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Decarbonising Sustainable Aviation Fuel (SAF) Pathways: Emerging Perspectives on Hydrogen Integration

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Abstract

The growing demand for air connectivity, coupled with the forecasted increase in passengers by 2040, implies an exigency in the aviation sector to adopt sustainable approaches for net zero emission by 2050. Sustainable Aviation Fuel (SAF) is currently the most promising short-term solution; however, ensuring its overall sustainability depends on reducing the life cycle carbon footprints. A key challenge prevails in hydrogen usage as a reactant for the approved ASTM routes of SAF. The processing, conversion and refinement of feed entailing hydrodeoxygenation (HDO), decarboxylation, hydrogenation, isomerisation and hydrocracking requires substantial hydrogen input. This hydrogen is sourced either in situ or ex situ, with the supply chain encompassing renewables or non-renewables origins. Addressing this hydrogen usage and recognising the emission implications thereof has therefore become a novel research priority. Aside from the preferred adoption of renewable water electrolysis to generate hydrogen, other promising pathways encompass hydrothermal gasification, biomass gasification (with or without carbon capture) and biomethane with steam methane reforming (with or without carbon capture) owing to the lower greenhouse emissions, the convincing status of the technology readiness level and the lower acidification potential. Equally imperative are measures for reducing hydrogen demand in SAF pathways. Strategies involve identifying the appropriate catalyst (monometallic and bimetallic sulphide catalyst), increasing the catalyst life in the deoxygenation process, deploying low-cost iso-propanol (hydrogen donor), developing the aerobic fermentation of sugar to 1,4 dimethyl cyclooctane with the intermediate formation of isoprene and advancing aqueous phase reforming or single-stage hydro processing. Other supportive alternatives include implementing the catalytic and co-pyrolysis of waste oil with solid feedstocks and selecting highly saturated feedstock. Thus, future progress demands coordinated innovation and research endeavours to bolster the seamless integration of the cutting-edge hydrogen production processes with the SAF infrastructure. Rigorous techno-economic and life cycle assessments, alongside technological breakthroughs and biomass characterisation, are indispensable for ensuring scalability and sustainability.

Keywords: hydrogen; SAF; hydrogenation; isomerisation; hydrodeoxygenation; hydrocracking; gasification

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1. Introduction

Amidst efforts to foster economic growth through global connectedness, the aviation industry currently faces an absolute necessity for decarbonisation endeavours, with a

specified aim of attaining net-zero emissions by 2050. The anticipated growth in air travel to over 8 billion passengers by 2040 emphasises this urgency. The primary challenge is the ascending climate change caused by constant greenhouse gas emissions (with around 2.5% of global emissions originating from aviation), impacting the growing economy and the airline sector. To tackle this, the shift to renewable energy (targeting a 35–65% share by 2050) demands a substantial annual supply boost in Sustainable Aviation Fuels (SAF) to surpass production capacity of over 400 billion litres. Currently SAF represents only 0.1% of the total jet fuel supply [1]. However, attaining sustainability should involve identifying major contributors to the final fuel carbon footprint throughout the complete life cycle assessment of the SAF. Are sustainability criteria genuinely considered in relation to the raw material, utility consumption, production, transportation, utilisation and disposal of SAF? Each drop of SAF should be complaint with the ambition of achieving the net zero goals and the broader sustainability objectives. Continuing technological advancements and concerted efforts are deployed to produce environmentally responsible SAF, with the prevailing challenges being related to feedstock sourcing, utility consumption and the strict fuel production and refining process. One such essential prospect lies in confronting the sustainability challenges and opportunities associated with hydrogen used as a reagent in obtaining SAF, as shown in Figure 1 (flow chart illustrating the progression from biomass feedstock to SAF) and Figure 2.

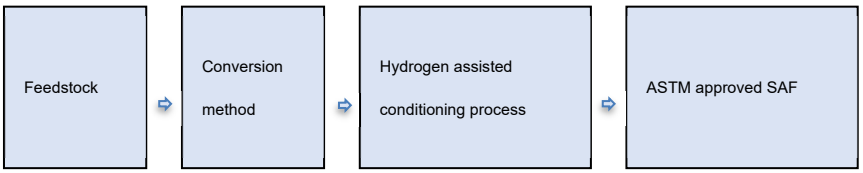


Figure 1. Conceptual flow of SAF production with a hydrogen-rich environment.

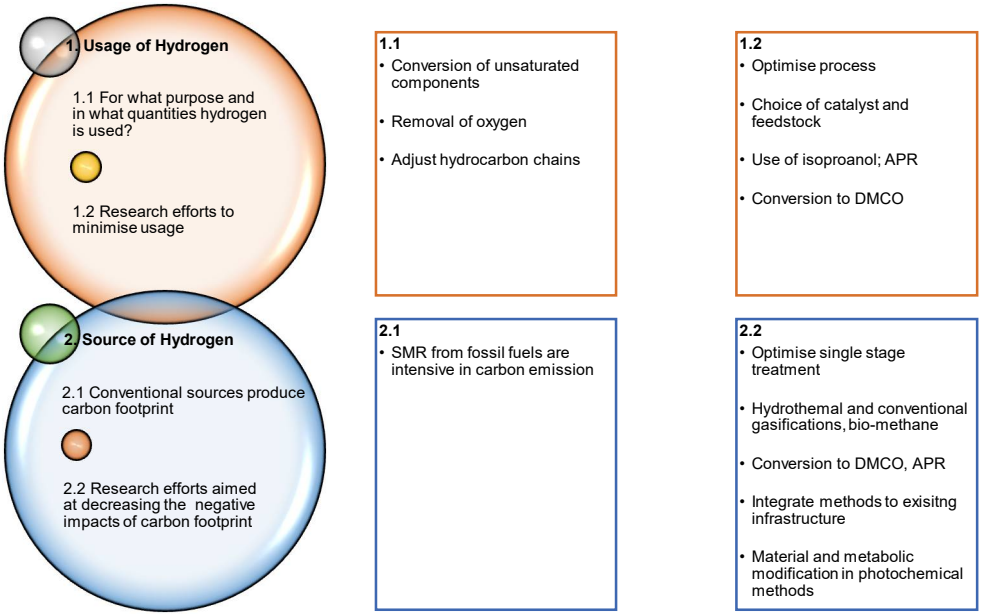


Figure 2. Realm of challenges and opportunities with hydrogen usage.

Various previous studies have solely examined hydrogen production for power generation or fuel applications from technical, economic and life cycle standpoints. Nonetheless, no authors have critically evaluated the challenges of specifically using hydrogen as a reactant in the synthesis of SAF, thereby overlooking the broader implication and role of hydrogen in the refining and upgrading processes. Conventional fossil-based hydrogen

production contributes to carbon emission and emphasises reliance on non-renewable resources; thus, it presents a significant barrier in achieving sustainability and carbon-neutrality objectives. This research gap underscores the uniqueness of the present study and delivers a comprehensive perspective into the wider challenges related to this purpose. It will reveal the prevailing research limitations and identify vital avenues of future research activities associated with the sourcing and usage of hydrogen towards sustainable pathways for SAF production. The approach to conducting this research is primarily categorised into two sections, as illustrated in Figure 2, established through the critical incorporation of the limited data from the available scientific literature. This study systematically evaluated alternative hydrogen production pathways and innovative strategies aimed at reducing hydrogen intensity, thereby highlighting potential future research pathways.

2. Usage of Hydrogen

The American Society for Testing and Materials (ASTM, under references D7566 [2] and D1655 [3]) has chronologically certified nine distinct SAF production routes between 2009 and 2020, as revealed in the review study by Shahriyar and Khanal (2022) [4]. It is found that biomass and other carbon-based feedstock contain a substantial degree of unsaturation [4–7]. Hence, hydrogen is notably used as a fundamental component in producing a suitable biofuel with high volumetric density, as pointed out in the various studies (Table 1).

Considering the approved SAF pathways, various processes are conducted within a hydrogen-rich environment such as the liquid fuel derived from the Fischer–Tropsch (FT) process, hydrodeoxygenation (HDO), decarboxylation, hydrogenation, isomerisation and hydrocracking. For Hydroprocessed Easters and Fatty Acids (HEFA) [7], subsequent to the cleaning and upgrading of the feedstock is a hydrogenation process that marks the initial conversion to saturated fatty acids using hydrogen. Additionally, hydrogen also serves to remove oxygen from the feedstock (HDO), yielding a blend of linear hydrocarbon chains along with the co-products water, carbon monoxide and carbon dioxide through decarboxylation and decarbonylation (DCOX). The resulting hydrocarbons are further adjusted to the SAF specification via hydrogen-rich isomersation and severe cracking methods. The problems associated with oxygen (acidity, corrosiveness, viscosity, high diffusivity and heating value) are detailed in the review [8]. All the major chemical reactions are illustrated in [4,9], including HDO, DCOX and cracking that convert the fatty acids to hydrocarbons in catalytic reactions. For the hydrogenation step in HEFA, 3, 6 and 9 mol of hydrogen are required for each mole of triolein, trilinolein and trilinolenin, as referred to in the techno-economic study by Tao et al. (2017) [10].

A previous techno-economic study [9] of producing bio-jet fuel from vegetable oil concluded that hydrogen is the second highest contributor to the annual cost of the plant. However, the availability of affordable sources of hydrogen is crucial for the large-scale production of SAF [6]. Unlike in the other SAF-approved routes, in the refining of FT synthesised output, the addition of hydrogen is aimed at the achievement of sufficiently high H2/CO ratios in upstream syngas production, as per the stoichiometric requirements of downstream catalytic syngas conversion [6,7]. Similarly, hydrogen use in the hydrogenation of olefins for Alcohol to Jet (ATJ) incurs additional costs [4]. For example, a hydrogen flowrate of 41.58 kg/h was used, as indicated in the techno-economic evaluation study [11] of ATJ of the assessed plant capacity processing feed rate of 6993 kg/h ethanol and 5557 kg/h isobutanol. Also, hydrogen contributed 7.5% (from ethanol) and 10.71% (from isobutanol) of the total yearly operating cost; therefore, the reactant represented a major expense item in the cost inventory of the operation. Similarly, hydrogen production is the second major contributor to the total capital expenditure in the case

of HEFA and ATJ [12]. The post-refining steps in Catalytic Hydrothermolysis Jet (CHJ) such as hydrogenation, hydrotreatment and decarboxylation also consume hydrogen [7]. In CHJ, the further anaerobic fermentation process produces hydrogen to be of use in the hydrogenation process [5]. Hydrogen is also fed to the hydrotreating of farnesene in SIP [4]. The unsaturated farnesene undergoes hydrogenation for its eligible use as a jet fuel. Moreover, the HDO process is absent in Synthetic Isoparaffins from Hydroprocessed Fermented Sugars (SIP) but the hydrocracking and hydro isomerisation steps are similar to the ones adopted in the conventional refining of oil [5,13]. The consumption of hydrogen also increases to eliminate oxygen in the catalytic hydro processing step for the Fats, Oils and Grease (FOG) Coprocessing, which depends on the level of saturation of the renewable feedstock, as explained by Bezergianni et al. (2018) in their review study of a co-processing refinery with biomass based feedstocks [14]. Likewise, in an experimental study of the co-hydroprocessing of the canola oil, the reaction stoichiometry of the hydrogen requirement is 15 hydrogen moles (HDO step) and 6 hydrogen molecules (hydrodecarboxylation step) for each mole of triglyceride [15]. Hydrogen consumption for HDO lies between 26 and 30 kg per tonne of input oil seed [16].

Table 1. Hydrogen for producing SAF.

Methods	**Purpose**	**Quantity of Hydrogen Normalised (kgH_2/kg Feedstock or kgH_2/kg Fuel Output)**	**Remarks**
FT-SPK (Synthetic Paraffinic Kerosene) & FT-SPK/A (Synthetic Paraffinic Kerosene with Aromatics) ~Carbon-containing biomass	a. Refining fuel [4,5]	- No use of hydrogen (comparative study in [17]) - **0.01** kgH_2/kg feedstock (corn stover) [13]	- Make-up hydrogen is used in the refining of FT product [7] - Theoretically, 0.351 kgH_2/kg lignocellulosic biomass for the synthesis of fuel [13]
HEFA-SPK & HC-HEFA-SPK (Hydrocarbon) ~Oil-based including algae	a. Hydrogenation [5] b. HDO [13] c. Decarboxylation [5] d. Isomerisation [5] e. Hydrocracking [5]	- For per kg feedstock HDO—0.033 kg; Isomerisation—0.019 kg [9]. Total: **0.052** kgH_2/kg feedstock - Hydrotreating and isomerisation/hydrocracking: **0.020 to 0.04** kgH_2/kg feedstock (varied feedstock), cross refer [5] - **0.04** kgH_2/kg feedstock: oil based feedstock (comparative study [13]) - **0.15** kgH_2/kg renewable jet fuel (RJF) (comparative study as referred [17]) - **0.043** kgH_2/kg feedstock (soyabean oil) [13] - **0.0317** kgH_2/kg feedstock (palm oil), **0.033** kgH_2/kg feedstock (macuaba oil) and **0.0377** kgH_2/kg feedstock (soyabean oil). Up to 2000 kg/h processing 4 million tonnes of feedstock/annum [12]	- Transform unsaturated triglyceride and fatty acids to saturated compounds [18] - HDO & DCOX convert a saturated substance to linear alkanes of C_{15} to C_{18} [19] - Branched alkanes-based liquid fuel produced via isomerisation and hydrocracking [4] - Hydrogen is used to deoxygenate [17]
ATJ-SPK ~Alcohol- and sugar-based	a. Hydrogenation [1,4,5,20]	- **0.0016** kgH_2/kg feedstock (comparative study [13]) - **0.08** kgH_2/kg (RJF) (comparative study as referred [17]) - **0.02** kgH_2/kg feedstock (corn stover) [13]	- Paraffins are produced after saturating double bonds in olefins [4]

Table 1. *Cont.*

Methods	Purpose	Quantity of Hydrogen Normalised (kgH_2/kg Feedstock or kgH_2/kg Fuel Output)	Remarks
CHJ ~Algae, oil derived from waste and plant	a. Hydrogenation [5,20] b. Decarboxylation [5] c. Hydrotreatment [5]	-	- Hydrogen is used in hydrogenation [4] - Straight, branched and cyclo-olefins are transformed to alkanes [7]
SIP-HFS or DSHC (Direct Sugars to Hydrocarbons) ~Lignocellulosic, sugar-based feedstock	a. Hydrotreating [1,4,20]	- **0.0104** kgH_2/kg feedstock (from the comparative study [13]) - 0.52 kgH_2/kg (RJF) (for a high blending ratio and 0.12 kgH_2/kg RJF 10% blending ratio (comparative study as referred [17]) - **0.011** kgH_2/kg feedstock (corn stover) [13]	- Sugar-containing feedstocks are modified to farnesene and further transformed to jet fuel [4,17] - Branched molecules are formed after hydroisomerisation and hydrocracking [21] - High hydrogen consumption contributes to GHG emission [17]
FOG Co-processing ~Oil-based inputs	a. HDO [4]	- **0.03** kgH_2/kg feedstock (for hydro processing) [14]	- Oil-based feedstock deoxygenated in the presence of hydrogen [4] - Hydrogen consumption increases by 7% [14], if lipid-based feedstock blending (waste cooking oil) increases from 10 to 30%. - Saturated feedstocks consume less hydrogen (such as palm oil, animal fats, etc. targeted for renewable diesel) [14] - Lipid feed such as algae oil, camelina oil, linseed oil, etc. with unsaturated fatty acids are suitable for aviation fuels [14] - Different catalyst combinations to be further explored to comprehend its effect on the extent of deoxygenation and the hydrotreatment process apart from CoMo and NiMo catalysts [14].

The conceptual plot, as shown in Figure 3, proves that hydrogen intensity is a function of SAF production pathways (green), hydrogen-rich product upgrading processes (blue) and hydrogen usage categories (orange). The lines specify directional relationship, where the selected pathway is linked to hydrogen requirements and processing technologies. The orange nodes in the diagram differentiate pathways into the low, moderate and heavy usage of hydrogen categories.

a. Low-hydrogen pathways (FT-SPK, ATJ) consume less hydrogen.
b. Moderate-hydrogen pathways (DSHC, SIP-HFS) are involved in selective hydrotreating.
c. High-hydrogen pathways (HEFA-SPK, HC-HEFA-SPK, FOG) are related to multiple hydrogen-rich upgrading functions, evident as resource-intensive.

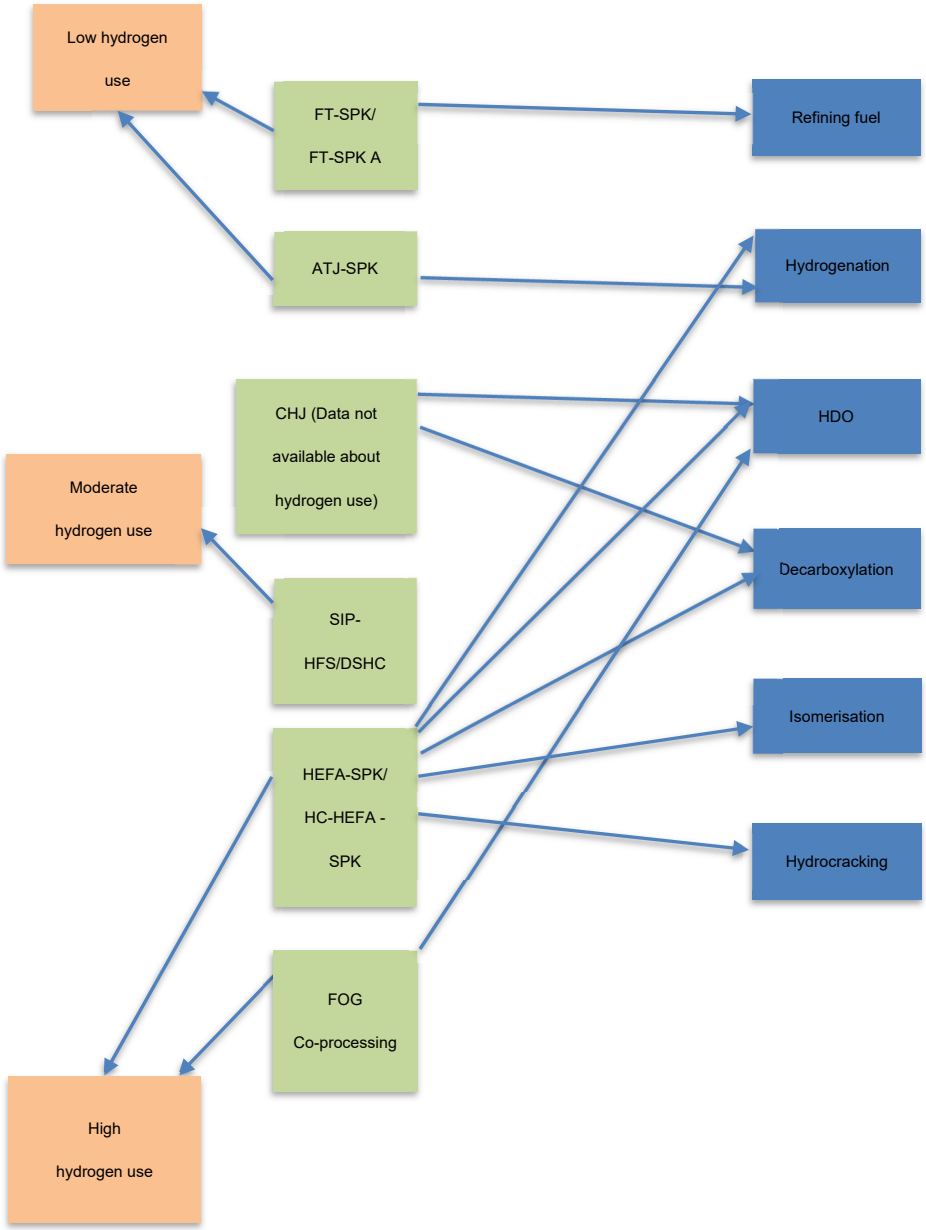


Figure 3. SAF pathways by hydrogen intensity.

This underscores the hierarchy of hydrogen intensity to comprehend the scalable process routes under hydrogen constraints. The blue nodes are hydrogen-dependent processes, as already explained earlier.

Thus, the above diagram reinforces the heterogeneous behaviour of hydrogen consumption in SAF pathways. It offers a system-level perspective where upgrading intensity, process route and type of feedstock congregate to define the normalised overall hydrogen usage, as shown in the comparative hydrogen demand (Figure 4) extracted from Table 1.

This classification provides a foundation for targeted research urgencies (directed towards reducing hydrogen consumption in the intensive pathways or hydrogen-free upgrading process) and the importance of policy development in incentivising the adoption of renewable hydrogen sources, without which the sustainability goal cannot be accomplished. It highlights the potential strategies for lowering hydrogen consumption via optimising catalyst performance, the application of hydrogen donors or sourcing renewable hydrogen, as described in the subsequent paragraphs, which must be tailored to the considered

pathway. The variation in the consumption of hydrogen is correspondingly relevant to the process type and choice of feedstock.

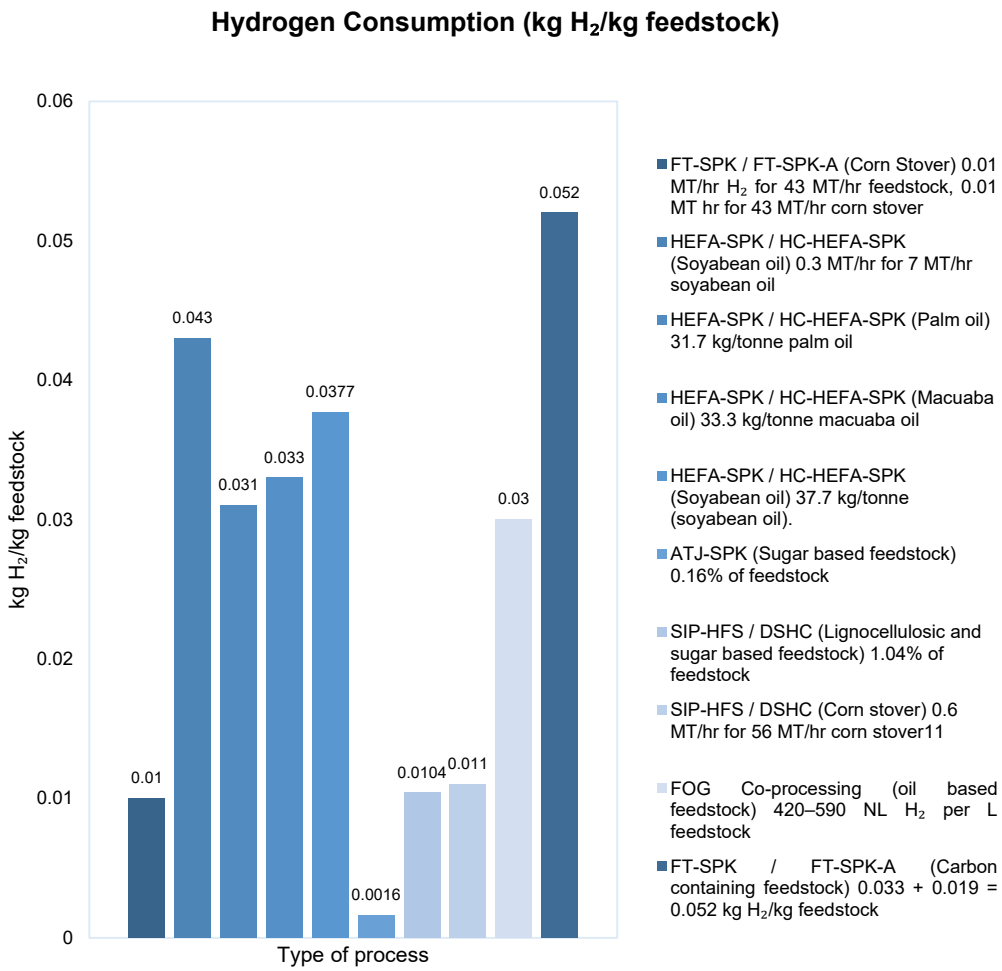


Figure 4. Comparative hydrogen consumption for approved SAF pathways.

Overall, hydrogen is a crucial reactant for various stages involved in producing SAF and cannot be overlooked.

3. Source of Hydrogen

Addressing the production of hydrogen is a noteworthy aspect for consideration from the perspective of reducing environmental impacts in SAF synthesis. In the HEFA or Hydroprocessed renewable jet fuel (HRJ) process, the steam reforming of propane produced via isomerisation or cracking is the main source of hydrogen [13]. Researchers [17] mentioned that the existing production methodology involves obtaining hydrogen from natural gas through steam methane reforming (SMR). The hydrogen supply within SAF pathways can be delivered through either in situ or ex situ approaches. Hydrogen has contributed significantly to the overall well-to-wake release of harmful emissions, as confirmed in the comparative life cycle study [17] analysis of HEFA, HTL, pyrolysis, DSHC and ATJ. The scenarios were evaluated using hydrogen produced via electrolysis from renewable electricity and the gasification of switchgrass technology, which have specifically proven a reduction in the well to wake greenhouse emissions by 34% (HEFA) and between 20 and 30% (DSHC). Additionally, the sensitive study mentioned that in situ hydrogen production can generate low emissions compared to the ex situ hydrogen process (for example, hydrogen is produced from the process of gases in the pyrolysis method for jet

fuel instead of directly using natural gas). The output ranges of emissions were mainly dependent on either the variation in consumption or the production route of hydrogen. The alternative source of feedstock and the method used for hydrogen production substantially impact the fuel's Global Warming Potential (GWP), which ranges from 60 to 66 g CO_2 equivalent/MJ for natural gas and 32 to 73 g CO_2 equivalent/MJ for the gasification of lignin. This was evidenced in a life cycle assessment undertaken by Budsberg et al. (2016) [22], which investigated a novel fermentation technology utilising an acetogen pathway instead of an ethanologen pathway to produce jet fuel from poplar. Additionally, the study concluded that the gasification of hog fuel dictates lower emission outputs compared to using natural gas for hydrogen production.

Overall, it is observed that the production pathways for hydrogen used as a reactant in SAF synthesis play a crucial role in the life cycle greenhouse gas performance of SAF and thus to its ability to contribute towards net zero goals.

4. Strategy for Alleviating the Issues of the Source of Hydrogen and Usage of Hydrogen

There is no denying the fact that lifecycle greenhouse gas emissions related to aviation can be minimised through SAF. Hence, it is imperative to identify alternative hydrogen production methods and also assess the possible variability in hydrogen consumption that directly or indirectly impacts greenhouse emissions throughout the entire life cycle of SAF [17].

4.1. Conventional Approach Impacting Greenhouse Gas Emission

Life cycle assessment studies carried out by de Jong et al. (2017) [17] and Seber et al. (2022) [23] specifically implied that the emission intensity of jet fuel can be alleviated via electrolysis using renewable electricity. The sensitivity study [17] on various biomass sources for hydrogen production has shown that the electrolysis method using renewable electricity, followed by the gasification of biomass, offers a considerable advantage in lowering cradle-to-grave greenhouse emissions for six different SAF pathways. The water electrolysis method for producing hydrogen could reduce emissions by 9% in the sensitivity study of HEFA [23]. Hydrogen produced via water electrolysis represents an environmentally friendly alternative for ATJ and HEFA. This was confirmed in a techno-economic and environmental study focused on sugarcane bio-refineries in Brazil. The study found that the maximum value [12] of climate change impacts were 25 g CO_2 equivalent/MJ jet fuel (ATJ) and 22.3 g CO_2 equivalent/MJ jet fuel (HEFA).

4.2. Alternative Perspectives Impacting Variability in Hydrogen Usage and Greenhouse Gas Emission

Apart from the established potential of green hydrogen, the effectiveness of alternative methods for hydrogen production or the utilisation of hydrogen depends on the choice of feedstock, catalyst, process condition and other parameters [17].

For instance, one process condition is the potential use of isopropanol as an in situ hydrogen donor, which could replace the consumption of hydrogen (typically used for hydrogenation in HEFA) for saturating waste cooking oils containing up to 70 wt.% unsaturated components. The isopropanol used as a solvent (along with an activated carbon as a catalyst in a fixed bed reactor) is available at an affordable cost and can be easily separated from the reaction system [24].

Alternatively, another process is proposed wherein the aerobic fermentation of sugars produces isoprene as an intermediate. Being oxygen-free, this eliminates the need for the deoxygenation step [25]. Further, the dimerisation of isoprene into high-energy-density

1,4 dimethylcyclooctane (DMCO) holds the potential to lower the lifecycle greenhouse gas emissions when hydrogenated with renewable hydrogen sources.

A single-step hydroprocessing (either deoxygenation or the simultaneous occurrence of deoxygenation, cracking and isomerisation) of renewable jet fuel has potential with the proper selection of solid or liquid biomass, an optimum catalyst and process conditions for a better yield and less dependence on hydrogen [8,16,26]. To identify a catalyst, Zulkepli et al. (2018) [26] affirmed that the Ni/HMS catalyst offers a promising option for producing sustainable biofuel from non-edible oil by enabling the deoxygenation process without requiring hydrogen or a solvent. Selecting feedstock with a high degree of saturation and making use of monometallic and bimetallic sulphide catalysts with proper acidic strength influence the consumption of hydrogen and the necessity for further isomerisation and cracking [27].

Moreover, the prospect of hydrothermal gasification has emerged as a promising solution despite the low yield [28]. The authors concluded that optimising the process parameters could further increase the hydrogen yield and reduce the associated cost.

Additionally, the Aqueous Phase Reforming (APR) of glycerol (obtained as a by-product during the hydrolysis of feedstock) is an eco-environmentally alternative option for providing in situ hydrogen for use in the HDO, hydroisomerisation and hydrocracking of SAF from vegetable oils [29]. In this approach, external hydrogen consumption is reduced compared to that in the conventional HEFA process, due to the increased in situ hydrogen production via the APR of glycerol. However, selecting feedstock with a lower content of triglycerides may reduce the glycerol fraction, thereby impacting the amount of in situ hydrogen produced.

Superior-grade biofuels can be produced via the catalytic and co-pyrolysis of waste oil with solid wastes containing high hydrogen content (waste cooking oil, waste lard, vegetable oil soap stock, waste motor oil, waste engine oil, lamb and chicken fats, waste polyolefins, waste polypropylene, high density polyethylene and others) [30]. A minor decline in emissions (approx. 1.2 g CO_2 equivalent/MJ) can be achieved for advanced bio-jet fuels by replacing fossil methane steam reforming with bio-methane [31]. Finally, the bio-methane unit (via the anaerobic digestion of agricultural residues and waste) integrated with SMR and carbon capture has immediate potential in Europe as an alternative hydrogen supply source (produces up to 12.5 Mt hydrogen per year and removes 133 Mt CO_2 from the atmosphere yearly). These, however, require improvements in scaling up rates and commercialisation due to the status of the technology readiness level (TRL) [32]. The emissions and TRL of different technologies are highlighted in Figures 5 and 6. Further benefits of these processes as indicated by Dincer and Acar [33] include the lower acidification potential and a comparable cost with the other studied methods. Nonetheless, the GWP of biomass gasification is 5.83 kg CO_2 eq. compared to 3.33 kg CO_2 eq. for electrolysis. Hydrogen sourced via the gasification of biomass has the potential to lessen GHG emissions, as affirmed by the sensitivity study performed by de Jong et al. (2017) [17].

The above comparative emission graph provides an overview of the carbon footprint across diverse pathways, revealing variation in their eco-friendly performance. Fossil-based technologies demonstrate the maximum emission profiles, mainly due to their dependency on carbon-rich feedstocks and the absence of integrated carbon mitigation measures. Contrarily, renewable hydrogen systems, particularly electrolysis, show minimal direct emissions, sustaining their orientation with long-term decarbonisation ideas.

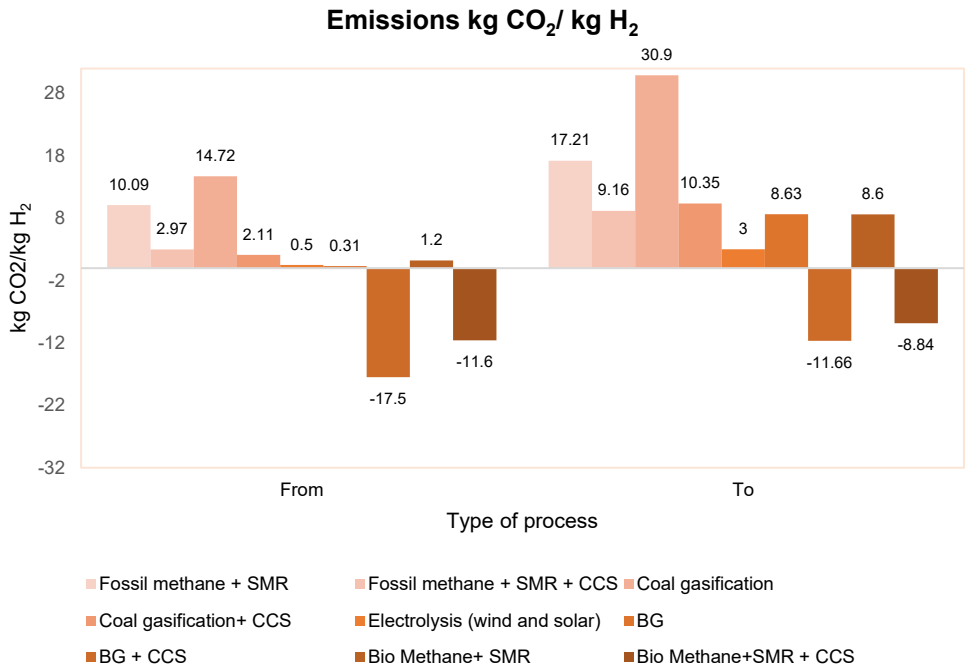


Figure 5. Comparative emissions for different production methods of hydrogen adapted from Rosa and Mazzotti (2022) [32].

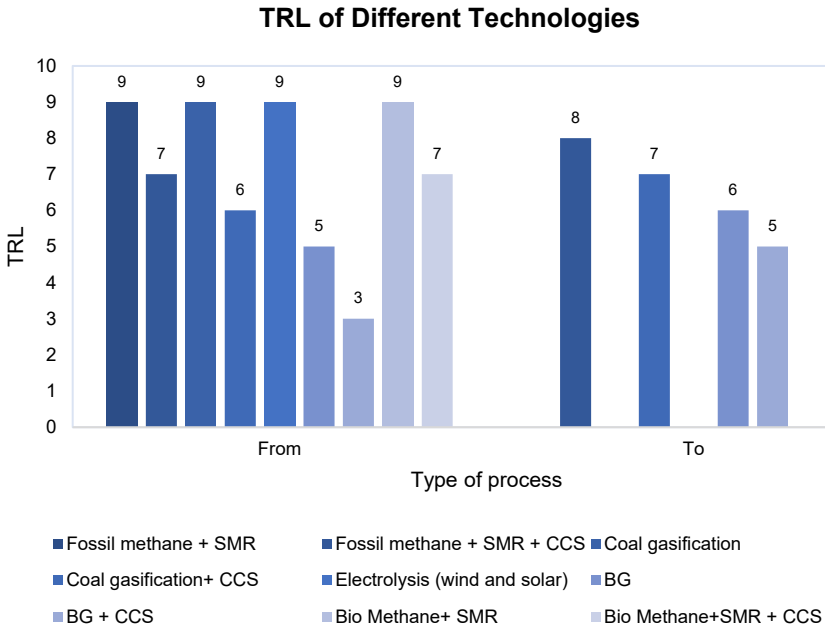


Figure 6. Comparative TRL for different production methods of hydrogen adapted from Rosa and Mazzotti (2022) [32].

Bio-based methods, including biomass gasification and biomethane reforming with carbon capture and storage (CCS), occupy a midway spot, contributing substantial emission reductions while upholding operational feasibility. This reasonable emission analysis underscores the deep influence of the source of feedstock and process design on the environmental emission of hydrogen systems.

Collectively, the results in Figure 6 focus on a strong development gradient within hydrogen production strategies: whereas established methods and electrolysis have achieved commercial feasibility, the integration of carbon capture and bio-derived routes neces-

sitates continuous investigation for scaling and policy sustenance to obtain comparable technological maturity.

Additionally, Figure 7 describes the economic disparities among various hydrogen pathways applicable to SAF systems. Non-renewable hydrogen paths, chiefly SMR and coal gasification, continue as the most cost-effective option, relevant to direct production expenses. Nevertheless, these systems incur substantial carbon externalities that challenge their sustainability within a net-zero context. On the contrary, renewable hydrogen production approaches such as solar- and wind-power driven electrolysis exhibit higher upfront costs but provide long-term economic competitiveness after lifecycle emissions are incorporated. Biomass gasification and biomethane reforming with carbon capture and storage (CCS) dominate an intermediate cost range, representing the potential to balance affordability with environmental performance.

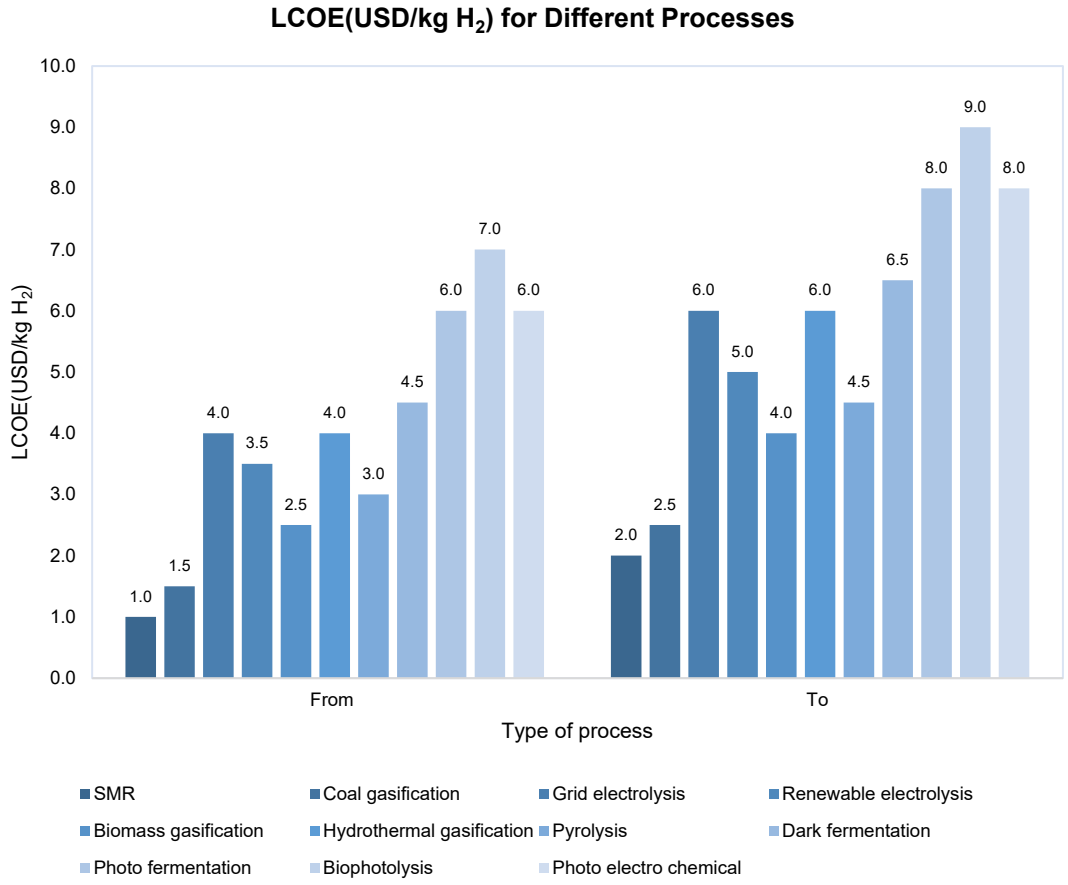


Figure 7. Comparative LCOH for different production methods of hydrogen adapted from Abawalo et al. (2025) [34].

Overall, the relative assessment signifies that technological advancement, process efficiency, feedstock accessibility and policy support instruments could be important determinants in lowering cost variation. Progressing towards renewable hydrogen lanes with economic feasibility assessments is indispensable for realising the decarbonisation objectives of global aviation.

The energy efficiency in Figure 8 reveals notable variation in their conversion performance and the effectiveness of energy consumption. Among the examined pathways, renewable electrolysis establishes moderate-to-elevated energy efficiency, subject to system integration and electricity input. In contrast, conventional fossil-based paths, comprising steam methane reforming (SMR) and coal gasification, display relatively higher thermody-

namic efficiencies but are compromised by substantial carbon emissions and diminished environmental performance when evaluated over their entire life cycle.

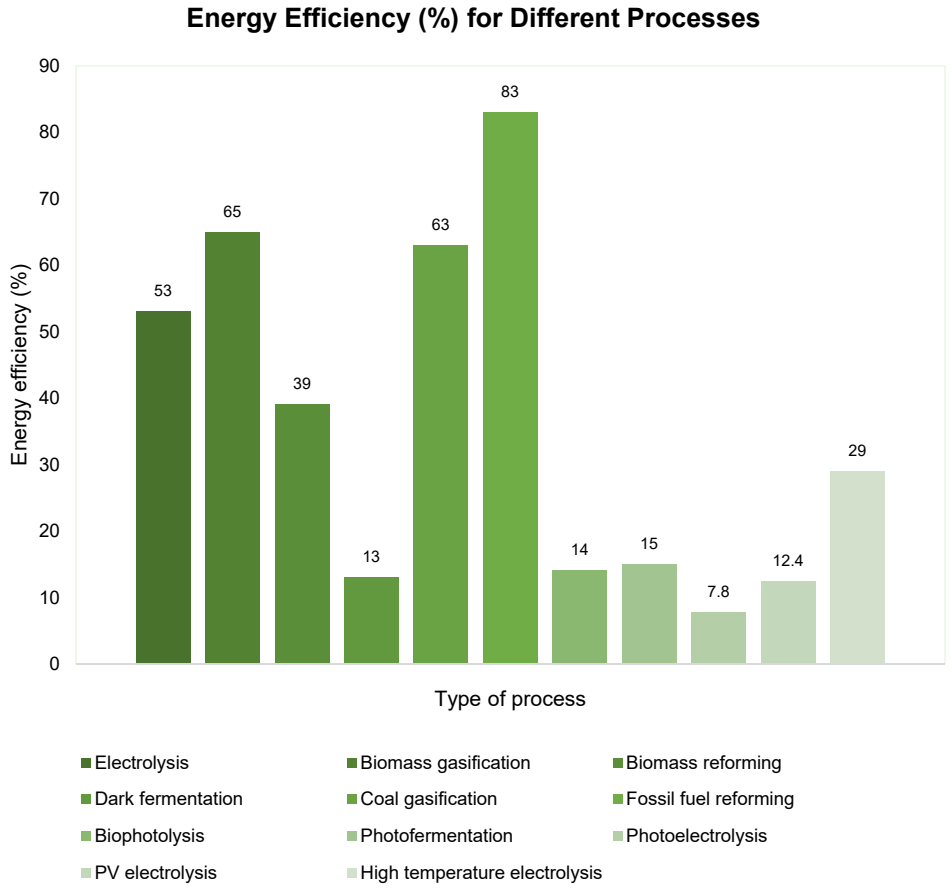


Figure 8. Comparative energy efficiency for different production methods of hydrogen adapted from Dincer and Acar (2016) [33].

Biomass gasification and biomethane reforming with carbon capture occupy an intermediate position, emerging as viable transitional alternatives. The analysis highlights that process configuration, optimised heat recovery and appropriate catalyst selection could influence overall system efficiency.

Collectively, the comparative evidence affirms that enhancing energy efficiency in hydrogen necessitates a comprehensive process intensification, non-conventional energy coupling and improved thermal management. Despite limitations in renewable systems, their potential to produce carbon-neutral hydrogen positions them as tactically imperative to the sustainable renovation of aviation fuel.

Similarly, Figure 9 provides a comprehensive comparison of emissions across varied hydrogen production routes, exemplifying the intensity of the overall climate impact. The results specify that fossil-sourced hydrogen, predominantly coal gasification and SMR, reveal the maximum GWP values, principally attributable to direct CO_2 emissions and energy-intensive processing dependent on conventional feedstocks.

Conversely, renewable hydrogen production methods, such as electrolysis, validate noticeably lower GWP outcomes, reflecting their lesser carbon footprint and higher compatibility with decarbonised energy systems. Biomass gasification and biomethane reforming integrated with CCS conquer an intermediate position, offering considerable GWP bargains while maintaining technological feasibility.

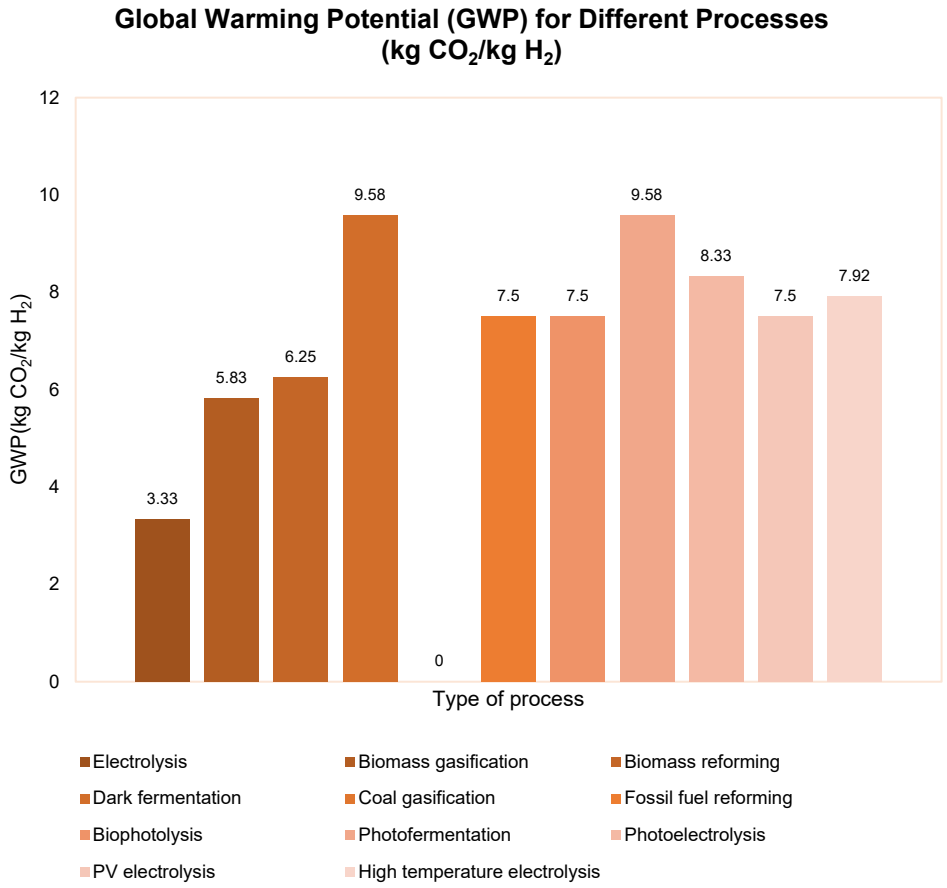


Figure 9. Comparative GWP for different production methods of hydrogen adapted from Dincer and Acar (2016) [33].

The above trend highlights the critical influence of the energy source, process design and carbon management approach on the eco-friendly profile of hydrogen generation. Transitioning from conventional to renewable hydrogen pathways could lessen lifecycle emissions, based on the carbon capture efficiency and energy matrix.

The above analysis reiterates that integrating net-zero aviation fuel systems entails the adoption of low-GWP pathways, supported by the deployment of renewable energy, acceptance of carbon capture and development of supportive policy instruments. Such a paradigm transition is a prerequisite for the arrangement of hydrogen utilisation within SAF production.

The comparative analysis of previous studies in Table 2 directs the significance of hydrogen sourcing and utilisation in shaping the sustainability of SAF. However, the data presented in Table 2 and discussed in the preceding paragraph invite limitations in specific inferences as the selected studied pathways and process parameters differ among authors. Nonetheless, innovative approaches such as in situ catalytic transfer hydrogenation, APR and hydrothermal gasification reveal strong advantages in carbon footprint and capital costs over conventional-based hydrogen systems. Likewise, the integration of renewable hydrogen sources and BECCS presents promising avenues. Furthermore, identifying and categorising specific types of metallic or non-metallic catalysts are equally essential to optimising and suiting the operating parameters of a chosen pathway. Collectively, the above studies expose that sustainability in jet fuel depends on allying process optimisation with the incorporation of renewable hydrogen and improved methods.

Table 2. Summary of stances appropriate for hydrogen as a reactant for producing SAF.

Study Description	Research Problem	Emission Benefit	Cost	Opportunity
Feasibility of in-situ Catalytic Transfer Hydrogenation (CTH) to generate jet fuel from waste cooking oil in comparison to commercial Hydroprocessed Renewable Jet (HRJ) [24]	a. High cost associated with the use of high-pressure hydrogen (25 to 100 bar) in HRJ/HEFA for proper mixing with oil b. Storage and transportation issue c. Relies on fossil source of hydrogen	a. 100-years GWP is 8% low in CTH without sequestering carbon	a. 95% reduction in capital expenditure (CAPEX) of CTH compared to HRJ b. CTH performs well in term of revenues c. Isopropanol contributes 68% of the total operation and maintenance cost (O&M)	a. CTH profitable despite the large input cost of isopropanol b. Gas compression is costly compared to pumping isopropanol c. CTH operates with a cheaper catalyst (Activated carbon) unlike the nickel-molybdenum-based catalyst in hydrotreating HRJ d. Operates at atmospheric conditions
Environmental assessment of first grade biorefinery based on conversion of sugar-based feedstock (corn) to (DMCO) [25]	a. How to produce SAF with the existing commercial first-grade biorefineries? b. To evaluate the environmental performance	a. The obtained average life cycle emissions with and without carbon capture are 36 g CO_2 equivalent/MJ and 5 g CO_2 equivalent/MJ	—	a. Corn to DMCO can bridge the SAF targets b. The use of renewable sources of hydrogen could reduce emissions during the hydrogenation of DMCO c. Effectual crop management practices could reduce the land use emissions d. Prospect for economic viability study
Study of modified Nickel supported hexagonal mesoporous silica (HMS) in absence of hydrogen to produce renewable fuel [26]	a. To identify the connection between the tested catalyst and to perform deoxygenation (DO) in the absence of hydrogen	a. Improved the DO at 380 °C and free of hydrogen b. 10 wt.% Nickel led to 92.5% conversion and 95.2% selectivity c. Pore size and surface area of HMS played a critical part	—	a. Ni/HMS is a promising catalyst to produce sustainable oil from non-edible oil feed in the absence of hydrogen
Study of the enviro-economic effects for producing SAF from TOFA via catalytic deoxygenation under two scenarios of source of hydrogen—grey hydrogen (Case 1) and using hydrothermal gasification (Case 2) [28]	a. Evaluate the integration of hydrothermal gasification to produce SAF	a. Greenhouse reductions: 94% (Case 2) and 76% (Case 1)	a. Minimum fuel selling price (MSP): USD 0.39/L (Case 2) against USD 0.62/L (Case 1)	a. Economically and environmentally viable b. Can process a variety of waste feedstock such as sewage sludge, agricultural residues, FOG and others c. Optimisation of the process
Study of enviro-economic implications on HEFA using in-situ hydrogen via APR [29]	a. To assess the technical, economical and environmental capacity of APR for improving the HEFA process	a. Emission: 54% lower (11.7 g CO_2 equivalent/MJ) than in the conventional method	a. MSP: USD 1.84/kg, i.e., 17% lesser than SAF produced using hydrogen generated via electrolysis b. 6.6% higher CAPEX c. Direct manufacturing cost: 22% lower due to the lesser hydrogen demand externally and compression	a. Can be integrated into other approved SAF routes b. Effect of the cost of feedstock, plant capacity and yield of SAF requires further investigation for marketability

Table 2. *Cont.*

Study Description	Research Problem	Emission Benefit	Cost	Opportunity
Study of cost, environmental impact, energy and exergy analysis of producing hydrogen from conventional and renewable sources [33]	a. To compare and evaluate the different technologies depending on efficiencies for energy and exergy, the cost of generation, the warming effect globally and the acidification potential (AP) inclusive of social cost	a. Energy efficiency is greatest in fossil fuel (83%) reforming and lowest in photocatalysis (2%) b. Biomass gasification has the best exergy efficiency (60%) c. Photonic-based hydrogen has almost zero GWP and AP and hence a negligible social cost of carbon (SCC) d. Hydrogen via electrical methods has high GWP and SCC e. Hybrid- and thermal-based production methods perform better	a. Photoelectrochemical hydrogen is expensive (USD 10.36/kg hydrogen)	a. Integrating technologies with minimal environmental impacts can be the source of hydrogen.
Analysis of Bioenergy with carbon capture and storage (BECCS) for hydrogen production [32]	a. To identify opportunities for removing carbon dioxide, renewable hydrogen from agricultural residues and other biomass wastes and provide insight for the net zero economy of Europe	a. Biohydrogen Carbon Capture Storage (BHCCS) can produce 12.5 Mtons of low carbon hydrogen and 133 Mtons of CO_2 b. Potential location for bio-hydrogen within the desirable range from the suitable industries		a. Opportunity occurs for the use of BECCS

Thus, these mentioned perspectives could hold promising conditions for technological integration with the existing infrastructure of aviation fuel.

5. Supplementary Opportunities for Future Research and Development

Renewable oils derived from biomass via catalytic HDO still face challenges pertaining to the high oxygen content, coking and impurities, which reduce the withstanding capacity of the applied catalyst. Future research endeavours prevail in optimising the catalyst system, process condition and overall applied technology, as concluded in the study [35,36]. The selection of catalysts with a suitable pore size, a suitable surface area and suitable preparation methods enhances the catalytic DO of non-edible oils to produce renewable fuel [26,37]. Other prospective research activities entail studying the usage of the CoMo catalyst for DO under different process conditions (solvent-free and hydrogen-free) to produce jet range typical biofuel [37]. Furthermore, the potential application of the nanosized Zn Al_2O_4 catalyst to decrease hydrogen consumption should be explored for the production of aviation fuel from varied biomass sources. This catalyst has shown promising results in producing aviation fuel from waste cooking oils, as declared by El-Araby et al. (2020) [38], mainly due to its efficacy in reducing the H/C ratio. The techno-economic research of single-stage hydroprocessing with an appropriate catalyst and feedstock has delivered important results relative to the feasibility of these processes. Research should also focus on the refinement of data collection from industrial practices and pilot and laboratory-scale

projects to integrate other thermochemical routes such as gasification and biochemical paths with the present infrastructure of SAF pertaining to the availability of all raw materials. For instance, a research database containing saturation, lipid and oil profiles will ensure the selection of the right feedstock without compromising sustainability. Opportunities exist to impact the consumption of hydrogen via modifying the catalyst and increasing the oil content of algal oil and lipids through genetic and advanced biotechnology methods [39]. In addition, exploring the viability of integrating APR with the other approved SAF pathways is a further opportunity to lower ex situ hydrogen requirements [29]. To produce renewable fuels from bio-oils via catalytic HDO, future research objectives include overcoming the challenges of the tolerance of catalysts to coking and the presence of impurities. Non-noble metal catalysts balance the functionality of hydrogenation with decreased hydrogen input while reducing poisoning risks [36]. More research is needed on the pyrolysis of waste oils and solid feedstock for SAF to compensate for the aforementioned issue of hydrogen [40]. Regarding biomass gasification, although many research studies have been undertaken, the profitability of the integrated system depends on the investigation studies for various feedstocks, gasifying agents, subsequent uses and capital investment [41]. The laboratory and pilot-scale development of advancing technologies for producing hydrogen paves the way for intensifying the research activities as follows: identifying opportunities to integrate alternative hydrogen methods with more established SAF pathways, reliable life cycle assessments for the chosen integration, a breakthrough in materials and metabolic science for photoelectrochemical methods, process optimisation, a low cost output, an efficient process design and an automated regulating system [33]. As evident, the sensitivity study performed by de Jong et al. [17] discussed that irrespective of the conversion technologies, low emission is also attributed to the use of residues or lignocellulosic-type biomass compared to the oil- and food-based resources. The second type of feedstock uses fertilisers for cultivation, thereby impacting the emission output. Thus, it is essential to investigate the crucial factors influencing emission during feedstock production and its treatment for hydrogen production.

Overall, alongside process innovation, an in-depth study scientifically assessing and categorising catalyst types for optimising hydrogen intensity within approved Sustainable Aviation Fuel (SAF) pathways is essential to advancing sustainable production strategies for SAF.

6. Conclusions

To summarise, the current adopted treatment and upgrading processes in SAF synthesis have a considerable effect on the sustainability of the fuel. Its environmental performance is fundamentally linked to the source and consumption of hydrogen across its production chain. The conclusive conceptual framework developed as shown in Figure 10 delineates the interdependent dimensions that govern the sustainability of SAF. The nodes characterise critical factors, and the connecting lines signify functional interdependencies.

The above perspective explicates the multifaceted implication of hydrogen in SAF production and its predominant influence on the decarbonisation route of the aviation sector. It distinguishes hydrogen not only as a chemical reactant but also as a vital determinant within the broader energy transition framework. Hydrogen is a crucial reactant in SAF production, most notably in HDO, hydrogenation, isomerisation and hydrocracking reactions. These reactions facilitate converting feedstock into hydrocarbons that comply with the aviation fuel standards. Nevertheless, the predominant dependence on fossil-derived hydrogen, mainly steam methane reforming, undermines the sustainability objectives of net zero carbon emission envisioned for the aviation sector by 2050.

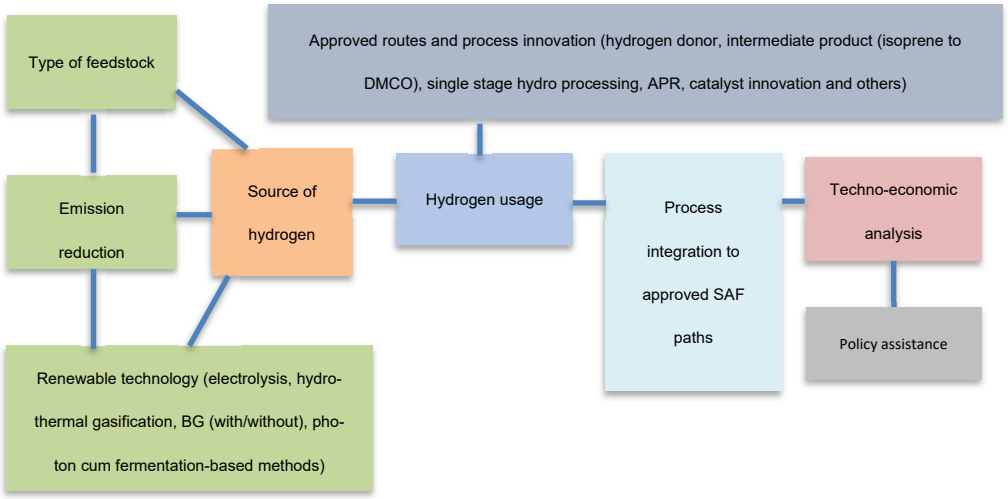


Figure 10. Interconnections in a hydrogen-assisted SAF system.

Alternative hydrogen generation routes with low carbon footprints and advancing the technology readiness level, such as biomass and hydrothermal gasification, renewable electrolysis and biomethane reforming with carbon capture, may offer a promising answer if integrated with SAF pathways. These possibilities could contribute to decarbonisation and align with enhanced resource recovery and waste utilisation. Besides these, examining the technical feasibility and economic challenges of integrating newly developed photo-chemical and fermentation-based hydrogen generation methods and single-stage hydroprocessing into the existing SAF infrastructure is equally imperative in guiding strategic investments.

Furthermore, from a technological and process innovation perspective, this issue underscores the necessity of minimising hydrogen intensity through hydrogen-reduction approaches such as improving catalyst performance, extending the catalyst lifespan, sourcing alternative metallic and non-metallic catalysts (examples: Ni/HMS, CoMo, nanosized Zn Al_2O_4), engaging hydrogen donors (isopropanol) and developing integrated hydro processing systems (such as the formation of intermediate production isoprene to DMCO, APR, the co-processing of waste feedstocks and others). Nonetheless, this study recognises continuing limitations for practical implementation considering process integration into the approved SAF pathways and techno-economic scalability. Tackling these research gaps demands techno-economic evaluation, life cycle emission, pilot-scale justification and further research innovations in innovative photoelectrochemical hydrogen production routes. Moreover, the development of biomass characterisation databases could assist in ideal feedstock selection built on hydrogen efficiency and saturation levels.

Although the present study does not explicitly explore the integration of policy and governance frameworks, subsequent research should conduct detailed local and region-specific analysis to determine how targeted policy interferences (examples: feedstock pricing, renewable hydrogen incentives and others) can reinforce the effective realisation of certain technological routes. This advocates for the imperative of an integrated research and innovation framework that encourages interdisciplinary collaboration to expedite the advancement and deployment of sustainable hydrogen technology in SAF systems.

Eventually, the findings declare that hydrogen demand in the upgrading of SAF represents a serious sustainability challenge unless both the source of hydrogen and usage are carefully managed, as these cannot be assessed in isolation. Notwithstanding economic uncertainty, stressing the environmental footprint is an obligation for a harmonised approach towards the selection of feedstock and technology. Careful considerations in the immediate and future research pursuits encompassing progressive policy instruments and

technology innovation are essential for the integration of potentially promising processes into the existing and prospective SAF corridors.

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