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Zero-emission transportation and aviation through green hydrogen innovation

Maha Awjan Alreshidi [a], Krishna Kumar Yadav [b,c,*], Amel Gacem [d], S. Padmanabhan [e], S. Ganesan [f], S. Mahalingam [g], T. Vinod Kumar [h], P. Saravanan [i], Kamal Y. Thajudeen [j], Ahmed M. Fallatah [k], Mohammed Muqtader Ahmed [l], G. Shoba [m], C. Kavitha [n], P. Tamizhdurai [n,**], Mohammad Khalid [o]

[a] Department of Chemistry, College of Science, University of Ha'il, Ha'il, 81451, Saudi Arabia
[b] Department of VLSI Microelectronics, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences (SIMATS), Saveetha University, Chennai, Tamil Nadu, 602105, India
[c] Environmental and Atmospheric Sciences Research Group, Scientific Research Center, Al Ayen University, Nasiriyah, Thi-Qar, Iraq
[d] Department of Physics, Faculty of Sciences, University 20 Août 1955, Skikda, Algeria
[e] Department of Mechanical Engineering, Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, Chennai, Tamil Nadu, India
[f] Department of Mechanical Engineering, Sathyabama Institute of Science and Technology, Chennai, Tamil Nadu, India
[g] Department of Mechanical Engineering, Sona College of Technology, Salem, India
[h] Department of Mechanical Engineering, Vels Institute of Science, Technology & Advanced Studies (VISTAS), Chennai, India
[i] Department of Chemistry, St. Joseph's College of Engineering, OMR, Chennai, 600119, India
[j] Department of Pharmacognosy, College of Pharmacy, King Khalid University, Abha, 62529, Saudi Arabia
[k] Department of Chemistry, College of Science, Taif University, P.O. Box 11099, Taif, 21944, Saudi Arabia
[l] Department of Pharmaceutics, College of Pharmacy, Prince Sattam Bin Abdulaziz University, P.O. Box 173, AlKharj, 11942, Saudi Arabia
[m] Department of Biotechnology, Dwaraka Doss Goverdhan Doss Vaishnav College, (833, Gokul Bagh, E.V.R. Periyar Road, Arumbakkam, Chennai, Tamil Nadu, 600 106, India
[n] Department of Chemistry, Dwaraka Doss Goverdhan Doss Vaishnav College (Autonomous)(Affiliated to the University of Madras, Chennai), 833, Gokul Bagh, E.V.R. Periyar Road, Arumbakkam, Chennai, Tamil Nadu, 600 106, India
[o] Department of Pharmaceutics, College of Pharmacy, King Khalid University, Asir, Abha, 61421, Saudi Arabia

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ABSTRACT

In today's dynamic energy landscape, the shift toward sustainable sources is more urgent than ever. Among emerging solutions, green hydrogen stands out especially for hard-to-decarbonize sectors like transportation and aviation. Sustainable hydrogen originates by electrolysis through renewable energy, providing a zero-carbon substitute for conventional hydrogen, which is primarily generated by carbon-intensive steam methane reforming. Hydrogen's unique properties such as a high energy-to-weight ratio and compatibility with existing infrastructure make it more than just a clean fuel. It represents a paradigm shift in how energy is produced, stored, and used. According to the authoritative International Energy Agency (IEA), by 2040, worldwide consumption of energy could increase by as much as 30 %. Considering this prerequisite with fossil fuels would only worsen climate change, making green hydrogen not just viable but essential. Despite its promise, challenges persist. Safety concerns around hydrogen's flammability have been addressed through modern handling protocols However, its low volumetric energy density presents storage and transportation issues—particularly in aerospace. Encouragingly, technological advancements in high-pressure tanks, cryogenic systems, and solid-state hydrogen carriers are enhancing feasibility and safety.

This review examines the potential and challenges of green hydrogen, with a focus on its application in aviation. It highlights advances in fuel cells, liquefaction, and hydrogen storage that enhance efficiency and safety. Hydrogen-powered aircraft prototypes show projected emission cuts of 50–75 % compared to conventional jet fuels. The review identifies key challenges—scaling infrastructure, reducing costs, and regulatory

* Corresponding author. Department of VLSI Microelectronics, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences (SIMATS), Saveetha University, Chennai 602105 Tamil Nadu, India.
** Corresponding author.
E-mail addresses: envirokrishna@gmail.com (K.K. Yadav), p.tamizhdurai@dgvaishnavcollege.edu.in (P. Tamizhdurai).

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alignment—and proposes solutions including investment incentives and global safety standards. It also outlines future research directions in materials, hybrid propulsion, and life-cycle assessment, reinforcing green hydrogen's role in sustainable aviation.

1. Introduction

Over the past two decades, aviation emissions have nearly doubled due to the rising number of travelers, despite improvements in productivity [1]. It is anticipated that the demand for jet fuel would rise by about 3 % yearly by 2030, while the global aviation sector will expand by roughly 5 % annually [2]. At the moment, jet fuel accounts for almost 8 % of global oil consumption every day. Aviation contributes approximately 11.6 % of transportation-related CO_2 emissions annually, yet this accounts for less than one billion tons, or about 2.5 % of total global CO_2 emissions each year [3,4]. In 2018, biofuels made up a minuscule share of aviation fuel consumption, totalling just around 15 million litters, or less than 0.1 % of the total. Commercial airlines face growing pressure to curb their carbon footprint due to reliance on fossil-based jet fuels [5]. The development and adoption of low-carbon liquid fuels are critical to achieving these emission reductions. Looking ahead, the aviation industry has set ambitious medium- and long-term targets to lower its carbon output [6]. The International Air Transport Association (IATA) has advocated for the increased use of renewable fuels certified under the Sustainable Aviation Fuel (SAF) standard [7].

In accordance with numerous studies, the cost for manufacturing fuel from renewable resources is frequently higher than that of traditional jet fuel obtained from fossil fuels [8,9]. Recently, the generation of jet fuel using macroalgae has shown promise as a sustainable alternative [10]. This is largely due to their rapid growth rates, absence of lignocellulosic material which simplifies and reduces the energy demand during refining their cultivation not requiring arable land or freshwater resources, and their potential scalability for commercial applications [11–13]. A detailed comparison of hydrogen production costs is provided in Table 1 below.

Aviation, as one of the fastest-growing transportation sectors, contributes approximately 2 % of global anthropogenic CO_2 emissions. The industry has pledged to reduce its carbon footprint by 50 % relative to 2005 levels by the year 2050 [20]. In pursuit of more environmentally friendly options, the aviation sector continually explores alternative fuels. Unlike ground transportation, which can adopt electricity, hydrogen, or biodiesel, these options currently face significant challenges for widespread use in aircraft [21,22]. Sustainable aviation fuels, commonly known as biojet fuels, have emerged as promising substitutes to lower aviation's carbon emissions [23]. Researchers worldwide are actively developing efficient production methods for biojet fuel using a variety of raw materials [24]. When it comes to safety, biojet fuel matches the standards of hydrogen fuel systems hydrogen itself is non-toxic, disperses quickly, and burns cleanly. To ensure safe operations, fuel storage tanks must be designed to resist embrittlement, and personnel should receive thorough training on handling procedures [25,26].

Despite its promising attributes, hydrogen adoption in aviation remains at a nascent stage and is constrained by several technical, economic, and infrastructural challenges. Recent literature provides a comprehensive overview of these barriers. For instance, Bhuiyan and Siddique (2025) highlight that while hydrogen offers an efficient and clean energy vector, over 96 % of global hydrogen is currently produced from fossil fuels (grey hydrogen), with green hydrogen comprising a mere 4 %, primarily due to high production costs ($2.28–7.39/kg) and limited infrastructure for storage and distribution [27]. Additionally, Sakib et al. (2024) emphasize the lack of harmonized policies and commercialization strategies, noting that many national efforts remain fragmented or overly focused on short-term milestones [28]. The broader material science perspective, including storage materials, embrittlement concerns, and fuel cell integration, is elaborated by Ahad et al. (2023), who stress the urgency of addressing hydrogen's interaction with pipeline materials, composites, and safety systems, particularly in high-demand sectors such as aviation [29].

2. Sustainable fuel for aviation

The following feedstocks and associated technologies align with the global pursuit of low-emission alternative fuels [29]. These include specialized energy crops cultivated specifically for biofuel production, as well as oilseeds and oil palm plantations, which serve as significant sources of biodiesel. Corn kernels remain a widely used feedstock for

Table 1
Innovative technologies for hydrogen gas production.

S. No	Production Technology	Feedstock/Energy Source	Process Description	CO_2 Emissions	Hydrogen Color Code	CCS Applicable	Commercial Status	Refs.
1	Steam Methane Reforming (SMR)	Natural Gas	High-temp reaction of methane with steam to produce H_2 and CO_2	High	Grey	Yes	Widely commercial	[14,15]
2	SMR + CCS	Natural Gas with CCS	Same as SMR, but with carbon capture & storage to reduce CO_2 emissions	Low to Moderate	Blue	Yes	Commercial, growing	[15,16]
3	Electrolysis (Grid Electricity)	Grid Electricity (non-renewable)	Electric current splits water into H_2 and O_2; depends on grid's energy mix	Medium to High	Grey or Blue*	Possible	Emerging, depends on grid	[16,17]
4	Electrolysis (Renewables)	Renewable Electricity (e.g., solar)	Uses clean electricity to split water	Near Zero	Green	Not needed	Growing, key for green H_2	[17,18]
5	Autothermal Reforming (ATR)	Natural Gas	Partial oxidation + reforming in a single reactor	High (Lower than SMR)	Grey or Blue (with CCS)	Yes	Pilot to commercial	[14,16]
6	Coal Gasification	Coal	Reacts coal with oxygen/steam to release syngas, then extract H_2	Very High	Brown/Black	Yes (costly)	Limited, mostly in China	[15,16]
7	Biomass Gasification	Biomass	Similar to coal gasification but with biomass	Low to Moderate	Green or Bio-H_2	Not typical	Pilot/ Demonstration scale	[14,17]
8	Photoelectrochemical (PEC)	Solar Energy	Direct solar splitting of water using photoelectrodes	Zero	Green	Not needed	Experimental	[16,18]
9	Thermochemical Water Splitting	High-temp Solar/ Nuclear Heat	Uses heat to drive chemical reactions that split water	Zero	Green	Not needed	Research phase	[16,19]

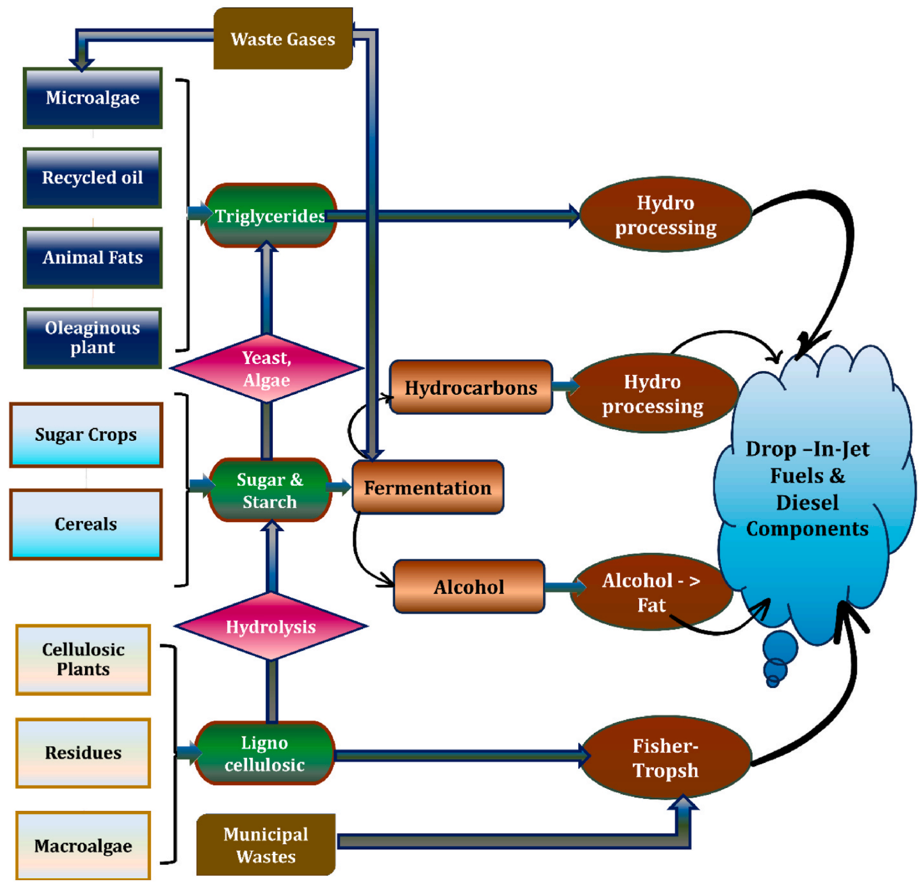

Fig. 1. Routes to sustainable aviation fuel production [34].

bioethanol production due to their high starch content. Additionally, both microalgae and macroalgae have garnered attention for their rapid growth rates and high lipid or carbohydrate yields, making them promising candidates for third-generation biofuels. Various fats, oils, and greases (FOGs), often derived from waste streams, also contribute to biodiesel production through transesterification processes. Agricultural and forestry by-products, such as crop residues and lignocellulosic biomass, offer a renewable and abundant resource for second-generation biofuels. Furthermore, residues from wood processing mills and municipal waste—including organic matter from animals and humans—present viable options for waste-to-energy technologies, thus supporting the transition toward a circular bioeconomy and reduced greenhouse gas emissions.

Macroalgae, or seaweeds, are particularly compatible with wet fuel processing techniques like fermentation and anaerobic digestion because of their naturally high moisture content, typically ranging between 85 % and 90 % [30]. Unlike woody biomass, seaweeds contain very little lignin, which eliminates the need for energy-intensive pre--treatment processes commonly required in wood-based bioethanol production [31]. Additionally, seaweeds exhibit faster regeneration cycles compared to forest biomass, enabling continuous cultivation and making them a renewable source for biofuel applications [32].

To achieve the global demand for sustainable aviation fuel, it is essential to explore and develop a variety of large-scale production methods. A number of advanced technologies are being engineered specifically for jet fuel synthesis [33]. Among the most widely employed approaches are chemical and biochemical conversion techniques, which serve as key routes for transforming raw materials into aviation-grade fuel, is apparent in Fig. 1.

The most common thermochemical conversion pathways are Gasification process, the implementation of pyrolysis and Fischer-Tropsch synthesis, High-Temperature Liquefaction (HTL) method, and hydrothermal upgrading (HTU). Biochemical conversion strategies include anaerobic digestion and fermentation influenced significantly by the type of biomass feedstock utilized. The efficiency and outcome of these processes largely depend on the specific characteristics and composition of the biomass input [35–37].

3. Pros of sustainable aviation fuel (SAF) and its drawbacks

The possibility of creating biologically produced jet fuel from various feedstocks was thoroughly evaluated by examining the complete value chain, from the procurement of resources to the ultimate fuel consumption [38]. A conceptual analysis was conducted in order to assess the potential benefits of sustainable aviation fuel (SAF) in minimizing carbon emissions. Table .2 outlines the key benefits and limitations associated with SAF options.

3.1. Advantages of sustainable aviation fuel (SAF)

Sustainable Aviation Fuel offers significant environmental benefits, primarily through its potential to reduce lifecycle greenhouse gas (GHG) emissions by up to 80 % compared to conventional jet fuels. This makes SAF a critical transitional solution for decarbonizing the aviation sector. Furthermore, SAF can be produced from a wide variety of renewable feedstocks, including agricultural residues, municipal solid waste, and used cooking oil, thus reducing dependence on fossil resources while promoting waste valorization [49,50].

Another major advantage of SAF is its drop-in compatibility with existing aircraft engines and fuel infrastructure. Unlike hydrogen or battery-electric alternatives, SAF requires no major modifications to current airport fueling systems or aircraft designs, enabling immediate

Table 2
The Advantages and Disadvantages of sustainable aviation fuel.

S. No	Aspect	Advantages	Disadvantages	Ref
1.	Environmental Impact	- Significantly reduces greenhouse gas (GHG) emissions (up to 80 %)	- May still produce some emissions during production and combustion	[39]
2.	Compatibility	- Compatible with existing aircraft and airport infrastructure	- Blend limits (usually up to 50 %) with conventional jet fuel	[40]
3.	Feedstock Variety	- Can be produced from diverse sources (waste oils, biomass, algae, etc.)	- Limited availability of sustainable feedstock at scale	[41]
4.	Energy Security	- Reduces reliance on fossil fuels and enhances fuel diversity	- Geopolitical or local competition for biomass resources	[42]
5.	Economic Impact	- Potential for job creation in renewable fuel production	- Higher cost compared to conventional jet fuel	[43]
6.	Performance	- Offers similar or better performance than conventional jet fuel	- Requires rigorous certification and testing processes	[44]
7.	Carbon Neutrality	- Life-cycle emissions can be close to neutral with proper sourcing	- Land use changes can negate carbon savings if not managed properly	[45]
8.	Scalability	- Ongoing technological improvements are enhancing scalability	- Current production volume is low; large-scale deployment is challenging	[46]
9.	Waste Management	- Utilizes waste materials, helping reduce environmental waste burden	- Waste collection and preprocessing can be logistically complex and costly	[47]
10.	Public Perception	- Growing public support for greener aviation initiatives, especially among climate-aware consumers	- Limited public awareness and potential doubts regarding the effectiveness and safety of sustainable aviation fuels (SAFs).	[48]

Table 3
Fuel property comparison: Hydrogen, natural gas, and gasoline.

S. No	Property	Hydrogen (H_2)	Natural Gas (Methane, CH_4)	Gasoline	
1	Energy Content (by mass)	~120 MJ/kg	~55 MJ/kg	~46 MJ/kg	[54]
2	Energy Content (by volume)	~10.8 MJ/m^3 (at 1 atm)	~38 MJ/m^3	~34 MJ/L	[54]
3	Density (at STP)	0.0899 kg/m^3	0.717 kg/m^3	~750 kg/m^3	[54]
4	Flammability Range in Air (%)	4–75 %	5–15 %	1.4–7.6 %	[55]
5	Autoignition Temperature	~500 °C	~540 °C	~280 °C	[55]
6	CO_2 Emissions (kg/GJ)	0 (green H_2)	~50–56	~69–73	[56]
7	Pollutants (NOx, particulates)	NOx possible at high temps	NOx, CO_2	CO_2, NOx, CO, particulates	[56]
8	Storage State	Gas (compressed or liquefied)	Gas (compressed or liquefied)	Liquid	[54]
9	Renewability	Renewable (if from electrolysis)	Non-renewable (fossil source)	Non-renewable (fossil fuel)	[19]
10	Environmental Impact	Very low (green H_2)	Moderate (methane leaks, CO_2)	High (GHG emissions, pollution)	[19]

integration into today's aviation fleet. This compatibility accelerates adoption and allows airlines to reduce emissions with minimal operational disruption. Additionally, SAF offers improved combustion properties, such as higher energy density and better thermal stability, which can enhance engine performance and reduce particulate emissions during flight [51].

3.2. Limitations and challenges of sustainable aviation fuel (SAF)

Despite its advantages, SAF faces several challenges that limit its widespread adoption. The most significant barrier is its high production cost, which can be 2–5 times more expensive than conventional jet fuel. This price disparity arises from limited commercial-scale production facilities, high feedstock costs, and energy-intensive conversion processes. Without substantial government subsidies or market-based mechanisms (e.g., carbon pricing or blending mandates), SAF remains economically uncompetitive in most markets [49,50].

Another constraint is the limited availability of sustainable feedstocks, which raises concerns about scalability. Many feedstocks compete with food production or land use, potentially leading to indirect environmental or social impacts. Additionally, while SAF is a near-term solution for reducing emissions, it does not fully eliminate non-CO_2 effects such as contrail formation and nitrogen oxide emissions, which also contribute to aviation's climate impact. Finally, regulatory inconsistencies across countries and lack of harmonized certification pathways hinder global SAF deployment [52,53].

4. The role of hydrogen in future air travel

4.1. Fundamental properties of hydrogen gas

There are certain distinctive characteristics that hydrogen possesses. The key properties of hydrogen are listed below, with the primary concepts compiled in Table 3.

Hydrogen is often characterized based on two standard reference conditions: Normal Temperature and Pressure (NTP), defined as 1 bar and 293 K, and Standard Temperature and Pressure (STP), typically set at 1 atm and 273.15 K. At these conditions, hydrogen is recognized as the least dense element, with an average density of approximately 0.08345 kg/m^3 at NTP and 0.08990 kg/m^3 at STP, which corresponds to just about 7 % of the bulk density of ambient air [57]. The energy potential of hydrogen is generally expressed through two metrics—volumetric energy density (energy per unit volume) and gravimetric energy density (energy per unit mass). Hydrogen's unique chemical composition, devoid of carbon atoms, distinguishes it from other fuel gases. It also exhibits the highest thermal conductivity among gases and, when combusted with oxygen, reaches flame temperatures as high as 2834 °C. Furthermore, hydrogen has a low calorific value (LCV) of 120 MJ/kg, equivalent to 33.3 kWh/kg or approximately 2.9 kWh per cubic meter. In terms of molecular structure, hydrogen exists as ortho- and para-isomers, differentiated by the spin orientation of the two protons. Ortho-hydrogen has parallel spins, while para-hydrogen has antiparallel spins, resulting in slightly different physical properties. At STP, hydrogen gas (referred to as "normal hydrogen") comprises roughly 75 % ortho-hydrogen and 25 % para-hydrogen. Since para-hydrogen is in a lower energy state, additional energy is required during the liquefaction process to convert ortho-into para-hydrogen, further influencing storage and handling considerations [57,58].

4.2. Pathway for production

The production of hydrogen can follow various technological pathways, each with distinct feedstocks, energy inputs, efficiencies, environmental footprints, and cost implications. The most prominent methods are broadly categorized based on their carbon intensity and source of energy, namely grey, blue, and green hydrogen. Grey

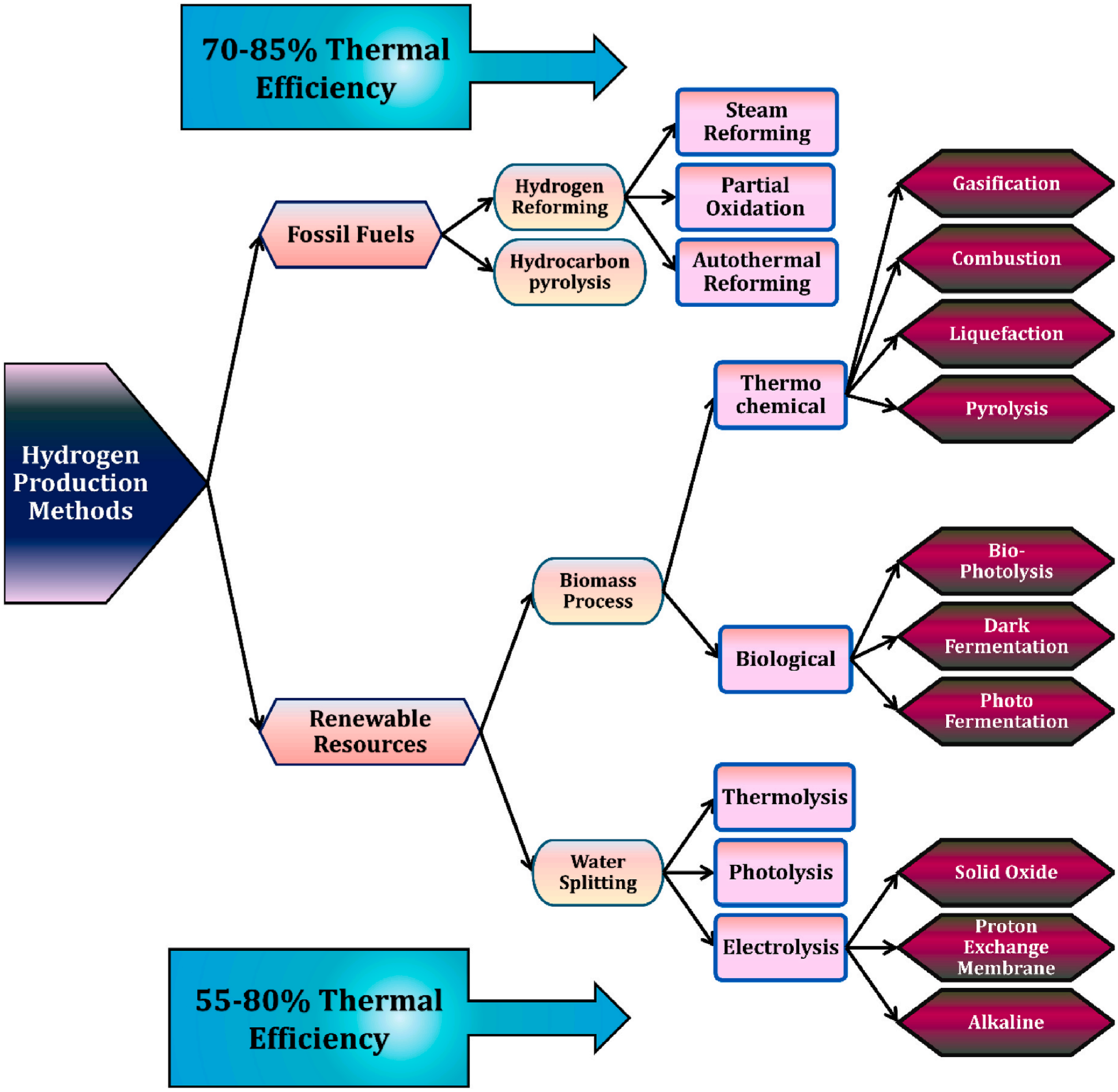

Fig. 2. Energy-Efficient methods for producing sustainable hydrogen [59].

hydrogen is conventionally produced via steam methane reforming (SMR) of natural gas, which emits significant CO_2. In contrast, blue hydrogen follows a similar pathway but integrates carbon capture, utilization, and storage (CCUS) technologies to reduce emissions. Green hydrogen is produced by electrolyzing water using renewable electricity, offering a zero-emission solution when powered by solar, wind, hydroelectric, or geothermal energy.

Electrolysis technologies include alkaline electrolysis (AEL), proton exchange membrane (PEM) electrolysis, and solid oxide electrolysis (SOEC). AEL is mature and cost-effective but less dynamic. PEM offers higher efficiency and faster response times, making it suitable for variable renewable energy inputs, though it remains more expensive. SOEC, still in development, operates at high temperatures and can achieve high efficiencies when integrated with industrial heat sources [14].

In addition to water electrolysis, thermochemical and photochemical methods are being investigated, such as solar thermolysis, photoelectrochemical water splitting, and biological pathways using microalgae or cyanobacteria. These processes aim to harness sunlight or biological activity to split water into hydrogen and oxygen, though they remain in early stages of development.

Biomass gasification and biomethane reforming are alternative renewable methods for hydrogen production, enabling waste valorization and circular economy integration. Plasma reforming and microwave-assisted reforming are emerging methods showing potential for high efficiency and low emissions.

Once produced, hydrogen must be safely conveyed and stored. Liquefaction and compression are common transport methods, though they require significant energy input and pose technical challenges. Innovative storage technologies such as metal hydrides, complex hydrides, liquid organic hydrogen carriers (LOHCs), and cryogenic tanks are being developed to enhance storage density and safety [14].

From an economic perspective, the cost of hydrogen production varies significantly. Grey hydrogen is currently the cheapest ($1–2/kg), while blue hydrogen adds a premium for carbon capture ($1.5–2.5/kg), and green hydrogen is more expensive (~$3–6/kg), depending on renewable electricity prices and electrolyzer efficiency. However, green hydrogen is expected to become cost-competitive by 2030 with the expansion of renewable capacity and technological advancements.

Moreover, policy support—such as tax incentives, renewable energy mandates, and carbon pricing—is crucial to scaling up clean hydrogen production. The implementation of hydrogen hubs, public-private partnerships, and international collaborations is accelerating the development of hydrogen infrastructure worldwide.

Overall, a diversified mix of hydrogen production technologies (Fig. 2) is essential to meet global decarbonization goals. The integration of hydrogen into energy systems requires not only technological innovation but also supportive regulatory frameworks, investment in infrastructure, and international cooperation to ensure long-term sustainability and affordability.

Cost competitiveness is one of the primary obstacles facing the generation of hydrogen. The goal of the Hydrogen and Fuel- Cell Technologies Office of the US Ministry of Energy is to develop production technologies in order to reach the cost targets of $1 per kilogram by 2030 and $2 per kilogram by 2025, through carbon-neutral approaches. In the long term, clean hydrogen offers a promising solution for large-scale energy storage and the global distribution of renewable energy [60,61].

4.3. Hydrogen in aviation: prospects and barriers

Hydrogen presents both significant hurdles and promising prospects for application in the aviation sector, as outlined below [62]. On the one hand, hydrogen offers a transformative opportunity to drastically reduce greenhouse gas emissions in aviation, either through its direct use in combustion turbines or via fuel cells in electric propulsion systems. Green hydrogen, produced using renewable energy through water electrolysis, emits no carbon dioxide during use and can potentially enable zero-emission flight. Moreover, hydrogen's adaptability allows for multiple configurations in aviation—ranging from hybrid electric-hydrogen systems to its integration into synthetic aviation fuels, enhancing fuel flexibility and decarbonization pathways. The aviation sector may also benefit from pushing beyond the existing 50 % blending cap on Sustainable Aviation Fuels (SAFs), enabling a higher share of clean fuels in the short term. Further, advancements in cryogenic storage, aircraft aerodynamics, and fuel cell technology are steadily addressing key technical limitations, while industry initiatives—such as Airbus's ZEROe concepts and various hydrogen-powered regional aircraft prototypes—demonstrate growing momentum in R&D and policy support.

4.3.1. Challenges in the adoption of hydrogen and electric aviation

The transition toward hydrogen and electric aviation presents several critical challenges that must be addressed to enable large-scale adoption. Battery-powered aircraft, while promising for short-haul routes, currently suffer from limited energy density, restricting their use to short-distance flights with light payloads—rendering them impractical for long-haul or high-capacity operations. Hydrogen, despite its high gravimetric energy density, poses significant volumetric challenges; cryogenic hydrogen requires much more storage space than conventional jet fuel, complicating integration within standard aircraft designs. Additionally, aircraft designed with novel configurations to accommodate hydrogen propulsion must undergo lengthy and complex certification processes, which can delay deployment. The replacement of existing aircraft fleets with hydrogen-compatible models also depends heavily on the economic and logistical feasibility for airlines. Moreover, transitioning to hydrogen or electric propulsion demands extensive and systemic changes across the aviation ecosystem, including modifications to manufacturing processes, aircraft design protocols, airport infrastructure, maintenance practices, and regulatory frameworks. These multifaceted challenges highlight the need for coordinated global efforts, sustained investment, and technological innovation to facilitate a viable shift to zero-emission aviation [63].

4.3.2. Opportunities for green hydrogen integration in aviation

The transition to hydrogen-based aviation presents several compelling opportunities that could redefine the environmental footprint of the sector. One of the most significant advantages lies in hydrogen's versatility: it can be used directly in combustion engines or integrated into fuel cells to power electric propulsion systems, offering multiple pathways for cleaner aviation. Additionally, hydrogen can be incorporated into the production of synthetic aviation fuels, contributing to the development of drop-in alternatives that reduce reliance on fossil-based jet fuels. Emerging aircraft designs may also adopt hybrid propulsion systems, combining electric motors with conventional combustion engines to enhance energy efficiency and reduce emissions, especially during low-demand flight phases such as taxiing and landing. Furthermore, there is potential to exceed the current 50 % blending limit of sustainable aviation fuels (SAF) in jet engines, paving the way for higher proportions of cleaner fuels and accelerating the decarbonization of existing fleets. Most notably, the use of green hydrogen, produced via renewable-powered electrolysis, offers the potential to eliminate CO_2 emissions entirely at the point of use. However, it is important to note that hydrogen combustion still produces water vapor, which at high altitudes can lead to contrail formation—a phenomenon that contributes to radiative forcing and climate warming. Therefore, while green hydrogen represents a transformative opportunity for aviation sustainability, its deployment must be accompanied by further research into non-CO_2 climate effects, aircraft design optimization, and policy frameworks that promote lifecycle emission reductions [64].

4.4. The role of hydrogen in decarbonizing aviation

Hydrogen is recognized for its unique characteristics that position it as a key element in the global shift toward cleaner energy. It holds potential advantages across both the energy supply chain and final consumption, particularly in sectors with high emissions [65]. Aviation especially long-distance air travel is among the most challenging sectors to decarbonize. While battery-powered solutions may become viable for short-to medium-range flights in the coming years, long-haul routes are more likely to rely on sustainable alternatives like biofuels and synthetic aviation fuels (SAFs) [66,67]. These substitutes closely mimic the properties of conventional jet fuel, allowing for blending with kerosene and use within current fuelling systems without the need for major modifications [68]. Although hydrogen raises concern due to its flammability and high reactivity, these risks can be mitigated through robust safety protocols [69]. Despite persistent hurdles such as technological readiness, storage challenges, limited infrastructure, and cost some aerospace companies still view hydrogen as a future-ready fuel option. However, key limitations include: i. The necessity to store hydrogen in liquid form, which requires complex and heavy cryogenic systems.; ii. Comparing with conventional aviation fuels, liquid hydrogen has a comparatively low volumetric energy density, which is a significant drawback in aviation where space and weight are critical, particularly during take-off [70].

4.4.1. Electrolysis as a key technology for hydrogen generation

When there is an excess of electricity generation, electrolysis can be employed to transform this surplus energy into hydrogen. This hydrogen can then serve as a reserve energy source during grid failures or be utilized across various sectors, including transportation, industrial processes, and household applications. In this way, surplus power is effectively harnessed rather than wasted [71].

4.4.2. Extended energy storage using hydrogen

It is apparent that hydrogen is the best option for long-term, emission-free cyclic energy storage [72]. While technologies like batteries, supercapacitors, and compressed air systems can support short-term energy balancing, they fall short in terms of storage capacity and duration necessary for addressing seasonal or prolonged supply-demand mismatches [73]. In contrast, hydrogen-based systems, particularly those involving hydrogen generation and reconversion through power-to-gas and gas-to-power pathways, offer a viable and scalable method for extended energy storage [74].

Table 4
Airports actively distributing sustainable aviation fuels [87,88].

S. No	Airport	Location	Annual SAF Volume/ Adoption Target	Type of SAF Used
1	San Francisco International Airport	San Francisco, USA	Target: 5 % SAF by 2025	HEFA (Hydroprocessed Esters and Fatty Acids)
2	Los Angeles International Airport	Los Angeles, USA	Airline-specific usage (United, Delta began SAF flights in 2024)	HEFA, ATJ-SPK (Alcohol-to-Jet Synthetic Paraffin)
3	Oslo Airport (Gardermoen)	Oslo, Norway	Mandated 0.5 % SAF blending since 2020	HEFA
4	Stockholm Arlanda Airport	Stockholm, Sweden	National target: 30 % SAF by 2030	HEFA
5	Amsterdam Schiphol Airport	Amsterdam, Netherlands	KLM operates SAF flights; target 14 % by 2030	HEFA, FT-SPK (Fischer–Tropsch Synthetic Paraffin)
6	London Heathrow Airport	London, UK	70 kt used in 2023; targets: 155 kt (2024), 187 kt (2025), 11 % by 2030	HEFA
7	Frankfurt Airport	Frankfurt, Germany	Lufthansa operates SAF flights; part of EU ReFuel Aviation goals	HEFA
8	Zurich Airport	Zurich, Switzerland	SAF supply available on request; Swiss mandates expected	HEFA
9	Paris Charles de Gaulle Airport	Paris, France	SAF use encouraged; part of France's national plan for 2 % SAF in 2025	HEFA
10	Tokyo Haneda Airport	Tokyo, Japan	Japan aims for 10 % SAF use by 2030	HEFA, ATJ-SPK
11	Singapore Changi Airport	Singapore	SAF launched in 2023 in partnership with Neste and Shell	HEFA (from used cooking oil & animal fats)
12	Brisbane Airport	Brisbane, Australia	Qantas and Virgin use SAF in some flights	HEFA
13	Rotterdam The Hague Airport	Rotterdam, Netherlands	Home to Europe's first SAF plant by SkyNRG; supplies regional airports	HEFA
14	Helsinki Airport	Helsinki, Finland	Finnair uses Neste SAF blends; Finland targets 30 % SAF by 2030	HEFA

4.4.3. *Buffer systems for enhanced operational resilience*

Hydrogen's versatility to respond to shifting power demands could improve worldwide conservation of energy. Its versatility, long-term storage potential, and high energy density across sectors make it a strong candidate for serving as both an energy reservoir and a backup source [75]. At present, global energy systems maintain a backup reserve of approximately 90 EJ—equivalent to about 24 % of total annual energy consumption—most of which is still stored in fossil-based fuels. Looking ahead, there is little indication that the need for such large-scale energy buffering will diminish significantly [76,77].

4.4.4. *Green mobility: reducing emissions from vehicles*

Fuel cell electric vehicles (FCEVs) play a vital role in reducing carbon footprints. At present, the transportation sector is heavily reliant on oil-based fuels, with gasoline and diesel making up nearly 96 % of the total fuel consumption for vehicles worldwide. These conventional fuels are responsible for about 21 % of the world's fossil fuel-related greenhouse gas emissions [70–80]

5. Greening airports and aviation: sustainable approaches

5.1. *Renewable energy solutions in modern airports*

The significant drop in prices combined with generous subsidies has made large-scale renewable energy projects, particularly solar power, highly attractive options for development [81]. These systems enable airports to secure stable electricity costs for periods of 25–30 years, helping to reduce uncertainties in long-term financial planning [82]. Additionally, these installations can generate revenue through lease agreements and supply airports with clean, carbon-free energy. Airports may profit economically from green energy without making large upfront capital commitments in response to innovative financing techniques via power purchase agreements [83]. Third-party ownership models also help by eliminating maintenance expenses and enabling airports to capitalize on tax incentives that are set to expire soon. Furthermore, advancements include more fuel-efficient aircraft producing fewer emissions, efforts to reduce aircraft weight to lower fuel consumption, and significant progress in increasing the availability of high-quality biofuels [84]. The Inflation Reduction Act of 2022 (IRA) supports clean energy growth through acclaims for taxes and additional policies designed to boost domestic renewable energy production [85]. The following tax credit schemes are extended, improved, or created as part of this law to increase and introduce federal incentives towards sustainable hydrogen and fuel-cell technologies [86].

The United States has implemented a broad array of federal tax incentives and credits to stimulate clean energy development and decarbonization efforts across various sectors. The Advanced Energy Project Tax Incentive, established under Section 48C of the Internal Revenue Code (IRC), has been extended to support investments in clean energy manufacturing. Similarly, the Credit for Installation of Alternative Fuel Refueling Stations under Section 30C continues to promote infrastructure for alternative fuels, including hydrogen and electric vehicle charging. The Tax Credit for Carbon Capture and Storage Technologies, extended under Section 45Q, provides financial incentives for facilities that capture and store carbon dioxide emissions. A key new provision is the Clean Hydrogen Production Incentive, introduced under Section 45V, which specifically encourages the production of low-emission hydrogen. In the transportation sector, the Clean Vehicle Tax Benefit under Section 30D supports the purchase of zero-emission vehicles, while Section 45W offers a new credit for specified commercial clean vehicles. Additionally, the legislation includes the Option for Elective Payment on Energy-Related Property, giving eligible entities a direct pay option for qualifying energy projects. Investments in renewable energy continue to be supported through the extended Renewable Energy Investment Credit (Section 48), which now also includes a new credit for energy storage systems, further broadening the scope of support for grid resiliency and sustainable energy solutions.

5.2. *Reducing aviation emissions with sustainable aviation fuel (SAF)*

SAFs derived from diverse biomass sources have the potential to earn carbon credits while substantially reducing emissions of ozone-depleting substances, thereby enhancing the sustainability of the aviation industry, as outlined in Table 4. [87]. Classified as carbon-neutral, SAFs can lower nearly 80 % of the greenhouse gas emissions associated with traditional jet fuel when bio-jet fuels are used as a replacement [89]. The economic viability of flying sustainably offers significant

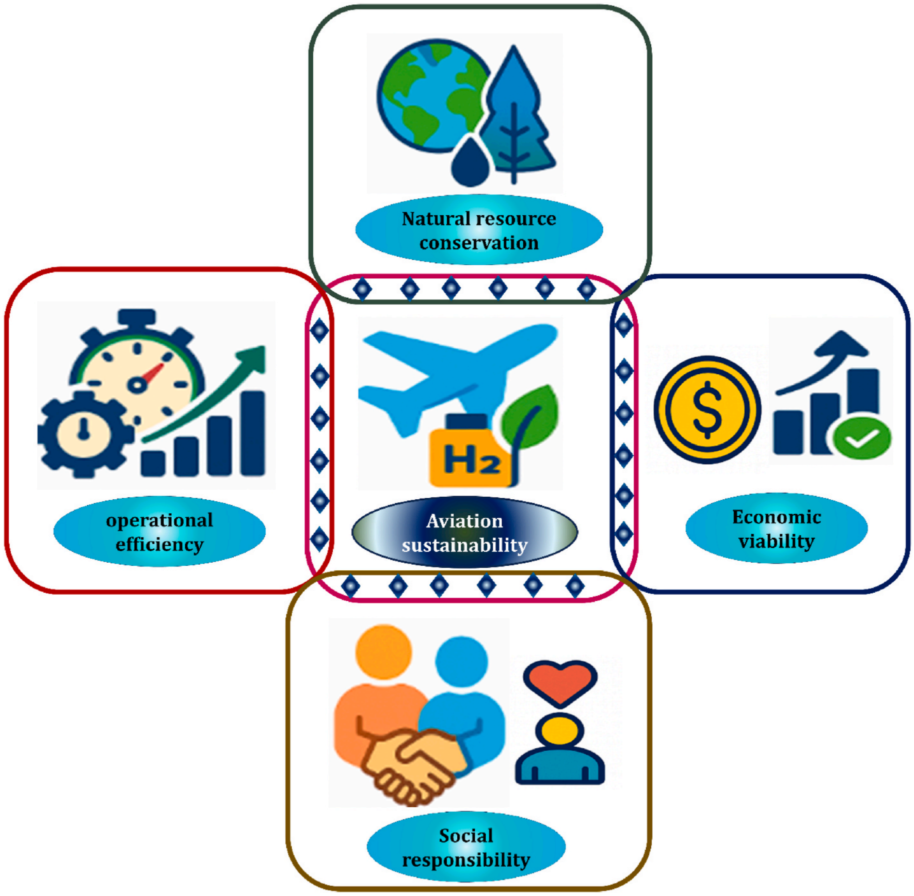

Fig. 3. Environmental strategies for sustainable airports [106].

opportunities for greenhouse gas reduction and carbon market growth within aviation [90]. However, the current higher cost of SAF compared to conventional jet fuel remains a significant barrier to its widespread implementation [91]. Despite this, SAF is poised to become a crucial component in the future of environmentally friendly aviation. The production of future-generation aviation biofuels from animal fats, used cooking oils, municipal solid waste, and agricultural waste has enormous potential. It is anticipated that sustainable fuels will be essential to significantly lowering carbon footprints in the aviation industry by 2050 [92–94].

5.3. CDM and CERs: tools for global emission reduction

Airlines have significant potential to earn carbon emission reductions (CER) through clean development mechanism initiatives, which will contribute to making the aviation industry more sustainable. The sector presents numerous possibilities for reducing carbon footprints by utilizing green carbon credit programs. Although many international airports have already reached carbon-neutral status, achieving substantial emissions reductions for aircraft remains a vast and intricate challenge [95].

5.3.1. Innovative approaches

Innovative aircraft designs, energy conservation, hydrogen fuel cell engineering, electronic mobility, and sustainable aviation fuels are merely a few of the innovative projects that have emerged from this are included [96]. The outlined approach indicates that the ambitious shift toward Sustainable Aviation Fuels (SAF) can be supported by utilizing a wide range of feedstocks and waste materials sourced from various regions [97]. This diversification has the potential to stimulate job creation, develop local supply chains, and foster a resilient and green economy [98]. Implementing customized subsidies to encourage the growth of a robust and competitive sustainable aviation fuel (SAF) sector offers multiple long-term benefits. Chief among these are the potential for significant employment growth, substantial contributions to climate change mitigation, and the development of more resilient and efficient global transportation networks. These advantages align with broader sustainability goals and are supported by complementary initiatives currently gaining traction across the aviation industry. For instance, many airlines are actively working to phase out single-use plastics in favor of recyclable alternatives, minimize food waste generated during flights, and promote the use of sustainably sourced ingredients in on-board catering. Together, these efforts underscore a growing commitment to holistic sustainability practices within the aviation sector [99].

Hydrogen has emerged as a promising alternative fuel in the aviation sector due to its high specific energy and potential for zero carbon emissions at the point of use. Leading aerospace companies are actively developing hydrogen-powered aircraft, exploring both fuel cell-based and hydrogen combustion technologies. A prominent example is Airbus's ZEROe program, which introduces three conceptual hydrogen-powered aircraft designs: a turboprop, a turbofan, and a blended-wing body configuration. These concepts aim to carry between 100 and 200 passengers over ranges exceeding 1000 nautical miles, with a targeted entry into service by 2035 [100]. In parallel, companies such as ZeroAvia have demonstrated practical progress with successful test flights of hydrogen-electric propulsion systems, including a six-seat Piper Malibu and a 19-seat Dornier 228 aircraft, marking significant milestones in regional hydrogen aviation [101]. While these developments highlight the feasibility of hydrogen in aviation, considerable challenges remain, particularly in the areas of storage, refueling infrastructure, and the energy-intensive process of hydrogen liquefaction. Nonetheless, the

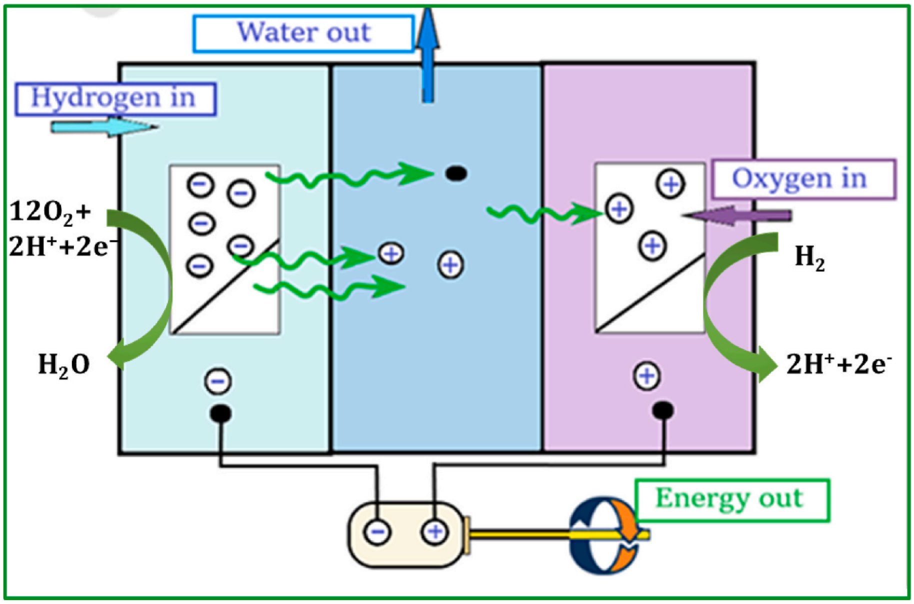

Fig. 4. Hydrogen fuel cell reactions and their by-products [115].

ongoing investments and pilot projects underscore the growing commitment of the aviation industry to decarbonize through hydrogen technologies [102].

5.3.2. Sustainable practices and strategies

Sustainability must be seamlessly incorporated into all phases of airport development, including planning, design, construction, and daily operations. Achieving lasting sustainability requires a holistic strategy that balances economic viability with operational realities unique to airports [103]. Efforts should focus on lowering demand and optimizing supply chains by selecting materials with minimal environmental footprints. Additionally, innovative approaches to waste management and procurement are essential for maintaining sustainable systems over the long term. For instance, airlines can help reduce waste and support local communities by donating unsold perishable goods to charities or healthcare providers [104,105]. This practice of food donation exemplifies effective sustainability measures. Furthermore, adopting emerging technologies enhances consumer health, safety, sanitation, and overall well-being, as illustrated in Fig. 3.

6. Hydrogen technological advancement applications in the aviation field

Hydrogen-powered aviation has garnered a lot of interest lately due to its promising role in reducing carbon emissions and mitigating the environmental impact of air travel [107]. Decarbonizing the aviation sector remains one of the most pressing challenges faced by society today [108]. The French government, for example, has pledged approximately 1.5 billion euros to help the aviation sector create zero-carbon aviation by 2035. In 2019, aviation accounted for about 2–3 % of all globally generated carbon footprints, and as air traffic continues to grow, the demand for eco-friendly aircraft will intensify [109].

Hydrogen can be utilized to power airplanes either through fuel cells, which generate electricity via electrochemical reactions, or by combusting hydrogen in traditional engines. Fuel cells operate by combining hydrogen fuel with an oxidizer to produce electricity, with water and heat as the only by-products [110]. Although similar in design to batteries, fuel cells do not require recharging and can operate continuously as long as fuel is supplied. Since hydrogen energy conversion in fuel cells involves no combustion, this process is notably quiet, clean, and efficient [111]. Depending on the energy demands, hydrogen combustion is suited for medium to long-haul flights, while hydrogen fuel cells are more appropriate for short-haul routes. Both technologies result in zero emissions of nitrogen oxides and carbon dioxide. Furthermore, burning hydrogen reduces soot emissions significantly; with hydrogen fuel cell-powered aircraft, soot emissions can be eliminated entirely [112,113].

6.1. Benefits of fuel cell technology in aviation sector

One major benefit of using hydrogen in aircraft is the elimination of harmful emissions, as hydrogen combustion produces only water vapor, thereby safeguarding the environment and meeting air quality regulations [114]. Unlike conventional fuels, hydrogen burns cleanly without releasing pollutants, as illustrated in Fig. 4. While other fuels such as jet fuel can be processed to generate hydrogen for fuel cells, this requires a reforming step where the fuel is chemically converted into hydrogen gas. Although this reforming process may generate some emissions, they are significantly lower than those produced by traditional combustion engines [116]. The level of emissions generated by fuel cells depends largely on three aspects: the type of fuel cell used, the reforming technology, and the original fuel source. For example, reforming hydrocarbons to obtain hydrogen-rich gas can produce minor quantities of by-products such as hydrogen sulfide, carbon dioxide, carbon monoxide, and small amounts of hydrocarbons (alkynes, alkenes, methane), which remain contained within the reformer and are removed during routine maintenance [117,118].

Anode Reaction (Oxidation):

At the anode, hydrogen gas is split into protons and electrons.

$$H_2 \rightarrow 2H^+ + 2e^-$$

Cathode Reaction (Reduction):

At the cathode, oxygen gas combines with the protons (from the anode) and electrons (via external circuit) to form water.

$$12O_2 + 2H^+ + 2e^- \rightarrow H_2O$$

Overall Cell Reaction:

$$H_2 + 12O_2 \rightarrow H_2O + \text{Electricity} + \text{Heat}$$

Another advantage of fuel cells is their quiet operation, which is

Fig. 5. Three core concerns for hydrogen Integration in aviation [124].

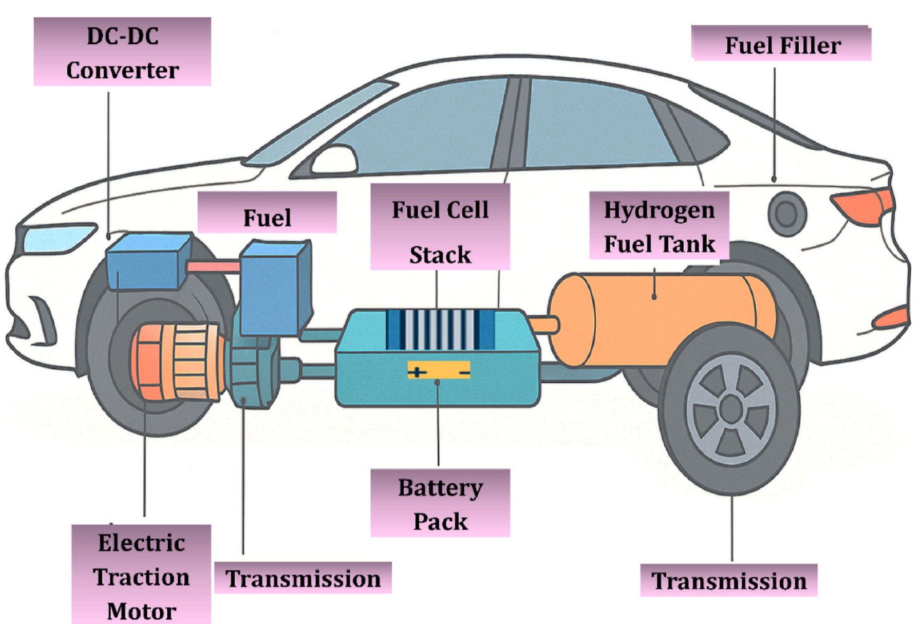

Fig. 6. Revolutionizing transport with hydrogen fuel [133].

especially beneficial for reducing noise pollution on the ground, such as for airport auxiliary power units. Furthermore, fuel cells offer superior energy density and efficiency [119]. Liquid hydrogen has around three times as much energy as diesel fuel on a weight basis. This high gravimetric energy density means fuel cells can generate more power per unit of fuel compared to other energy sources. Consequently, fuel cells convert fuel into useable energy more efficiently, resulting in greater energy output per pound of fuel [120].

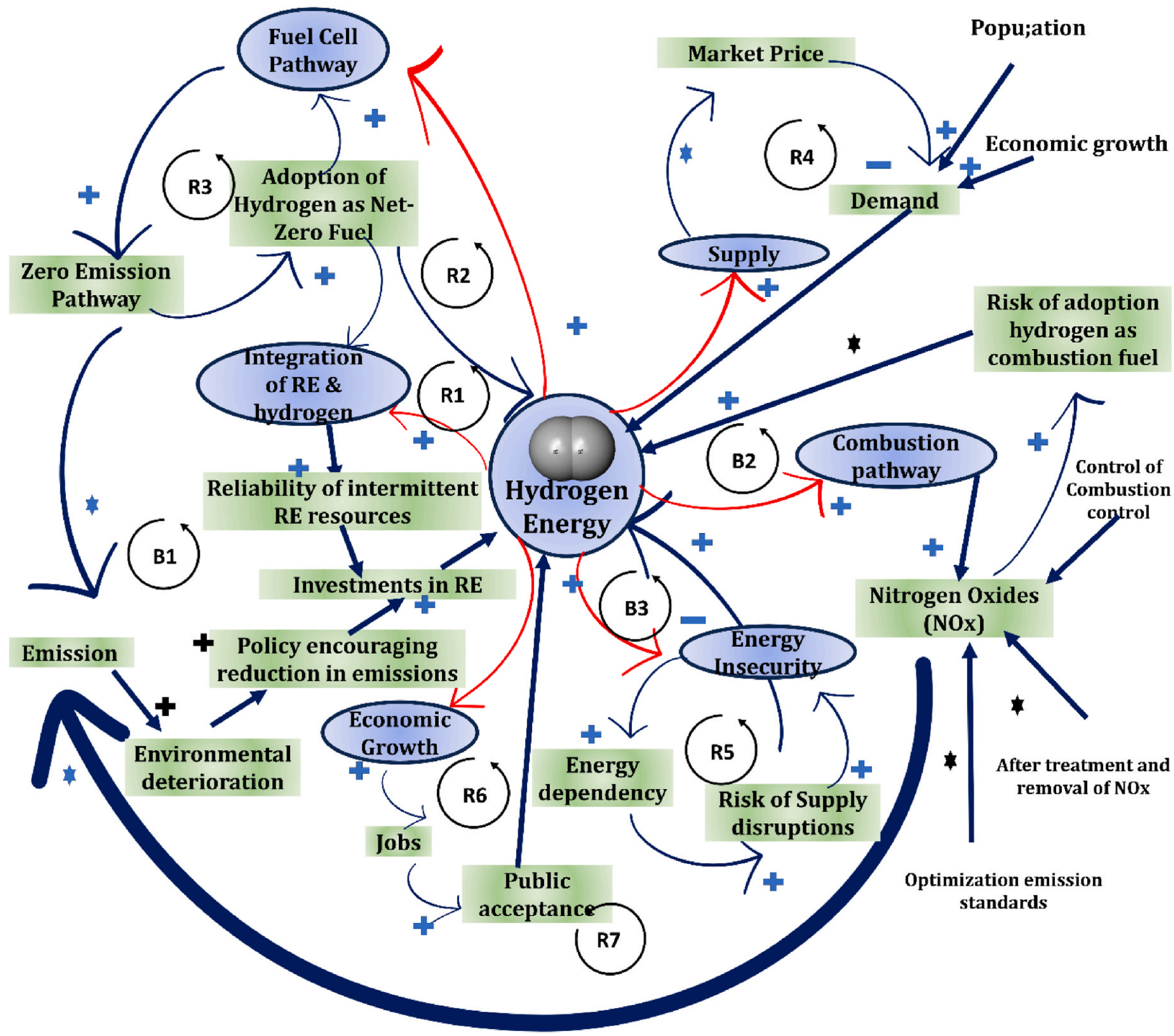

Fig. 7. Hydrogen energy density: A comparative analysis [139].

6.2. Technical and infrastructural challenges of hydrogen-powered flight

Hydrogen extraction typically involves either splitting water through electrolysis or isolating it from fossil-based carbon fuels. Both methods demand a significant amount of energy, which can sometimes exceed the energy obtained from the hydrogen itself, leading to high operational costs. Moreover, substantial investment is needed to advance hydrogen fuel cell technology before it becomes a commercially viable energy option. A key global challenge lies in identifying the most efficient strategy to steadily grow both the supply and demand chains for hydrogen, while keeping costs manageable [121]. The production of fuel cells requires precious metals like iridium and platinum as catalysts, along with specialized water electrolyzers, which significantly raise initial expenses. Due to these high costs, many investors remain hesitant to fund fuel cell development [122]. Reducing these expenses is essential to make hydrogen fuel cells a practical energy solution for aviation. Storage also presents difficulties; for example, liquid hydrogen has roughly one-quarter the energy density of conventional jet fuel, necessitating storage tanks approximately four-fold larger [123]. The three primary issues underlying the utilization of hydrogen are portrayed in Fig. 5. In modern times, producing hydrogen, particularly from renewable resources, is expensive to execute and safeguarding it needs either extremely intense pressure or exceptionally cold temperatures, resulting in raises the complexity and expenses [125]. The largest barriers to the widespread use of hydrogen are aforementioned high manufacturing and logistics costs. Grey hydrogen, which comes through fossil fuels, is less expensive, but it is not environmentally sustainable because it emits a lot of carbon dioxide [126]. In contrast, green hydrogen, generated from renewable energy sources, is emission-free but remains expensive due to high electricity costs. The storage requirements, whether involving pressurized tanks or cryogenic cooling, add further financial and technical burdens [127].

6.3. Flying into the future with hydrogen

Conventional aircraft rely on kerosene fuel, which releases carbon dioxide and other pollutants into the atmosphere. Hydrogen is gaining attention as a promising alternative fuel for aviation since it produces no harmful emissions when burned. Experimental trials are currently underway to evaluate hydrogen's viability for powering airplanes [128]. Early results suggest that hydrogen-fueled aircraft can achieve speeds comparable to traditional planes while carrying over a hundred passengers on long-distance flights. Commercial aircraft that run on hydrogen are expected to be available by 2035. Despite a number of obstacles that still need to be overcome, doing so might allow the aviation industry to drastically lessen its environmental effect and contribute greatly to international efforts to decarbonize [129].

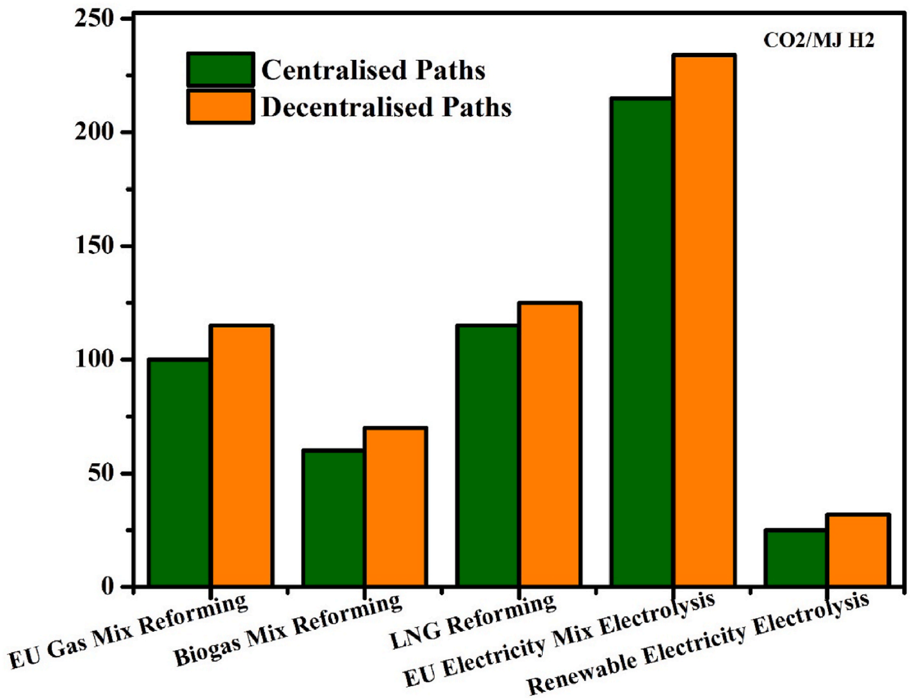

Fig. 8. Environmental impact of liquid hydrogen production [142].

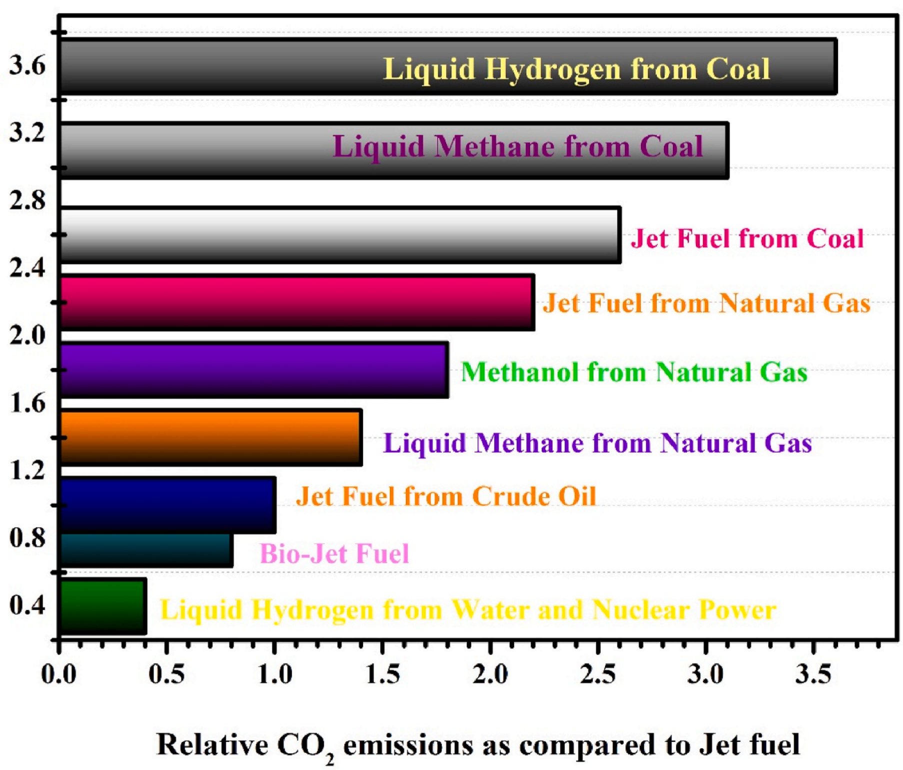

Fig. 9. CO_2 Emission comparison between hydrogen and jet fuels [145].

7. Hydrogen integration in the automotive sector

Instead of depending just on battery power, hydrogen-powered fuel cells provide electricity in hydrogen-powered automobiles (U.S. Ministry of Energy, n.d.). These vehicles power their electric motors using a hybrid system that combines batteries and fuel cells. The battery's role is to recover energy during braking, provide extra power during brief acceleration, and stabilize the output from the fuel cell by allowing it to idle or shut down when only low power is needed [130,131]. During operation, hydrogen and oxygen react to produce electricity and water vapor as a harmless by-product. The vehicle's movement depends on the scale of this chemical reaction. The size of the hydrogen storage tank

Table 5
Design and performance challenges of aircraft fueled by liquid hydrogen.

S. No	Aspect	Details
	Properties	
1.	Energy Density (Volumetric)	~8.5 MJ/L (much lower than Jet-A fuel ~35 MJ/L) due to low density (~70 kg/m^3 at LH_2 state)
2.	Energy Density (Gravimetric)	~120 MJ/kg (about 2.75x higher than Jet-A fuel ~43 MJ/kg)
3.	State at Storage	Cryogenic liquid at ~ −253 °C (20 K)
4.	Storage Requirements	Requires insulated, vacuum-jacketed tanks to maintain cryogenic temperature
5.	Density	Very low density (~1/14th of gasoline) causing larger storage volume
6.	Combustion Properties	High flame speed, wide flammability range, no carbon emissions
7.	Boil-off Rate	Continuous boil-off losses due to heat leak; needs venting or utilization system
	Benefits	
1.	High Specific Energy	Enables potentially longer flight ranges per unit mass of fuel
2.	Zero Carbon Emissions	Burning hydrogen produces only water vapor, drastically reducing CO2 and particulate emissions
3.	Reduced NOx Potential	Lower combustion temperatures possible with proper design, reducing nitrogen oxide emissions
4.	Lightweight Fuel	Potential for weight savings in fuel for equivalent energy compared to conventional fuels
5.	Renewable Production	Can be produced via electrolysis using renewable energy, enabling sustainable fuel cycle
6.	Enhanced Efficiency	Potential for high thermal efficiency in advanced engines tailored for hydrogen
7.	Safety in Use	Non-toxic, non-corrosive, and rises quickly if leaked, reducing ground hazard zones
	Downsides	
1.	Storage Volume	Large tank volume needed due to low volumetric energy density, impacting aircraft design
2.	Cryogenic Handling	Requires complex, heavy insulation systems to maintain cryogenic temperatures
3.	Tank Weight	Insulated LH_2 tanks are heavier and bulkier compared to conventional fuel tanks
4.	Infrastructure Needs	Requires new refueling infrastructure, including cryogenic fuel systems at airports
5.	Fuel Boil-off Losses	Continuous fuel loss due to boil-off during ground storage and flight
6.	Materials Challenges	Hydrogen embrittlement risks require special materials for tanks and piping
7.	Safety Risks	High flammability and wide flammability limits pose explosion risk if leaked or mishandled
8.	Design Complexity	Aircraft needs redesign for tank placement, insulation, and fuel delivery systems
9.	Range and Payload	Large fuel volume tanks can reduce payload or require larger airframes
10.	Engine Adaptation	Existing jet engines need modifications or replacement by hydrogen-compatible engines
11.	Environmental Concerns	Water vapor emissions at high altitudes can contribute to contrail formation and climate effects

directly influences the amount of energy the vehicle can carry. Refueling hydrogen tanks is a process similar to filling up conventional petrol or diesel vehicles. In contrast, fully electric vehicles rely solely on the battery's ability to determine the supply of electricity and power [132]. A automobile that runs on hydrogen is shown in Fig. 6. The number of hydrogen refueling stations installed in France, the Netherlands, and Germany increased significantly in the first part of 2020; Germany even met its target of 100 stations. To meet future targets, such as Germany's aim of 400 stations by 2025, ongoing progress and greater vehicle adoption are essential [134].

7.1. Advantages of hydrogen fuel for automobile application

Hydrogen fuel cells in automotive applications demonstrate superior efficiency compared to other energy sources. Fuel cell vehicles convert approximately 40–60 percent of the hydrogen's energy into useable power, resulting in about a 50 percent reduction in fuel consumption.

Table 6
Comparison of Grey, Blue, and Green Hydrogen: Feedstock, production methods, costs, carbon emissions, infrastructure needs, technological maturity, and scalability [102,150,151].

Parameter	Grey Hydrogen	Blue Hydrogen	Green Hydrogen
Feedstock	Natural gas (methane)	Natural gas + CCS	Renewable electricity (water)
Production method	Steam methane reforming (SMR)	SMR + Carbon Capture & Storage (CCS)	Electrolysis using RES
Hydrogen production cost	\$1–2 per kg H_2	\$2–3 per kg H_2	\$4–6 per kg H_2 (dropping rapidly)
Carbon emissions	High (9–12 kg CO_2/kg H_2)	Low (1–3 kg CO_2/kg H_2)	Near zero
Infrastructure costs	Existing pipelines useable	Requires CCS infrastructure	Requires new RES + electrolyzer setup
Technology maturity	Mature	Moderate (developing CCS)	Emerging, improving rapidly
Scalability	High	Moderate to high	Currently limited, but improving

Another key benefit is the rapid refueling capability of hydrogen fuel cells, which significantly outperforms battery electric vehicles [135]. While electric cars typically require anywhere from 30 min to several hours to recharge, hydrogen fuel cell vehicles can be refuelled in under 5 min, providing convenience and flexibility comparable to traditional gasoline-powered cars. Additionally, hydrogen vehicles offer driving ranges similar to conventional fossil fuel vehicles, exceeding those of many electric vehicles. Moreover, hydrogen fuel cells maintain their performance even in cold climates, showing minimal impact from low temperatures, unlike battery electric vehicles whose efficiency can decline in such conditions [136].

7.2. Hydrogen-powered transport: challenges and constraints

A hydrogen-based economy depends on various storage solutions, including refueling stations, production facilities, national strategic reserves, and storage during vehicle integration. Effective hydrogen storage remains a significant obstacle to establishing a thriving hydrogen economy. Before developing a hydrogen transport network, it is crucial to implement reliable storage systems for hydrogen-powered vehicles [137]. Due to hydrogen's low density, transportation demands large storage tanks. Compressed tanks are the most commonly used physical storage option because of their availability. However, scaling up these tanks presents challenges, mainly due to the high costs of manufacturing the specialized materials required. Additionally, public safety concerns arise with the use of high-pressure tanks in vehicles, emphasizing the need for further research to enable widespread hydrogen storage adoption.

Furthermore, an improved logistics framework is essential to transport hydrogen efficiently from production sites to refueling stations. Among the modes of transportation are compressed gas pipelines, cryogenic fluid transport trucks, and CNG tube trailers. Moving hydrogen, whether as a pressurized gas or a liquid, is difficult because of its inherently low density. The financial investment necessary for building transportation infrastructure is considerable; for example, pipeline installation involves high capital expenditure, and liquefying hydrogen for shipping demands significant electrical energy, increasing operational costs [138].

8. Impact of hydrogen integration in aviation

8.1. Hydrogen as a strategic propellant for aviation

Despite being the most prevalent element in the cosmos, hydrogen is mostly found on Earth bound together in molecules such as water and

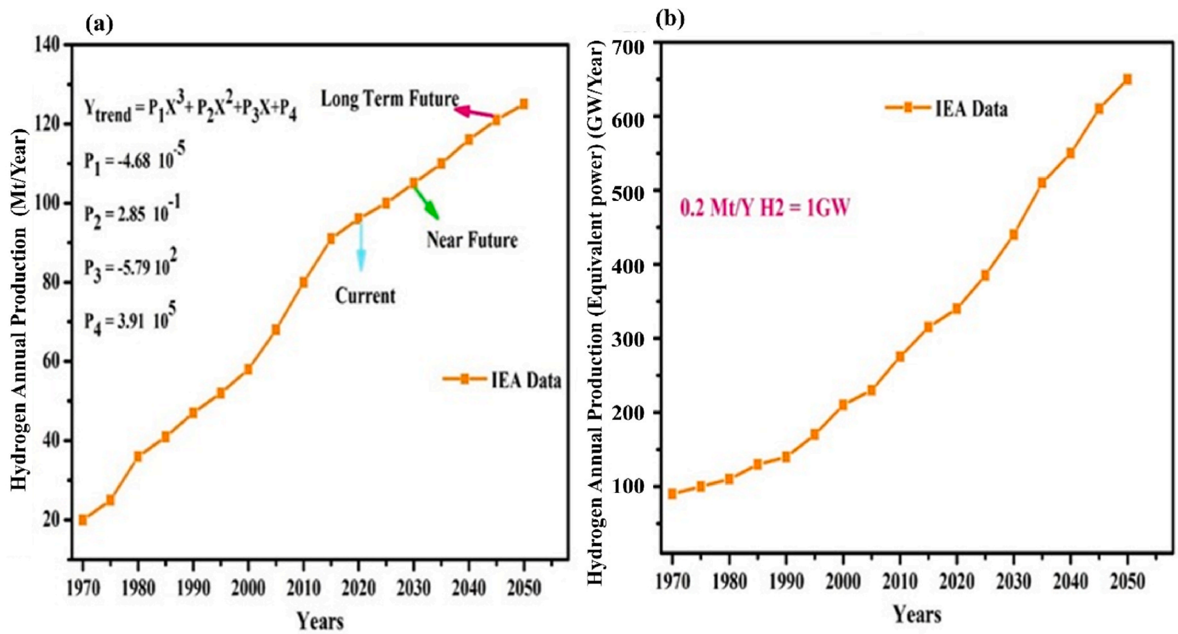

Fig. 10. International outlook on hydrogen production [152].

hydrocarbons, necessitating its extraction for practical applications. Hydrogen's appeal in aviation stems from its exceptionally high energy content per unit mass. However, as shown in Fig. 7, its impressive gravimetric energy density (around 120 MJ/kg) contrasts sharply with its low energy density by volume. Moreover, employing hydrogen as a fuel offers the possibility of eliminating carbon emissions entirely during operation, provided its full life cycle—from production to use—is sustainably managed [140,141].

When produced using renewable energy, liquid hydrogen demonstrates strong environmental advantages, releasing only minimal CO_2 emissions per unit of energy, as illustrated in Fig. 8. Furthermore, nitrogen oxide (NOx) emissions, which can occur even in the absence of particulate matter, unburned hydrocarbons, CO_2, or carbon monoxide, can be decreased by using liquid hydrogen to promote stable combustion under a variety of engine settings [143].

The generation of NOx is influenced linearly by the time the reaction zone remains active and exponentially by the flame temperature. The secret to reaching NOx levels that are on par with those of traditional jet fuels with the ideal carbon content is to comprehend these linkages [144]. Burning kerosene, methane, and hydrogen for the same energy output results in different CO_2 emissions, depicted in Fig. 9. Although hydrogen combustion primarily produces water vapor, the climatic impact of this vapor depends on how long it lingers at various altitudes, necessitating further study to accurately assess its greenhouse gas effects. From a materials perspective, hydrogen's use as a fuel raises concerns about embrittlement, which restricts the choice of construction materials. Additionally, cryogenic storage remains the only feasible option for aviation, presenting challenges such as the need for well-insulated fuel tanks. Despite these difficulties, on-board cryogenic hydrogen fuel can offer advantages in thermal management during flight [146].

Table 5 outlines the key advantages and disadvantages of utilizing liquid hydrogen as fuel for aircraft, especially in context of upcoming long-distance commercial hypersonic flights [147].

8.2. Ecological impacts of green, blue, and grey hydrogen

According to the International Energies Agency (IEA), green hydrogen is essential to establishing an ethical global energy system. A strategic framework for developing cost-effective and environmentally friendly hydrogen production can be outlined based on available resources, end-use applications, and technological approaches. Nowadays, fossil fuel-based innovations are employed to manufacture a significant proportion of hydrogen, commonly referred to as "grey" hydrogen, which results in substantial carbon dioxide emissions [148]. The use of Carbon Capture, Utilization, and Storage (CCUS) technologies to capture and recycle these emissions makes "blue" hydrogen, a cleaner alternative, feasible. The most environmentally friendly choice is "green" hydrogen, which comes from renewable energy sources and emits no carbon dioxide at all [149]. Table 6. Comparison of Grey, Blue, and Green Hydrogen: Feedstock, production methods, costs, carbon emissions, infrastructure needs, technological maturity, and scalability.

This section attempts to assess the main economic and environmental issues related to the generation of hydrogen using different feedstocks and process routes. Since the 1970s, the production of hydrogen has steadily increased worldwide, according to IEA data, currently exceeding 77 million tonnes annually, with projections indicating an increase of approximately 20 % by 2030 and up to 60 % by 2050 (see Fig. 10, left). Beyond serving as a clean fuel, hydrogen also acts as an efficient energy carrier. Its production capacity is often measured in gigawatts (GW), reflecting the thermal energy released upon combustion [153] (refer to Fig. 10, right).

Hydrogen production methods are broadly classified into two categories: Hydrogen extraction from hydrocarbons and 2. Water-based hydrogen production.

The first strategy makes use of coal and natural gas, although the methods used varies resulting in diverse environmental impacts [154]. Table .7 outlines key parameters for hydrogen production from hydrocarbon sources. For hydrogen derived from water, a variety of energy sources must be considered. While electrolysis systems can run on electricity from multiple sources, hydrogen can also be synthesized through thermochemical methods powered by advanced nuclear reactors. To comprehensively assess both the environmental and economic impacts, the origin of the electricity used must be analyzed in depth, especially when prioritizing renewable sources (see Table 8) [155].

Nowadays, alkaline electrolysis as well as PEM electrolysis are the two main electrolysis methods that control large-scale hydrogen generation. Rashid, Al Mesfer, Naseem, and Danish [156] compared these methods, outlining their respective strengths and limitations (Table 9). Although PEM systems are technologically promising due to their high

Table 7
Environmental impact of hydrogen production from coal and natural gas.

S. No	Aspect	Coal-Derived Hydrogen	Natural Gas-Derived Hydrogen
1.	Production Process	Coal gasification followed by water-gas shift reaction	Steam methane reforming (SMR) followed by water-gas shift reaction
2.	Carbon Intensity	Very high CO_2 emissions (~300–400 kg CO_2 per GJ hydrogen)	High CO_2 emissions but lower than coal (~200–250 kg CO_2 per GJ)
3.	CO_2 Emissions per kg H_2	~15–20 kg CO_2/kg H_2 without carbon capture	~9–12 kg CO_2/kg H_2 without carbon capture
4.	Air Pollutants	Significant SO_2, NOx, particulate matter emissions	Lower SO_2 and particulates, but NOx present
5.	Water Usage	High water consumption for gasification and cleaning	Moderate water use for steam methane reforming
6.	Methane Leakage Risk	Low methane leakage (coal feedstock)	Risk of methane leakage in natural gas extraction and transport
7.	Energy Efficiency	Low to moderate (45–60 %) due to energy intensive gasification	Moderate to high (60–75 %) in SMR
8.	Carbon Capture Potential	Carbon capture and storage (CCS) can reduce CO_2 emissions by 70–90 % but costly	CCS also effective (~60–90 % CO_2 reduction), more established
9.	Environmental Impact on Ecosystems	Mining impacts (habitat destruction, soil erosion, water pollution)	Extraction impacts (fracking risks, groundwater contamination)
10.	Fossil Fuel Dependency	Coal mining reliance, non-renewable, high environmental footprint	Natural gas reliance, still fossil fuel but cleaner than coal
11.	GHG Lifecycle Emissions	Very high total GHG emissions including mining and processing	High GHG but lower lifecycle emissions than coal
12.	Byproducts & Waste	Coal ash, slag, potential heavy metals pollution	Less solid waste, but natural gas processing waste possible
13.	Cost Implications	Generally lower production cost but high environmental externalities	Competitive cost, often cheaper than coal hydrogen
14.	Scalability & Infrastructure	Existing coal plants convertible but require retrofit for CCS	Mature technology with widespread infrastructure
15.	Use in Blue Hydrogen Context	Limited due to high emissions and capture costs	Commonly used in blue hydrogen production with CCS
16.	Policy and Regulatory Pressure	High pressure to phase out due to pollution and emissions	Increasing regulation due to methane and CO_2 emissions

efficiency and compact design, they require a larger upfront investment, primarily because of the specialized materials involved [157].

9. Utilizing hydrogen straightaway as airlines fuel

Although hydrogen's gravimetric energy density is about threefold larger than that of conventional jet fuel (HHV: 39.4 kWh/kg; LHV value: 33.3 kWh/kg), its volumetric energy density is still much lower. With a density of only 70.9 g/L along with a volumetric energy density of HHV: 2.8 kWh/L and LHV: 2.36 kWh/L, hydrogen in liquid form offers around 75 % significantly fewer volumetric energy density than energy sources composed of hydrocarbons [158]. When stored as compressed gas, hydrogen requires two to four times the volume of its liquid form, depending on the compression level (typically at 700 or 350 bar). Furthermore, high-pressure storage tanks are relatively heavy, with the stored hydrogen accounting for only 5–6 % of the tank's total weight. While compressed hydrogen has been tested in smaller aircraft, liquid

Table 8
Environmental impacts of hydrogen production via electrolysis.

S. No	Methods	Effect on the environment:	Effect on the economy:
1.	Hydrogen produced by electrolysis with fossil fuel electricity	Compared to hydrogen production methods like coal gasification and natural gas reforming, electrolysis using standard grid electricity can result in nearly double the environmental impact in terms of carbon emissions. When the electricity used for electrolysis is sourced from an average power grid, the associated emissions typically range between 10 and 25 kg of CO_2 per kilogram of hydrogen produced.	Electrolyzers producing hydrogen at 99.7–99.999 % purity (15 bar, 0.5–30 Nm^3/h) cost between €34,200 and €456,000. Hydrogen prices remain high—around €13/kg—due to low demand, especially in industry, and are much higher than for transport fuels. The main goal is to cut production costs to about €2/kg to compete with conventional fuels. Hydrogen production costs via electrolysis are mainly from electricity use and capital recovery. Operation and maintenance add 3–5 % annually. Variable costs depend on electricity prices and efficiency, while fixed costs cover the electrolyzer and related infrastructure. For a 480 kg/day system, capital recovery is about 1000 €/kW input power, excluding compression and dispensing costs.
2.	Hydrogen produced by electrolysis with nuclear power plant electricity	Thermochemical cycle technology is still in development, with few cycles proven at the lab scale. While nuclear reactors emit no CO_2 during operation, upstream activities like uranium mining, fuel processing, and plant construction consume energy—often from fossil fuels—leading to indirect emissions. High material demands (steel, concrete) also contribute. The primary environmental issue during operation is the production and long-term handling of radioactive waste.	The cost of producing hydrogen through thermochemical methods primarily depends on the capital investment for building the nuclear reactor, the efficiency of converting nuclear energy into hydrogen, and the infrastructure of the hydrogen production facility. Studies have shown that large-scale, integrated plants using gas-cooled nuclear reactors and advanced cycles like the Hybrid Sulfur process can potentially achieve hydrogen production costs as low as 2.10 €/kg or below.
3.	Hydrogen produced by electrolysis using wind-generated electricity	Producing hydrogen through electrolysis powered by wind energy is a promising zero-emission method. However, if electricity from the grid is used as a supplementary source, especially under hybrid operating conditions, more than 3 kg of CO_2 can be emitted for every kilogram of hydrogen produced.	Hydrogen production via water electrolysis using wind energy is a sustainable option but requires significant cost reductions. Since the 1980s, wind energy costs have fallen by about 80 % to around 0.04 €/kWh, thanks to better turbine designs and control systems. Wind-powered hydrogen offers location flexibility, reducing infrastructure costs. In the U.S., purely wind-based hydrogen

(*continued on next page*)

Table 8 (*continued*)

S. No	Methods	Effect on the environment:	Effect on the economy:
			costs about 7 €/kg, while using grid backup during low wind raises costs above 10 €/kg.
4.	Hydrogen produced by electrolysis with solar-generated electricity	Completely sustainable option	Electricity produced from photovoltaic solar technology currently costs at least six times more than electricity generated from fossil fuels. This significant price gap is also reflected in the cost of producing hydrogen. However, employing the most advanced solar cell and electrolyzer technologies could potentially bring hydrogen production costs down to approximately 6 €/kg.
5.	Hydrogen is produced by electrolysis with electricity generated from biomass	CO_2 emissions come only from petroleum fuels used in biomass harvesting, transport, gasification, and electricity generation. Producing hydrogen from biomass also requires more fertilizers, energy, and water. Like crop farming, biomass cultivation can cause soil erosion, nutrient loss, and changes in water use.	To maintain a sustainable balance, biomass production must match consumption rates. However, small-scale projects cannot significantly meet the demand for hydrogen.

Table 9
Alkaline vs. PEM Electrolysis: A comparative study.

S. No	Parameter	Alkaline Electrolysis	PEM Electrolysis
1.	Technology	Uses liquid alkaline electrolyte (e.g., KOH or NaOH); porous diaphragm separates electrodes	Uses solid polymer electrolyte (proton exchange membrane)
2.	Operating Temperature	60–90 °C	50–80 °C
3.	Electrolyte	Aqueous alkaline solution	Solid polymer membrane (e.g., Nafion)
4.	Purity of Hydrogen	~99.5 %	>99.999 % (high purity)
5.	Current Density	~0.2–0.4 A/cm^2	~1–2 A/cm^2
6.	Efficiency	~60–70 %	~65–75 %
7.	Start-up Time	Long (minutes to hours)	Short (seconds to minutes)
8.	Dynamic Operation	Poor (less suitable for intermittent power)	Excellent (well-suited for variable renewable input)
9.	Material Cost	Low (non-precious materials)	High (uses precious metals like Pt, Ir)
10.	Durability	High (longer lifetime)	Moderate (shorter lifespan compared to alkaline)
11.	Benefits	- Mature and low-cost technology - Long lifespan	- Compact design - Fast response to power changes - Higher purity H_2
12.	Downsides	- Slow response time - Lower H_2 purity - Risk of electrolyte leakage	- High capital cost - Shorter lifespan - Expensive materials
13.	Hydrogen Cost (USD/kg)*	\$3 – \$5	\$4 – \$7

hydrogen is generally favored for larger, long-haul aviation concepts due to its higher storage efficiency. Between 2000 and 2003, the European Cryoplane initiative evaluated several aircraft designs powered by liquid hydrogen [159]. They discovered that these arrangements might lead to a 34 % increase in energy consumption for business planes and a 9 % increase for extended-range flights per passenger. However, compared to traditional designs, a liquid-fueled hydrogen-powered commercial jet may be able to improve its energy efficiency by 7 %, according to a study done by Hamburg University [160].

10. Environmental impact of hydrogen use in aviation

The European Commission's Climatic Strategy aims to reduce greenhouse gas emissions by 55 % by 2030 and achieve net-zero emissions by 2050. As a result, by 2030, a group of four companies called Norsk e-Fuel hopes to build Europe's first facility for making hydrogen-based aviation fuel. However, inadequate infrastructure is presently preventing hydrogen from being widely used in aviation. According to the International Air Transportation Association (IATA), aviation-related CO_2 emissions will be dropped in half from 2005 levels by 2050 as part of the worldwide response to climate change. Between 2009 and 2020, the sector saw an annual fuel efficiency improvement of approximately 1.5 % [161].

Biofuels, due to their lower carbon intensity compared to traditional jet fuels, are increasingly being adopted as sustainable aviation fuels (SAFs). The U.S. Environmental Protection Agency reports that SAFs have contributed to a 9–12 % reduction in national greenhouse gas emissions. Despite aviation accounting for less than 3 % of total global emissions, its role in climate change is magnified by high-altitude emissions, which can disrupt atmospheric stability and intensify warming effects. Experimental studies further highlight the potential of alternative fuels. Hydrogen, biofuel, and JP-8 were tested in turbojet engines [162]. Explored a mixture of kerosene with a small percentage of hydrogen in gas turbines. The inclusion of hydrogen reduced specific fuel consumption and resulted in fewer pollutants, though it produced 2.6 times more water vapor than kerosene. To ensure compatibility with fuel cell systems, hydrogen purity must meet specific standards such as ISO 14687-2 and SAE J2719. Overall, these findings underscore hydrogen's significant promise as a clean aviation fuel. Its adoption could represent a transformative step in mitigating climate change, potentially reshaping the global climate trajectory by offering a cleaner, future-oriented energy source [163].

11. Impact of aircraft Non-CO_2 emissions at cruise altitude on the climate

The widespread adoption of hydrogen along with other synthetic petroleum products in aviation raises serious concerns about the environmental effects of non-CO_2 carbon dioxide emissions at cruising altitudes. Regardless of the region, the aggregate quantity of carbon dioxide released from fuel production and burning is typically calculated, but their effects on the climate differ. For example, carbon dioxide absorbed during the fuel synthesis process can counterbalance emissions released during combustion. The climate consequences of pollutants such as water vapor, nitrogen oxides (NOx), sulfur oxides (SOx), and soot, however, differ substantially according on the air conditions and altitude at which they are released. Penke et al. [164] provide a detailed analysis of aviation's broader climatic effects, and this section emphasizes the variability in non-CO_2 impacts when alternative fuels are used [165,166].

Research has shown that traditional jet fuel combustion can produce warming effects beyond those caused by CO_2 alone. Renewable fuels like Power-to-Liquid (PtL) have shown the potential to reduce net GHG emissions by approximately 80 %. Reducing sustainable aviation fuels' non-CO_2 impacts is equally as crucial to effectively addressing climate change as reducing CO_2 emissions.

The deployment of renewable jet fuels can lead to a measurable decrease in aviation's non-CO_2 environmental impacts, mainly through the reduction of particulate matter and soot. One key factor influencing these reductions is the low aromatic content typically found in synthetic aviation fuels. Compared to conventional hydrocarbon fuels, hydrogen combustion is expected to generate fewer particulate emissions and significantly reduce NOx output. Nevertheless, it also leads to increased emissions of water vapor. According to research by Ponater and associates [167,168] aircraft powered by hydrogen may lessen the overall climatic impact of aviation by reducing radiative forcing, which is caused by transformations in contrail attributes and a decrease in NOx emissions. These changes stem from the lack of particles in hydrogen exhaust, which affects the formation and structure of ice crystals in contrails [169].

12. Conclusion

Hydrogen plays a vital role in supporting the global shift toward cleaner energy due to its distinct properties, which offer advantages across both the energy system and various end-use applications. Its chemical similarities to conventional jet fuel, such as kerosene, allow it to be blended and utilized within existing fuel infrastructure with minimal modifications. Although hydrogen's flammability and explosive potential raise safety concerns, these can be mitigated through proper engineering controls and safety protocols. Notwithstanding these advantages, liquid hydrogen (liq H_2) has drawbacks, such as a lower volumetric energy density than conventional liquid petroleum products such as biofuels, kerosene, and synthetic gasoline and diesel. In aviation, the weight and storage requirements of hydrogen are particularly significant when contrasted with current jet fuel systems.

Hydrogen-powered aviation presents a transformative opportunity for decarbonizing the aviation sector, but several challenges must be addressed to enable its large-scale adoption. First, the energy density and storage limitations of hydrogen, particularly the need for cryogenic or high-pressure systems, pose significant design and weight challenges for aircraft. Second, the lack of hydrogen refueling infrastructure at airports globally inhibits operational feasibility. Third, the high production cost of green hydrogen continues to limit its commercial competitiveness, especially in comparison with conventional jet fuels.

To accelerate the transition, targeted policy interventions are essential. Governments and aviation regulatory bodies should: Invest in hydrogen infrastructure development, including airport refueling systems and supply chain logistics; Provide subsidies or carbon pricing mechanisms to improve the economic viability of hydrogen production and usage in aviation; Support cross-sector collaboration between aviation manufacturers, energy companies, and research institutions to facilitate innovation and commercialization.

Nevertheless, hydrogen can be repurposed as a reliable backup energy source during grid failures and used across multiple sectors including transportation, industrial processes, and residential energy supply. For long-duration energy storage, hydrogen offers a carbon-free and scalable solution. Its flexibility and compatibility with evolving energy needs position it as a key technology in aligning global energy storage capacity with future demand.

Declaration of competing interest

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

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Data availability

The authors do not have permission to share data.

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