such as large-scale hydrogen production cost, infrastructure investments, bulk storage, transport, and distribution, safety considerations, the absence of an existing value chain, and the requirement for international standards and so on.

- The major challenge for developing a hydrogen economy is scaling up HP, and the transition from carbon-intensive to low-carbon HP.
- Costs for green HP are still too high to be competitive with other energy sources economically. An analysis by the IEA found that the HP costs for green hydrogen ($2.5–5/kg), blue hydrogen ($1.50–3.50/kg), and grey hydrogen are all roughly $1.50/kg [401]. The cost of HP technologies like EL, RED, and PECM must be reduced to make hydrogen a viable fuel source for everyone.
- The need for ultrapure water poses one of the biggest obstacles since it takes 2.38 gal, or 9 L, of water to produce 1 kg of hydrogen gas, which could trigger a water shortage in the future HE.
- Another difficulty is that hydrogen as a fuel cell component requires ultra-high purity hydrogen with values up to 99.999 % [201].
- A significant barrier to developing a low-carbon HE is the absence of a clean hydrogen value chain, which depends on supply, handling, and demand chains.
- The massive infrastructure development and the necessity for international cooperation will be the key challenges in transport and storage.
- Hydrogen storage is more challenging due to hydrogen's low volumetric energy density. High-pressure tanks (350–700 bar pressure) are needed for hydrogen gas storage at a cryogenic temperature 252.8 °C [402].
- One major obstacle to the production of hydrogen from SW and urine has been the lack of cutting-edge technologies.
- The environmental and safety problems are one of the other significant obstacles because hydrogen is so explosive and combustible in the presence of air; it can explode if it leaks into the atmosphere [403].
- Matching supply and demand uncertainty is a significant hurdle. The selection of the site for hydrogen production, developing a workable transportation network, and checking the resources for hydrogen

Table 15
Case studies of hydrogen production and WI.

SN	Case studies	Country	Start Year	Status	Electrolysis Technology	Types of electricity	Types of renewable	Products	Announced size	End uses	References
1.	Fukushima hydrogen energy research field	JPN	2020	Active	ALK	Renewable	Solar PV	H_2	10 MW	Mobility, power	[404]
2.	Hydrospider - St Gallen	CHE	2020	Active	PEM	Renewable	Hydropower	H_2	2 MW	Mobility	[405]
3.	Apex energy, Rostock-Laage	DEU	2020	Active	ALK	Grid	–	H_2	2 MW	Power	[406]
4.	Leuchtturmprojekt power-to-gas Baden-Württemberg	DEU	2020	Active	PEM	Renewable	Hydropower	H_2	1.3 MW	Mobility, power	[407]
5.	eFarm	DEU	2020	Active	PEM	Renewable	Onshore wind	H_2	1.125 MW	Mobility	[408]
6.	Hydrogen plant - Orkney Islands - BIG HIT 2n phase	GBR	2020	Active	PEM	Renewable	Onshore wind	H_2	1 MW	Mobility	[409]
7.	Wyhlen hydroelectric power plant	DEU	2020	Active	ALK	Renewable	Hydropower	H_2	1 MW	Mobility, domestic heat	[410]
8.	GrInHy2.0	DEU	2020	Active	SOEC	Grid	–	H_2	0.72 MW - 200 m^3 H_2/h	Industry, mobility, power	[411]
9.	Power2Met	DNK	2020	Active	Other Electrolysis	Grid	–	MeOH	0.25 MW - 50 m^3 H_2/h	Industry, mobility, power	[412]
10.	REMOTE - Norway	NOR	2020	Active	PEM	Renewable	Others	H_2	50 kW	Mobility, power	[413]
11.	H_2One - Toranomon Hills Business Tower	JPN	2020	Active	PEM	Grid	–	H_2	1 m^3/h	Mobility	[414]
12.	H_2One - Toyama city environment centre	JPN	2020	Active	PEM	Grid	–	H_2	1 m^3/h	Mobility	[415]
13.	H_2One - Tsuruga City	JPN	2020	Active	PEM	Grid	–	H_2	1 m^3/h	Power	[416]
14.	H_2FUTURE	AUT	2019	Active	PEM	Grid	–	H_2	6 MW	Power	[417]
15.	Guangdong Synergy Hydrogen Power Technology Co. 1st phase	CHN	2019	Active	PEM	Renewable	Unknown	H_2	4 MW	Industry	[418]
16.	Markham Energy Storage, Ontario	CAN	2019	Active	PEM	Grid	–	H_2	2.5 MW	Power	[419]
17.	PFI - Pirmasens-Winzeln	DEU	2019	Active	Other Electrolysis	Renewable	Others	CH_4	2.5 MW	Power	[420]
18.	HRS CMB	BEL	2019	Active	PEM	Unknown	NA	H_2	1 MW	Mobility	[421]
19.	$MEFCO_2$	DEU	2019	Active	PEM	Grid	–	MeOH	1 MW – 200 m^3 H_2/h - 1 t MeOH/d	Mobility	[422]
20.	Windgas Haurup, 2nd phase	DEU	2021	Active	PEM	Renewable	Onshore wind	H_2	1 MW	Mobility	[423]
21.	Parnu refuelling station	EST	2019	Active	ALK	Unknown	NA	H_2	1 MW - 200 m^3 H_2/h	Mobility	[424]
22.	H_2Nodes, Parnu	EST	2019	Active	PEM	Unknown	NA	H_2	185 m^3 H_2/h	Industry, mobility	[425]
23.	H_2Nodes, Riga	EST	2019	Active	PEM	Unknown	NA	H_2	140 m^3 H_2/h	Industry, mobility, power	[426]
24.	SMT-AG Artois-Gohelle	FRA	2019	Active	ALK	Grid	–	H_2	0.5 MW	Mobility	[427]
25.	HyDeploy	GBR	2019	Active	PEM	Grid	–	H_2	0.5 MW	Mobility, power	[428]
26.	Quebec great Toronto area east	CAN	2019	Active	ALK	Unknown	NA	H_2	0.5 MW - 100 m^3 H_2/h	Mobility, power, domestic heat	[429]
27.	Pau bus station HRS	FRA	2019	Active	PEM	Grid	–	H_2	0.5 MW	Mobility	[360]
28.	Solothurn, STORE&GO	CHE	2019	Active	PEM	Grid	–	CH_4	0.35 MW	Methanol	[430]
29.	Sarawak Energy	MYS	2019	Active	ALK	Unknown	NA	H_2	60 m^3 /h	Mobility	[431]
30.	Vårgårda Bostäder housing complex	SWE	2019	Active	ALK	Renewable	Solar PV	H_2	60 m^3 /h	Mobility	[432]
31.	SoCalGas-NREL	USA	2019	Active	Other Electrolysis	Unknown	NA	CH_4	0.25 MW	Mobility, power	[433]
32.	Stromlückenfüller 2nd phase	DEU	2019	Active	PEM	Grid	–	H_2	0.2 MW	Methanol	[434]
33.	ATCO clean energy innovation hub	AUS	2019	Active	PEM	Grid	–	H_2	0.15 MW	Mobility	[435]
34.	Tauron CO_2-SNG	POL	2019	Active	Other Electrolysis	Grid	–	H_2	18 m^3 /h	Industry, mobility, power, grid injection	[436]

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Table 15 (*continued*)

SN	Case studies	Country	Start Year	Status	Electrolysis Technology	Types of electricity	Types of renewable	Products	Announced size	End uses	References
35.	H_2One - SP Group	SGP	2019	Active	PEM	Unknown	NA	H_2	1 m^3 H_2/h	Power	[437]
36.	Falkenhagen STORE&GO	DEU	2018	Active	PEM	Grid	–	H_2	1 MW - 180 m^3 H_2/h	Industry, mobility	[438]
37.	NEDO kofu city, Yamanashi Prefecture	JPN	2019	Active	PEM	Unknown	NA	H_2	1.5 MW	Mobility	[439]
38.	Semakau island microgrid Engie (SPORE)	SGP	2019	Active	Other Electrolysis	Unknown	NA	H_2	50 kW	Mobility	[440]
39.	H_2PLAZA - Toyota Industries Corporation's Takahama	JPN	2019	Active	Other Electrolysis	Renewable	Unknown	H_2	10 nm^3 H_2/h	Industry, mobility	[441]
40.	Localhy	DEU	2019	Active	Other Electrolysis	Renewable	Unknown	H_2		Mobility	[442]
41.	Wind to gas Brunsbüttel	DEU	2018	Active	PEM	Renewable	Onshore wind	H_2	2.4 MW - 450 m^3 H_2/h	Mobility	[443]
42.	Carbon2Chem	DEU	2018	Active	ALK	Grid	–	Various	2 MW	Iron and steel	[444]
43.	SunLine Transit Agency	USA	2018	Active	PEM	Unknown	NA	H_2	1.5 MW	Power	[445]
44.	HyBALANCE	DNK	2018	Active	PEM	Renewable	Onshore wind	H_2	1.2 MW	Mobility	[446]
45.	Aberdeen Conference Center	GBR	2018	Active	ALK	Unknown	NA	H_2	1 MW - 200m^3 H_2/h	Grid injection	[447]
46.	Lam Takhong Wind Hydrogen Hybrid Project-EGAT	THA	2018	Active	PEM	Unknown	NA	H_2	1 MW - 200m^3 H_2/h	Mobility	[448]
47.	H_2ORIZON	DEU	2018	Active	PEM	Unknown	NA	H_2	1 MW	Grid injection	[449]
48.	ASKO Midt-Norge	NOR	2018	Active	ALK	Unknown	NA	H_2	150 m3 H_2/h	Refining	[450]
49.	Underground Sun Storage	AUT	2018	Active	ALK	Renewable	Solar PV	CH_4	0.6 MW	Industry, mobility	[451]
50.	Hydrogen plant - Orkney Islands - BIG HIT 1st phase	GBR	2018	Active	PEM	Renewable	Onshore wind	H_2	0.5 MW	Mobility	[452]
51.	Windgas Haurup, 1st phase	DEU	2018	Active	PEM	Renewable	Onshore wind	H_2	0.225 MW	Mobility	[391]
52.	Troia, STORE&GO	ITA	2018	Active	PEM	Grid	–	CH_4	0.2 MW	Mobility	[453]
53.	GNVert H_2	FRA	2018	Active	PEM	Renewable	Unknown	H_2	37 m3 H_2/h	Mobility, power	[454]
54.	Tongji solar hybrid hydrogen refuelling station	CHN	2018	Active	Other Electrolysis	Renewable	Solar PV	H_2	25 m3 H_2/h	Mobility	[455]
55.	Methanation at Eichhof	DEU	2018	Active	PEM	Renewable	Unknown	CH_4	0.05 MW	Mobility, power	[456]
56.	CoSin: Synthetic Natural Gas from Sewage, Barcelona	ESP	2018	Active	SOEC	Renewable	Unknown	CH_4	20 m^3 CH_4/h	Mobility	[457]
57.	REFLEX	ITA	2018	Active	SOEC	Renewable	Unknown	H_2	10 m^3 H_2/h	Mobility	[458]
58.	Sendai City	JPN	2018	Active	PEM	Renewable	Unknown	H_2	0.025 MW	Mobility	[459]
59.	Rostock, Exytron Demonstrationsanlage	DEU	2018	Active	ALK	Grid	–	CH_4	4 m^3 H_2/h	Mobility	[460]
60.	Tokyo construction institute of technology	JPN	2018	Active	PEM	Unknown	NA	H_2	1 m^3 H_2/h	Mobility	[461]
61.	Rakuten seimei park miyagi	JPN	2018	Active	PEM	Unknown	NA	H_2	1 m^3 H_2/h	Industry	[462]
62.	MicroPyros, Altenstant	DEU	2018	Active	Other Electrolysis	Unknown	NA	CH_4	0.25 m^3 H_2/h	Methanol	[463]
63.	Oxelösund forklifts	SWE	2018	Active	PEM	Unknown	NA	H_2		Mobility	[464]
64.	Alzey, Exytron Null-E	DEU	2017	Active	ALK	Unknown	NA	H_2	0.0625 MW	Mobility, power	[465]
65.	Energy observer	FRA	2017	Active	PEM	Unknown	NA	H_2	9 m^3 /h	Mobility	[466]
66.	Musashi-mizonokuchi station	JPN	2017	Active	PEM	Unknown	NA	H_2	1 m^3 /h	Mobility	[467]
67.	H_2One - hydrogen application center, Fuchu complex	JPN	2017	Active	PEM	Unknown	NA	H_2	1 m^3 /h	Mobility	[468]
68.	H_2One - Asahi Breweries in Ibaraki	JPN	2017	Active	PEM	Unknown	NA	H_2	1 m^3 /h	Mobility	[469]
69.	Costa Rica transportation ecosystem project	CRI	2017	Active	PEM	Renewable	Others	H_2	1 m^3 /h	Mobility	[430]
70.	Cerro Pabellon microgrid 450 kWh hydrogen ESS	CHL	2017	Active	Other Electrolysis	Renewable	Solar PV	H_2	50 kW	Industries	[470]
71.	Hassfurt	DEU	2016	Active	PEM	Grid	–	H_2	1.25 MW	Mobility	[471]
72.	HPEM2GAS (R&D)	DEU	2016	Active	PEM	Unknown	NA	H_2	0.2 MW	Mobility, power	[472]
73.	Hamburg - Schnackenburgallee	DEU	2016	Active	PEM	Grid	–	H_2	0.185 MW	Mobility, power	[473]

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Table 15 (*continued*)

SN	Case studies	Country	Start Year	Status	Electrolysis Technology	Types of electricity	Types of renewable	Products	Announced size	End uses	References
74.	Laboratory system at IFE Kjeller Phase 2	NOR	2016	Active	PEM	Unknown	NA	H_2	2 m^3 H_2/h	Mobility, power	[474]
75.	H_2One - Kyushu Resort Hotel, Huis Ten Bosch	JPN	2016	Active	PEM	Grid	–	H_2	1 m^3 H_2/h	Mobility, power	[475]
76.	H_2One - Yokohama Cargo Center	JPN	2016	Active	PEM	Grid	–	H_2	1 m^3 H_2/h	Mobility, power	[476]
77.	WindGas Hamburg-Reitbrook	DEU	2015	Active	PEM	Renewable	Onshore wind	H_2	1.5 MW	Mobility, power	[477]
78.	RH_2 Grapzow, Mecklenburg Vorpommern	DEU	2015	Active	ALK	Renewable	Onshore wind	H_2	1 MW - 200 m^3 H_2/h	Grid injection	[478]
79.	P2G-Biocat	DNK	2015	Active	ALK	Unknown	NA	CH_4	0.5 MW - 100 m^3 H_2/h	Mobility, power	[479]
80.	Raglan Nickel mine	CAN	2015	Active	ALK	Unknown	NA	H_2	60 m^3 /h	Mobility	[480]
81.	Don Quichote	BEL	2015	Active	ALK	Renewable	Onshore wind	H_2	0.3 MW - 60 m^3 H_2/h	Mobility, heat	[481]
82.	RWE PtG plant Ibbenbüren	DEU	2015	Active	PEM	Grid	–	H_2	0.15 MW	Mobility	[482]
83.	Stromlückenfüller 1st phase	DEU	2015	Active	PEM	Grid	–	H_2	0.02 MW	Mobility	[483]
84.	Hydrogen Valley South Tyrol - Bolzano, CHIC	ITA	2014	Active	ALK	Unknown	NA	H_2	1 MW - 180 m^3 H_2/h	Mobility, power, grid inj.	[484]
85.	H2BER (Berlin airport)	DEU	2014	Active	ALK	Renewable	Onshore wind	H_2	0.5 MW - 100 m^3 H_2/h	Power	[485]
86.	Hanau, Wolfgang Industrial Park	DEU	2014	Active	PEM	Unknown	NA	H_2	4m^3 H_2/h	Iron and steel	[66]
87.	MicroPyros, Staubing	DEU	2014	Active	Other Electrolysis	Unknown	NA	CH_4		Power	[486]
88.	ETOGAS, Solar Fuel Beta-plant AUDI, Werlte (Audi e-gas)	DEU	2013	Active	ALK	Grid	–	CH_4	6 MW	Power	[487]
89.	H_2 Logic HRS with onsite electrolysis Aalborg	DNK	2013	Active	ALK	Grid	–	H_2	200 kg H_2/h	Power	[488]
90.	Uniper/E-ON WindGas Falkenhagen Hydrogen Pilot Project	DEU	2013	Active	ALK	Renewable	Onshore wind	H_2	1 MW - 180 m^3 H_2/h	Mobility	[489]
91.	P2G plant Erdgas Schwaben	DEU	2013	Active	PEM	Unknown	NA	H_2	1 MW - 180 m3 H_2/h	Mobility	[490]
92.	Oslo, CHIC	NOR	2013	Active	ALK	Unknown	NA	H_2	0.6 MW - 120 m^3 H_2/h	Iron and steel	[491]
93.	CO_2RRECT-Niederaussem	DEU	2013	Active	PEM	Grid	–	CH_4	50 m^3 H_2/h	Mobility	[66]
94.	Sir Samuel building Griffith Center, Brisbane, Australia	AUS	2013	Active	ALK	Unknown	NA	H_2	0.2 MW - 30 m^3 H_2/h	Grid injection	[492]
95.	MicrobEnergy GmbH, Schwandorf	DEU	2013	Active	PEM	Grid	–	CH_4	0.18 MW	Grid injection	[493]
96.	H_2Move, Fraunhofer ISE	DEU	2013	Active	PEM	Renewable	Solar PV	H_2	0.04 MW	Mobility	[494]
97.	Hazira, Reliance, back-up hydrogen supply	IND	2005	Active	ALK	Unknown	NA	H_2		Power	[495]
98.	Refhyne	DEU	2021	Active	PEM	Unknown	NA	H_2	10 MW	Mobility	[496]
99.	H&R Ölwerke Hamburg-Neuhof	DEU	2018	Active	PEM	Grid	–	H_2	5 MW	Mobility	[497]
100.	H_2Herten	DEU	2012	Active	ALK	Unknown	NA	H_2	0.165 MW	Mobility	[498]
101.	H_2 research center BTU Cottbus	DEU	2012	Active	ALK	Unknown	NA	H_2	0.14 MW	Mobility	[499]
102.	Cotbus	DEU	2012	Active	ALK	Unknown	NA	H_2	0.12 MW - 30 m^3 H_2/h	Mobility	[500]
103.	Eucolino Schwandorf	DEU	2012	Active	Other Electrolysis	Unknown	NA	H_2	24 m^3 H_2/h	Mobility	[501]
104.	Agios Efstratios	GRC	2012	Active	Other Electrolysis	Unknown	NA	H_2	0.1 MW	Mobility	[502]
105.	Hydrogen mini-grid system Yorkshire (Rotherham)	GBR	2012	Active	ALK	Unknown	NA	H_2	0.03 MW	Mobility	[503]
106.	Commercial plant Svartsengi/George Olah plant	ISL	2011	Active	Other Electrolysis	Renewable	Others	MeOH	6 MW - 1200 m^3 H_2/h	Ammonia	[87]
107.	Hamburg Hafen City, CEP	DEU	2011	Active	ALK	Unknown	NA	H_2	0.6 MW - 120 m^3 H_2/h	Grid injection	[504]
108.	Hybrid power plant enertrag, Prenzlau	DEU	2011	Active	ALK	Unknown	NA	H_2	0.5 MW - 120 m^3 H_2/h	Power	[505]
109.	EnBW H_2 station, stuttgart	DEU	2011	Active	ALK	Unknown	NA	H_2	0.3 MW - 60 m^3 H_2/h	Domestic heat	[506]

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Table 15 (*continued*)

SN	Case studies	Country	Start Year	Status	Electrolysis Technology	Types of electricity	Types of renewable	Products	Announced size	End uses	References
110.	Ramea wind-hydrogen-diesel project	CAN	2011	Active	ALK	Unknown	NA	H_2	27 m^3 H_2/h	Mobility	[507]
111.	Hydrogen Island Bozcaada	TUR	2011	Active	Other Electrolysis	Unknown	NA	H_2	11 m^3 H_2/h	Mobility, power	[508]
112.	DNV Kema/DNV GL	NLD	2011	Active	PEM	Unknown	NA	H_2	0.01 MW	Mobility, power	[509]
113.	HARP System, Bella coola	CAN	2010	Active	ALK	Unknown	NA	H_2	0.3 MW - 60 m^3 H_2/h	Mobility	[510]
114.	H_2KT - hydrogen energy storage in nuuk	DNK	2010	Active	ALK	Unknown	NA	H_2	19 m^3 H_2/h	Mobility	[378]
115.	Nukissiorfiit nuuk hydrogen plant	DNK	2010	Active	ALK	Unknown	NA	H_2		Grid injection	[378]
116.	Centre of fuel cell technology, Chennai	IND	2012	Active	PEM	Unknown	NA	H_2	2 m^3 /h	Mobility	[511]
117.	Hychico, comodoro rivadavia	ARG	2009	Active	ALK	Renewable	Onshore wind	H_2	120 + 60 m^3 H_2/h	Mobility, power	[512]
118.	Taleghan solar hydrogen energy system	IRN	2009	Active	Other Electrolysis	Unknown	NA	H_2	0.2 MW	Mobility, heat	[513]
119.	Istanbul hydrogen project	TUR	2009	Active	ALK	Unknown	NA	H_2	0.16 MW - 30 m^3 H_2/h	Mobility	[514]
120.	Hybrid renewable energy park (HREP)	DEU	2009	Active	ALK	Grid	–	H_2	0.006 MW	Mobility, power, grid inj.	[66]
121.	Baglan energy park wales	GBR	2008	Active	ALK	Unknown	NA	H_2	10 m^3 /h	Mobility	[426]
122.	Savli wind-hydrogen demo project	IND	2013	Active	Other Electrolysis	Unknown	NA	H_2	0.005 MW	Mobility, power, grid inj.	[515]
123.	Dahej, reliance, back-up hydrogen supply	IND	2014	Active	ALK	Unknown	NA	H_2	444 m^3 H_2/h	Power	[516]
124.	HARI project, west beacon farm	GBR	2004	Active	ALK	Unknown	NA	H_2	0.034 MW	Mobility	[517]
125.	Energiepark mainz	DEU	2014	Active	PEM	Renewable	Onshore wind	H_2	6 MW	Mobility	[518]
126.	INGRID	ITA	2016	Active	ALK	Unknown	NA	H_2	1.15 MW	Power	[519]
127.	Gwalpahari solar-hydrogen demonstration	IND	2015	Active	Other Electrolysis	Renewable	Solar PV	H_2	0.12 MW	Power	[520]
128.	Solar energy centre SmartFuel hydrogen station	IND	2015	Active	Other Electrolysis	Renewable	Solar PV	H_2		Mobility	[521]
129.	FaHyence	FRA	2017	Active	ALK	Unknown	NA	H_2	30 m^3 /h	Mobility	[522]
130.	CPI Zaoquan thermal power plant in China's Ningxia region	CHN	2017	Active	ALK	Unknown	NA	H_2	20 m^3 /h	Mobility	[523]
131.	The power plant in Lebanon for a power plant cooling application	LBN	2018	Active	ALK	Unknown	NA	H_2	0.114 MW	Domestic heat	[487]
132.	Minatec's semiconductor labs in Grenoble	FRA	2018	Active	ALK	Unknown	NA	H_2	12 m^3 H_2/h	Mobility, power	[524]
133.	Grimstad renewable energy park	NOR	2000	Active	ALK	Grid	–	H_2	0.05 MW	Power	[525]
134.	REMOTE - Agkistro (Greece)	GRC	2021	Active	Other Electrolysis	Renewable	Hydropower	H_2	0.025 MW	Mobility	[526]
135.	HRS CMB port of Antwerp	BEL	2021	Active	PEM	Unknown	NA	H_2	1.2 MW	Mobility	[527]
136.	H_2 Logic HRS with onsite electrolysis in Vejle	DNK	2013	Active	ALK	Grid	–	H_2	200 kg H_2/d	Mobility	[418]
137.	H_2 Logic HRS with onsite electrolysis Holstebro	DNK	2013	Active	ALK	Grid	–	H_2	200 kg H_2/d	Power	[418]
138.	H_2 Logic 3 HRS with onsite electrolysis in Copenhagen	DNK	2013	Active	ALK	Grid	–	H_2	3 × 200 kg H_2/d	Mobility, power, grid inj.	[418]
139.	Hystock (Energy Stock)	NLD	2019	Active	PEM	Renewable	Solar PV	H_2	1 MW - 220 m^3 H_2/h	Grid injection	[64]
140.	HAEOLUS	NOR	2022	Active	PEM	Renewable	Onshore wind	H_2	2.5 MW - 500 m3 H_2/h	Mobility	[528]
141.	HRS Aalborg	DNK	2020	Active	ALK	Grid	–	H_2	0.25 MW - 60 m3 H_2/h	Power	[87]
142.	Fife, Levenmouth community energy project	GBR	2016	Active	Other Electrolysis	Renewable	Onshore wind	H_2	0.37 MW	Power	[529]
143.	PURE Project, Unst	GBR	2005	Active	ALK	Unknown	NA	H_2	0.015 MW	Power	[530]
144.	Tyseley energy park refuelling hub	GBR	2021	Active	PEM	Renewable	Others	H_2	3 MW	Mobility	[531]
145.	Ningxia solar hydrogen project, phase 1	CHN	2021	Active	ALK	Unknown	NA	H_2	30 MW	Power	[499]

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Table 15 (*continued*)

SN	Case studies	Country	Start Year	Status	Electrolysis Technology	Types of electricity	Types of renewable	Products	Announced size	End uses	References
146.	vHyGO - 1st facility for H_2 buses in Bouin (H_2 Ouest)	FRA	2021	Active	ALK	Renewable	Unknown	H_2	1 MW - 300 kg H_2/d	Mobility	[532]
147.	H_2One - SP group	SGP	2019	Active	PEM	Grid	–	H_2	1m^3 H_2/h	Mobility, power, grid inj.	[533]
148.	Semakau island microgrid engie (SPORE)	SGP	2019	Active	Other Electrolysis	Unknown	NA	H_2		Mobility	[534]
149.	Fine chemical industry park of Lanzhou	CHN	2020	Active	ALK	Renewable	Solar PV	MeOH	1000m^3 H_2/h - 1440 t MeOH	Mobility	[390]
150.	AuxHYGen, phase 1	FRA	2021	Active	ALK	Unknown	NA	H_2	1 MW - 200m^3 H_2/h	Mobility	[492]
151.	HYPOS	DEU	2019	Active	Other Electrolysis	Unknown	NA	H_2	1.25 MW	Power	[500]
152.	Hazira, reliance, back-up hydrogen supply	IND	2005	Active	ALK	Unknown	NA	H_2	680m^3 H_2/h	Power, grid inj.	[535]
153.	Air Liquide Becancour	CAN	2020	Active	PEM	Renewable	Hydropower	H_2	20 MW - 8 t H_2/d	Mobility	[536]
154.	Hebei Jiantou Guyuan wind project - 2nd phase	CHN	2021	Active	Other Electrolysis	Renewable	Onshore wind	H_2	10 MW	Grid inj.	[492]
155.	Hypor hydrogen energy Zhangjiakou wind power Hebei - first phase	CHN	2020	Active	Other Electrolysis	Renewable	Onshore wind	H_2	4.3 t H_2/d	Grid inj.	[500]
156.	DEMO4GRID	AUT	2022	Active	ALK	Grid	–	H_2	4 MW	Mobility	[537]
157.	Anglo-American Mogalakwena mine	ZAF	2022	Active	ALK	Renewable	Others	H_2	3.5 MW	Power	[538]
158.	Wuppertal refuelling station	DEU	2020	Active	PEM	Renewable	Others	H_2	2.5 MW - 500 m3 H_2/h	Mobility	[539]
159.	SALCOS - WindH_2	DEU	2021	Active	PEM	Renewable	Onshore wind	H_2	2 × 1.25 MW - 450 m3 H_2/h	Refining	[540]
160.	Hebei Jiantou Guyuan wind project - 1st phase	CHN	2019	Active	ALK	Renewable	Onshore wind	H_2	10 MW	Refining	[541]
161.	Green hydrogen project, Mohammad Bin Rashid solar park	ARE	2021	Active	PEM	Renewable	Solar PV	H_2	1.25 MW	Mobility, power, grid inj.	[542]
162.	Hydrogen Park south Australia - HyPSA	AUS	2021	Active	PEM	Renewable	Others	H_2	1.25 MW	Mobility, power, grid inj.	[543]
163.	NEL-Champaign-Urbana mass transit district	USA	2021	Active	PEM	Unknown	NA	H_2	1 MW	Power	[544]
164.	Jemena Western Sydney - H_2GO project	AUS	2021	Active	PEM	Grid	–	H_2	0.5 MW	Mobility	[545]
165.	Alliander Oosterwolde - solar park of GroenLeven	NLD	2022	Active	ALK	Renewable	Solar PV	H_2	1.4 MW	Grid inj.	[546]
166.	HRS TMB Barcelona	ESP	2022	Active	PEM	Renewable	Others	H_2	2 MW	Power	[547]
167.	HRS CNH_2 Puertollano	ESP	2015	Active	ALK	Renewable	Solar PV	H_2	0.06 MW	Mobility, power, grid inj.	[548]
168.	Chongli wind-solar hydrogen project - first phase	CHN	2021	Active	PEM	Renewable	Others	H_2	1.7 t H_2/d	Mobility	[549]
169.	Halcyon power	NZL	2021	Active	PEM	Renewable	Others	H_2	1.5 MW - 250 m3 H_2/h	Mobility, power, grid inj., biofuels	[550]
170.	Toyota hydrogen centre, Altona, Victoria	AUS	2021	Active	Other Electrolysis	Grid	–	H_2	0.2 MW	Mobility	[551]
171.	H_2One multistation-Tsuruga City	JPN	2020	Active	PEM	Grid	–	H_2	1 m^3/h	Power	[552]
172.	Canberra HRS	AUS	2021	Active	PEM	Renewable	Others	H_2	10 m3/h	Power	[553]
173.	SunLine palms springs	USA	2018	Active	PEM	Other	NA	H_2	2 MW	Power, grid inj.	[413]
174.	HRS Gatwick airport	GBR	2019	Active	PEM	Grid	NA	H_2		Mobility, power	[554]
175.	4 projects of ITM in Australia	AUS	2018	Active	PEM	Unknown	NA	H_2	4 × 0.25 MW	Mobility, power, grid inj.	[555]
176.	HRS Swindon	GBR	2018	Active	PEM	Grid	NA	H_2		Mobility	[556]
177.	HRS Beaconsfield	GBR	2018	Active	PEM	Grid	NA	H_2		Grid inj., domestic heat	[557]
178.	Steklarna hrastnik glass manufactuing plant	SVN	2019	Active	Other Electrolysis	Renewable	Solar PV	H_2	0.15 MW	Mobility	[558]
179.	Thermal power plant sostanj	SVN	2022	Active	Other Electrolysis	Unknown	NA	H_2	0.1 MW	Power	[559]

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Table 15 (*continued*)

SN	Case studies	Country	Start Year	Status	Electrolysis Technology	Types of electricity	Types of renewable	Products	Announced size	End uses	References
180.	TPJ jesenice	SVN	2018	Active	Other Electrolysis	Unknown	NA	H_2	0.35 MW	Mobility, power, grid inj.	[560]
181.	Sirea - castres site	FRA	2021	Active	Other Electrolysis	Renewable	Solar PV	H_2	0.43 MW	Mobility	[561]
182.	Hydrogen lab leuna (phase 1)	DEU	2021	Active	SOEC	Renewable	Onshore wind	MeOH	1 MW	Mobility	[562]
183.	Rajasthan pilot plant	IND	2021	Active	Other Electrolysis	Renewable	Solar PV	H_2		Mobility	[563]
184.	3 × 1250 kW projects in USA	USA	2000	Active	PEM	Unknown	NA	H_2	3 × 1250kw	Mobility	[528]
185.	1 × 500 kW projects in USA	USA	2000	Active	PEM	Unknown	NA	H_2	500kw	Mobility	[528]
186.	18 × 180 kW projects in USA	USA	2000	Active	PEM	Unknown	NA	H_2	18 × 180kw	Mobility	[528]
187.	12 × 120 kW projects in USA	USA	2000	Active	PEM	Unknown	NA	H_2	12 × 120kw	Industries	[528]
188.	H_2V Las Tortolas	CHL	2021	Active	PEM	Renewable	Solar PV	H_2	2 kg H_2/d	Mobility	[413]
189.	H_2PiyR pamiers	FRA	2021	Active	Other Electrolysis	Unknown	NA	H_2		Power	[413]
190.	Ningxia solar hydrogen project, phase 2	CHN	2021	Active	ALK	Unknown	NA	H_2	150 MW	Mobility, power	[564]
191.	Oskarshamn nuclear plant	SWE	2021	Active	ALK	Nuclear	NA	H_2	12 kg H_2/h	Mobility	[565]
192.	Trzebinia refinery	POL	2021	Active	Other Electrolysis	Unknown	NA	H_2	350 t H_2/y	Mobility	[566]
193.	Promigas	COL	2022	Active	PEM	Renewable	Solar PV	H_2	22 kW	Mobility	[490]

inputs and delivery systems are the obstacles to creating the optimal delivery system for hydrogen.

- One of the biggest challenges to the growth of a worldwide hydrogen market is the requirement for international standards and regulations on hydrogen. Due to the absence of a unified regulation, hydrogen's potential is constrained in its ability to diffuse.

10. Conclusions and future perspectives

The ever-increasing global energy crisis, environmental degradation and climate change issues impacted by excessive consumption of fossil fuels (FFs) are pushing the world to find a suitable and green energy source for ensuring net-zero emissions and attaining the sustainable development goals (SDGs)-6, 7 and 13 through decarbonization of the global energy system (GES). The following conclusions can be drawn from the present study:

1. Current global energy production and consumption patterns are FF-based, which needs a transition towards sustainable green energy. In pursuit, the CRE and energy transition framework and their relationship (industrial symbiosis) will lead to achieving the objective of sustainable production and consumption of goods and energy.
2. Considering the environmental pollution, GWP issues, and future energy security, a two-fold revolutionary energy transition is immediately necessary. The earliest movement can be the energy revolution: the steady and intensive transition from FF-based primary energy to sustainable and renewable energy sources such as solar, wind, geothermal, biomass and water. The subsequent phase would be the development of a sustainable hydrogen economy based on the extensive usage of hydrogen as a green secondary energy carrier.
3. The CRE does not concentrate on WI at a large-scale, also the applications, scopes, opportunities, limitations, and challenges of CRE implementation in water industries are still unexplored. Thus, identification and the potential implications of CRE in WI are essential for sustainable water resources management and resource recovery.
4. Japan is the leading HP technology patent-holding nation with 2829 patent filings for inventions related to hydrogen production technologies over the past 20 years. All patent applications submitted over the last five years; renewable-based innovations have received much more attention than FF-based ones.
5. Compared with the overall production method, the most environmentally friendly HP offers photonic energy, and the highest efficiency offers thermal energy.
6. Considering feed sources PEM is the most suitable technology for HP in pure water whereas MECs are the most appropriate technology for HP in wastewater. If we consider seawater as a feed source ED and RED are the most competitive technologies for simultaneous desalination and HP. Although, all these HP technologies are in their R& D stage.
7. An analysis by the IEA found that the HP costs for green hydrogen (\$2.5–5/kg), blue hydrogen (\$1.50–3.50/kg), and grey hydrogen are all roughly \$1.50/kg (Yue et al., 2021). The cost of HP technologies like EL, RED, and PECM must be reduced to make hydrogen a viable fuel source for everyone.
8. Human urine has immense potential for HP and resource recovery as it contains between 90 and 96 percentages of water. CPTC, PEL, PC, MECs, catalysis by aluminum nanoparticles (ALNPs) and urea adsorption and catalytic reduction, are some of the technologies used for HP from human and synthetic urine. Although, most of these technologies are on the laboratory scale. Future research and development are required to commercialize these technologies.
9. Case studies analysis in HP technologies and WI suggested European countries were the dominant hydrogen producers having 62.69 % of active projects. Germany had the highest number of active hydrogen production case studies recorded to be 50. Most active case studies employed PEM electrolysis accounting to be 46.63 % followed by AEL electrolysis and SOEL reported being 34.19 % and 2.10 % respectively.
10. The major challenge for developing a hydrogen economy is scaling up HP, and the transition from carbon-intensive to low-carbon HP. Costs for green HP are still too high to be competitive with other energy sources economically. The hydrogen price

per kg should be approximately \$1.5 for HP to be profitable. The need for ultrapure water poses one of the biggest obstacles since it takes 2.38 gal, or 9 L of water to produce 1 kg of hydrogen gas, which could trigger a water shortage in the future HE.

The future perspectives and research directions of green hydroge production in WI for CRE framework are recommended as follows:

- ✓ Establishment of a CRE-based, self-hydrogen energy-generating WI can be a plausible solution for the future energy crisis and sustainable resources management. Since, one of the significant requirements of water electrolysis is the need for highly pure water feeds. Before further proceeding to develop a HE by 2030, the feasibility study of pure water requirement is highly recommended.
- ✓ It was estimated that 21 billion m^3 of pure fresh water would be required to meet the meet ambitious demand for HE by 2030. Accessible freshwater makes up just <1 % of the planet's water. It is best to avoid burdening freshwater usage, especially in areas where drinking water is difficult to attain such as in Asia, Africa and some highly industrialized Cities like Sydney, Dhaka and Beijing. Almost all the remaining 99 %, or about 1.4 billion km^3, is seawater, which can be purified through desalination processes before being used as an electrolysis feedstock by electrodialysis or reverse osmosis techniques.
- ✓ Special consideration should be focuse on wastewater to hydrogen production because it was estimated that 359 billion m^3 of wastewater is produced each year and 785 million people lack access to clean drinking water. Simultaneous WW treatment, resource recovery (Nitroge, potassium and phosphours) and hydrogen production could be a feasible option to clean green hydrogen production for a better HE without burdening the fresh water.
- ✓ To support future HE, alternative faormats of hydrogen fuels such as ammonia, hydrogen peroxide and methanol, to name but a few must be considered. Easy, simple, and efficient production technologies of these fuels should be explored.
- ✓ Green hydrogen cost could be one of the most significant obstacles to proceed with the HE, hence measures should be taken to maintain the hydrogen cost within 1–1.5 \$/kg hydrogen to compete with the alternative FFs-based energy.
- ✓ Research on developing cost-effective catalysts and inexpensive membrane materials for PEM electrolysis for HP are needed from PW whereas MECs needs simple cell design, high membranes stability and minimal operational costs.
- ✓ Hydrogen storage and safety issues also be needed to consider. Research and development should be focused on development of low-cost hydrogen storage materials. Inorder to minimize possible hazards and risks of hydrogen, health and environmental safety guidelines should be followed strictly such as OSHAS 18001 and ISO 14001.
- ✓ International standards and regulations on the growth of worldwide H_2 market and development of a proper hydrogen supply chain system would be necessary for the future HE.

CRediT authorship contribution statement

Mohammad Mahbub Kabir: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – original draft. **Mst. Mahmoda Akter:** Formal analysis, Data curation, Validation, Writing – review & editing. **Zhenguo Huang:** Data curation, Validation, Writing – review & editing. **Leonard Tijing:** Supervision, Validation, Writing – review & editing. **Ho Kyong Shon:** Supervision, Project administration, Resources, Funding acquisition, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

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