



## Review

## Hydrogen combustion, production, and applications: A review



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## ABSTRACT

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The demand for fossil fuels is rising rapidly, leading to increased greenhouse gas emissions. Hydrogen has emerged as a promising clean energy alternative that could help meet future demands sustainably, especially if produced using renewable methods. For hydrogen to meaningfully contribute to energy transitions, it needs more integration into sectors like transportation, buildings, and power that currently have minimal hydrogen usage. This requires developing extensive cross-sector hydrogen infrastructure. This review examines hydrogen combustion as a fuel by exploring and comparing production techniques, enriching ammonia with hydrogen as a CO<sub>2</sub>-free option, and hydrogen applications in engines. Additionally, a techno-economic environmental risk analysis is discussed. Results showed steam methane reforming is the most established and cost-effective production method at \$1.3–1.5/kg H<sub>2</sub> and 70–85% efficiency but generates CO<sub>2</sub>. Biomass gasification costs \$1.25–2.20/kg H<sub>2</sub> and pyrolysis \$1.77–2.05/kg H<sub>2</sub> offering renewable options. However, bio-photolysis currently has high costs of \$1.42–2.13/kg H<sub>2</sub> due to low conversion rates requiring large reactors. Blending H<sub>2</sub>/NH<sub>3</sub> could enable carbon-free combustion, aiding carbon neutrality pursuits, but minimizing resultant NOx is crucial. Hydrogen's wide uses from transportation to power underline its potential as a transformational energy carrier.

## 1. Introduction

Hydrogen as a fuel has attracted significant attention recently due to its potential as a clean and sustainable energy source. One of its unique properties is its high gravimetric energy density, which enables efficient energy storage and conversion. Hydrogen fuel, when used in combustion processes or fuel cells, produces water as the primary byproduct, resulting in minimal environmental impact and near zero greenhouse gas (GHG) emissions [1]. In the combustion field, hydrogen has been applied in various settings, such as internal combustion engines, gas turbines, and homogeneous charge compression ignition (HCCI) systems, to improve performance and reduce harmful emissions [2]. Furthermore, hydrogen can be blended with other fuels, such as ammonia, to enhance combustion efficiency and mitigate the formation

of nitrogen oxides (NOx) [3].

Production techniques for hydrogen are also of critical importance, as they determine the sustainability and economic viability of hydrogen as an energy source. Some common hydrogen production methods include steam methane reforming, electrolysis of water, thermochemical processes, and biological methods [4]. Each technique has advantages and drawbacks concerning energy efficiency, cost, and environmental impact. As research and development in hydrogen production technologies continue, it is essential to optimize these methods to ensure the widespread adoption of hydrogen fuel as a clean and sustainable energy source for various applications in the combustion field and beyond [5] (see Fig. 1). Moreover, Hydrogen demand is projected to increase significantly over the next 20 years [6]. However, potential challenges like lengthy permitting processes, higher equipment expenses, and lack of capital access could hinder the growth of hydrogen supply. Major

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<b>Nomenclature</b>	
ATR	Auto-thermal reforming
CG	Coal gasification
CPOX	Catalytic partial oxidation
DF	Dark fermentation
DR	Dry reforming
EGR	Exhaust gas recirculation
GHG	Greenhouse gas
H2ICE	Hydrogen-powered internal combustion engine
HCCI	Homogeneous charge compression ignition
HEM	Hydrogen-enriched methane
HENG	Hydrogen-enriched natural gas
IMEP	Indicated mean effective pressure
LCA	Life cycle assessment
LES	Large eddy simulation
LFL	Lower flammability limit
LH <sub>2</sub>	liquid hydrogen
MEC	Membrane electrolysis cell
MRR	Membrane-integrated reformer reactor
NG	Natural gas
NOx	Nitrogen oxides
NREL	National Renewable Energy Laboratory
PEMFC	Proton exchange membrane fuel cell
PF	Photo-fermentation
POR	Partial oxidation reforming
RPM	Revelation per minute
SCR	Selective catalytic reduction
S <sub>L</sub>	Laminar flame speed (m/s)
SMR	Steam-methane reforming
SR	Steam reforming
TEA	Techno-economic analysis
TRL	Technology readiness level
UAV	Unmanned aerial vehicle
WGSR	Water gas shift reaction
WTH	Waste-to-hydrogen

obstacles to increasing hydrogen supply include long permitting times for new projects, higher capital costs of production equipment, and challenges securing financing due to perceptions of risk around new hydrogen technologies and infrastructure. These limitations could slow the rapid rise in hydrogen supply needed to satisfy sharply growing demand projections over the next two decades [6]. Currently, hydrogen is mainly supplied through fossil fuel-based methods like steam methane reforming. Major users are fertilizer production and oil refining. These industries are projected to lead the transition to clean hydrogen through 2030 by switching their operations. Emerging applications like steel, synthetic fuels, and heavy transport may start adopting hydrogen in faster transition scenarios. Nearly all hydrogen is currently gray, but demand is projected to decline as clean hydrogen costs fall. By 2050, clean hydrogen could meet 73–100% of total demand depending on scenarios [7]. After 2025, new hydrogen production will mainly be clean. This coincides with the phasing out of gray hydrogen due to clean hydrogen costs and decarbonization commitments. Until 2030, clean adoption will involve existing users switching fuels. Between 2030 and 2040, new applications without prior demand will drive increases [7]. Post-2040, commitments are expected to spur emerging clean hydrogen applications in scenarios with further acceleration or achieved commitments. Support mechanisms like carbon pricing or sustainable fuel quotas may be needed. Slower scenarios rely more on underlying market growth and limited new policies.

Adding hydrogen fuel to ammonia for combustion engines has

recently emerged as a promising avenue for enhancing engine performance and reducing emissions. By combining the advantageous properties of both hydrogen and ammonia, this blended fuel offers several benefits over traditional fossil fuels [8]. Hydrogen, known for its high energy density and clean combustion, contributes to improved combustion efficiency and a reduced environmental impact. Ammonia, on the other hand, contains no carbon atoms, which eliminates the production of carbon dioxide and other harmful greenhouse gases during combustion [9]. However, ammonia has a lower energy density than hydrogen and exhibits a slower ignition, which can be mitigated by the addition of hydrogen. This synergy results in a more efficient combustion process with reduced ignition delay and increased flame propagation speeds [10]. The combustion characteristics of hydrogen-ammonia mixtures can be further optimized by adjusting parameters such as the hydrogen-ammonia ratio, equivalence ratio, and engine operating conditions. Additionally, the use of advanced combustion strategies, such as HCCI and exhaust gas recirculation (EGR), can help to minimize the formation of NOx and other emissions while maintaining engine performance [11,12].

Investigating hydrogen combustion is of practical importance for two primary reasons: utilization and safety. From a utilization perspective, hydrogen is an attractive option for power generation due to its environmentally friendly nature and reduced pollutant emissions during combustion compared to traditional fuels. Unlike fossil fuels, hydrogen combustion does not produce carbon dioxide, a key

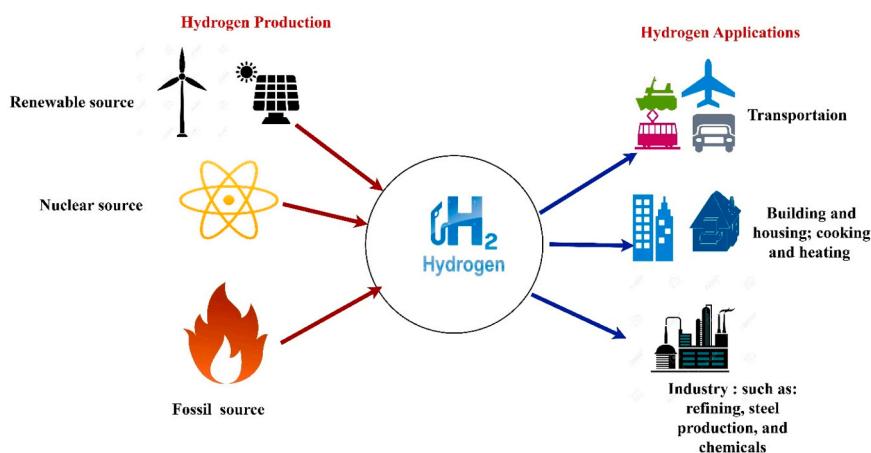


Fig. 1. Schematic of various hydrogen production sources and applications.

contributor to greenhouse gas emissions. It is essential to consider that hydrogen, unlike fossil or nuclear fuels, must be produced through energy-intensive processes, making it more suitable as an energy carrier rather than a primary energy source. In addition to its role as an effective energy carrier, hydrogen is a potent propellant for rocket and air-breathing engines, making it valuable for various energy, power, and propulsion applications. As a result, continued research into hydrogen combustion is crucial for its effective utilization and ensuring safety across its diverse applications [13]. Overall, in hydrogen combustion, there is a need for a detailed understanding of combustion mechanisms, the development of advanced combustion technologies, and optimization of fuel-air mixing. For hydrogen production, research should focus on developing cost-effective and sustainable production methods, exploring novel materials and catalysts, and optimizing process conditions. In terms of hydrogen applications, further research is needed for integration into the transportation sector, utilization in industrial processes, and development of hydrogen-based energy storage systems. Addressing these research gaps is crucial for the advancement of hydrogen technologies and their widespread adoption as a clean and sustainable energy source.

This overview addresses different hydrogen fuel topics, such as hydrogen characteristics, combustion, production, techno-economic environmental risk analysis, and applications. The effect of adding hydrogen to ammonia for combustion purposes is also reviewed. Different hydrogen combustion engine applications are represented in this review, as well as general remarks and future research directions. What sets this review apart is its comprehensive coverage of multiple inter-disciplinary topics related to hydrogen including hydrogen fuel properties, reactions, productions, blending with other fuels, techno-economic analysis, and applications. Additionally, the emphasis on incorporating recent research papers allows readers to gain insights into the latest advancements in hydrogen combustion and applications in this rapidly growing field. By integrating current studies, this review offers a novel perspective, enhancing the understanding of hydrogen's role as a clean and versatile fuel source which the reader can find comprehensive and updated information regarding the hydrogen fuel.

## 2. Hydrogen combustion

This section discusses hydrogen properties and combustion reactions.

### 2.1. Properties and characteristics

Henry Cavendish discovered the hydrogen atom in 1766 when he broke down water. Antoine Lavoisier named it hydrogen. H (hydrogen) is very common since it is in 93% of all molecules. Hydrogen is a pure

chemical compound that has two atoms ( $H_2$ ). It has no smell, taste, or color at normal temperature ( $25^\circ C$ ) and pressure (1 atm) and does not dissolve in water. It burns easily and spreads quickly because it is lighter than air and turns into a liquid at  $-253^\circ C$  in special storage systems that keep things very cold [14,15].

Hydrogen has the highest specific energy of all fuels, which implies that 1 g of H has the equivalent energy of 2.8 g of gasoline. When liquefied by cooling, this fuel with low molar mass occupies a volume 700 times smaller than in its gaseous state. Its density ( $0.08967 \text{ kg/m}^3$ ) is 14.4 times lower than that of air ( $1.2928 \text{ kg/m}^3$ ) [14]. In other words, hydrogen has 2.6 times the specific energy of gasoline. Hydrogen also has superior combustion properties than any other hydrocarbon fuel in terms of ignitability, low ignition delay, and higher flame stability [16]. Hydrogen possesses numerous attributes that make it an attractive fuel source, one of which is its high calorific value, resulting in a substantial release of energy upon combustion. The physical and chemical properties of hydrogen fuel differ from other fossil fuels, as represented in Table 1.

These unique hydrogen properties' inherent advantages render hydrogen a potential fuel for space rockets and hypersonic (scramjet) and supersonic (ramjet) jet engines. However, its high flammability and low volumetric energy density introduce complexities in onboard storage systems for ground transportation and aircraft propulsion applications. Currently, two technically viable storage methods for on-board hydrogen storage are compressed  $H_2$  and liquid  $H_2$ . Nevertheless, both storage systems impose extreme conditions on fuel tanks. Compressed hydrogen necessitates four times the volume of gasoline to deliver the same energy content. Liquid hydrogen storage also presents challenges in cryogenic fuel transportation and metering. Given the substantial volume and weight constraints associated with hydrogen applications, there is a strong motivation for developing a hydrocarbon fuel-based airframe-integrated scramjet [17–20].

The flammability limit of mixtures containing hydrogen and oxidants is influenced by various factors, such as ignition energy, pressure, temperature, the presence of diluents, and the dimensions and configuration of the installation or equipment. To reduce the flammability of these mixtures, they can be diluted with any constituent until the concentration falls below the lower flammability limit (LFL). Hydrogen has a wide flammability range in normal air conditions, from 4 to 75 vol%, compared to methane (4.3–15 vol%) and gasoline (1.4–7.6 vol%) [15]. Hydrogen also needs very little energy to ignite (0.02 MJ), while gasoline and methane need more energy (0.24 and 0.28 MJ, respectively). The mixtures were derived from stoichiometric information. Confined hydrogen has the potential to detonate across a broad concentration spectrum, exhibiting a more rapid flame velocity (1.85 m/s) compared to gasoline vapor (0.42 m/s) and methane (0.38 m/s). Under identical stoichiometric conditions, the hydrogen-air flame temperature is higher

**Table 1**  
Properties and characteristics of hydrogen and other gases at 1 atm and room temperature.

Property	Hydrogen	Gasoline	Diesel	Methane	Propane	Ammonia
Molar mass (kg/kmol)	2.015	60–150	100.2	16.043	44.097	17.02
Density ( $\text{kg/m}^3$ )	0.09	700–800	0.78	0.65	2.01	0.73
Lower heating value (MJ/kg)	119.9	43.9	42.83	50	46.4	18.8
Upper heating value (MJ/kg)	141.80		44.80	55.5		22.5
Flammability limits in the air (vol%)	4–75	1.0–7.6	0.6–5.5	15	9.5	15–28
Detonability limit in air	18.3–59.0 %	-		6.3–14	1.1–1.3	
Detonation speed in air (m/s)	2055	-	-	-	-	
Laminar Flame speed in air (cm/s)	275	51	30	38	45.5	7.1
Minimum ignition energy (MJ)	0.02	0.25	0.24	0.29	-	8
Ignition Temperature ( $^\circ C$ )	560	228–471	250	540	-	650
Maximum flame temperature in air ( $^\circ C$ )	2045			1957	1980	
Adiabatic flame temperature ( $^\circ C$ )	2207	2307	2027	1941	1980	1800
Stoichiometric A/F mass ratio	34.4	14.5	14.5	17.2	-	6.05
Evaporation heat (kJ/kg)	456	350–400	275	510	428	23.37
Quenching distance (mm)	0.64	2	-	2.1	-	7
Research Octane Number	>100	90–98				130

than that of methane but lower than gasoline, with respective values of 2207, 1917, and 2307 °C. [21].

## 2.2. Combustion reactions

The fundamental reactions involved in the combustion of hydrogen play a pivotal role in describing the combustion processes of various hydrocarbon and oxygenated hydrocarbon fuels. Additionally, hydrogen itself holds considerable importance as a fuel source, particularly in domains such as carbon-free economies, fuel safety concerns, and rocket propulsion. Reflecting its profound significance, several novel mechanisms describing hydrogen combustion have been published over the past decade [22–25].

Marcus et al. [24] developed a detailed kinetic model for hydrogen-oxygen combustion over wide ranges of temperatures (298–2700 K), pressures (0.05–87 atm), and equivalence ratios (0.2–6). The comprehensive mechanism and testing covered combustion behavior from low to high temperatures at sub-atmospheric to elevated pressures for fuel-lean to fuel-rich mixtures. This stringent evaluation provided insights into critical reaction pathways over wide combustion regimes relevant to both fundamental kinetics and practical applications. The validated mechanism can be a useful tool for simulations of hydrogen combustion spanning the parametric ranges examined. Moreover, Li et al [25] comprehensively validated the chemical kinetic mechanism for H<sub>2</sub>/O<sub>2</sub> combustion based on previous work mentioned in ref [24] and recent kinetic and thermodynamic data. The mechanism was tested against a wide range of experimental conditions including shock tubes, flow reactors, and laminar premixed flames. They concluded that the H + OH + M reaction was found to be important primarily for modeling high-pressure flame propagation, with flame speeds matched using various literature transport coefficients by adjusting the rate within uncertainties.

The hydrogen-oxygen reaction mechanism is critical for both fundamental kinetics research and applied combustion systems like fire safety, energy conversion, and propulsion [25]. Hydrogen's use as a fuel in these areas necessitates understanding its oxidation chemistry. Additionally, the elementary reactions with the species H, O, OH, HO<sub>2</sub>, and H<sub>2</sub>O<sub>2</sub> are integral in establishing the reactive radical pool that drives oxidation in hydrocarbon fuels. Therefore, advancing H<sub>2</sub>/O<sub>2</sub> kinetics provides foundational knowledge for broader combustion science and supports the development of hydrogen-based technologies across a range of fields [24]. The detailed H<sub>2</sub>/O<sub>2</sub> reaction mechanism mentioned in ref [25] is shown in Table 2.

In recent years, several studies have improved the understanding of hydrogen combustion chemistry [26]. For the reaction, H<sub>2</sub> + OH = H<sub>2</sub>O + H, theoretical investigations [27–29] found good agreement with earlier experimental data. However, the differences between calculated rate constants were larger than the differences in rate constants used in kinetic models from 2015 [26], hampering the selection of an updated expression. An experimental study from 295 to 701 K of the reaction OH + OH = H<sub>2</sub>O + O, not included in a [26,30,31] hydrogen kinetic mechanism, found the rate constant from Sangwan and Krasnoperov study [32] below 834 K was lower than other measurements. The low-temperature rate constant agreed well with theoretical work by Nguyen and Stanton [33]. Another study [34] proposed a fit to this theoretical data, showing good agreement with high-temperature experiments by Wooldridge et al. [35] and a reverse rate from Sutherland et al. [36]. Hong et al. [37] also supported Wooldridge et al.'s [35] results.

Konnov [38] investigated recent suggestions by Burke and Klippenstein [39,40] that chemically termolecular reactions like H + O<sub>2</sub> + R could significantly impact hydrogen combustion kinetics under common conditions, requiring careful analysis of their inclusion in mechanisms since they affect reactivity and laminar flame burning velocities. To explore this, a detailed hydrogen combustion scheme was investigated to counteract enhanced chain termination from these reactions while

**Table 2**

Detailed H<sub>2</sub>/O<sub>2</sub> reaction mechanism (units are cm<sup>3</sup>·mol·s·kcal·K, and k = A·T<sup>n</sup>·exp(−E/RT)) mentioned in ref [25].

No	Reaction	A	n	E
Chain reaction of H <sub>2</sub> /O <sub>2</sub>				
1	H + O <sub>2</sub> = O + OH	3.55 × 10 <sup>15</sup>	-0.41	16.6
2	O + H <sub>2</sub> = H + OH	5.08 × 10 <sup>4</sup>	2.67	6.29
3	H <sub>2</sub> + OH = H <sub>2</sub> O + H	2.16 × 10 <sup>8</sup>	1.51	3.43
4	O + H <sub>2</sub> O = OH + OH	2.97 × 10 <sup>6</sup>	2.02	13.4
H <sub>2</sub> /O <sub>2</sub> dissociation/recombination reactions				
5	H <sub>2</sub> + M = H + H + Ar	4.58 × 10 <sup>19</sup> 5.84	-1.40–1.10–1.10	104.38104.38104.38
	= H + H + Ar	×		
	ArH <sub>2</sub> + He = H + He <sub>a</sub>	10 <sup>18</sup> 5.84 × 10 <sup>18</sup>		
	Efficiency factors are:			
	ε <sub>H2O</sub> = 12.0,			
	ε <sub>H2</sub> = 2.5, ε <sub>Ar</sub> = 0.75, and ε <sub>He</sub> = 0.75			
6	O + O + M = O <sub>2</sub> + M <sup>a</sup> O + O + Ar = O <sub>2</sub> + O <sub>2</sub> + He = O <sub>2</sub> + He	6.16 × 10 <sup>15</sup> 1.89 × 10 <sup>13</sup> 1.89 × 10 <sup>13</sup>	-0.500.000.00	0.00–1.79 to 1.79
7	O + H + M = OH + M <sup>a</sup>	4.71 × 10 <sup>18</sup>	-1.0	0.00
8	H + OH + M = H <sub>2</sub> O + M <sup>b</sup>	3.8 × 10 <sup>22</sup>	-2.00	0.00
	Efficiency factors are ε <sub>H2O</sub> = 12.0, ε <sub>H2</sub> = 2.5, ε <sub>Ar</sub> = 0.38, and ε <sub>He</sub> = 0.38			
HO <sub>2</sub> Formation and consumption				
9	H + O <sub>2</sub> + M = HO <sub>2</sub> + M <sup>c</sup> k <sub>0</sub> H + O <sub>2</sub> + M = HO <sub>2</sub> + M <sup>d</sup>	6.37 × 10 <sup>20</sup> 9.04 × 10 <sup>19</sup> 1.48 × 10 <sup>12</sup>	-1.72–1.500.60	0.520.490.00
	k <sub>0</sub> k <sub>∞</sub> c: When the main bath gas is N <sub>2</sub> (M = N <sub>2</sub> ). Troe parameter is F <sub>c</sub> = 0.8.			
	Efficiency factors are ε <sub>H2O</sub> = 11.0, ε <sub>H2</sub> = 2.0, and ε <sub>O2</sub> = 0.78.d: When the main bath gas is Ar or He (M = Ar or He). Troe parameter is F <sub>c</sub> = 0.5.			
	Efficiency factors are ε <sub>H2O</sub> = 16.0, ε <sub>H2</sub> = 3.0, ε <sub>O2</sub> = 1.1, and ε <sub>He</sub> = 1.2			
10	HO <sub>2</sub> + H = H <sub>2</sub> + O <sub>2</sub>	1.66 × 10 <sup>13</sup>	0.00	0.82
11	HO <sub>2</sub> + H = OH + OH	7.08 × 10 <sup>13</sup>	0.00	0.30
12	HO <sub>2</sub> + O = OH + O <sub>2</sub>	3.25 × 10 <sup>13</sup>	0.00	0.00
13	HO <sub>2</sub> + OH = H <sub>2</sub> O + O <sub>2</sub>	2.89 × 10 <sup>13</sup>	0.00	-0.50
HO <sub>2</sub> formation and consumption				
14	HO <sub>2</sub> + HO <sub>2</sub> = H <sub>2</sub> O <sub>2</sub> + O <sub>2</sub> HO <sub>2</sub> + H <sub>2</sub> O <sub>2</sub> = H <sub>2</sub> O <sub>2</sub> + HO <sub>2</sub>	4.20 × 10 <sup>14</sup> 1.30 × 10 <sup>11</sup>	0.000.00 × 10 <sup>11</sup>	11.98–1.63

(continued on next page)

**Table 2 (continued)**

No	Reaction	A	n	E
	+ O <sub>2</sub> :			
	Reactions (14)			
	and (19) are			
	expressed as			
	the sum of the			
	two rate			
	expressions			
15	H <sub>2</sub> O <sub>2</sub> + M =	1.20 ×	0.000.00	45.548.4
	OH + OH + M <sup>f</sup>	10 <sup>17</sup> 2.95		
	k <sub>0</sub> k <sub>∞</sub> f: Troe	× 10 <sup>14</sup>		
	parameter is F <sub>c</sub>			
	= 0.5.			
	Efficiency			
	factors are ε <sub>H2O</sub>			
	= 12.0, ε <sub>H2</sub> =			
	2.5, ε <sub>Ar</sub> = 0.64,			
	and ε <sub>He</sub> = 0.64.			
16	H <sub>2</sub> O <sub>2</sub> + H =	2.41 ×	0.00	3.97
	H <sub>2</sub> O + OH	10 <sup>13</sup>		
17	H <sub>2</sub> O <sub>2</sub> + H = H <sub>2</sub>	4.82 ×	0.00	7.95
	+ HO <sub>2</sub>	10 <sup>13</sup>		
18	H <sub>2</sub> O <sub>2</sub> + O =	9.55 × 10 <sup>6</sup>	2.00	3.97
	OH + HO <sub>2</sub>			
19	H <sub>2</sub> O <sub>2</sub> + OH =	1.00 ×	0.000.00	0.009.56
	H <sub>2</sub> O +	10 <sup>12</sup> 5.8 ×		
	HO <sub>2</sub> H <sub>2</sub> O <sub>2</sub> +	10 <sup>14</sup>		
	OH = H <sub>2</sub> O +			
	HO <sub>2</sub>			

maintaining or improving performance. Updated kinetic studies were analyzed, resulting in four added reactions and three adjusted rate constants, though this significantly reduced calculated burning velocities compared to experiments and prior models due mostly to termolecular reactions. Implementing a new theoretical transport database from Jasper et al. [41,42] was then found to substantially improve the updated model's performance, bringing it into good accordance with experimental burning velocity measurements for H<sub>2</sub>+air flames at atmospheric pressure using heat flux methods, representing an improvement over the author's previous model that did not satisfactorily capture this behavior [38]. The mechanism incorporated new termolecular reactions and updated rate constants for existing reactions, as listed in Table 3. The inclusion of these chemical modifications did not significantly alter the mechanism's ability to model hydrogen autoignition and oxidation behavior in flow reactor configurations.

Olm et al. [22] comprehensively evaluated 19 hydrogen combustion mechanisms against a large experimental dataset spanning ignition

delays, species profiles, and flame velocities. They defined Error function values to evaluate the performance of each mechanism against various experimental datasets with numbers closer to unity indicating better performance. Details of the various kinetic mechanisms along with their error function values have been tabulated below in Table 4.

Based on the average error function values, the Kéromnès-2013 [23] mechanism had the best prediction for ignition delay times and flame speeds, while the experimental data for flow reactors was best fit by Starik-2009 [62]. In terms of the prediction of the overall experimental data, Kéromnès-2013 [23] demonstrated the best performance but is closely followed by other detailed mechanisms including NUIG-NGM [56], Konnov [53], and Li et al. [50].

### 3. Hydrogen production technologies

Hydrogen can be produced from diverse domestic energy sources, including nuclear, natural gas, coal, biomass, solar, wind, hydroelectric, and geothermal [63]. This wide range of potential feedstocks provides flexibility and enhances energy security. Various process technologies exist for generating hydrogen, including thermal processes like steam reforming of natural gas, gasification of renewables and waste streams, electrolytic water splitting using electricity from any source, and photolytic water splitting using solar energy and biological/electrochemical materials [4]. With multiple production pathways viable, hydrogen acts as an energy carrier that can enable greater utilization of domestic renewable resources [64,65]. This is due to its high energy yield and efficiency compared to fossil fuels. It is considered the "fuel of the future" for both stationary and transportation applications [66]. However, approximately 96% of current global hydrogen production utilizes fossil fuel processes, including steam methane reforming of natural gas and gasification of oil and coal [67–69]. These methods generate greenhouse gases, conflicting with hydrogen's potential as a clean fuel. Only about 4 % of hydrogen is produced by electrolysis, which can be carbon-neutral if paired with renewable electricity [68]. However, electrolytic hydrogen production is energy intensive. Biohydrogen from microbial and biological routes has been proposed as a more sustainable, lower-energy alternative to conventional hydrogen production pathways. Moreover, biohydrogen processes require further development and scaling to be commercially viable [68]. Fig. 2 represents different hydrogen production technologies, and in this section, some common production technologies are discussed. In this section, we discuss some common hydrogen production technologies such as the production methods from fossil fuels and renewable energy sources.

#### 3.1. Fossil fuel sources

Approximately 96% of global hydrogen production utilizes fossil fuel feedstocks like natural gas, coal, and oil [67,68]. Conventional production methods involve breaking down, gasifying, and catalytically reforming these resources to generate hydrogen along with carbon dioxide and other pollutants like nitrogen and sulfur oxides [70]. This contributes to environmental degradation. Specific technologies for hydrogen production from fossil fuels include steam reforming (SR) [71–75], partial oxidation reforming (POR) [76–78], auto-thermal reforming (ATR) [32,33], and dry reforming (DR) [79,80]. The SR is the most common industrial process.

##### 3.1.1. Steam reforming

Natural gas, mainly methane, is the primary fossil fuel source for hydrogen production through thermochemical processes [81]. The most common technique is steam methane reforming, which involves using steam to react with methane at high temperatures. This produces a synthesis gas composed of carbon dioxide and hydrogen. Subsequently, a water gas shift reaction occurs where the syngas carbon monoxide reacts with steam to produce more hydrogen and carbon dioxide [82].

**Table 3**

updated reactions in the H/O kinetic mechanism, units are cm<sup>3</sup> – mole – s – cal – K, k = AT<sup>n</sup> exp(-E<sub>a</sub>/RT). UF – uncertainty factor mentioned in ref [38].

No.	Reaction	A	n	E <sub>a</sub>	T range (K)	UF
1	H + O <sub>2</sub> +H =	8.80 ×	-1.835	800	300–3000	2
	H <sub>2</sub> O+O <sub>2</sub>	10 <sup>22</sup>				
2	H + O <sub>2</sub> +H =	4.00 ×	-1.835	800	300–3000	2
	OH+OH	10 <sup>22</sup>				
3	H +	7.35 ×	-1.835	800	300–3000	2
	O <sub>2</sub> +O=OH+O <sub>2</sub>	10 <sup>22</sup>				
4	H +	2.56 ×	-1.835	800	300–3000	2
	O <sub>2</sub> +OH=H <sub>2</sub> O+O <sub>2</sub>	10 <sup>22</sup>				
5	OH+OH=H <sub>2</sub> O+O	2.668 × 10 <sup>22</sup>	1.82	-1647	200–2000	1.4
6	H + O <sub>2</sub> (+M) =	4.66 ×	0.44	0	300–2000	1.2
	HO <sub>2</sub> (+M)	10 <sup>12</sup>				
	Low-pressure limit:	1.225 × 10 <sup>19</sup>	-1.2	0.0	1000–1430	1.2
7	OH+HO <sub>2</sub> =	2.14 × 10 <sup>6</sup>	1.65	2180	200–2500	2
	H <sub>2</sub> O+O <sub>2</sub> (1Δ)					

Fcent = 0.5Enhanced third-body efficiencies (relative to N<sub>2</sub>):Ar = 0.72, H<sub>2</sub>O = 16.6,

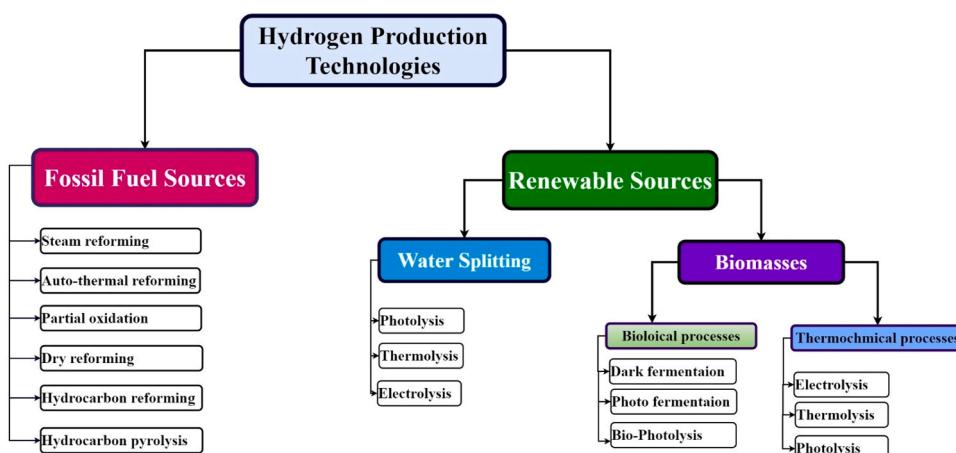
CO<sub>2</sub> = 3.61, He = 0.57, H<sub>2</sub> = 1.5

C<sub>2</sub>H<sub>6</sub> = 1.0, C<sub>3</sub>H<sub>8</sub> = 1.0, C<sub>4</sub>H<sub>10</sub> = 1.0, C<sub>5</sub>H<sub>12</sub> = 1.0, C<sub>6</sub>H<sub>14</sub> = 1.0, C<sub>7</sub>H<sub>16</sub> = 1.0, C<sub>8</sub>H<sub>18</sub> = 1.0, C<sub>9</sub>H<sub>20</sub> = 1.0, C<sub>10</sub>H<sub>22</sub> = 1.0, C<sub>11</sub>H<sub>24</sub> = 1.0, C<sub>12</sub>H<sub>26</sub> = 1.0, C<sub>13</sub>H<sub>28</sub> = 1.0, C<sub>14</sub>H<sub>30</sub> = 1.0, C<sub>15</sub>H<sub>32</sub> = 1.0, C<sub>16</sub>H<sub>34</sub> = 1.0, C<sub>17</sub>H<sub>36</sub> = 1.0, C<sub>18</sub>H<sub>38</sub> = 1.0, C<sub>19</sub>H<sub>40</sub> = 1.0, C<sub>20</sub>H<sub>42</sub> = 1.0, C<sub>21</sub>H<sub>44</sub> = 1.0, C<sub>22</sub>H<sub>46</sub> = 1.0, C<sub>23</sub>H<sub>48</sub> = 1.0, C<sub>24</sub>H<sub>50</sub> = 1.0, C<sub>25</sub>H<sub>52</sub> = 1.0, C<sub>26</sub>H<sub>54</sub> = 1.0, C<sub>27</sub>H<sub>56</sub> = 1.0, C<sub>28</sub>H<sub>58</sub> = 1.0, C<sub>29</sub>H<sub>60</sub> = 1.0, C<sub>30</sub>H<sub>62</sub> = 1.0, C<sub>31</sub>H<sub>64</sub> = 1.0, C<sub>32</sub>H<sub>66</sub> = 1.0, C<sub>33</sub>H<sub>68</sub> = 1.0, C<sub>34</sub>H<sub>70</sub> = 1.0, C<sub>35</sub>H<sub>72</sub> = 1.0, C<sub>36</sub>H<sub>74</sub> = 1.0, C<sub>37</sub>H<sub>76</sub> = 1.0, C<sub>38</sub>H<sub>78</sub> = 1.0, C<sub>39</sub>H<sub>80</sub> = 1.0, C<sub>40</sub>H<sub>82</sub> = 1.0, C<sub>41</sub>H<sub>84</sub> = 1.0, C<sub>42</sub>H<sub>86</sub> = 1.0, C<sub>43</sub>H<sub>88</sub> = 1.0, C<sub>44</sub>H<sub>90</sub> = 1.0, C<sub>45</sub>H<sub>92</sub> = 1.0, C<sub>46</sub>H<sub>94</sub> = 1.0, C<sub>47</sub>H<sub>96</sub> = 1.0, C<sub>48</sub>H<sub>98</sub> = 1.0, C<sub>49</sub>H<sub>100</sub> = 1.0, C<sub>50</sub>H<sub>102</sub> = 1.0, C<sub>51</sub>H<sub>104</sub> = 1.0, C<sub>52</sub>H<sub>106</sub> = 1.0, C<sub>53</sub>H<sub>108</sub> = 1.0, C<sub>54</sub>H<sub>110</sub> = 1.0, C<sub>55</sub>H<sub>112</sub> = 1.0, C<sub>56</sub>H<sub>114</sub> = 1.0, C<sub>57</sub>H<sub>116</sub> = 1.0, C<sub>58</sub>H<sub>118</sub> = 1.0, C<sub>59</sub>H<sub>120</sub> = 1.0, C<sub>60</sub>H<sub>122</sub> = 1.0, C<sub>61</sub>H<sub>124</sub> = 1.0, C<sub>62</sub>H<sub>126</sub> = 1.0, C<sub>63</sub>H<sub>128</sub> = 1.0, C<sub>64</sub>H<sub>130</sub> = 1.0, C<sub>65</sub>H<sub>132</sub> = 1.0, C<sub>66</sub>H<sub>134</sub> = 1.0, C<sub>67</sub>H<sub>136</sub> = 1.0, C<sub>68</sub>H<sub>138</sub> = 1.0, C<sub>69</sub>H<sub>140</sub> = 1.0, C<sub>70</sub>H<sub>142</sub> = 1.0, C<sub>71</sub>H<sub>144</sub> = 1.0, C<sub>72</sub>H<sub>146</sub> = 1.0, C<sub>73</sub>H<sub>148</sub> = 1.0, C<sub>74</sub>H<sub>150</sub> = 1.0, C<sub>75</sub>H<sub>152</sub> = 1.0, C<sub>76</sub>H<sub>154</sub> = 1.0, C<sub>77</sub>H<sub>156</sub> = 1.0, C<sub>78</sub>H<sub>158</sub> = 1.0, C<sub>79</sub>H<sub>160</sub> = 1.0, C<sub>80</sub>H<sub>162</sub> = 1.0, C<sub>81</sub>H<sub>164</sub> = 1.0, C<sub>82</sub>H<sub>166</sub> = 1.0, C<sub>83</sub>H<sub>168</sub> = 1.0, C<sub>84</sub>H<sub>170</sub> = 1.0, C<sub>85</sub>H<sub>172</sub> = 1.0, C<sub>86</sub>H<sub>174</sub> = 1.0, C<sub>87</sub>H<sub>176</sub> = 1.0, C<sub>88</sub>H<sub>178</sub> = 1.0, C<sub>89</sub>H<sub>180</sub> = 1.0, C<sub>90</sub>H<sub>182</sub> = 1.0, C<sub>91</sub>H<sub>184</sub> = 1.0, C<sub>92</sub>H<sub>186</sub> = 1.0, C<sub>93</sub>H<sub>188</sub> = 1.0, C<sub>94</sub>H<sub>190</sub> = 1.0, C<sub>95</sub>H<sub>192</sub> = 1.0, C<sub>96</sub>H<sub>194</sub> = 1.0, C<sub>97</sub>H<sub>196</sub> = 1.0, C<sub>98</sub>H<sub>198</sub> = 1.0, C<sub>99</sub>H<sub>200</sub> = 1.0, C<sub>100</sub>H<sub>202</sub> = 1.0, C<sub>101</sub>H<sub>204</sub> = 1.0, C<sub>102</sub>H<sub>206</sub> = 1.0, C<sub>103</sub>H<sub>208</sub> = 1.0, C<sub>104</sub>H<sub>210</sub> = 1.0, C<sub>105</sub>H<sub>212</sub> = 1.0, C<sub>106</sub>H<sub>214</sub> = 1.0, C<sub>107</sub>H<sub>216</sub> = 1.0, C<sub>108</sub>H<sub>218</sub> = 1.0, C<sub>109</sub>H<sub>220</sub> = 1.0, C<sub>110</sub>H<sub>222</sub> = 1.0, C<sub>111</sub>H<sub>224</sub> = 1.0, C<sub>112</sub>H<sub>226</sub> = 1.0, C<sub>113</sub>H<sub>228</sub> = 1.0, C<sub>114</sub>H<sub>230</sub> = 1.0, C<sub>115</sub>H<sub>232</sub> = 1.0, C<sub>116</sub>H<sub>234</sub> = 1.0, C<sub>117</sub>H<sub>236</sub> = 1.0, C<sub>118</sub>H<sub>238</sub> = 1.0, C<sub>119</sub>H<sub>240</sub> = 1.0, C<sub>120</sub>H<sub>242</sub> = 1.0, C<sub>121</sub>H<sub>244</sub> = 1.0, C<sub>122</sub>H<sub>246</sub> = 1.0, C<sub>123</sub>H<sub>248</sub> = 1.0, C<sub>124</sub>H<sub>250</sub> = 1.0, C<sub>125</sub>H<sub>252</sub> = 1.0, C<sub>126</sub>H<sub>254</sub> = 1.0, C<sub>127</sub>H<sub>256</sub> = 1.0, C<sub>128</sub>H<sub>258</sub> = 1.0, C<sub>129</sub>H<sub>260</sub> = 1.0, C<sub>130</sub>H<sub>262</sub> = 1.0, C<sub>131</sub>H<sub>264</sub> = 1.0, C<sub>132</sub>H<sub>266</sub> = 1.0, C<sub>133</sub>H<sub>268</sub> = 1.0, C<sub>134</sub>H<sub>270</sub> = 1.0, C<sub>135</sub>H<sub>272</sub> = 1.0, C<sub>136</sub>H<sub>274</sub> = 1.0, C<sub>137</sub>H<sub>276</sub> = 1.0, C<sub>138</sub>H<sub>278</sub> = 1.0, C<sub>139</sub>H<sub>280</sub> = 1.0, C<sub>140</sub>H<sub>282</sub> = 1.0, C<sub>141</sub>H<sub>284</sub> = 1.0, C<sub>142</sub>H<sub>286</sub> = 1.0, C<sub>143</sub>H<sub>288</sub> = 1.0, C<sub>144</sub>H<sub>290</sub> = 1.0, C<sub>145</sub>H<sub>292</sub> = 1.0, C<sub>146</sub>H<sub>294</sub> = 1.0, C<sub>147</sub>H<sub>296</sub> = 1.0, C<sub>148</sub>H<sub>298</sub> = 1.0, C<sub>149</sub>H<sub>300</sub> = 1.0, C<sub>150</sub>H<sub>302</sub> = 1.0, C<sub>151</sub>H<sub>304</sub> = 1.0, C<sub>152</sub>H<sub>306</sub> = 1.0, C<sub>153</sub>H<sub>308</sub> = 1.0, C<sub>154</sub>H<sub>310</sub> = 1.0, C<sub>155</sub>H<sub>312</sub> = 1.0, C<sub>156</sub>H<sub>314</sub> = 1.0, C<sub>157</sub>H<sub>316</sub> = 1.0, C<sub>158</sub>H<sub>318</sub> = 1.0, C<sub>159</sub>H<sub>320</sub> = 1.0, C<sub>160</sub>H<sub>322</sub> = 1.0, C<sub>161</sub>H<sub>324</sub> = 1.0, 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C<sub>266</sub>H<sub>534</sub> = 1.0, C<sub>267</sub>H<sub>536</sub> = 1.0, C<sub>268</sub>H<sub>538</sub> = 1.0, C<sub>269</sub>H<sub>540</sub> = 1.0, C<sub>270</sub>H<sub>542</sub> = 1.0, C<sub>271</sub>H<sub>544</sub> = 1.0, C<sub>272</sub>H<sub>546</sub> = 1.0, C<sub>273</sub>H<sub>548</sub> = 1.0, C<sub>274</sub>H<sub>550</sub> = 1.0, C<sub>275</sub>H<sub>552</sub> = 1.0, C<sub>276</sub>H<sub>554</sub> = 1.0, C<sub>277</sub>H<sub>556</sub> = 1.0, C<sub>278</sub>H<sub>558</sub> = 1.0, C<sub>279</sub>H<sub>560</sub> = 1.0, C<sub>280</sub>H<sub>562</sub> = 1.0, C<sub>281</sub>H<sub>564</sub> = 1.0, C<sub>282</sub>H<sub>566</sub> = 1.0, C<sub>283</sub>H<sub>568</sub> = 1.0, C<sub>284</sub>H<sub>570</sub> = 1.0, C<sub>285</</sub>

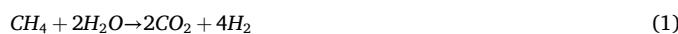
**Table 4**

Comparison among different hydrogen combustion mechanisms in the open literature adapted from ref [22].

Mechanism study	Year	Number of reactions	Number of species	Average error function values					
				Ignition delay times (ms)	Jet-stirred reactor concentrations (%)	Flow reactor concentrations (%)	Flame velocity (cm/s)	Overall results, all diluents except He (%)	Overall results (%)
GR13.0 [43]	1999	29	10	71.4	2.4	11.6	32.0	48.0	-
Dagaut et al. [44]	2003	21	9	-	3.1	4.9	-	-	-
ÓConaire et al. [45]	2004	21	10	15.4	3.0	8.2	18.5	15.0	-
Zsély et al. [46]	2005	32	10	544.3	3.2	15.6	26.0	284.5	-
Davis et al. [47]	2005	25	11	36.7	3.0	4.9	16.4	24.4	21.8
Saxena & Williams [48]	2006	21	11	23.8	3.0	28.3	16.5	20.5	19.0
Sun et al. [49]	2007	32	11	97.9	3.1	25.4	26.4	61.0	53.8
Li et al. [50]	2007	25	11	20.7	3.0	7.8	16.0	16.8	15.8
Ahmed et al. [51]	2007	20	10	257.9	3.1	3.9	20.7	137.4	-
USC-II [52]	2007	28	10	36.2	3.0	4.7	26.1	27.7	-
Konnov [53]	2008	33	10	19.7	3.1	10.9	15.2	16.3	-
Rasmussen et al. [54]	2008	30	10	197.1	3.0	17.8	35.4	113.1	-
Starik et al. [55]	2009	26	12	37.4	3.4	3.8	24.4	27.7	24.7
NUIG-NGM [56]	2010	21	10	14.0	3.0	7.30	20.2	14.8	13.3
Hong et al. [57]	2011	31	10	14.5	3.0	8.1	28.5	17.9	-
SanDiego [58]	2011	21	11	78.0	3.0	27.7	16.5	47.7	42.0
Burke et al. [59]	2012	27	11	26.6	3.1	3.9	14.6	18.9	16.7
CRECK [60]	2012	21	11	15.2	2.9	21.4	56.9	29.1	25.6
Kérommès et al. [61]	2013	33	12	11.9	3.0	13.3	13.9	12.2	12.4

**Fig. 2.** Various hydrogen production technologies.

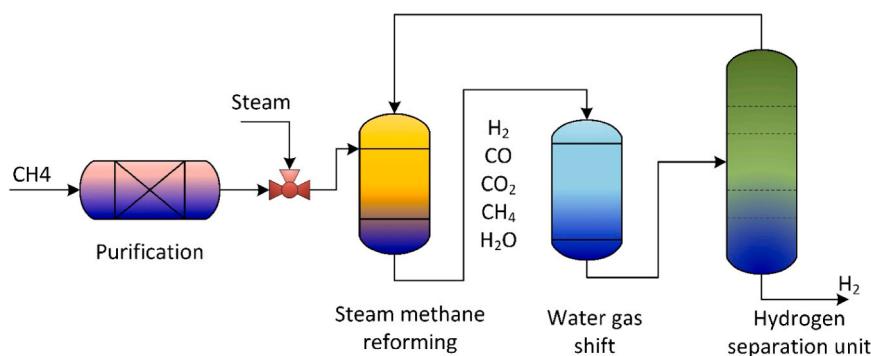
The key chemical reaction in this process is [83]:



Hydrogen production from fossil fuels via reforming reactions is highly endothermic and requires significant heat input [84]. Typically, temperatures in the range of 800–1000 °C are needed in the presence of a metal catalyst, typically nickel, to obtain 60 – 70 % hydrogen yield [72,85]. Operating at such high temperatures necessitates the use of specialized heat-resistant materials to withstand the thermal stresses [86]. To produce high-purity hydrogen, it is essential to effectively separate the carbon dioxide and carbon monoxide byproducts generated

during the shift reaction. Conventional steam methane reforming systems consist of three integrated units: the reformer, shift conversion reactor, and separation unit. This arrangement facilitates hydrogen production while ensuring the effective separation of byproducts [87]. Fig. 3 depicts the typical methane reforming unit used in hydrogen production.

Recently, we conducted a comprehensive computational analysis to examine the effects of various thermal boundary conditions on SMR and hydrogen recovery [89]. The thermal boundary conditions investigated included constant and variable inlet temperature, outer wall temperature, and heat flux on the outer wall of the reactor. The key parameters



**Fig. 3.** Schematic diagram of traditional methane steam reforming unit [88].

analyzed were methane conversion, hydrogen recovery percentage, hydrogen mass flow rates, and hydrogen flux through the membrane. The results showed that methane conversion increased up to 1.7 times when the temperature was raised from 500°C to 700°C. However, hydrogen recovery decreased with higher temperatures. In addition, in another study [90], we examined various parameters such as steam-to-carbon ratio, flow rates, sweeping conditions, flow direction, pressure, and membrane length in a membrane-integrated reformer reactor (MRR). The results showed that methane conversion significantly increased from 34% to 63% when varying the steam-to-carbon ratio from 2 to 6 with a fixed methane flow rate, while hydrogen recovery decreased with higher feed flow rates. Sweeping steam was also found to considerably boost hydrogen recovery from 15% to 33% when using an equal sweep and feed flow rate.

### 3.1.2. Partial oxidation reforming

Partial oxidation reforming (POR) is a viable alternative to steam reforming for producing hydrogen. This method can utilize a variety of feedstocks, including methane, heavy fuel oil, and coal [5]. Partial oxidation is best suited for generating hydrogen from heavy fuel oil and coal. The partial oxidation process involves partially oxidizing the feedstock material with only a portion of the oxygen required for complete combustion. This partial oxidation reaction is highly endothermic, requiring heat input. For example, partially oxidizing methane to carbon monoxide and hydrogen (synthesis gas) requires high temperatures between 700 and 900 °C at atmospheric pressure to ensure full conversion and minimize soot formation. However, a small reduction in carbon monoxide selectivity can cause methane to fully oxidize to carbon dioxide through complete combustion, a strong exothermic reaction that significantly increases temperatures. This can lead to hot spots developing in the reactor bed and coke deposition on catalyst surfaces [77,78,91,92].

The mean reaction of this process is shown as [93]:



Research efforts have been directed toward developing high-activity and stable catalysts for methane partial oxidation reactions. Various studies have reported the effectiveness of mixed metal oxides, solid solutions of NiO-MgO, Ni-Mg-Cr-La-O, and Ca-Sr-Ti-Ni as highly active and selective catalysts at elevated temperatures exceeding 800°C, with greater resistance to carbon deposition [91,94]. Fig. 4 illustrates the basic flow diagram of a gasification plant using the partial oxidation technique.

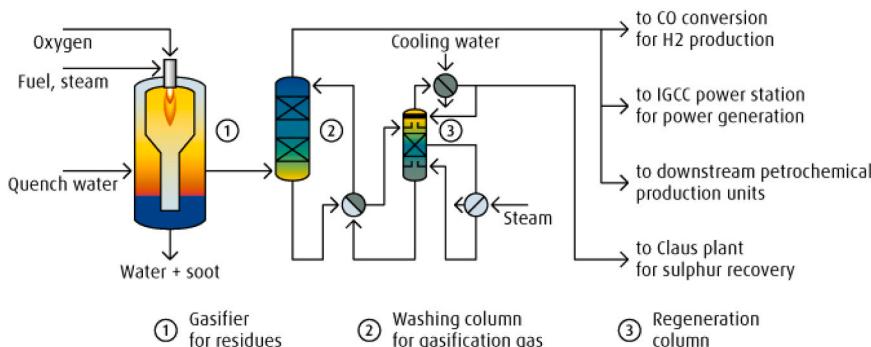
### 3.1.3. Auto-thermal reforming

Auto-thermal reforming (ATR) combines steam with catalytic partial oxidation (CPOX) to produce hydrogen. The process involves both a thermal zone where partial oxidation or catalytic partial oxidation generates heat and a catalytic zone where endothermic steam reforming reactions occur using this heat [96,97]. The temperature profile within the reactor shows a sharp rise in the thermal zone followed by a gradual decrease in the catalytic zone due to endothermic reactions [96]. By utilizing heat from partial oxidation, ATR eliminates the need for external heat sources, simplifying the system and reducing start-up time [63].

ATR offers several advantages over steam reforming (SR), such as faster start-up and shut-down times and higher hydrogen yields compared to partial oxidation alone. For effective operation, maintaining both the oxygen-to-fuel ratio and the steam-to-carbon ratio is crucial to control reaction temperature and product gas composition and prevent coke formation [98]. The gas and liquids industry may increasingly adopt ATR due to its compatibility with Fischer-Tropsch synthesis, compact design, lower capital cost, and potential for economies of scale [98]. In terms of thermal efficiency, ATR is comparable to partial oxidation reactors (60–75% based on higher heating values) but slightly lower than steam reformers [99].

### 3.1.4. Dry reforming

Methane dry reforming (DR) is a reaction whereby methane ( $\text{CH}_4$ ) and  $\text{CO}_2$  react to form carbon monoxide (CO) and hydrogen gas, as



**Fig. 4.** Schematic of partial oxidation technology [95].

described by the chemical equation:



This reaction offers environmental benefits by consuming two potent greenhouse gases, methane, and carbon dioxide. However, the endothermic nature of methane dry reforming means that the overall reduction in  $CO_2$  emissions is limited since the  $CO_2$  generated during the combustion of fuel to provide the heat of the reaction must also be accounted for. From an industrial perspective, methane dry reforming is valuable for the synthesis of oxygenated hydrocarbons and liquid fuels via processes such as Fischer-Tropsch synthesis. It also enables efficient production of synthesis gas with an  $H_2/CO$  ratio close to unity, making it useful as a feedstock for synthetic chemistry. Overall, methane dry reforming couples the consumption of greenhouse gases with the generation of industrially relevant syngas. However, the endothermic heat requirement somewhat lessens the net reduction of  $CO_2$  emissions [79, 100–102].

The most efficient catalysts for methane dry reforming, as documented in scientific literature, utilize metals belonging to groups 8, 9, and 10 of the Periodic Table, such as Rhodium (Rh), Ruthenium (Ru), and Platinum (Pt). However, these metals are costly and not readily available, making them unsuitable for industrial use. Consequently, alternative catalysts have been developed that are more abundant and cost-effective, such as Nickel (Ni) and Cobalt (Co) catalysts, but these are more prone to coke formation [80,103–105]. A typical schematic diagram of the dry reforming process introduced by Al-Doghachi et al. [106] is presented in Fig. 5.

### 3.2. Renewable biomass sources

The primary source of hydrogen production currently involves hydrocarbons; however, there is a growing interest in utilizing renewable resources to produce "green hydrogen" [4,84]. This type of hydrogen has a low-carbon footprint, which can significantly reduce  $CO_2$  emissions related to energy production and help limit global temperature increase to  $2^{\circ}C$ . Green hydrogen can be produced from water or biomass-derived compounds, and its potential as a sustainable energy source has garnered significant attention [84].

Biomass shows significant promise as a renewable feedstock to replace petroleum in the near term, owing to its abundance and renewability as an organic resource [107]. Diverse sources of biomass can be utilized, including animal manure, municipal refuse, crop stubble, purpose-grown woody plants, waste from food production, sawdust, aquatic vegetation, dedicated energy crops like switch grass, paper waste, corn residue, and many other plant materials [108]. Numerous technologies exist to produce hydrogen from biomass feedstocks.

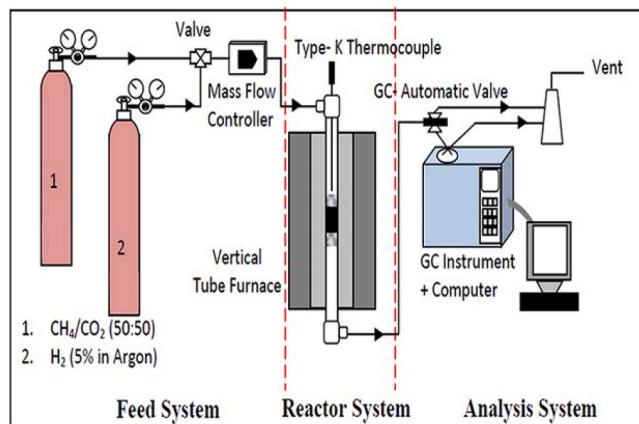


Fig. 5. A typical schematic diagram of the dry reforming process introduced in ref [106].

Thermochemical routes like gasification, pyrolysis, supercritical liquefaction, hydrothermal liquefaction, and hydrolysis can generate hydrogen by breaking down biomass. Additionally, biological approaches that use microorganisms or enzymes to convert biomass to hydrogen represent alternative production pathways. Overall, the diversity of potential biomass sources coupled with a variety of conversion processes makes biomass a versatile and renewable feedstock for sustainable hydrogen production in the near future [63].

The National Renewable Energy Laboratory (NREL) is actively involved in developing and validating models for various components and systems related to renewable hydrogen production and the combined generation of electricity and hydrogen. They focus on optimizing system scenarios and control strategies [109]. NREL's work includes the development of power electronic interfaces specifically for renewable electrolysis systems. They aim to evaluate the performance of electrochemical devices, considering the variable power output of wind turbines and its impact on electrolyzer operation. The efficiency and capacity of both the stack and electrolyzer systems are measured, with a focus on accommodating renewable electricity sources. NREL investigated renewable electrolysis systems with a standard direct current (DC) bus, which included a battery bank connected to a wind turbine, a photovoltaic array, and an electrolyzer. Smaller wind turbines typically charged batteries and required a connection to a constant voltage DC bus and power electronics to regulate power output and convert fluctuating alternating current (AC) to DC [109] (see Fig. 6).

#### 3.2.1. Biomass gasification

Gasification technology is a well-established and widely used process for biomass and coal. This type of pyrolysis technology partially oxidizes the materials into a mixture of gases, including hydrogen, methane, carbon monoxide, carbon dioxide, and nitrogen, known as producer gas [110]. Gasification can be performed with or without a catalyst and in either a fixed bed or fluidized bed reactor, with the latter typically yielding better performance. However, the gasification process is hindered by low thermal efficiency, as the moisture in the biomass must also be vaporized [111]. The addition of steam and/or oxygen to the gasification process can lead to steam reforming, resulting in a syngas stream with an  $H_2$  to  $CO$  ratio of 2:1. This syngas can then be used as feed for a Fischer-Tropsch reactor to produce higher hydrocarbons or for hydrogen production using a water gas shift (WGS) process [112].

Gasification reactors are designed on a large scale and demand a continuous influx of significant amounts of material to operate effectively. Based on the lower heating value, these reactors can attain efficiencies ranging from 35% to 50% [63]. However, one of the major issues with this technology is that gathering a substantial amount of biomass for the central processing plant requires enormous resources. Additionally, the high logistics costs associated with operating gasification plants and the difficulty of reducing tar levels to acceptable levels for pure hydrogen production currently limit the commercialization of biomass-based hydrogen production [4]. Fig. 7 shows the hydrogen production via the biomass gasification process.

Pyrolysis represents another promising method for hydrogen production. In this thermochemical process, raw organic feedstocks are heated and gasified at moderate pressures (0.1–0.5 MPa) and temperatures of 500–900°C in the absence of oxygen [114–117]. By avoiding oxidation conditions, pyrolysis minimizes the generation of carbon oxides ( $CO$ ,  $CO_2$ ) and largely precludes dioxin formation [2]. The hydrogen-rich pyrolysis gas requires little downstream processing like water-gas shift or preferential oxidation reactions. Pyrolysis offers benefits, including feedstock flexibility, process simplicity, and compactness, clean carbon co-product, and reduced  $CO_2$  emissions compared to other gasification approaches [114–117]. Pyrolysis processes are categorized by temperature range, with low (<500°C), medium (500–800°C), and high (>800°C) temperature variants [4]. Fast pyrolysis, which utilizes high heating rates and short reaction times, represents an active area of research for converting biomass into bio-oil

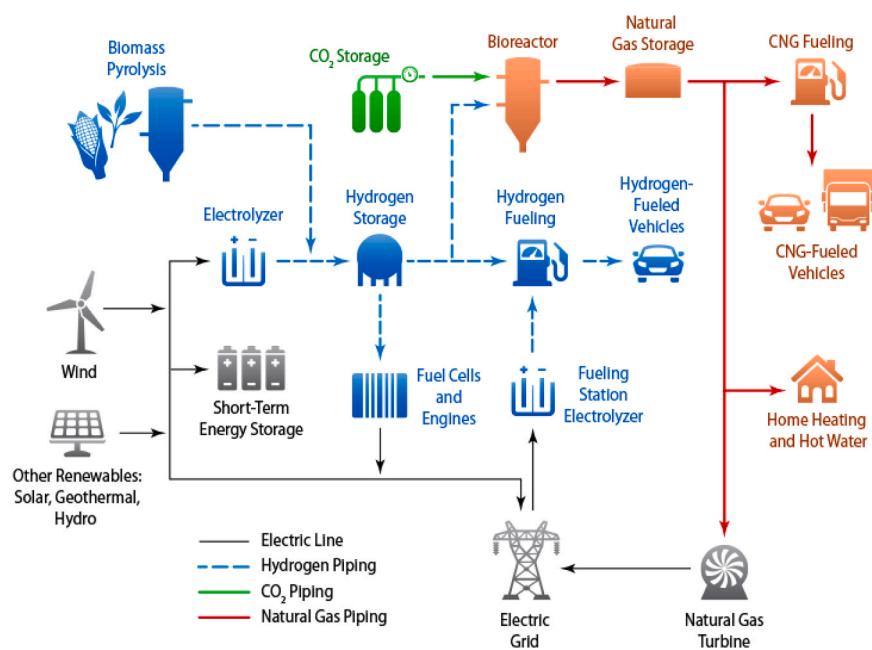


Fig. 6. Various scenarios for producing renewable hydrogen and electricity [109].

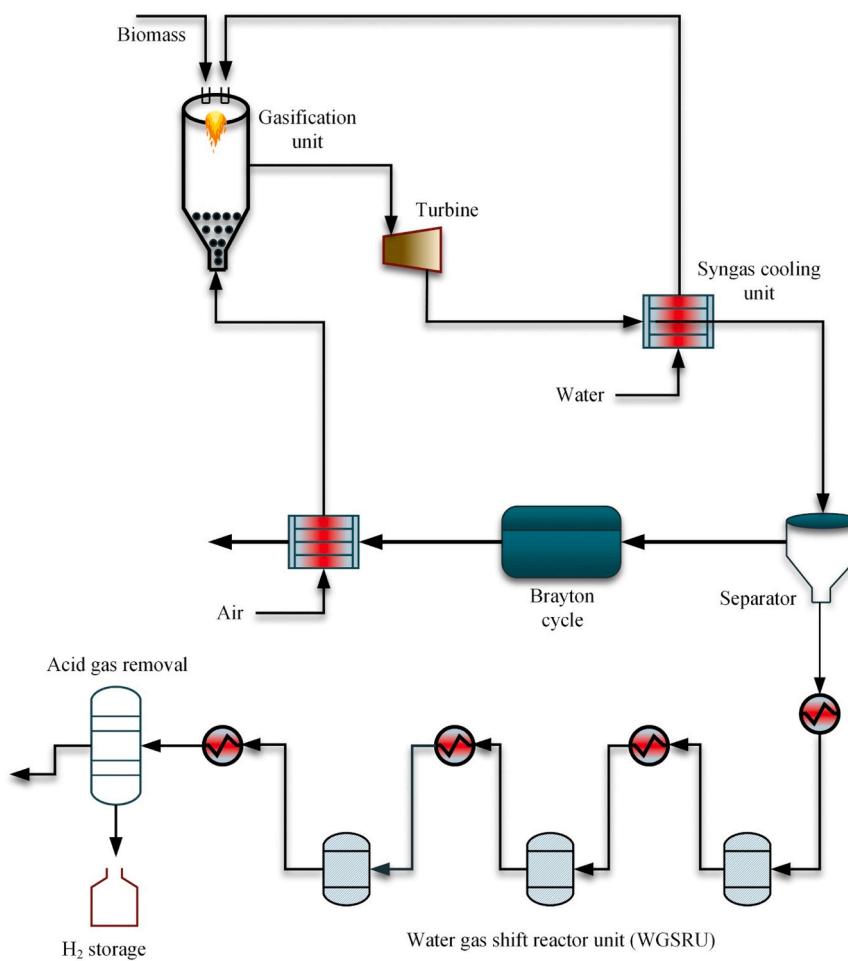


Fig. 7. Schematic diagram of biomass gasification-based hydrogen production [113].

and gases [5]. Challenges include managing solid carbon fouling, though process engineering solutions are being explored [6]. With tailored operating conditions, pyrolysis can achieve relatively low CO<sub>x</sub> emissions and valuable carbon sequestration via char production. Consequently, pyrolysis has significant potential as a flexible, efficient thermochemical route for sustainable hydrogen production [114–118].

### 3.2.2. Hydrogen production from water

Water is the most abundant resource for hydrogen production, and it can be separated into hydrogen and oxygen without producing harmful emissions, provided that enough energy is supplied [119,120]. The most basic method for water splitting involves passing an electric current through two electrodes in a process known as electrolysis. However, water can also be split using other energy sources, such as thermal energy (thermolysis), photonic energy (photo electrolysis), and bio-photolysis using microorganisms [63].

Water electrolysis is a potential method for hydrogen production in the future, but currently, it only accounts for approximately 4% of global hydrogen production [121]. This process involves breaking down water into hydrogen and oxygen and has been commercially utilized since 1890. Electrolysis occurs when a direct current passes through two electrodes in a water solution, separating the chemical bonds within the water molecule and producing hydrogen and oxygen [4].

Certain microorganisms can utilize light energy to split water molecules and produce molecular hydrogen through a process called bio-photolysis. Bio-photolysis is categorized as either direct or indirect. Both green algae and cyanobacteria play key roles in these light-driven biological hydrogen production pathways [122]. In direct bio-photolysis, microalgae, including green algae (*Chlamydomonas reinhardtii*) and cyanobacteria (*Synechocystis*), directly convert water and carbon dioxide into hydrogen and oxygen gas in the presence of light during photosynthesis [123]. These microalgae have simple

nutritional requirements, are readily cultivated, and exhibit efficient carbon dioxide fixation [122]. Indirect bio-photolysis differs in that oxygen evolution is temporally separated from hydrogen production [124]. First, photosynthesis by cyanobacteria converts carbon dioxide and water into organic compounds and oxygen. Subsequently, in a light-independent phase, these organic intermediates are catabolized by the cyanobacteria to generate hydrogen, carbon dioxide, and soluble metabolites [125]. By segregating the oxygen-producing reactions, indirect bio-photolysis circumvents oxygen inhibition of hydrogenase enzymes and explosive hydrogen-oxygen mixtures that impair direct bio-photolysis [126]. However, reported hydrogen yields remain low, partially attributable to enzymatic hydrogen consumption pathways [127]. Additionally, the two-stage process requires complex systems with high capital and operating costs [125].

Recently, Nemitallah et al. [128] outlined numerical investigations into oxygen permeation, hydrogen generation via water splitting using an oxygen transport membrane, and oxy-combustion of syngas. Two models were developed - one for hydrogen and oxygen production from water splitting using a user-defined function to enable oxygen transfer across the membrane, and another for syngas reaction kinetics. The simulations revealed reactive syngas flow leads to higher oxygen permeation and hydrogen generation rates than non-reactive cases. Effects of various parameters like fuel composition, membrane thickness, temperature, sweep gas flow rate, and CO<sub>2</sub> circulation were examined. Key results showed increasing sweep flow rate and inlet temperature enhance hydrogen and oxygen output, while rises in CO/H<sub>2</sub> ratio, membrane thickness, and CO<sub>2</sub> circulation reduce hydrogen and oxygen yields.

### 3.3. Comparison and remarks among hydrogen production techniques

Table 5 provides a summary of the characteristics of various

**Table 5**  
Characteristics summary of hydrogen production technologies.

Technology	Efficiency	Advantages	Disadvantages	Feedstock	Operating conditions	Technology readiness level (TRL)	Cost (USD/kg-H <sub>2</sub> )
<b>Fossil fuel sources</b>							
Steam reforming	70–85%	<ul style="list-style-type: none"> <li>Developed technology.</li> <li>Existing infrastructure.</li> <li>No need for oxygen</li> <li>Low temperature</li> </ul>	<ul style="list-style-type: none"> <li>CO<sub>2</sub> emissions</li> <li>Unstable supply</li> </ul>	Hydrocarbons	800–1000 °C	9	1.3–1.5
Partial oxidation (POX)	60–75%	<ul style="list-style-type: none"> <li>Low requirement of Desulphurization</li> <li>No catalyst</li> <li>Low methane emission</li> <li>Established technology</li> </ul>	<ul style="list-style-type: none"> <li>Complex process</li> <li>High temperature</li> <li>Low hydrogen/ CO ratio</li> </ul>	Hydrocarbons	000 °C	9	1–1.83
Auto-thermal reforming	60–75%	<ul style="list-style-type: none"> <li>Compared to POX, it requires less temperature</li> <li>Lower methane slip</li> <li>Established technology</li> </ul>	<ul style="list-style-type: none"> <li>Produced CO<sub>2</sub> as a byproduct.</li> <li>Requires air and O<sub>2</sub>.</li> <li>New technology, use of fossil fuels.</li> </ul>	Hydrocarbons	000 °C		1.48
Dry reforming	50 %	H <sub>2</sub> /CO ratio close to 1	<ul style="list-style-type: none"> <li>Greater tendency to form coke</li> </ul>	Hydrocarbons	700–900 °C		
<b>Renewable energy sources</b>							
Biomass gasification	35–50 %	<ul style="list-style-type: none"> <li>Feedstock is abundant.</li> <li>Inexpensive</li> <li>CO<sub>2</sub> neutral</li> </ul>	<ul style="list-style-type: none"> <li>Tar formation.</li> <li>H<sub>2</sub> content depends on feedstock availability.</li> </ul>	Dried biomass	800–900 °C	5–6	1.77–2.05; 4.63
Biomass pyrolysis		<ul style="list-style-type: none"> <li>Abundant</li> <li>Cheap feedstock,</li> <li>CO<sub>2</sub> neutral</li> </ul>	<ul style="list-style-type: none"> <li>Impurities</li> <li>Less H<sub>2</sub> production.</li> <li>Fluctuating H<sub>2</sub> amount because of feedstock.</li> <li>Impurities</li> </ul>	Biomass	500–800 °C in the absence of oxygen.	7	1.25–2.20; 3.8
Bio-photolysis	0.5–10	<ul style="list-style-type: none"> <li>operate under mild conditions.</li> <li>CO<sub>2</sub> is consumed in an abundant supply.</li> </ul>	<ul style="list-style-type: none"> <li>Need sunlight.</li> <li>Low H<sub>2</sub> rates.</li> <li>Need large reactor volume.</li> <li>Expensive.</li> </ul>	Water and sunlight		3	1.42–2.13

hydrogen production technologies. The table compares different technologies based on their efficiency, advantages, disadvantages, feedstock, operating conditions, technology readiness level (TRL), and cost of hydrogen production in USD per kilogram (kg-H<sub>2</sub>). Under the category of fossil fuel sources, steam reforming is a developed technology with existing infrastructure, high efficiency (70–85%), and no need for oxygen. However, it has disadvantages such as CO<sub>2</sub> emissions and an unstable supply of feedstock. Partial oxidation (POX) is an established technology with low requirements for desulfurization and no catalyst, but it has a complex process and a low hydrogen/CO ratio. Auto-thermal reforming is similar to POX but requires less temperature, while dry reforming has a lower efficiency (50%) and a greater tendency to form coke.

In the renewable energy sources category, biomass gasification offers an abundant and inexpensive feedstock, but it has challenges such as tar formation and impurities. Biomass pyrolysis, on the other hand, provides cheap and abundant feedstock but has fluctuating hydrogen production and impurities. Bio-photolysis operates under mild conditions and consumes CO<sub>2</sub>, but it requires sunlight, has low hydrogen rates, and requires a large reactor volume. Each technology is assigned a technology readiness level (TRL) indicating its development stage, and the cost of hydrogen production is given in USD per kilogram (kg-H<sub>2</sub>).

### 3.4. Hydrogen production challenges and prospectives

Hydrogen production pathways are divided into non-renewable and renewable categories. Steam methane reforming is a well-established process providing over 80% of global hydrogen supply but relies on fossil fuels and emits CO<sub>2</sub>. While SMR is mature, fully capturing CO<sub>2</sub> emissions remains difficult, and additional equipment is energy-intensive [129]. Coal and biomass gasification can also produce hydrogen, with co-gasification more efficiently through higher gas yields. However, tar formation challenges gasification [130]. More aggressive conditions require serial gasifiers. Gasification also relies on fossil fuels. Pyrolysis is an older pathway still in the early commercial stages. Issues include low hydrogen yields, separation/purification challenges, competition with food production, tar deposition, and costs. Auxiliary equipment is also needed to remove contaminants, presenting challenges for large-scale pyrolysis hydrogen. Methane pyrolysis at high temperatures can produce hydrogen and solid carbon without CO<sub>2</sub>, potentially eliminating downstream processing like water–gas shift reaction (WGSR) and reducing costs versus SMR [131,132]. Natural gas pricing, technique, and solid carbon impact costs significantly. As indicated in a study by Qureshi et al. [132], Coal gasification yields synthesis gas of H<sub>2</sub>, CO, CO<sub>2</sub>, and methane at high temperatures and pressures, and WGSR enhances hydrogen recovery but with lower efficiency than SMR. Biogas pyrolysis capturing airborne carbon could yield negative-carbon hydrogen. The solid carbon from methane pyrolysis may enable nanostructured materials like carbon nanotubes if costs decreased. Key challenges to scaling methane pyrolysis commercially include meeting large heat demands for yields; managing accumulated solid carbon; using natural gas feedstocks and impurity effects; and enhancing solid carbon treatment and economic use.

Among renewable pathways, biohydrogen is pollution-free but faces challenges like low yields, high moisture content, separation/purity issues, and competition with food production and it remains in R&D [129]. Photocatalysis depends on photons and is clean, but requires developing affordable catalytic materials with high bandgaps, expensive catalysts, and difficult regeneration. It's also still in R&D. Furthermore, thermochemical cycles have higher temperatures and complexity than other options but have lower costs. Moreover, water electrolysis provides around 4% of global supply without needing separation but is energy-intensive and must overcome high capital/maintenance costs to reduce price. In addition, Plasmolysis is proposed as efficient due to reduced equipment size and power usage, with reported hydrogen rates competitive to electrolysis. Literature shows plasmolysis as more energy

efficient compared to other technologies, making it a potentially viable option [133,134]. However, renewable pathways overall are still in the R&D stages to overcome challenges and commercialize at scale. The cost of green electricity used in electrolysis is the second most important factor impacting the cost of green hydrogen. Green hydrogen costs are primarily determined by renewable power costs. Declining prices of wind and solar could lower green hydrogen costs over time. However, current renewable power rates remain too high to scale up green hydrogen [132]. Long term, lowering renewable costs is critical to broader deployment. Increasing solar and wind output is key to cheaper renewable energy. The electrolyzer market is predicted to grow 1000-fold by 2040, with 213.5 GW of projects expected by 2040 versus 200 MW currently installed. Europe accounts for 85% of predicted projects, with Germany comprising 23% of forecast electrolyzer capacity worldwide [132]. The EU target is 40 GW by 2030, able to produce 32 MT of hydrogen per year or half current needs. Meeting 24% of energy needs with hydrogen under climate mitigation would require over 31,320 TWh of electricity annually, far exceeding current global generation from all sources combined, requiring \$11 trillion for production, storage, and distribution infrastructure.

According to Qureshi et al. [135–137], there are near-term, mid-term, and long-term emerging options for producing hydrogen. Long-term solutions have low technology readiness but could yield zero or low greenhouse gas emissions. Thermochemical production combines water chemical dissociation with heat recovery from nuclear/chemical plants or concentrated solar power at 500–2000°C. Two-step and hybrid cycles have been studied, but material corrosion challenges remain. Photoelectrochemical production uses specialized semiconductors and light to split water into hydrogen and oxygen, operating efficiently through electrodes or panels like solar, without high temperatures. Another long-term approach is biologically or photobiologically synthesizing hydrogen by exploiting bacteria, microalgae, or cyanobacteria that split water. The current focus is on electrolysis and other technologies that can rapidly produce significant hydrogen daily to meet global energy demand, though cutting-edge methods use modest water amounts. Scale remains a key limitation for advanced options.

### 4. Effect of hydrogen enrichment on ammonia

Ammonia has been proposed as an effective hydrogen carrier due to its higher volumetric hydrogen density compared to pure hydrogen [138]. Its long-standing commercial production and stable supply of over 100 years support its potential as an alternative to hydrogen [139]. Ammonia also has similar storage requirements to propane and is easier to liquefy than hydrogen, reducing transportation and infrastructure costs [140]. Numerous reviews have highlighted ammonia's potential as an energy vector, investigating areas like production pathways, applications, and challenges to large-scale implementation [141–145]. While ammonia offers benefits as an energy carrier, its primary drawbacks for combustion include low flame propagation speed, high minimum ignition energy, and elevated NO<sub>x</sub> emissions [145]. A reduced flame speed is linked to lower combustion efficiency in engines, while increased NO<sub>x</sub> raises environmental concerns. Previous studies have explored enhancing ammonia flames through fuel additives to boost speed and mitigate NO<sub>x</sub> [146–148]. Further characterization of potential interactions between ammonia and hydrogen during combustion is needed. Ammonia-hydrogen mixtures can also yield very low NO<sub>x</sub> below certain pressure thresholds. Though other additives have been investigated, these studies remain limited.

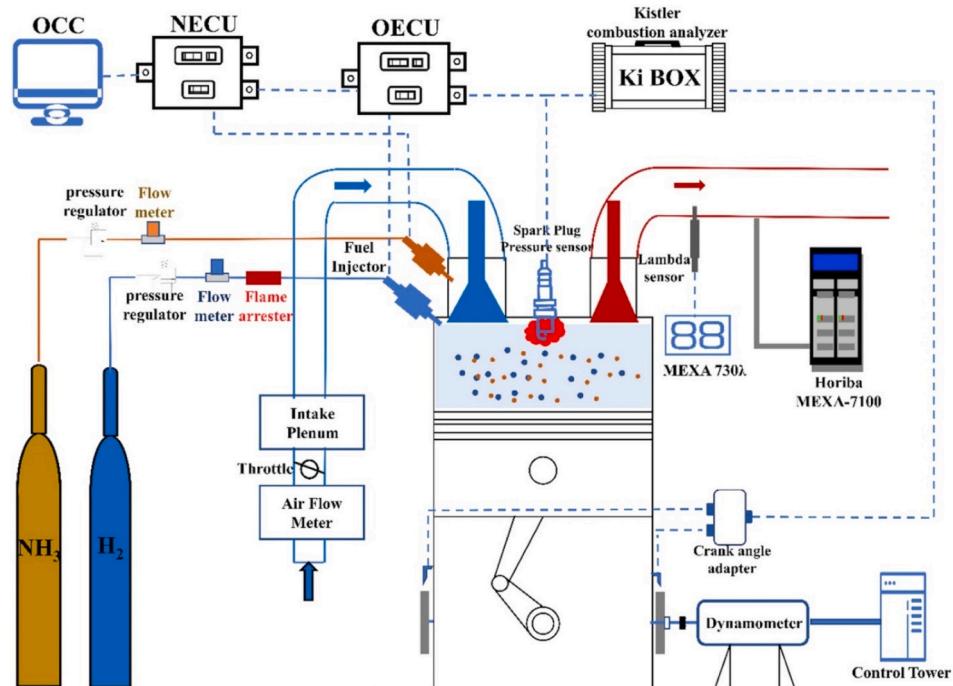
A lot of research studies have been studying the NH<sub>3</sub>/H<sub>2</sub> applications in internal combustion engines, especially in dual-fuel engines [3, 149–153] and gas turbines [149,154–158]. For instance, Frigo et al. [159] investigated the viability of employing ammonia and hydrogen mixtures to power a four-stroke spark-ignition engine. To maintain stable operation and prevent cyclic variations, they determined that the minimum energy ratio of hydrogen to ammonia should be 7 % at a full

load and 11% at a half load. Peak NOx emissions were estimated to be only 1700 ppm under full load circumstances, with increased hydrogen ratios leading to improved engine stability. Moreover, Lhuillier et al. [160] experimentally investigated the performance of ammonia/hydrogen blends as a fuel in conventional spark-ignition engines. Their results demonstrated that ammonia/hydrogen mixtures could be utilized in SI engines with minimal modifications. Recently, an experimental study evaluated the spark ignition engine performance and emissions [9]. The engine was fueled by a premixed hydrogen/ammonia/air mixture. The experimental bench schematic is illustrated in Fig. 8. The manifold absolute pressure was set to 61 kPa, and the engine speed was maintained at 1300 RPM. The study compared a mixture containing 2.2% ammonia by volume with pure hydrogen fuel. The addition of ammonia led to increased ignition delay and flame development periods and a decreased rate of in-cylinder pressure rise. However, the engine performance remained unaffected when combined with the ignition timing strategy. Nitrogen oxide emissions increased due to ammonia addition. These results suggested that ammonia can act as a combustion inhibitor, offering valuable insights for the development of hydrogen-fueled engines.

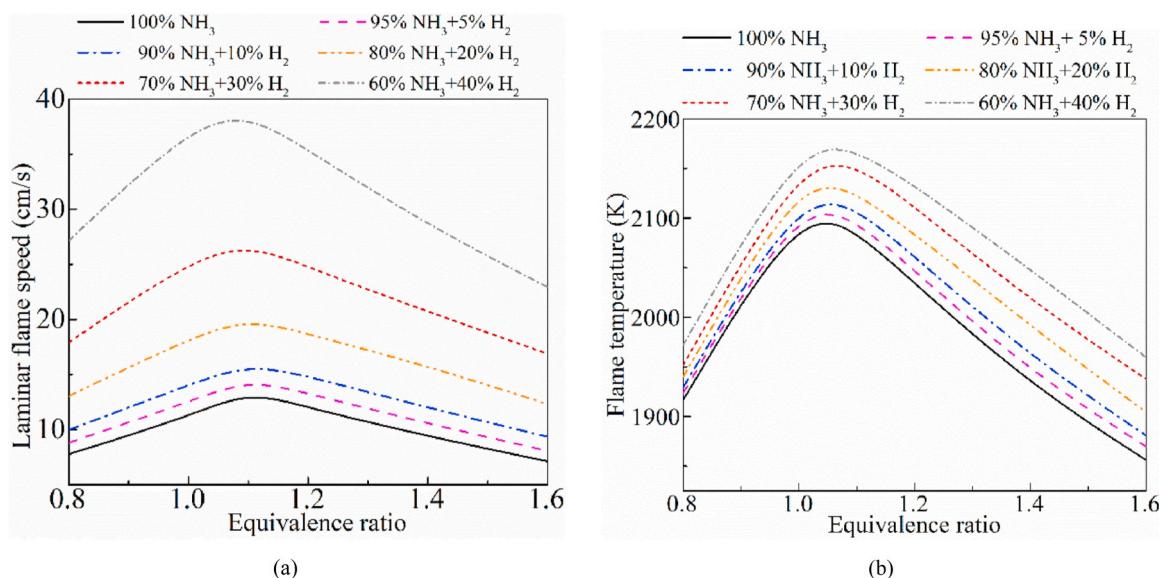
Pochet et al. [161] investigated blending ammonia/hydrogen fuels for use in a homogeneous charge compression ignition (HCCI) engine for combined heat and power. Due to ammonia's high auto-ignition resistance, hydrogen addition promotes stable HCCI combustion. Experiments were conducted in a single-cylinder, constant-speed HCCI engine at intake pressures of 1–1.5 bar and temperatures of 428–473 K. Stable combustion was achieved for blends up to 70 % ammonia by volume at 1.5 bar, 473 K intake, and equivalence ratio of 0.28. Efficiency only declined 0.6 points from pure hydrogen to 60 % ammonia. NOx increased from <6 ppm for hydrogen to 750–2000 ppm for ammonia blends. In addition, a theoretical study by Wang et al. [10] investigated the combustion characteristics of ammonia-hydrogen blends in a medium-speed marine diesel engine operated under homogenous HCCI mode to minimize thermal NOx production. The ignition properties of NH<sub>3</sub>-H<sub>2</sub> mixtures were analyzed by varying the equivalence ratio, hydrogen fraction, intake air temperature, and pressure. The addition of hydrogen increased the laminar flame velocity of ammonia, likely influencing NOx emissions (Fig. 9a). For NH<sub>3</sub>-H<sub>2</sub> fueled medium-speed

marine engines, strategies such as reducing combustion temperature (Fig. 9 ab), incorporating exhaust gas recirculation, and applying aftertreatment technologies could potentially decrease NOx emissions.

In terms of emissions studies, Valera-Medina et al. [162] studied the combustion properties and emissions of ammonia/hydrogen mixtures in a swirl burner, aiming to inform the development of fuel-flexible gas turbines. They found that intense swirling flows enabled stable combustion and low emissions for ammonia/hydrogen blends, although over a limited equivalence ratio range. The same group also conducted chemical kinetic modeling studies to understand the combustion characteristics of ammonia/methane mixtures under gas turbine conditions [11,163]. Furthermore, Zhang et al. [164] investigated the effects of methane and hydrogen addition on ammonia/air flame emissions in a gas turbine combustor by measuring instantaneous OH profiles and outlet emissions with PLIF and FTIR, respectively, as well as simulating flames via LES. The results showed ammonia/air flame emissions trends matched 1D modeling when controlled around an equivalence ratio of 1.15, while low blending ratios of 0.1 for methane or hydrogen-enhanced flames without increasing NOx; however, higher ratios of 0.3 led to high NOx and CO for ammonia/methane but hydrogen performed better for emissions regulation, especially below 0.3 due to less carbon. In addition, the effects of ammonia addition on combustion and emissions in hydrogen internal combustion engines have been experimentally investigated in ref [165]. Tests were conducted on a modified engine under part-load, stoichiometric conditions with varying ammonia fractions. Results showed that increasing ammonia extended the flame development and propagation periods and reduced peak heat release rates, moderating hydrogen's fast combustion. In another study, the behavior of an SI engine fueled with Ammonia/Hydrogen blends was investigated by Dinesh et al. [166]. The compression ratio (CR) and hydrogen fraction were varied, and the engine was operated under wide-open throttle conditions at different speeds. The results indicated that the addition of hydrogen increased peak temperatures and consequently increased NOx emissions despite reducing ammonia emissions. To mitigate excessive NOx emissions, selective catalytic reduction (SCR) was proposed as a practical solution. Based on the findings, the best compromise for engine performance was found to be a 21 % hydrogen fraction and a CR of 15 at 1400 RPM,



**Fig. 8.** Test bench schematic diagram used in reference [9].



**Fig. 9.** Variation of equivalence ratio with (a) laminar flame speed and (b) flame temperature for different mixing hydrogen-ammonia ratios presented in reference [10].

making it a recommended mixing ratio for ammonia/hydrogen blends.

In general, hydrogen enrichment into other fuels has been investigated experimentally and numerically in the open literature. We have several studies investigating the combustion of hydrogen-enriched methane including oxy-combustion [167–169], H<sub>2</sub>/N<sub>2</sub>/air combustion [170], methane-air combustion [171], and oxy-methane combustion in gas turbine burners, [172–174], swirl combustors [175], micromixer burner [168,176,177], and plate burner [178]. In addition, we reviewed the progress made in understanding the effects of fuel composition on premixed gas turbine combustion, with a special emphasis on system stability and emissions, for hydrogen-rich synthetic gas (syngas) mixtures [179].

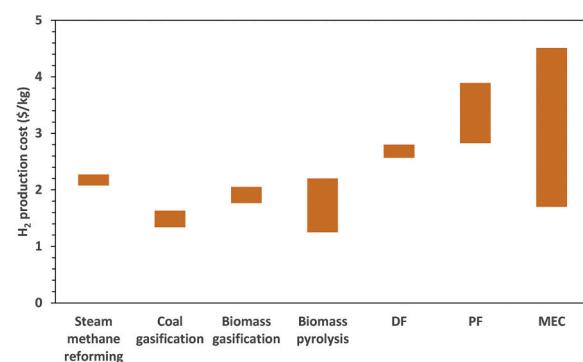
## 5. Technoeconomic environmental risk analysis

Currently, 98% of hydrogen is produced from fossil fuels via methane reforming or coal gasification, which presents sustainability and emissions challenges. As a result, there is a shift towards producing biogases from renewable biomass sources based on lifecycle analysis principles [180]. Techno-economic analysis (TEA) provides a framework to evaluate the technical, economic, and environmental performance of hydrogen production processes at both lab and commercial scales [181]. TEA examines capital and operating costs, profitability, and greenhouse gas emissions over the short and long term. It has been applied to assess biomass and wastewater treatment methods for their hydrogen production potential [182]. Simulation software is used to identify optimum plant sizes and cost structures based on local fuel, feedstock, transportation, and material prices [183]. However, new biological and electrochemical processes have lower technology readiness than steam reforming, significantly increasing costs [181]. Combined with high biomass feedstock and transportation expenditures, current biomass-based hydrogen ranges from \$1.2–2.4/kg compared to under \$0.8/kg for natural gas [184,185]. Individual economic and lifecycle assessments are needed to improve process competitiveness towards a target \$0.3/kg hydrogen price equivalent to gasoline [186].

Life Cycle Assessment (LCA) is widely used to comprehensively assess the environmental impacts of hydrogen production processes over their full lifecycles [187]. Recent LCA studies have predominantly evaluated thermochemical technologies like biomass gasification, finding greenhouse gas emissions are 5–30 times lower than natural gas reforming, coal gasification, and electrolysis [188–190]. Emissions

depend on system boundaries and whether displaced fossil fuels are considered. Cradle-to-gate and well-to-wheel analyses report a range of 0.18–0.46 kg CO<sub>2</sub>-eq per kg H<sub>2</sub> [188]. Functional units and feedstocks also influence results. Fewer studies have analyzed biochemical routes, but dark fermentation alone or coupled with other processes showed both lower and higher emissions than gasification depending on conditions [187]. Integrated biochemical approaches and optimizations have the potential to lower greenhouse gases comparable to coal gasification [191]. Overall, more LCA data is still needed, particularly for understudied methods. Still, cradle-to-gate assessments indicate Waste-to-hydrogen (WTH) pathways produce significantly fewer emissions than petroleum baselines.

While fossil fuels like coal and natural gas have traditionally been used for hydrogen production due to their low costs, their excessive usage also contributes significantly to environmental issues, driving research into alternative resources. Generalized estimates show coal gasification currently has the lowest unit production costs [192]. However, coal also carries major negative impacts. Biomass gasification can provide environmental benefits compared to coal but has higher unit costs, estimated to be up to three times greater than coal gasification [193]. As such, innovative improvements are still needed to reduce the operational expenses of biomass gasification pathways and make them cost-competitive with petroleum-based processes [187]. One study found hydrogen produced from various biomass waste feedstocks ranged from \$25–40 per GJ in costs [191,193,194], demonstrating



**Fig. 10.** Unit costs of current H<sub>2</sub> production routes including WTH processes based on ref [187,191,195].

potential cost-effectiveness compared to synthetic gasoline or diesel produced via gasification and Fischer-Tropsch synthesis from the same feedstocks at \$42–67 per GJ. Overall, while alternative routes are being pursued for their environmental advantages, cost reductions through further optimization will also be important for commercial viability. Fig. 10 illustrates the unit costs of different hydrogen production methods such as SMR, coal and biomass gasification, biomass pyrolysis, dark fermentation (DF), Photo-fermentation (PF), and membrane electrolysis cell (MEC).

Recently, Arcos et al. [196] systematically reviewed the production methods, energy sources, and emissions of each hydrogen color based on techno-economic analysis. An economic assessment then compared costs and examined the feasibility of options, to provide industry and research with a clear understanding of advantages, drawbacks, and evolution potential for each color. Table 6 summarizes their results.

## 6. Applications

Recent literature has extensively focused on the potential applications of hydrogen across various facets of society, including industrial, domestic, and space applications [197–199]. The primary current uses of hydrogen are in petroleum refining [200], ammonia production [201], and, to a lesser degree, metal refining of nickel, tungsten, molybdenum, copper, zinc, uranium, and lead [202,203]. Global hydrogen production exceeded 50 million metric tons in 2006 [204,205]. Looking ahead, hydrogen has promise as a fuel source to replace fossil fuels in many applications where they are currently used, particularly in transportation, where hydrogen would provide immediate reductions in pollution and cleaner environments [206].

Hydrogen has potential as a fuel for internal combustion engines or in fuel cells to power electric motors. In contrast to directly using hydrogen in engines, small modifications to the combustion system allow different combustion modes. In many studies on using hydrogen in automobile spark ignition gasoline engines, hydrogen is introduced into the combustion chamber via injection or carburetor systems from the intake manifold [207,208]. It is important to utilize hydrogen as a fuel in internal combustion engines due to its high ignition temperature and suitability for high compression ratio conditions. Hydrogen's properties make it suitable for use in fuel injection systems of gasoline engines [209]. In engines fueled by hydrogen, spark plugs with lower energy are used. Whereas knocking limits power in gasoline-fueled engines, early ignition limits power in hydrogen-fueled engines [210].

In most studies, researchers introduced hydrogen into the engine combustion chamber via the intake manifold using either injection or carburetor systems. The structural properties of hydrogen make it suitable for use in fuel injection systems of gasoline engines. Spark plugs with lower energy are needed for engines fueled by hydrogen since hydrogen has a high ignition temperature and can be used under high compression conditions. Whereas knocking limits power in gasoline engines, early ignition limits power in hydrogen-fueled engines due to hydrogen's lower density [211].

**Table 6**

A comparison between the hydrogen colors in terms of costs and carbon emissions mentioned in ref [196].

Color	Cost [USD/kgH <sub>2</sub> ]	Emissions [kgCO <sub>2</sub> /kgH <sub>2</sub> ]
Aqua	0.23	0
Black/brown	1.2–2.0	20
Blue	0.99–2.05	1–2
Green	2.28–7.39	0
Grey	0.67–1.31	8.5
Purple, pink, and red	2.18–5.92	0
Turquoise	2.0	**
Yellow	6.06–8.81	*

\* Yellow hydrogen emissions depend on the location and its respective power mix. \*\* Turquoise hydrogen produces a solid carbon byproduct.

Many researchers have tried to use hydrogen as a fuel for engines with different levels of success over the years, and their findings are widely published. Several experiments have shown that hydrogen has many advantages over current automotive fuels [212,213]. Andrea [214] studied how the engine speed and the fuel-air ratio affect the combustion of a gasoline engine mixed with hydrogen. The results showed that the combustion time becomes shorter, and the nitrogen emission becomes higher as more hydrogen is added to the gasoline.

Finally, in terms of hydrogen applications, hydrogen is currently used primarily in oil refining, ammonia production, and metal refining. However, it has significant potential as a renewable fuel to replace fossil fuels, especially for transportation applications where it can immediately reduce emissions. Hydrogen can power internal combustion engines or fuel cells for electric vehicles. Its high ignition temperature and suitability for high compression ratios in engines make hydrogen preferable over gasoline. However, early ignition limits power output compared to knocking in gasoline engines. Overall, hydrogen's properties confer advantages over conventional fuels that make it a promising sustainable fuel option, especially for the transportation sector. Further research and development can help overcome technical barriers and realize hydrogen's benefits.

### 6.1. Spark ignition engines

Using hydrogen as a fuel in spark ignition engines has several advantages compared to compression ignition engines. These include increased lean operating limits, improved combustion stability, higher braking thermal efficiency, and lower carbon monoxide and unburned hydrocarbon emissions [215–218]. However, commercializing hydrogen-fueled compression ignition (HCCI) engines has been challenging due to issues like high cyclic variability, narrow operating ranges, and ignition timing control difficulties [219–221]. Compared to hydrocarbon fuels, hydrogen has a higher heating value, faster laminar flame speed, and higher-octane rating. These properties can result in reduced knocking and improved combustion stability [222]. As a result, several studies have investigated using hydrogen blended with gasoline in spark ignition engines [223–227]. For instance, Li et al. [228] found that adding hydrogen to a gasoline spark ignition engine reduced hydrocarbon and carbon monoxide emissions compared to a pure gasoline engine. In another study [229], researchers investigated the effects of hydrogen addition on the performance and emissions of a gasoline-fueled spark ignition engine under varied operating conditions. The results showed that blending hydrogen improved the indicated thermal efficiency and most emissions, except for slightly higher hydrocarbon and CO emissions at hydrogen volume fractions above 4.88%. Additionally, Rahaman [230] examined the impacts of air-fuel ratio and engine speed on the performance of a single-cylinder spark-ignited engine fueled by hydrogen-gasoline blends. The study found that brake mean effective pressure and brake thermal efficiency initially increased but then decreased at higher air-fuel ratios and speeds, likely due to hydrogen's lower density and flammability compared to gasoline and reduced volumetric efficiency.

Spark ignition engines can be fueled with hydrogen with minimal modifications [231]. Higher hydrogen flame speeds improve combustion and allow for greater brake thermal efficiency. Emissions of hydrocarbons and carbon monoxide are virtually nonexistent. Trace amounts of these emissions originate from the vaporization and combustion of lubricating oil on cylinder walls [232–236]. Hydrogen engine performance exceeds that of gasoline engines, particularly at part load. Hydrogen can also be blended with methane or gasoline. This enables the combustion of very lean mixtures with equivalence ratios as low as 0.1. However, spark ignition engines are suboptimal, requiring high torque at low engine speeds. In such cases, compression ignition engines operating at higher compression ratios, like diesel, are typically used. Hydrogen flame speed improvement enhances combustion and brake thermal efficiency in spark-ignited hydrogen engines. Hydrocarbon and

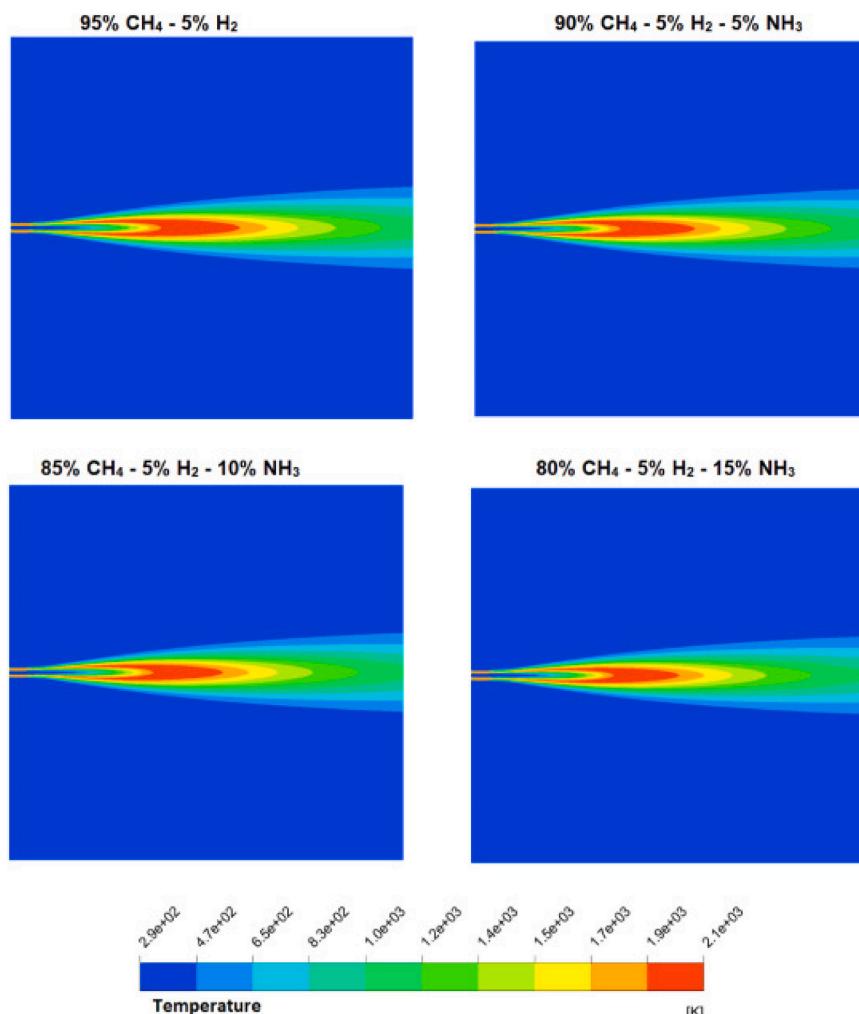
carbon monoxide emissions are essentially zero, with trace amounts coming from lubricating oil combustion. Hydrogen engine performance exceeds gasoline engines, especially at part load. Hydrogen can also be blended with other fuels to enable very lean combustion. However, spark ignition engines perform poorly under conditions requiring high torque at low engine speeds. In these situations, compression ignition engines operating at higher compression ratios, like diesel, are generally implemented instead [231].

## 6.2. Hydrogen-fueled internal combustion engines

Hydrogen internal combustion engines (H<sub>2</sub>ICEs) have demonstrated potential as clean and efficient power sources for vehicles, with studies showing they can achieve near-zero emissions and higher efficiencies compared to gasoline engines [237–240]. This is largely due to two key properties of hydrogen fuel. First, in theory, the only unwanted emissions from H<sub>2</sub>ICEs are nitrogen oxides (NOx) formed from high-temperature air nitrogen reactions during combustion. Second, hydrogen's low flammability limit enables stable combustion even when highly diluted with air. Together, these allow very lean mixtures that generate such low combustion temperatures that NOx formation is minimized, leading to near-zero emissions. The lean operation also enables efficient un-throttled operation at low loads [241]. However, these same hydrogen properties cause issues with high engine loads. Hydrogen's easy ignitability promotes abnormal combustion events as

mixtures ignite too readily. Less diluted mixtures also increase temperatures and NOx. This limits power output. Current research aims to create hydrogen engines with greater power and lower NOx at high loads through optimized designs for hydrogen combustion characteristics. The unique properties providing clean and efficient low-load operation also present high-load design challenges that ongoing research seeks to address [242].

Ammonia and hydrogen have been studied as potential fuels for diesel engines using various injection systems and combustion strategies with different volumetric blending ratios. The lack of carbon in ammonia and hydrogen and their different physical states (liquid and gas) suggest they could be used in combination as fuels. Methane's carbon atoms produce CO<sub>2</sub> emissions during combustion that contribute to greenhouse gas emissions. In contrast, ammonia and hydrogen combustion do not generate harmful emissions since these fuels do not contain carbon. Although hydrogen has a high heating value, its low auto-ignition temperature leads to engine knocking when used in internal combustion engines. Thus, hydrogen cannot be utilized alone or at high blending levels. Consequently, blended fuels comprised of methane, hydrogen, and ammonia appear to be a viable approach to improve the combustion performance of methane-fueled engines [243, 244]. However, combustion of methane, hydrogen, and ammonia blends has not been studied. Bayramoğlu et al. [245] numerically investigated and validated the effects of binary and ternary methane blends with hydrogen and ammonia on combustion chamber temperature and



**Fig. 11.** Steady-state temperature distribution contours of combustion flame for various hydrogen and ammonia blend fractions. conducted by Bayramoğlu et al. [245].

emissions. The study used numerical modeling to examine the effects of combusting methane blended with hydrogen and ammonia on performance and emissions. Blends of methane with 5 %, 10 %, and 15 % hydrogen were first modeled. Methane with 5 % hydrogen and 5 %, 10 %, and 15 % ammonia were then examined. Adding 15 % hydrogen to methane increased chamber temperature by 100 K while adding 15 % ammonia decreased temperature by 200 K and shifted the temperature peak (see Fig. 11). Increasing hydrogen content by 10 % resulted in a 28 % NOx emission increase while increasing ammonia by 10% caused a 3000 ppm NOx increase. At a location 0.444-cylinder diameters from the injector, adding 5 %, 10%, and 15% ammonia to methane-hydrogen blends increased NOx emissions by 1970, 3010, and 3790 ppm, respectively. Combusting 85 % methane/15% hydrogen and 80% methane/5% hydrogen/15% ammonia reduced CO<sub>2</sub> emissions by 30.7% and 14%, respectively, compared to pure methane.

### 6.3. Aviation and aerospace sectors

Hydrogen holds significant potential as a power source for diverse applications within the aerospace industry [246,247]. Presently, the scientific community is actively supporting research into hydrogen as an energy source due to its abundant availability, favorable specific energy properties, and environmentally friendly nature [246,248,249]. Hydrogen use in the aviation sector can be classified into two primary pathways: utilizing hydrogen as a substitute for kerosene in large airplanes and employing fuel cells to replace jet engines in smaller aircraft [199]. The history of hydrogen in aeronautics dates to the late 18th century with hydrogen balloons and, subsequently, rigid airships such as the Zeppelin in the early 20th century. Since then, numerous projects have been initiated worldwide to evaluate and develop hydrogen-powered aircraft that utilize hydrogen as a propellant [250]. However, most early studies were theoretical [251–257], but flight tests were conducted in the 1950 s using a B-57 aircraft [258] and in the 1980 s using a Tupolev Tu-155 aircraft [259]. In both cases, only one engine was converted to run on cryogenic liquid hydrogen (LH<sub>2</sub>). In 2000, the European Commission funded the Cryoplane study, which analyzed the system requirements for hydrogen-fueled aircraft [260]. The study concluded that the energy consumption of hydrogen-fueled aircraft would be 9–14% higher than kerosene-fueled aircraft due to the excessive tank volume required for liquid hydrogen (LH<sub>2</sub>) [260]. This is in contrast with other studies, which found that energy utilization for hydrogen is lower than for kerosene [251,254,257]. The difference is likely due to the minimal change approach used in the Cryoplane study,

which did not account for the changes in aircraft design that would be necessary to optimize the use of hydrogen as a fuel [261–263].

Recently, Airbus aimed to introduce a zero-emission passenger aircraft by 2035, which necessitates strategic planning for technology development starting in 2025 [264]. Given the diverse range of aircraft types, including flying taxis, short-, medium-, and long-range airplanes, it is apparent that a single technology cannot fulfill the energy demands for all these categories. Although Airbus has previously emphasized electric aviation for small airplanes, the company has now shifted its focus to hydrogen as a potential solution for addressing the CO<sub>2</sub> challenges in the aviation industry. Fig. 12 indicates three different zero-emission passenger aircraft introduced in this project by Airbus.

Generally, employing hydrogen as an alternative to fossil fuels presents challenges, but the advantages generally outweigh the drawbacks. Hydrogen possesses the highest energy per unit mass among chemically derived fuels [265]. As an aviation fuel, hydrogen usage would significantly reduce GHG emissions, including carbon-based emissions, soot, and sulfur oxides [266]. Despite generating a larger volume of water vapor, which is considered a GHG, hydrogen still substantially reduces net GHG emissions compared to kerosene [248,267]. Furthermore, adopting hydrogen as a jet fuel can contribute to long-term fuel price stability and enhanced fuel supply reliability, reducing dependence on fossil fuels concentrated in specific regions [265,267].

The low density of hydrogen gas poses a significant challenge for its use as a fuel in aerospace applications. At standard temperature and pressure, hydrogen has a density of just 0.09 kg/m<sup>3</sup>, compared to approximately 750 kg/m<sup>3</sup> for gasoline and 800 kg/m<sup>3</sup> for jet propellant (JP-8). To provide equivalent energy content, hydrogen, therefore, requires a much larger storage volume. For this reason, hydrogen is typically stored cryogenically as a liquid at 20.46 K. Even in this condensed state, the volumetric energy density of liquid hydrogen remains lower than conventional jet fuel by a factor of approximately 4. The large storage volumes required for cryogenic liquid hydrogen present difficulties in terms of vehicle design and performance for aerospace applications. Overcoming this density disadvantage through advanced storage methods or fuel processing technologies is an active area of research for enabling the use of hydrogen as a sustainable aviation fuel [268].

Despite the larger storage volumes required, Brewer's [269] studies concluded that hydrogen-fueled aircraft can still achieve lower overall weight and direct operating costs compared to kerosene-fueled aircraft. Corchero et al.'s [270] analysis of a hydrogen-fueled regional jet found a 2.8 times lower specific fuel consumption and 37 K lower turbine inlet



Fig. 12. Airbus ZEROe demonstrator [264].

temperature relative to kerosene fueling. This indicated the potential benefits of hydrogen in terms of fuel efficiency and engine life. Verstraete's [271] evaluation of hydrogen for long-range transport aircraft determined that storing liquid hydrogen in the fuselage minimizes surface area and heat losses. This enabled a 31% reduction in wing size without sacrificing fuel storage capacity. The larger fuselage cross-section compensates for the smaller wing area in terms of aerodynamic efficiency. Combined with lower fuel weight, this results in an estimated 11% reduction in energy use for hydrogen-fueled aircraft. In summary, studies indicated that despite hydrogen's low density, optimized hydrogen-fueled aircraft designs can achieve improvements in efficiency, engine performance, and operating costs compared to conventional kerosene-fueled aircraft. Advanced storage methods and fuel systems are key to enabling these potential benefits.

Liquid hydrogen is uniquely suited as a fuel for hypersonic vehicles with Mach numbers greater than 5, including long-range passenger aircraft and launch vehicles for space applications. Successful demonstration of hydrogen-fueled scramjet technology includes NASA's X-43A test flight in 2004 [268,272], which achieved Mach 7–9.6 speeds and positive acceleration under scramjet power. More recently, the University of Queensland's HyShot program tested the supersonic combustion of a hydrogen-fueled scramjet during reentry from a high-altitude rocket launch [273]. The flight reached Mach 7.6 conditions between 23 and 35 km altitude. These demonstrations proved the feasibility of igniting and sustaining hydrogen-fueled supersonic combustion in flight. The European LAPCAT II project also investigated a long-range hypersonic aircraft concept using liquid hydrogen fuel for potential Bruxelles to Sydney routes. In general, liquid hydrogen's high energy density, cooling capacity, and combustion properties make it uniquely suitable to enable practical scramjet propulsion and efficient hypersonic flight, both for space launch systems as well as potential future commercial transports [268].

Scramjet engines are being researched as a propulsion system for hypersonic airbreathing vehicles [20]. Hydrogen is commonly used as scramjet fuel due to advantages including high energy density, reactivity, wide flammability limits, and diffusivity [274]. Stable combustion in scramjets depends on increasing fuel residence time and forming low-speed zones in the combustor. Strut injectors act as effective flame holders in scramjets by increasing fuel penetration depth and residence time. This enhances fuel-air mixing and combustion stability. Due to the ability to improve combustion performance, strut-based hydrogen injectors have been widely implemented in scramjet engine designs [20, 274]. Experimental and computational research by the scramjet community has primarily utilized H<sub>2</sub> fuel [274–277]. Compared to hydrocarbons, H<sub>2</sub> has faster combustion with shorter ignition delay times and better air-fuel mixing [278]. For instance, for strut-based scramjet combustors, H<sub>2</sub> injection improves combustion and mixing while also providing strut cooling [277–284]. In cavity-based designs, multi-port H<sub>2</sub> injection increases overall mixing rates [275,278,285–289]. It also enlarges the ignition and mixing zones within cavity flame holders. Lowering the H<sub>2</sub> equivalence ratio for rear wall expansion cavities enhances air-H<sub>2</sub> mixing. Transverse H<sub>2</sub> injection enables high combustion in short combustors, especially when combined with crossflow configurations [274]. Studies on transverse injectors found circular H<sub>2</sub> jets have 25 % greater penetration than elliptical injectors [290–293]. Wedge-shaped injectors significantly improved wall cooling and H<sub>2</sub>/air mixing compared to circular designs [294].

Unmanned aerial vehicles (UAVs) are increasingly adopting hydrogen proton-exchange membrane fuel cells (PEMFCs) for longer endurance and faster refueling compared to batteries. For instance, Abdulrahman and Qasem [295] explored optimal design scenarios for fixed-wing hydrogen PEMFC-powered UAVs up to 25 kg for enhanced efficiency and flight times. Key input design variables optimized include rate of climb, hydrogen energy density, hydrogen fuel amount, cruise altitude, aspect ratio, and cruise speed. Results showed that PEMFC-UAVs can fly continuously for over 5 h, exceeding other clean

methods like batteries. Optimized configurations achieved 3.76 times higher endurance versus literature vehicles. Hydrogen storage systems ranged from 1.6 to 2.9 kg for the takeoff weights studied. A 6.5 kg UAV with 580 Wh/kg fuel cell power density attained 17.15 flight hours at <1 kWh total power consumption with a 2.9 kg hydrogen system.

### 6.3.1. Hydrogen safety in the aviation industry

Hydrogen is being explored as a potential fuel for aircraft in the aviation industry due to its potential to reduce greenhouse gas emissions. However, safety is a critical concern when considering the use of hydrogen in aviation. Several key safety risks are associated with the use of compressed or cryogenic hydrogen on aircraft. For instance, hydrogen is highly flammable, with a wide flammability range allowing it to ignite in air concentrations between 4.3% and 75% by volume, requiring minimal oxygen [296,297]. Additionally, leaks pose a serious risk as hydrogen molecules are smaller than other gases, increasing leakage rates through storage casings. Leak detection would be critical given hydrogen is also odorless and colorless, making leaks difficult to identify. Hydrogen also ignites very easily, requiring only a minimal energy of 0.017MJ to ignite when mixed with air. Another concern is that hydrogen can cause embrittlement in some materials like steel through permeation over time, potentially leading to cracking. Careful consideration of storage materials is necessary to prevent this. Contact with liquid hydrogen can also cause injury and inhalation of leaking hydrogen risks asphyxiation. Proper safety precautions and risk mitigation protocols would need to be implemented to manage these risks introduced by using hydrogen as an aircraft fuel [298].

In the 1970 s, Lockheed conducted a safety study modeling four accident scenarios for LH<sub>2</sub> aircraft, from small fuel line cracks to deadly crashes, validated using previous LH<sub>2</sub> detonability and spill tests [299]. The results revealed that LH<sub>2</sub> spills vaporized and spread shorter on the ground than kerosene spills, and ignition increased vaporization while reducing spill spread. Interestingly, the study found LH<sub>2</sub> burnout times were shorter than the time taken for the fuselage to collapse from hydrogen flames, indicating passengers may have remained seated until collapse unlike kerosene fires requiring immediate evacuation, though window failure effects were not considered. Overall, the study concluded LH<sub>2</sub> offered safety advantages over traditional fuels. Subsequently, related projects explored LH<sub>2</sub> production, storage, and airport safety, including experiments simulating LH<sub>2</sub> releases. While later studies referenced unpublished reports on LH<sub>2</sub> tank safety and emergency landing, it was determined operating LH<sub>2</sub> aircraft was safely feasible. UK tests also provided data on LH<sub>2</sub> spill dispersion trajectories under varying wind conditions [300].

The ENABLE-H2 project has conducted extensive work researching hydrogen safety in aviation [301]. Benson et al.[302] performed a preliminary hazard analysis based on industrial standards and past experiments, identifying gaps and needs for future work in hydrogen storage, distribution, heat management, and combustion. To address knowledge gaps in altitude effects, an experimental rig was developed to test flammability and ignition up to -50°C and 150mbar pressure. Benson et al.[303] also suggested firefighting posed the highest risk at airports based on the need for new techniques and regulations for liquid hydrogen fires. Holborn et al. [304] used computational fluid dynamics modeling to simulate a large-scale LH<sub>2</sub> pool release, finding higher winds increase ground flammable distance and their model showed consistency with 1980 NASA spill test trends, though magnitudes were underpredicted. Holborn et al.[305] additionally modeled accident scenarios finding LH<sub>2</sub> spills resulted in rapid vaporization and intense but shorter flames with lower thermal radiation doses and hazardous distances similar to earlier Lockheed studies, helping advance the understanding of liquid hydrogen safety for aviation applications [300].

While the use and storage of compressed or cryogenic hydrogen on aircraft would introduce new safety risks, hydrogen may present some potential safety advantages compared to kerosene as well. Specifically, the rigidity of pressurized and cryogenic hydrogen storage tanks means

that if ruptured, the gas tends to dissipate quickly from the aircraft [298, 306]. However, for safety, the tanks would need to be designed to allow hydrogen to escape in the event of a rupture. Additionally, hydrogen-fueled fires are typically smaller and less intense than kerosene fires, with the heat radiation from a hydrogen flame being only 10% of that from a kerosene flame, making hydrogen fires easier to contain [298]. This means that in some ways hydrogen presents a safer option for aircraft use if the storage tanks can be incorporated to vent safely in an emergency. Strict risk management would still be required to address the new safety risks of hydrogen as a replacement fuel source for aircraft.

#### 6.4. Domestic and heating applications

In the context of hydrogen utilization in domestic settings, the implementation of low-temperature flameless catalytic combustion has demonstrated promising efficacy. This is primarily attributed to the superior catalytic oxidation capabilities of H<sub>2</sub> compared to other fuels [307]. For specific applications such as space heating and domestic hot water heating, the required temperatures remain considerably below 100 °C, while cooking applications typically necessitate temperatures below 700 °C. Haruta et al. [307,308] conducted a study on the utilization of H<sub>2</sub> in this regard, with a particular focus on H<sub>2</sub>/air pre-mixing. The research revealed that the catalytic combustion of H<sub>2</sub> offers a significant advantage in terms of straightforward temperature adjustment, particularly at lower oxidation temperatures. Nonetheless, it should be noted that the presence of non-uniform temperature distribution across the catalyst surface could pose a challenge, requiring careful consideration of design features [308]. Furthermore, Fumey et al. [309] investigated NOx emissions from a novel catalytic hydrogen combustion process operating without premixed hydrogen and air intended for domestic kitchen applications. The burner consisted of two platinum-coated silicon carbide foam disks through which hydrogen was supplied below and air blown between. Tests were conducted at varying hydrogen flow rates and hydrogen-to-oxygen ratios. Extremely low NOx emissions between 0.007 and 0.37 mg/kWh were achieved, significantly below the EU limit of 56 mg/kWh. Emissions depended on area-specific power and fuel-air ratio. This demonstrated the potential for safe domestic hydrogen heating and cooking without harmful emissions like CO, CO<sub>2</sub>, and NOx.

Gersen et al. [310] investigated a sustainable approach to reduce CO<sub>2</sub> emissions from industrial heating by blending hydrogen into natural gas, with the long-term goal of completely replacing natural gas with hydrogen. They developed and tested a burner system that enables

stable and reliable combustion of natural gas, natural gas/hydrogen mixtures, and pure hydrogen. The system consisted of a feed-forward fuel-adaptive burner controller connected to a forced draft industrial burner installed in a 475-kW boiler. Visually, no substantial changes in flame stability were observed when incrementally blending 0–100 % hydrogen into natural gas, and no burner overheating was measured. The fuel-adaptive controller successfully maintained constant flue gas oxygen percentage and thermal input independent of fuel hydrogen content. However, NOx emissions considerably increased with hydrogen blending, up to three times higher when switching from natural gas to pure hydrogen. Applying flue gas recirculation as a NOx mitigation strategy substantially reduced emissions; over 10-fold NOx reduction was achieved.

Schiro et al. [311] investigated the impact of blending hydrogen into natural gas (HENG) on end-user domestic boilers depicted in Fig. 13. With the drive to decarbonize energy systems, hydrogen is seen as a renewable energy vector that can be injected into existing natural gas infrastructure. However, the effects of HENG fuels on downstream combustion devices require study. The authors developed a model to calculate combustion parameters for HENG across different hydrogen blending ratios. Using this model, they evaluate the impact on critical components in premixed condensing boilers widely used in homes. Key findings show that minimal boiler redesign was needed below ~20% hydrogen blending beyond tuning controls and sizing fuel components. More substantial changes are required at higher blends, including redesigning the burner, heat exchanger, and condensate system.

Moreover, another study investigated the performance impacts of using hydrogen-enriched natural gas (HENG) in industrial steam boilers, which is important for reducing carbon emissions [312]. Different boiler operation strategies were evaluated when transitioning from natural gas to HENG fuels. Three scenarios were modeled - constant fuel/air valve opening, maintained boiler capacity with fixed controls, and maintained capacity with fixed excess air. Thermal efficiency and NOx emissions were analyzed using computational models of the combustion and heat transfer. Their results showed thermal efficiency and NOx emissions both decrease in the first two scenarios as hydrogen fraction increases due to lower flame temperatures. In the third scenario, efficiency increased, but NOx emissions increased sharply due to higher temperatures. Decarbonization potential was similar across scenarios. When implementing HENG in industry, the trade-off between efficiency and emissions must be balanced.

Yang et al. [313] examined the use of HENG in condensing boilers to reduce emissions and enable decarbonization. HENG combustion increases the water vapor in flue gas, which improves heat recovery in the

1	- Air blower
2	- Gas Valve
3	- Gas/Air Mixer — Venturi tube
4	- Primary heat exchanger (five coils)
5, 9, 10	- Collectors/distributors
6	- Final flue gas collector
7	- Separation wall for flue gas
8	- Premix burner with spark ignition
11	- Pump
12	- 3-Way Valve
13	- Secondary (Plate) Heat Exchanger
C1	- Gas Supply
C2	- CH Flow connection
C3	- DHW connection
C4	- Domestic cold water connection
C5	- CH Return connection

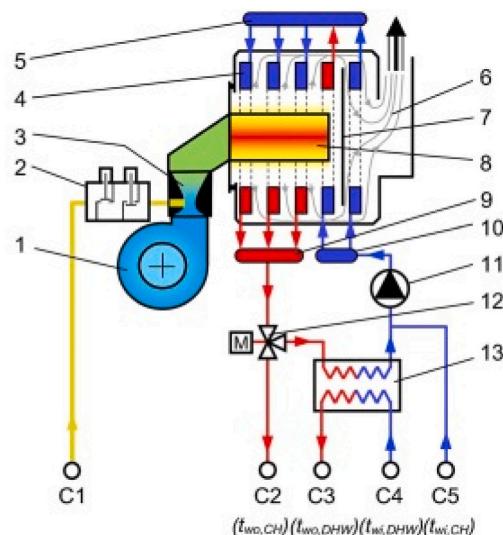


Fig. 13. Schematic of a condensing boiler system proposed by Schiro et al. [311].

condenser. The impact of HENG on combustion products, boiler efficiency, heat transfer, and condenser performance were analyzed through modeling. Results showed hydrogen addition increased flame radiation intensity due to higher triatomic gas concentrations. Heat absorption increased in the radiative section but decreased in the convective section as the hydrogen fraction went from 0% to 100%. Boiler efficiency was improved from 101.8% to 110.6% on an LHV basis. The condenser heat recovery and total area needed also improved with hydrogen enrichment. The study concluded that existing condenser systems designed for natural gas can meet the heat recovery demands of HENG without requiring more surface area. HENG in condensing boilers could reduce emissions while maintaining or improving efficiency and heat recovery performance. In addition, a 0.9% increase in the energy fraction of condensation was predicted for 30 % H<sub>2</sub>NG. Relative humidity played a major role in improving condensing efficiency by up to 4.8 %. Accurate humidity measurement was critical [314]. Bălănescu et al. [315] showed that condensation potential and boiler efficiency increased significantly with hydrogen fraction due to the higher water content. CO<sub>2</sub> emissions were reduced substantially. Excess air needed controlling to prevent elevated flame temperatures and NOx formation. For 80 % hydrogen, a 1.4 % efficiency gain was predicted, along with a 56 % CO<sub>2</sub> reduction compared to pure methane. The analysis verified hydrogen-enriched methane (HEM)'s viability as a lower carbon fuel for condensing boilers, with additional efficiency and heat recovery benefits.

A casing swirl burner model was simulated under six conditions of varying hydrogen fraction at constant boiler heating power and air excess [316]. Temperature distributions, flue gas composition, and emissions were analyzed. Results showed hydrogen addition increased combustion temperature and rate. It reduced total flue gas volume and CO<sub>2</sub> emissions while increasing water vapor. NOx and soot emissions decreased due to higher specific heat and more water. An optimal 24.7% hydrogen fraction was found to meet fuel interchangeability requirements. The study demonstrated hydrogen blending enabled lower emissions and improved combustion performance in gas boilers. This provided engineering guidance for implementing hydrogen-natural gas mixtures to support decarbonization through enhanced combustion properties and reduced carbon intensity. Yangaz et al. [227] also studied [225] the effects of adding hydrogen at increasing rates to various gaseous fuels (methane, propane, LPG, natural gas) in a premixed domestic burner through numerical simulations. Biogas and pure hydrogen cases were also analyzed. The results showed that combustion efficiency was positively affected for all fuels with hydrogen enrichment, except for some compositions. Hydrogen addition also generally decreased unburnt hydrocarbons and carbon monoxide emissions. In conclusion, the fuels examined included LPG, methane, propane, natural gas, biogas, and pure hydrogen. Hydrogen addition slightly increased combustion efficiency by up to 0.5% for most fuels. Overall efficiencies concerning useful heating energy ranged from 4% to 9% for all fuels except biogas, which was 35–88%. Unburnt emissions decreased with higher hydrogen rates, except in some cases. Temperature differences remained 70–80 K with hydrogen addition through effective fuel distribution. Therefore, hydrogen-enriched fuels are preferable to reduce carbon emissions for sustainability, though nitrogen oxides increased.

Boulahlib et al. [317] experimentally studied injecting hydrogen-methane mixtures into a domestic boiler to store excess renewable energy in the natural gas grid. A 15-kW boiler with 16 burners was tested under fuel-rich conditions and 0–45 % hydrogen blending. Results indicated that NOx and CO<sub>2</sub> emissions decreased, but CO and unburnt hydrocarbons increased with more hydrogen and higher fuel richness. The temperature peak was around 20 % hydrogen. Thermal efficiency declined with hydrogen fraction. An optimal point of 20 % hydrogen and fuel equivalence ratio of 2 was found to balance high power, efficiency, and low emissions.

## 7. Future prospects

There are several key areas for future research on hydrogen energy systems. Improving efficiency and sustainability involves developing more cost-effective electrolysis methods utilizing renewable energy sources, as well as novel catalysts for hydrogen production from biomass. Storage and infrastructure research can create lightweight, safe hydrogen storage and new transportation/distribution infrastructure like refueling stations. As hydrogen production and transport must be done safely, future work aims to establish safety standards, technologies, and regulations. Additional studies seek to integrate hydrogen systems with electricity and natural gas networks through hybrid systems. This includes combining hydrogen with other energy sources. Additionally, achieving economic viability necessitates lowering hydrogen production and storage costs. Innovative business models and funding can also promote hydrogen system development and deployment. Overall, addressing these technical, economic, and policy challenges will help advance the viability and deployment of hydrogen energy solutions. Finally, replacing fossil fuel usage with hydrogen in power generation, heating, transportation, and manufacturing can mitigate climate change risks and emissions. Hydrogen offers substantial room for innovations in technologies, techniques, and materials to further enable its clean energy applications. Overall, hydrogen's versatility as an energy vector and storage medium creates research opportunities to advance renewable integration, energy storage, fuel switching, and emissions reductions across sectors.

## 8. Conclusion and remarks

This work comprehensively reviews hydrogen combustion, production, hydrogen blend with NH<sub>3</sub>, techno-economic analysis, and applications. The unique characteristics of hydrogen in combustion, such as its wide flammability limits, rapid flame velocity, and high auto-ignition temperature, make it a promising candidate for future energy applications. Advancements in hydrogen production technologies, especially those utilizing renewable resources, are crucial for reducing reliance on fossil fuels and promoting sustainable energy systems. Furthermore, blending hydrogen with ammonia presents promising opportunities for carbon-free combustion, contributing to the pursuit of carbon neutrality. However, the produced NOx needs to be minimized. The diverse applications of hydrogen, ranging from transportation to power generation, underscore its significance as an energy carrier with the potential to transform the global energy landscape and enhance energy security.

The most established and lowest-cost hydrogen production technology currently is steam methane reforming, with costs of \$1.3–1.5/kg H<sub>2</sub> and an efficiency of 70–85%. However, it produces CO<sub>2</sub> emissions from the use of natural gas. Biomass gasification and pyrolysis provide renewable alternatives with costs ranging from \$1.25–2.20/kg H<sub>2</sub> and \$1.77–2.05/kg H<sub>2</sub> respectively but have technical challenges around tar and impurity formation and fluctuating hydrogen yields based on variable feedstocks. Electrolysis driven by renewable electricity offers a long-term greenhouse gas neutral solution, with bio-photolysis having the advantages of mild operating conditions and consuming CO<sub>2</sub>, but currently has high costs of \$1.42–2.13/kg H<sub>2</sub> due to low conversion rates and requiring large reactors. Additionally, Techno-economic analysis provides a framework to evaluate technical, economic, and environmental performance at different scales, examining costs, profitability, and greenhouse gas emissions. However, new biological and electrochemical processes have lower maturity than steam reforming, significantly increasing costs. Combined with high biomass costs, current biomass hydrogen ranges from \$1.2–2.4/kg versus under \$0.8/kg for natural gas.

Ammonia-blended hydrogen-fueled engines remain in early research and development stages. Further advances in engine technologies for ammonia-hydrogen blends and ammonia decomposition methods to produce hydrogen can enable broader utilization of ammonia as a

renewable fuel as well as a hydrogen carrier. With additional research, ammonia has the potential to be widely adopted as a clean, sustainable fuel alternative, addressing current carbon emissions while progressing the energy industry. Realizing ammonia's prospects requires maturing ammonia-hydrogen combustion systems and scalable, efficient ammonia cracking technologies. Ultimately, continued innovation in these areas can position ammonia as a viable option for decarbonized, reliable energy in the future.

Overall, Additional research is needed to advance hydrogen technologies and enable their widespread adoption as a clean energy source. Regarding hydrogen combustion, furthering the understanding of combustion mechanisms, progressing combustion technologies, and optimizing fuel-air mixing are important areas of study. For hydrogen production, the focus should be on developing low-cost, sustainable production methods through exploring novel materials, and catalysts, and optimizing process conditions. The application of hydrogen also requires additional research, such as integrating hydrogen into transportation, utilizing it in industry, and developing energy storage systems. Addressing these gaps through additional work is critical for the advancement and large-scale deployment of hydrogen as a versatile, low-carbon energy carrier.

#### CRediT authorship contribution statement

**M. A. Habib:** Conceptualization, Formal analysis, Project administration, Writing – original draft, Writing – review & editing. **Gubran A. Q. Abdulrahman:** Data curation, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. **Awad B.S. Alquaity:** Conceptualization, Methodology, Resources, Supervision, Writing – original draft, Writing – review & editing. **Naef A.A. Qasem:** Data curation, Formal analysis, Investigation, Writing – original draft.

#### Declaration of Competing Interest

We declare that there is no-conflict of interest.

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