ENVIRONMENTAL PERFORMANCE OF SUSTAINABLE AVIATION FUELS

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ABSTRACT

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Environmental Performance of Sustainable Aviation Fuels

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Climate change is one of the most urgent global challenges, and aviation plays a disproportionately large role in warming despite contributing only 2-3% of global CO_2 emissions. This heightened impact stems from non-CO_2 effects, such as contrails, cirrus clouds, and nitrogen oxides, which amplify radiative forcing and make decarbonising aviation a priority for international climate policy. Sustainable Aviation Fuels (SAFs) have emerged as a central mitigation strategy, particularly electro-kerosene, hydrogen, and ammonia, which offer substantial long-term potential when produced using renewable electricity.

This thesis applies an attributional life cycle assessment (LCA) to compare these three emerging SAF pathways using a well-to-tank (WTT) system boundary and a functional unit of 1 MJ of fuel. Using GaBi and ISO 14040/44 standards, upstream processes including electrolysis, CO_2 capture, nitrogen separation, Fischer-Tropsch synthesis, and ammonia synthesis are modelled. Six configurations combining solar or wind electricity with AEL, PEM, or SOE electrolysis are assessed. Additional midpoint categories, freshwater eutrophication, marine eutrophication, and terrestrial acidification are also included.

Results show that solar-based systems consistently exceed the upstream emissions of conventional jet fuel (CJF = 17.13 g CO_2-eq/MJ). Solar + AEL produces 22.8 g CO_2-eq/MJ for e-kerosene, 15.4 for hydrogen, and 21.3 for ammonia, with both e-kerosene (+33%) and ammonia (+24%) exceeding CJF. Solar + PEM intensifies this trend, reaching 28.9, 20.1, and 26.2 g CO_2-eq/MJ, all of which are significantly higher than CJF (+69% to +52%). Only hydrogen under Solar + AEL and Solar + SOE (15.4-12.2 g CO_2-eq/MJ) achieves values slightly below CJF (-10% to -29%).

In contrast, wind-powered systems substantially outperform CJF across all fuels. Wind + AEL results in 7.5, 4.8, and 17.2 g CO_2-eq/MJ for e-kerosene, hydrogen, and ammonia, where e-kerosene (-56%) and hydrogen (-72%) show large reductions; ammonia is approximately equal to CJF. The best-performing pathway, Wind + SOE, achieves 6.8 g CO_2-eq/MJ for e-kerosene, 4.2 for hydrogen, and 10.1 for ammonia, representing reductions of 60%, 75%, and 41% relative to CJF.

Across all pathways, hydrogen consistently exhibits the lowest WTT climate impacts (4.2-20.1 g CO_2-eq/MJ), followed by ammonia and electro-kerosene. However, electro-kerosene remains the most feasible near-term option because it is fully compatible with existing aircraft engines and refuelling systems. Hydrogen and ammonia offer deeper long-term reductions but require advancements in storage, engines, and safety systems.

Overall, the findings demonstrate that electricity carbon intensity is the dominant determinant of SAF environmental performance. Wind-based electrolysis reduces WTT emissions by 65-85% compared to solar pathways and consistently outperforms CJF. Electrolyser choice further influences results, with SOE technologies offering the lowest impacts due to high electrical efficiency. These conclusions highlight that meaningful climate benefits from SAFs are achievable only when production is paired with low-carbon electricity systems and high-efficiency electrolysers.

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Sincerely

Misagh Kas Aghaei Nahri

ABBREVIATIONS

Abbreviations

AD	anaerobic digestion
AEL	Alkaline
ATJ	Alcohol-to-Jet
CCS	carbon capture and storage
CJF	conventional jet fuel
PSC	Point Source capture
ERF	effective radiative forcing
FT	Fischer–Tropsch
FU	functional unit
GHG	Greenhouse Gas
GREET	Greenhouse gases, Regulated Emissions, and Energy Use in Technologies
GWP	Global Warming Potential
HEFA	Hydroprocessed Esters and Fatty Acids
IRR	internal rate of return
LCA	Life Cycle Assessment
LCI	life cycle inventory
LHV	lower heating value
LTAG	Long-Term Aspirational Goal
MEA	Monoethanolamine
MTK	methanol to kerosene
PEM	proton exchange membrane
PM	particulate matter

PSA	pressure swing adsorption
PSA	pressure swing adsorption
PSC	Point source capture
PV	photovoltaic
RFI	radiative forcing index
RWGS	reverse water gas shift
SAF	Sustainable Aviation Fuels
SCR	selective catalytic reduction
SMR	steam methane reforming
SOE	Solid oxide electrolysis
SPK	synthetic paraffinic kerosene
TRL	Technology Readiness Levels
TTW	tank to wake
WTT	well to tank
WTW	well to wake

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DECLARATIONS

Turnitin

The originality of this thesis has been reviewed with the Turnitin similarity checking service.

AI usage

The author of this thesis, Misagh Kas Aghaei Nahri, did not use any AI tools during the preparation of the thesis**.**

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The author, Misagh Kas Aghaei Nahri, takes full responsibility for the content of this thesis and has reviewed and edited the content generated by the possible use of AI tools.

1. Introduction

Aviation is vital today, enabling the fast movement of people and goods worldwide. It supports economic growth, tourism, and international collaboration (ICAO, 2019). Before the COVID-19 pandemic, air traffic was expected to triple by 2050 compared to 2020 levels, highlighting a major environmental challenge since aviation is a significant source of greenhouse gas (GHG) emissions and climate change (Gössling & Humpe, 2020).

The aviation sector currently contributes approximately 2–3% of global CO_2 emissions, with Europe's share slightly higher at around 4% (Destination 2050 Report, 2021). Although these percentages seem small, the impact is worsened by non-CO_2 effects, such as NO_x, contrails, and cirrus clouds from aircraft emissions, which greatly increase aviation's climate influence (Lee et al., 2010; Kärcher, 2016).

Global initiatives, including the International Civil Aviation Organization's (ICAO) Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) and commitments under the Paris Agreement, have promoted the utilization of sustainable aviation fuels (SAFs) to reduce aviation emissions. This includes biofuels, hydrogen, electro-kerosene (Power-to-Liquid), and ammonia-based fuels, all of which significantly decrease greenhouse gas emissions when produced sustainably (Bardon & Massol, 2023).
The European Union implemented the "Fit for 55" legislative package due to the recognition of the significance of mitigating aviation emissions. The objective is to reduce net greenhouse gas emissions by a minimum of 55% by 2030 relative to 1990 levels. The ReFuelEU Aviation regulation is central to this initiative. Sustainable aviation fuels must be incrementally blended into conventional jet fuel, achieving a minimum SAF proportion of 2% by 2025 and 63% by 2050. These regulations directly promote the adoption and advancement of novel fuel technologies within the aviation sector (European Commission, 2021).

To determine the total environmental effect of a product or system over its useful life, many turn to the scientifically sound and widely used Life Cycle Assessment (LCA) approach. Life cycle assessment (LCA) allows one to examine the entire process of using

alternative fuels in aviation, beginning with sourcing the materials, continuing through production, processing, use, and eventual disposal. This is referred to as the "well-to-wake" boundary in the context of aviation fuels (ICAO, 2019; Destination 2050 Report, 2021). Micheli et al. (2022) found that this method excels at identifying polluted areas, quantifying emissions, and consistently comparing fuel options.

This thesis examines current practices and technologies through the lens of attributional life cycle assessment (LCA), which makes use of verified data and widely accepted modeling tools. This approach offers a well-defined framework for assessing the performance of sustainable aviation fuels in real-world scenarios or in pilot and commercial trials (ISO, 2006a; ISO, 2006b). Using LCA, researchers, industry stakeholders, and policymakers can make more informed decisions by basing environmental benefits on actual data rather than hypothetical scenarios.

This thesis utilizes the GaBi software platform, adhering to ISO 14040 and 14044 standards (ISO, 2006a; ISO, 2006b), to perform a thorough environmental analysis of selected sustainable aviation fuels. These include options and situations involving hydrogen, ammonia, and electro-kerosene. We examine the greenhouse gas emissions and other environmental impacts of each fuel pathway to evaluate its sustainability relative to conventional jet fuel derived from fossil fuels.

The principal objective of this thesis is to assess the climate change impacts of sustainable aviation fuels (SAFs) via a thorough, data-driven life cycle analysis; additionally, I am evaluating other environmental impact categories, including freshwater eutrophication, marine eutrophication, and terrestrial acidification. This study aims to identify the most effective fuel pathways for mitigating climate change by examining greenhouse gas emissions and other climate-related factors throughout the entire production and utilization chain of sustainable aviation fuels (SAFs). The primary objective is to compare emissions from well-to-tank, encompassing variations at distinct flight altitudes, to demonstrate the actual atmospheric impact of SAF deployment. The study aims to generate actionable insights to promote decarbonization in the aviation sector and to enhance evidence-based policy decisions aligned with global climate goals through this methodology.

2. Background and Literature Review

2.1 Current Aviation Emissions Profile

Currently, the aviation sector accounts for nearly 2 to 3% of the world's energy-related CO_2 emissions, or just under 950 million tonnes (Mt) in 2023, with international travel rebounding to over 90% of pre-pandemic levels (IEA, 2024). While one may feel that the impact of aviation on climate may be small in comparison to other sectors in some ways, its overall climate impact is disproportionately higher due to non-CO_2 effects such as contrail-induced cirrus clouds, nitrogen oxides (NO_x), water vapour, and black carbon emissions at high altitudes. Given these considerations, total global warming contributions of this sector are roughly estimated to be between 3.5 percent and 5 percent, thereby greatly enhancing its environmental footprint (Lee et al., 2021; Ritchie, 2024).

Besides direct CO_2 emissions, aviation significantly contributes to climate change through various non-CO_2 effects. These include contrail-induced cirrus clouds, nitrogen oxides (NO_x), water vapor, and black carbon emissions, especially at high altitudes. Contrails and aviation-induced cirrus clouds trap outgoing infrared radiation, creating a warming effect known as radiative forcing, which is estimated to be 1.3 to 1.4 times greater than that caused by CO_2 alone (Lee et al., 2021; Kärcher, 2016). NO_x emissions, prevalent during combustion at high altitudes, further influence the climate by facilitating ozone (O_3) formation, thus increasing short-lived warming. Water vapor emissions contribute directly to contrail and cirrus cloud formation, amplifying the greenhouse effect. Addressing these non-CO_2 emissions is crucial for accurately assessing aviation’s climate impact and guiding the development and adoption of sustainable aviation fuels (Lee et al., 2021; ICAO, 2019).

Viewed from a historical standpoint, aviation emissions have rapidly expanded. From 1960 onwards, these aviation CO_2 emissions have almost multiplied sevenfold, going from approximately 150 Mt to in excess of 1,000 Mt every year (Ritchie, 2024). Thereafter, the trend continues with an average annual growth rate of 4–5% until the

COVID-19 pandemic was able to pause it for a while. By 2023, the industry was again nearly back on track by all accounts. (IEA, 2024).

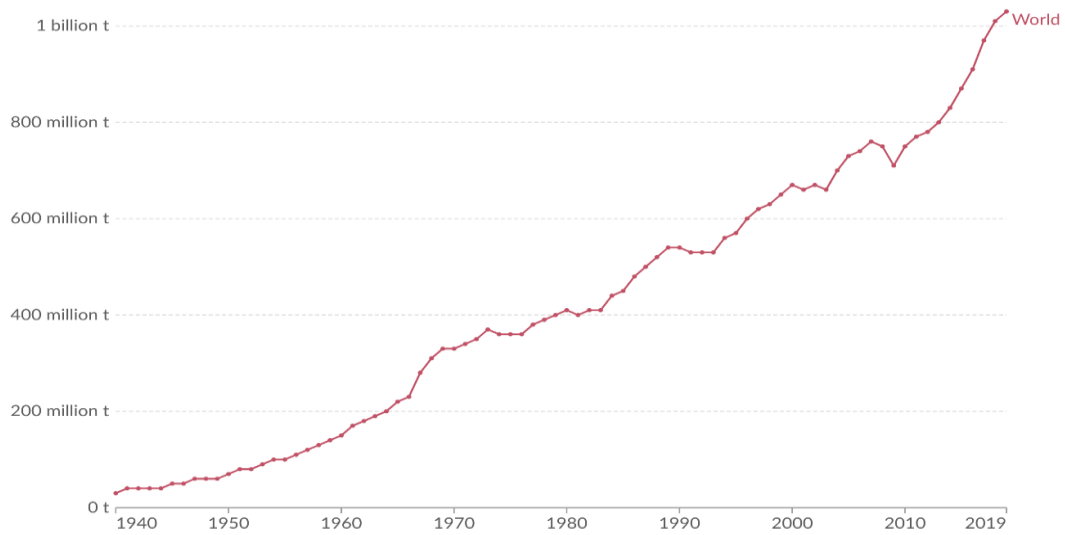

Figure 1. Global CO_2 emissions from aviation (1940–2020) Calculated by Our World in Data based on Lee et al. (2021), Bergero et al. (2023) – processed by Our World in Data.

Aviation-related CO_2 emissions have grown nearly tenfold since 1960, reaching over 1,000 Mt in 2018. The trend highlights the significant and sustained contribution of aviation to climate change (Lee et al. 2021).

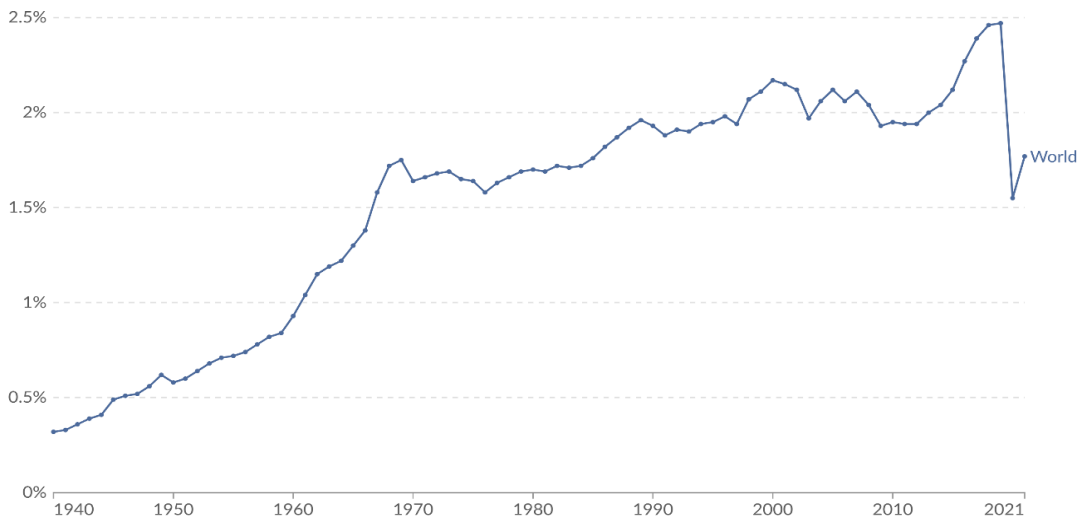

Figure 2. Aviation share of global CO2 emissions (1940–2020) Calculated by Our World in Data based on Lee et al. (2021), Bergero et al. (2023). – processed by Our World in Data.

Figure 2 shows the proportion of total anthropogenic CO_2 emissions attributable to aviation over time. Although aviation CO_2 emissions increased significantly in absolute terms, their share of global CO_2 emissions remained relatively stable at around 1.5–2.5%. (Lee et al., 2021).

With the industry's scale, air travel still remains an activity of just a fraction of the global population. It is estimated that just 10% of the world's population flies each year, with just 1% of frequent flyers responsible for more than half of the global aviation emissions (Ritchie, 2024). This creates an enormous inequality in the sectors' capacity for emissions responsibility.

Following CO_2, other pollution emissions weigh heavily in the total climate forcing by aviation. Contrails and cirrus clouds created by aircraft trap infrared radiation and contribute to the process of warming up the Earth. Hence, it is maintained that radiative forcing from the non-CO_2 impacts is actually 1.3 to 1.4 times more than the forcing caused by CO_2 emission alone (Lee et al., 2021). Together with CO_2 forcing, the total climate impact that aviation registers through non-CO_2 forcing pushes it far ahead in contrast to its direct emissions share.

A full breakdown of emissions by aircraft type and service type helps clarify how much each sector contributes to these emissions. In 2018, passenger transport emitted about 747 Mt of CO_2, depending on the mix between passenger transport in narrow, wide, or regional aircraft, and airports also used electricity and fuel. According to the International Council on Clean Transportation (ICCT) in 2019, narrow-body aircraft used mostly in short- and medium-haul flights emitted about 395 Mt CO_2, or 43% of the total; wide-body aircraft (the long-haul) emitted about 305 Mt CO_2, or 33%; and regional flights emitted about 47 Mt CO_2 (or 5% of the total). Finally, freight aviation emitted about 101 Mt of CO_2 in 2018, a direct result of airlines using both passenger and freight aircraft. The dedicated freighters emitted about 70 Mt CO_2 (8% of total aviation), and cargo transport in passenger aircraft belly holds emitted the remaining total (Graver et al., 2019).

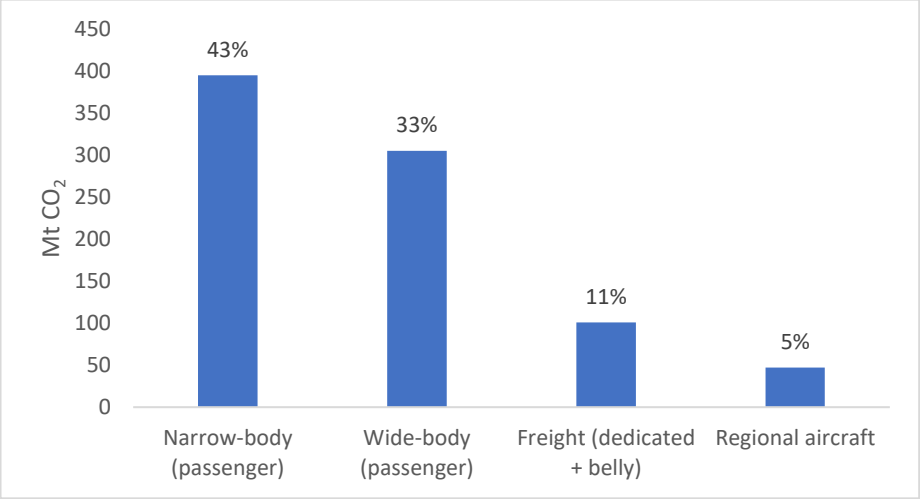

Figure 3. CO_2 Emissions by Aviation Segment (2018)

Another key factor related to emissions is the category of air travel. Premium seats, such as those available on business and first-class tickets, generate a notably larger carbon footprint per passenger due to larger space and more proportionate usage of resources. Studies have estimated that business class travel generates 2.6 times and first class generates up to 4.3 times as much CO_2 as economy class on a per passenger basis (Graver et al., 2019). This relates to the inequity in the likelihood of being held responsible for emissions in air travel.

Looking ahead, if we continue on the same path, aviation emissions are projected to double and possibly triple their contribution by 2050. Climate Action Tracker (2024) details that international aviation alone emitted roughly 600 Mt CO_2 in 2019, and this could rise to between 1,300 and 1,800 Mt CO_2 by 2050, depending on the rate of technological improvements, fuel substitutions, and regulatory action. The International Civil Aviation Organization (ICAO) estimates that the rate of emissions will continue to grow by 3-4% a year, and this growth would most likely only be mitigated by substantial gains in operational or fuel efficiencies (ICAO, 2019).

In light of the growing demand, technological constraints, and the urgency of climate change, it is essential to understand aviation's current emissions profile to assess the viability of sustainable aviation fuels. The emissions of aviation provide a baseline reference point for comparing alternative fuels, and they demonstrate where mitigation measures, such as improved aircraft design, efficiency improvements, operational changes, and sustainable fuels, will have the greatest impact. To build on this understanding, the next section explores

the full life cycle of conventional jet fuel, establishing a benchmark for comparison with sustainable alternatives.

2.2 Conventional Jet Fuel Lifecycle

The lifecycle of conventional petroleum-based jet fuel, referred to as "well-to-wake" (WtW), consists of two stages: the well-to-tank (WTT) stage, which includes extracting crude oil, moving it, refining it, and delivering it to airports, and the tank-to-wake (TTW) stage, which includes emissions from aircraft engines burning fuel. Jet A-1, the standard aviation kerosene, has a lower heating value (LHV) of approximately 43 MJ/kg (ICAO, 2019; IPCC, 2006). This fuel is the most popular for airplanes because it has a relatively high specific energy content, which means it provides a good balance between energy density and storage ease. According to ICAO, the global baseline for WtW emissions of conventional jet fuel is

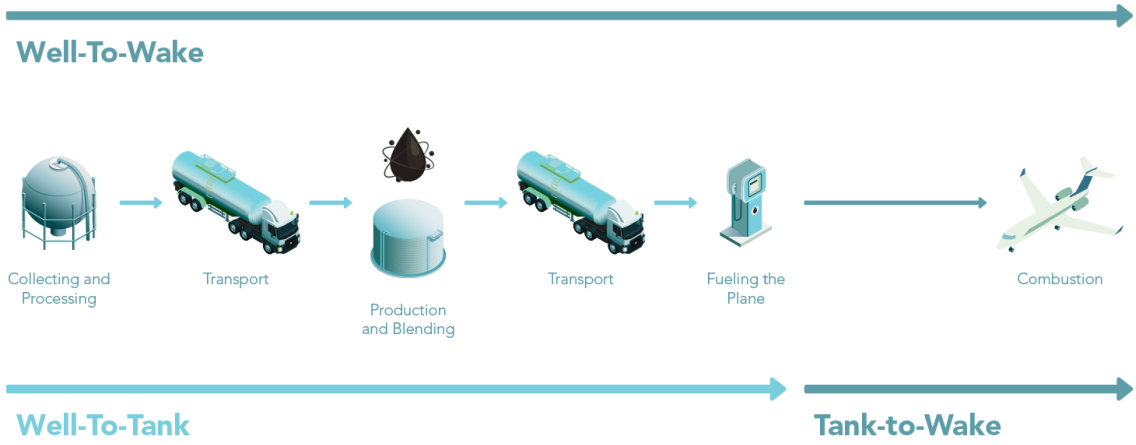

Figure 4. Well to Wake process (4AIR, 2022)

89.0 g CO_2e/MJ, nearly all of which is attributable to combustion (ICAO, 2019). A high-resolution study by Jing et al. (2022) reports a global volume-weighted average of 88.7 g CO_2e/MJ, with country-level variability ranging from 81.1 to 94.8 g CO_2e/MJ depending on crude type and refining configuration.

The TTW combustion stage contributes approximately 73.8 g CO_2e/MJ, equivalent to 3.16 kg CO_2 per kg of jet fuel, according to ICAO methodologies and confirmed by life cycle assessments (Jing et al., 2022; ICAO, 2019). Upstream activities in the WTT stage include crude production and transport (average 9.6 g CO_2e/MJ, with a range of 3.3–27.6 g/MJ) and refining/distribution (around 4.5 g CO_2e/MJ). These combine to yield a total WTT emission

intensity of approximately 14.1 g CO_2e/MJ, representing about 16% of total lifecycle emissions (Jing et al., 2022).

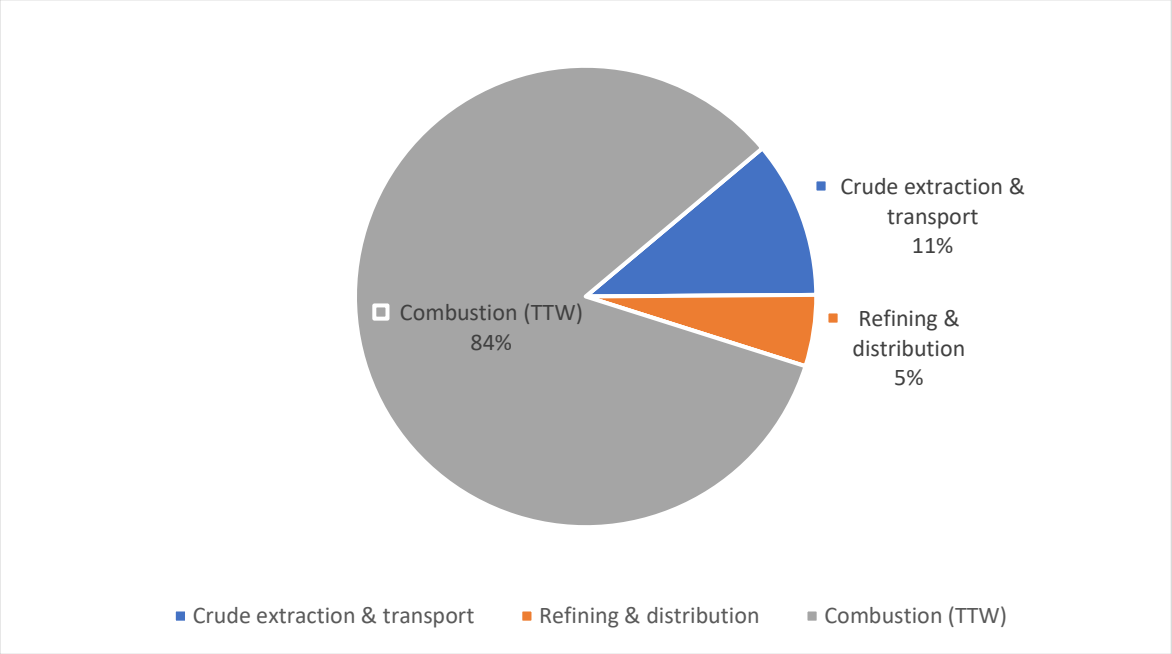

Figure 5. Lifecycle Emissions of Conventional Jet Fuel Jing et al. (2022); ICAO (2019)

The intensity of the lifecycle exhibits considerable variation across different regions. Jing et al. (2022) present values ranging from 81.1 to 94.8 g CO_2e/MJ, indicating variations due to crude type, extraction methods, and refinery technologies. U.S. petroleum jet fuel averages approximately 85.8 g CO_2e/MJ according to GREET modeling, in contrast to 88.0 g CO_2e/MJ reported in other studies.

The GREET model, created by Argonne National Laboratory in the U.S., serves as a recognized life cycle assessment tool that quantifies energy consumption and emissions associated with diverse fuel and vehicle technologies. This encompasses both upstream and downstream processes, from resource extraction to end-use, closely aligning with the well-to-wake (WtW) system boundary utilized in this study. GREET offers comprehensive, region-specific emission factors for various crude oil sources, refining techniques, and distribution systems, rendering it especially valuable for assessing fossil fuel baselines. The outputs are commonly utilized in comparative evaluations of sustainable aviation fuels to maintain consistency and transparency in life cycle assessment studies (Wang et al., 2020).

Opportunities for mitigation in the well-to-tank (WTT) stage, particularly in crude production and refining, may result in reductions of 2–7 g CO_2e/MJ, thereby decreasing the

total well-to-wheel (WTW) intensity to around 81–87 g CO_2e/MJ (Carvalho et al., 2023; Jing et al., 2022). Scenarios that include reduced flaring, enhanced energy efficiency, renewable energy integration in refineries, and carbon capture systems are anticipated to facilitate adherence to decarbonization objectives, such as those specified in the ICAO's Long-Term Aspirational Goal (LTAG) framework.

In summary, conventional jet fuel generates approximately 89 g CO_2e/MJ from well-to-wheel processes, with 84% attributed to combustion and 16% to upstream stages, while demonstrating considerable variability. Identifying and utilizing upstream emissions reduction opportunities is essential for meeting decarbonization targets, and this baseline is crucial for evaluating sustainable aviation fuels (SAF).

2.3 Emerging Fuel Pathways: Overview

The "Fit for 55" initiative set ambitious goals for the EU's regulatory environment, which is a key driver for the development and use of new SAF technologies. The ReFuelEU Aviation initiative, on the other hand, sets out a legally binding framework for gradually adding SAFs to commercial aviation fuel supplies. This push from regulators is meant to do more than just cut down on aviation's carbon footprint. It also encourages new technologies, better infrastructure, and strong markets for sustainable aviation fuels (European Commission, 2021; Destination 2050 Report, 2021).

The aviation industry is forging a diverse suite of promising low-carbon fuel options to move beyond fossil jet fuel. At the leading edge is HEFA-SPK, derived from hydroprocessing fats and oils (e.g., used cooking oil), currently ASTM-certified and widely deployed. According to the U.S. National Renewable Energy Laboratory, HEFA capacity could reach approximately 9.6 billion gallons annually in the U.S. alone by 2030, with life-cycle greenhouse gas (GHG) reductions between 50–80% depending on feedstock (NREL, 2023; Abayo et al., 2024).

FT-SPK, made via Fischer–Tropsch synthesis from biomass or municipal solid waste, is also blend-certified. The International Council on Clean Transportation estimates FT-SPK delivers 58–140% GHG savings compared to conventional fuel when lignocellulosic residues are used, thanks to carbon sequestration during biomass growth (ICCT, 2021).

Emerging alcohol-to-jet (ATJ-SPK) processes upgrade bioethanol or butanol into jet-range hydrocarbons. Plant-level techno-economic feasibility studies, including in Mexico,

highlight a return on investment of around 10–14% (Aburto et al., 2025). Although LCAs suggest that corn-based ATJ-SPK may offer less than 50% GHG reduction, which is lower than HEFA-SPK (Abayo et al., 2024).

An emerging route, sugar-to-jet (HFS-SPK), involves fermenting sugars to paraffinic hydrocarbons and has already received ASTM certification (Wang and Tao, 2016).

Pyrolysis or gasification-derived bio-SPKs convert woody or agricultural residues into intermediate bio-crude. These are currently in demonstration phases (e.g., DLR's European pilots) and offer feedstock flexibility (Braun, Grimme & Oesingmann, 2024).

On the synthetic fuel front, power-to-liquid (PtL), also called electrojet, uses renewable hydrogen and captured CO_2 via Fischer–Tropsch or methanol synthesis. German studies estimate PtL can achieve up to 70–90% life-cycle GHG savings, though system costs and scale-up remain hurdles (IEA-Bioenergy, 2024)

Ammonia has also entered the discussion as a long-term energy carrier for aviation. Research from the University of Manchester highlights its potential as a green hydrogen vector with zero combustion CO_2 emissions, while pointing to challenges such as nitrogen oxide (NO_x)/nitrous oxide (N_2O) emissions and the need for onboard cracking or hybrid combustion systems (Fullonton, Jones & Larkin, 2024). Ammonia's higher volumetric energy density compared to hydrogen makes it attractive, though energy storage needs increase due to lower gravimetric density. Projects in the UK and Australia are experimenting with ammonia propulsion for regional aircraft and ground operations (Plaza et al., 2023).

Finally, hydrogen propulsion, either through fuel cells or combustion of liquid or compressed hydrogen, remains a hopeful but longer-term option. Studies suggest regional aircraft may achieve flight-phase emission cuts of up to 75%, but major investments in cryogenic storage, fueling infrastructure, and airplane redesign are needed before scale-up (Sharma & Arief, 2024).

Table 1. Summary of Emerging SAF and Non-Hydrocarbon Pathways

Pathway	Feedstocks	Deployment Status
HEFA-SPK	Vegetable oil, used cooking oil	Commercial, ASTM-certified
FT-SPK	MSW, biomass residues	Near-commercial, ASTM-certified
ATJ-SPK	Ethanol, biobutanol	Pilot stages
HFS-SPK	Sugars (incl. lignocellulosic)	Newly ASTM-certified
Bio-SPK	Woody/agricultural residues	Demonstration phase
PtL/SPK	Green H_2 + captured CO_2	Pilot/early commercial
Ammonia	Green ammonia	Concept/pilot
Hydrogen	Liquid green H_2	Concept/pilot

These pathways reflect a rich landscape of innovation: HEFA-SPK and FT-SPK lead in near-term deployment; ATJ, HFS, and bio-SPK offer evolving flexibility; PtL stands out for its deep decarbonization; and ammonia, alongside hydrogen, may pave the way toward a zero-emission aviation future.

2.4 Hydrogen-Based Fuels for Aviation

Hydrogen has emerged as a highly promising option for sustainable aviation fuels, characterized by its impressive gravimetric energy density of around 120 MJ/kg, absence of direct CO_2 emissions, and the potential for production through renewable methods (Sharma & Arief, 2024). It greatly exceeds the specific energy of traditional jet fuels, which generally fall within the range of 43 MJ/kg (Soleymani et al., 2024). The elevated specific energy of hydrogen renders it particularly advantageous for aviation applications, where weight factors play a crucial role in influencing fuel efficiency and the overall performance of aircraft.

Hydrogen is categorized into three primary types according to the method of its production: grey, blue, and green hydrogen. Grey hydrogen is generated from fossil fuels, primarily natural gas, through steam methane reforming (SMR), a method that results in considerable CO_2 emissions. Blue hydrogen employs steam methane reforming (SMR) while integrating carbon capture and storage (CCS) technologies to mitigate related emissions. Green hydrogen is produced via water electrolysis that utilizes renewable electricity, leading to negligible lifecycle emissions (Tveitan, 2020; Cybulsky et al., 2024). Among these, green hydrogen stands out as the most environmentally sustainable option and presents significant potential for decarbonizing the aviation sector.

The production of hydrogen encompasses various technological processes that are influenced by the type of feedstock and the energy source utilized. The predominant approach for large-scale hydrogen production currently is Steam Methane Reforming (SMR), in which methane interacts with steam at elevated temperatures (700–1,000°C) with the aid of a catalyst to yield hydrogen and carbon monoxide. This is subsequently transformed into carbon dioxide and additional hydrogen via a water-gas shift reaction (Sharma & Arief, 2024). Although efficient, SMR that lacks carbon capture leads to significant CO_2 emissions, rendering it inappropriate for sustainable aviation fuel unless integrated with CCS.

In contrast, water electrolysis offers a carbon-free pathway when powered by renewable electricity. In this process, water (H_2O) is split into hydrogen and oxygen using an electric current. There are several types of electrolysis technologies, including:

Alkaline Electrolysis (AEL): Alkaline electrolysis is the most mature and industrially established method for hydrogen production via electrolysis. It typically uses a concentrated aqueous potassium hydroxide (KOH) solution as the electrolyte. It operates under mild conditions, generally between 65°C and 100°C, and at pressures of up to 30 bar (Li et al., 2022; Bessarabov, D. G. et al., 2016). The electrochemical reactions proceed as follows:

At the cathode: $2H_2O + 2e^- \rightarrow H_2(g) + 2OH^-$

At the anode: $2OH^- + \frac{1}{2}O_2(g) \rightarrow H_2O + 2e^-$

A diaphragm separates the anode and cathode compartments, preventing the mixing of hydrogen and oxygen gases while allowing ionic conduction. Nickel or nickel-coated steel is typically used for electrodes due to its corrosion resistance and catalytic properties (Shao et al., 2025). The system is relatively simple and cost-effective, though it typically exhibits lower current density and dynamic response compared to more advanced electrolyzer types (Bessarabov, D. G. et al., 2016).

Proton Exchange Membrane (PEM) Electrolysis: PEM electrolysis employs a solid polymer electrolyte membrane usually made from Nafion, which conducts protons (H^+) from the anode to the cathode while preventing gas crossover. Unlike alkaline systems, PEM electrolysis operates in acidic environments at 90 °C and can withstand pressures up to 200 bar (Bessarabov, D. G. et al., 2016).

The half-cell reactions in a PEM electrolyzer are:

At the anode: $H_2(l) \rightarrow 2H^+ + \frac{1}{2}O_2(g) + 2e^-$

At the cathode: $2H^+ + 2e^- \rightarrow H_2$

Water is fed into the anode, where it is split into protons and oxygen. The protons migrate through the membrane to the cathode, where they recombine with electrons to form hydrogen gas. PEM electrolyzers offer advantages such as compact design, fast start-up, and high current density. However, they rely heavily on expensive noble metals like platinum and iridium for catalysis (Bessarabov, D. G. et al., 2016).

Solid Oxide Electrolysis (SOE): Solid oxide electrolysis cells (SOECs) operate at high temperatures, typically between 800 °C and 1000 °C. They use a ceramic electrolyte material, such as yttria-stabilized zirconia (YSZ), that conducts oxygen ions (O^{2-}). This high-temperature environment significantly enhances electrode kinetics and allows for efficient integration of thermal and electrical energy inputs (Bessarabov, D. G. et al., 2016).

The electrochemical reactions in SOECs are:

At the cathode (hydrogen electrode): $H_2O + 2e^- \rightarrow H_2 + O^{2-}$, $CO_2 + 2e^- \rightarrow CO + O^{2-}$

At the anode (oxygen electrode): $2O^{2-} \rightarrow O_2 + 4e^-$

Water vapor is introduced at the cathode side, where it is reduced to hydrogen gas and oxygen ions. These ions migrate through the solid electrolyte and are oxidized at the anode, producing oxygen gas. SOECs offer high electrical efficiency and are especially suited for coupling with renewable electricity and industrial waste heat. However, long-term durability and material degradation, especially at the electrode/electrolyte interfaces, remain challenges (Bessarabov, D. G. et al., 2016; Song et al., 2019).

The efficiency of electrolysis generally varies between 60% and 80%, contingent upon the technology employed and the operational parameters. The environmental impact of hydrogen generated via electrolysis is directly linked to the carbon intensity of the electricity source; hydrogen can only be deemed genuinely green when derived from wind, solar, or other renewable sources (Tveitan, 2020).

There are two primary methods for utilizing hydrogen in aviation: direct combustion in gas turbine engines and conversion to electricity through fuel cells (Soleymani et al., 2024). Direct hydrogen combustion entails the incineration of hydrogen within modified gas turbine engines, utilizing current infrastructure while requiring modifications due to the unique combustion characteristics of hydrogen. Fuel cells, specifically proton exchange membrane (PEM) and solid oxide fuel cells (SOFC), provide a more efficient and environmentally friendly conversion process, producing negligible emissions aside from water vapor (Tveitan, 2020).

Liquid hydrogen (LH_2) is the favored storage medium in aviation owing to its reduced volume requirements relative to gaseous hydrogen, notwithstanding the challenges associated with cryogenic storage conditions at approximately -253°C (Cybulsky et al., 2024). The necessity for cryogenic storage adds complexity to tank design, insulation, and infrastructure, thereby significantly impacting the aircraft's overall design, payload, and operational efficiency (Sharma & Arief, 2024). Liquid hydrogen offers advantages over

alternative storage methods like compressed hydrogen, including superior gravimetric density, lighter storage tanks, and proven technological feasibility (Soleymani et al., 2024).

Numerous global aviation entities are diligently advancing hydrogen propulsion technology. Airbus's ZEROe initiative seeks to launch commercial hydrogen-powered aircraft by 2035, while research projects like ENABLEH2 and FlyZero anticipate commercial feasibility prior to 2050 (Ebrahimi et al., 2024). Moreover, hydrogen-electric aircraft utilizing fuel cells, like those created by ZeroAvia and Universal Hydrogen, are currently exhibiting feasibility for shorter-range regional flights (Ebrahimi et al., 2024).

Life cycle assessments (LCAs) demonstrate considerable potential for emission reductions when hydrogen is produced sustainably through renewable energy sources (Tveitan, 2020). Hydrogen generated through water electrolysis utilizing renewable electricity demonstrates nearly negligible lifecycle greenhouse gas emissions, markedly diminishing global warming potential (GWP) in comparison to traditional jet fuel (Tveitan, 2020; Bicer & Dincer, 2017). Nonetheless, the life cycle assessment of hydrogen aviation fuel must also account for high-altitude impacts. While hydrogen combustion generates no CO_2, it releases substantial amounts of water vapor (H_2O) at cruising altitudes. This water vapor facilitates contrail formation, which may subsequently result in enduring cirrus clouds. Contrails can entrap outgoing longwave radiation, leading to positive radiative forcing and contributing to climate warming (Kärcher, 2016).

Additionally, hydrogen combustion can generate trace quantities of nitrogen oxides (NO_x) as a result of high-temperature reactions between atmospheric nitrogen and oxygen (thermal NO_x mechanism). NO_x emissions can facilitate the formation of ozone (O_3), a transient climate pollutant, in the upper troposphere and lower stratosphere, thereby exacerbating the climatic impacts of hydrogen-based aviation fuels (Lee et al., 2021).

Although the direct CO_2 emissions from hydrogen are virtually nonexistent, indirect impacts, including contrail-induced cirrus cloudiness and NO_x-related ozone production, must be considered in life cycle assessment modeling. The current integration of these impacts into sophisticated LCA frameworks employs metrics such as Global Warming Potential over 100 years (GWP100) and Effective Radiative Forcing (ERF) (Tveitan, 2020; Lee et al., 2021)..

However, several technical and economic challenges remain. Key hurdles include optimizing fuel cell specific power, storage tank gravimetric efficiency, infrastructure development for hydrogen distribution, and onboard fuel management systems (Cybulsky et al., 2024; Sharma & Arief, 2024). Additionally, achieving economically competitive hydrogen production and building extensive fueling infrastructure requires coordinated international efforts and substantial investment (Cybulsky et al., 2024).

Table 2. Summary of Hydrogen-based Aviation Fuel Characteristics (Soleymani et al., 2024; Ebrahimi et al., 2024)

Attribute	Description
Specific Energy	120 MJ/kg (higher than conventional jet fuel, 43 MJ/kg)
Storage Conditions	Cryogenic (-253°C for LH_2)
Emissions	Zero direct CO_2 emissions (water vapor as byproduct)
Technology Readiness	Medium (gas turbine combustion), Low-Medium (fuel cell-based propulsion)
Infrastructure	Under development (requires significant adaptation of airports, storage, and distribution systems)
Primary Challenges	Cryogenic storage, onboard tank design, infrastructure, and economic competitiveness

In conclusion, hydrogen-based fuels hold significant potential for reducing aviation emissions and transitioning towards sustainability, provided technological and economic challenges can be effectively addressed.

2.5 Electro-Kerosene (Power-to-Liquid)

Electro-kerosene, or power-to-liquid (PtL) kerosene, is a synthetic aviation fuel generated by converting electricity into liquid hydrocarbons appropriate for aviation use. This production pathway utilizes hydrogen derived from water electrolysis, energized by renewable electricity, and integrates it with carbon dioxide (CO_2), generally obtained from

industrial emissions or directly from industries through point source capture technologies (Micheli et al., 2022; Papantoni et al., 2022; Tanzer, Blok, and Ramírez, 2023).

Two principal methods for synthesizing electro-kerosene are currently prominent: Fischer–Tropsch (FT) and Methanol-to-Kerosene (MTK) routes (Dell'Aversano et al., 2024).

The Fischer–Tropsch (FT) electro-kerosene production pathway encompasses several critical processes: hydrogen generation through electrolysis, CO_2 capture, synthesis gas (syngas) generation via reverse water gas shift (RWGS), and ultimately, hydrocarbon synthesis through Fischer-Tropsch (FT) synthesis (Gavril, 2023; Rojas-Michaga et al., 2023).

The Fischer-Tropsch process transforms syngas, predominantly consisting of hydrogen (H_2) and carbon monoxide (CO), into liquid hydrocarbons. Hydrogen for syngas production is generated via electrolysis, whereas carbon monoxide is typically produced from captured carbon dioxide through the reverse water-gas shift (RWGS) reaction. The FT synthesis is a well-established and commercially validated technology that produces synthetic crude oil (FT syncrude), which is then enhanced through hydrocracking and distillation to generate jet-range hydrocarbons (Gavril, 2023; Rojas-Michaga et al., 2023). The resultant product, commonly known as synthetic paraffinic kerosene (SPK), closely resembles the characteristics of conventional Jet A-1. The lower heating value is approximately 43 MJ/kg, virtually equivalent to fossil kerosene. The equivalence in energy density supports its designation as a drop-in fuel, enabling direct utilization in current aircraft engines and fueling infrastructure.

FT-based electro-kerosene is notably beneficial owing to its maturity and scalability, bolstered by substantial industrial experience from facilities like those of Shell and Sasol. Life cycle assessments demonstrate significant reductions in greenhouse gas (GHG) emissions, varying from 52.6% to over 88.9% in comparison to fossil-derived jet fuel when utilizing renewable electricity and direct air capture (DAC). There is a complete reduction of SO_2 and approximately a 10% reduction of NOx (Micheli et al., 2022; Ozkan et al., 2024).

The MTK pathway catalytically synthesizes hydrogen and CO_2 into methanol. Methanol is subsequently converted into kerosene through dehydration, oligomerization, and

hydrotreatment processes. This pathway provides benefits including elevated selectivity and adaptable integration with current chemical infrastructure. Commercial viability has been established through multiple pilot projects currently investigating scalability potential (Dell'Aversano et al., 2024).

Electro-kerosene produced by MTK has shown reductions in lifecycle greenhouse gas emissions, primarily influenced by the carbon intensity of electricity sources and the efficiencies in the methanol synthesis process. The primary challenge related to the MTK pathway is attaining efficient methanol synthesis on a large scale, necessitating significant enhancements in catalyst efficacy and energy management (Ozkan et al., 2024).

The electrolysis process is an essential element in the PtL chain, with alkaline electrolysis (AEL), proton exchange membrane (PEM) electrolysis, and solid oxide electrolysis (SOE) as the primary technologies. PEM electrolysis provides benefits including compactness and swift responsiveness to intermittent electricity, rendering it suitable for integration with renewable energy sources such as wind and solar power. Nonetheless, cost and energy efficiency continue to pose challenges necessitating additional optimization to diminish the total fuel expenditure (Dell'Aversano et al., 2024).

CO_2 capture profoundly impacts the environmental efficacy and sustainability of electro-kerosene. Direct Air Capture (DAC), which extracts atmospheric CO_2, can substantially diminish lifecycle emissions; however, it is energy-intensive and costly. Conversely, point-source capture from industrial processes can decrease expenses but may constrain carbon neutrality. Notwithstanding these constraints, progress in DAC technology, decreases in renewable electricity costs, and enhancements in FT synthesis indicate potential future reductions in production expenses and overall environmental effects (Ozkan et al., 2024).

Lifecycle assessments (LCA) indicate that PtL kerosene generated from renewable energy possesses significant potential to diminish greenhouse gas (GHG) emissions in comparison to fossil jet fuel. Research demonstrates that electro-kerosene can realize greenhouse gas emission reductions between approximately 52.6% and over 88.9%, contingent upon the electricity source and the particular technologies employed (Micheli et al., 2022; Rojas-Michaga et al., 2023). For instance, employing electricity generated from wind power in

conjunction with high-temperature electrolysis and low-temperature direct air capture produces notably advantageous lifecycle results (Micheli et al., 2022).

The overall well-to-wake energy efficiency of PtL fuels is typically low, generally falling between 10% and 15%, attributable to the numerous energy conversion steps required (Gavril, 2023).

One significant benefit of electro-kerosene is its compatibility as a drop-in fuel. It is chemically analogous to Jet-A and can be utilized in current aircraft engines and airport fueling systems without necessitating modifications. This compatibility minimizes the necessity for costly infrastructure modifications and enhances the potential for deployment in commercial aviation (Dell'Aversano et al., 2024).

While PtL kerosene exhibits zero upstream CO_2 emissions when produced with renewable electricity and direct air capture or point source capture, its combustion generates CO_2 emissions similar to those of fossil-derived kerosene. Nonetheless, the CO_2 emitted during combustion is regarded as part of a closed carbon cycle, as it was initially captured from the atmosphere or industrial sources. This cycle inhibits a net rise in atmospheric CO_2, a fundamental concept in carbon-neutral fuel strategies (Papantoni et al., 2022).

PtL fuels exhibit several critical differences from conventional jet fuels regarding their impacts on high-altitude atmospheric conditions. Both emit water vapor and nitrogen oxides (NO_x) during combustion; however, PtL fuels contain minimal sulfur or aromatic compounds, leading to negligible SO_2 and soot emissions. The lack of soot decreases the probability and duration of contrail formation, as ice crystals possess fewer nucleation sites. While NO_x emissions can contribute to ozone (O_3) formation at cruising altitudes and affect radiative forcing, PtL fuels typically present a markedly reduced non-CO_2 climate impact in comparison to fossil kerosene (Lee et al., 2021).

Consequently, although PtL fuels provide considerable advantages regarding carbon neutrality and lifecycle emissions, their total climate impact is affected by non-CO_2 effects. These effects are progressively integrated into sophisticated LCA models utilizing metrics such as Effective Radiative Forcing (ERF) and GWP100 (Micheli et al., 2022; Lee et al., 2021).

Economic evaluations highlight the difficulties associated with the scaling of PtL technologies. Current production costs exceed those of conventional jet fuel, primarily due to the substantial energy requirements associated with electrolysis and direct air capture (DAC) processes. Projected costs of e-fuels are expected to decline substantially by mid-century, influenced by technological advancements, economies of scale, carbon pricing, and supportive policy frameworks (Gavril, 2023).

Numerous international initiatives and pilot projects, especially in Europe and North America, are currently investigating PtL technologies. Germany, Denmark, and the United States have established strategic initiatives to enhance the commercialization and adoption of electro-fuels. These initiatives include production incentives, mandatory blending targets, and research funding aimed at addressing existing technological challenges (Dell'Aversano et al., 2024).

Table 3. Summary of Electro-Kerosene Aviation Fuel Characteristics (Dell'Aversano et al., 2024; Ozkan et al., 2024)

Attribute	Description
Energy Source	Renewable electricity (e.g., wind, solar)
Key Technologies	Electrolysis (PEM, AEL, SOE), DAC, MTK, Fischer-Tropsch synthesis
Emissions	Significant reduction compared to fossil fuels; it depends on the electricity source
Technological Readiness	Medium to high (FT synthesis); Low to medium (DAC, electrolysis integration at scale)
Infrastructure	Partially compatible with existing infrastructure; requires upgrades for full integration
Primary Challenges	Cost, energy intensity of DAC, and electrolysis efficiency

In conclusion, electro-kerosene produced through FT and MTK pathways represents a promising and technologically mature solution for achieving significant emissions reductions in aviation. Continued development, policy support, and infrastructure

investment are essential to overcoming economic barriers and enabling widespread adoption in the aviation sector.

2.6 Bio-Derived Jet Fuels

In this chapter, we are going through different types of biojet-fuels and explain their pathways and production methods, feedstocks, and their environmental impacts.

2.6.1 Hydroprocessed Esters and Fatty Acids

Hydroprocessed Esters and Fatty Acids (HEFA) represent the most commercially mature and widely adopted pathway for producing sustainable aviation fuels (SAFs). The HEFA process converts various lipid-based feedstocks, including used cooking oil, animal fats (tallow), and vegetable oils, into hydrocarbons suitable for aviation through catalytic hydrogenation. The resulting fuel, known as HEFA Synthetic Paraffinic Kerosene (HEFA-SPK), has received certification from ASTM for blending with conventional jet fuels at a ratio of up to 50%, allowing its deployment in existing aircraft and infrastructure without requiring modifications (Farooq et al., 2025).

The production of HEFA-SPK begins with the collection and pretreatment of feedstocks to remove contaminants and optimize the quality of the input. These lipid feedstocks are then subjected to catalytic hydrotreatment, where hydrogen gas is introduced under elevated pressure and temperature in the presence of catalysts, commonly nickel or platinum-based. This step facilitates several reactions, including hydrogenation, deoxygenation, and isomerization, ultimately converting triglycerides into straight and branched-chain hydrocarbons that mimic the properties of conventional jet fuel (John et al., 2024).

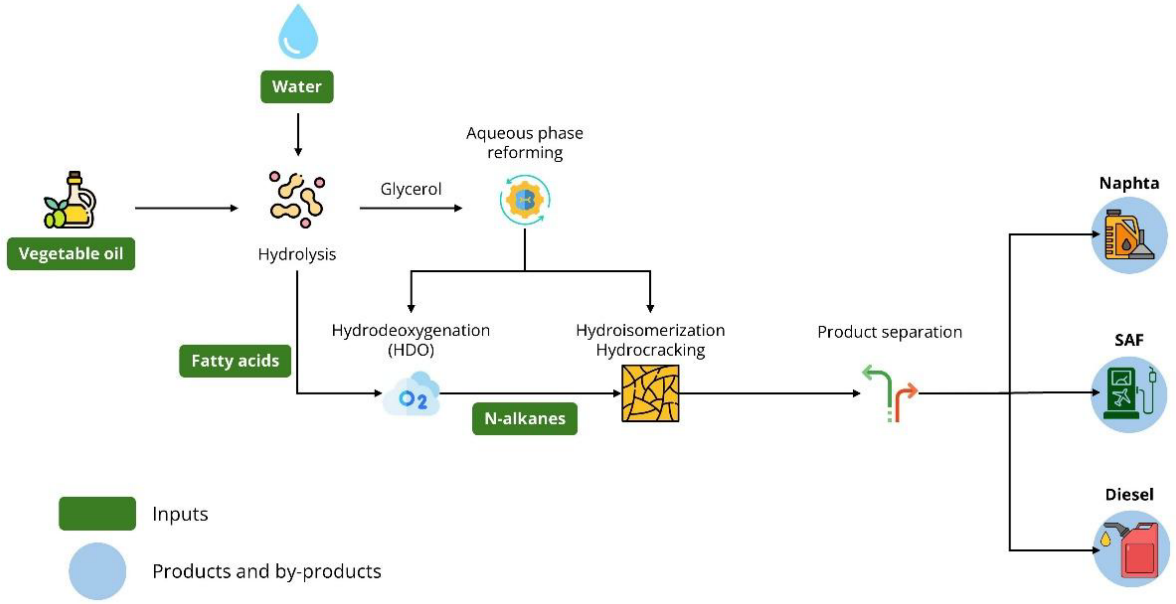

Figure 6. The Hydroprocessed Esters and Fatty Acids (HEFA) pathway to Sustainable Aviation Fuel (SAF) (adapted from https://www.czapp.com/analyst-insights/hydrogens-crucial-role-in-saf-production/).

After hydrotreatment, the product mixture is separated into different parts to get rid of the kerosene-range hydrocarbons. The finished HEFA-SPK product meets strict standards for aviation fuel, such as those for cold flow properties, energy content, and oxidation stability. Its low aromatic content is important because it not only makes combustion better, but it also cuts down on the amount of soot and particulate matter that is released during combustion (Rohkamp et al., 2025).

When it comes to aviation, HEFA-SPK can be used as a drop-in replacement fuel. This means that it can be mixed with fossil-derived Jet A-1 fuel and used in current aircraft engines without needing any technical changes. HEFA is one of the most practical short-term solutions for making air travel less carbon-intensive because it works with existing aviation infrastructure and propulsion systems. When you use HEFA-blended fuels in an airplane, it produces less carbon dioxide (CO_2), unburned hydrocarbons, carbon monoxide (CO), nitrogen oxides (NO_x), and particulate matter (PM). These reductions in emissions are very important for reducing the negative effects of aviation on the environment and climate. This is especially true because the industry contributes to radiative forcing and non-CO_2 effects like contrail formation and induced cirrus clouds (Gawron et al., 2020; Lee et al., 2021).

Recent research has shown that burning HEFA-SPK produces much less soot and non-volatile particulate matter (nvPM) than other fuels. For instance, substituting conventional Jet A-1 fuel with 100% HEFA-SPK can decrease nvPM emissions by as much as 81%, and the distribution of particle number size shifts toward smaller, less harmful particles (Rohkamp et al., 2025). This not only makes the air around airports cleaner, but it also cuts down on the high-altitude particles that warm the atmosphere (Dischl et al., 2024).

Over its whole life cycle, HEFA-SPK cuts greenhouse gas (GHG) emissions by a lot compared to regular jet fuels. Research on lifecycle assessment (LCA) indicates that emissions can be reduced by 48% to 83%, contingent upon the feedstock and its production method (Abayo et al., 2024). HEFA made from used cooking oil saves a lot of greenhouse gases because it is a waste product, which means it doesn't cause emissions from land use change. The aviation sector's goals for reducing carbon emissions, as outlined in frameworks like ICAO's CORSIA and the EU's Fit for 55 package (Seber et al., 2014; ICAO, 2019), are in line with these climate benefits.

The price and availability of feedstocks have the biggest impact on how cost-effective it is to make HEFA. Techno-economic studies show that the price of feedstock is the main thing that affects the minimum jet fuel selling price (MJSP). This means that HEFA's economic success depends a lot on how well it works with existing refinery infrastructure and how well it optimizes the supply chain (Farooq et al., 2025). These factors pose challenges for large-scale adoption, especially in regions where lipid feedstock supply is limited.

Despite these strengths, the HEFA pathway faces several challenges. One of the biggest concerns is that lipid feedstocks are hard to find and don't last very long. Using oils from crops like palm or soybean oil can cause deforestation, loss of biodiversity, and indirect land use change (ILUC), which could cancel out some of the environmental benefits of SAF deployment (Mai et al., 2024). Used cooking oil and tallow are also examples of residual feedstocks that are hard to use on a large scale because they are limited in quantity and location (Pilicita et al., 2025).

To alleviate these limitations, research is increasingly focusing on alternative and innovative feedstocks, including microbial oils, algae, and agro-industrial residues. Microbial oils, produced by oleaginous microorganisms from sugar-based or lignocellulosic substrates, offer a promising strategy for enhancing the HEFA feedstock base while simultaneously improving environmental performance and land-use efficiency (Marchesan et al., 2024).

The HEFA pathway is a high-tech and eco-friendly way to reduce carbon emissions in the aviation industry. It works well with the infrastructure we already have, has a lot of well-documented life-cycle assessment data, and has a lot of potential for cutting greenhouse gas emissions. It is also very important in the fight against climate change because it can lower climate impacts that aren't CO_2, like particulate emissions and contrail formation. But to reach its full potential, it will need to keep making progress in feedstock sustainability, process efficiency, and policy support to get past economic and scalability problems.

2.6.2 Fischer-Tropsch-Biofuels

Fischer–Tropsch (FT) synthesis is a crucial method for generating sustainable aviation fuels (SAFs) through the conversion of synthesis gas (syngas), mainly consisting of hydrogen (H_2) and carbon monoxide (CO), into liquid hydrocarbons. Feedstocks for FT-derived fuels comprise renewable sources, including biomass, carbon dioxide (CO_2), and waste streams, which are subjected to gasification or alternative processes to generate syngas (Davlatova, M. 2023).

The Fischer-Tropsch synthesis entails a catalytic process, commonly employing cobalt or iron catalysts at regulated temperatures (180°-280° C) and pressures (15-30 bar) to polymerize carbon monoxide and hydrogen molecules in a 1:2 ratio into diverse hydrocarbon chains. The generated hydrocarbons necessitate further upgrading processes, including hydrocracking, to conform to aviation fuel specifications by optimizing chain length and diminishing unsaturated hydrocarbons and oxygenates (Boilley et al., 2024; Soler et al., 2022).

Feedstock alternatives substantially affect the ecological impact and financial feasibility of FT-derived fuels. Biomass and waste-derived syngas exhibit comparatively lower greenhouse gas (GHG) emissions than fossil-based feedstocks. Nonetheless, syngas

generated from biomass gasification may harbor impurities such as ammonia (NH_3) and hydrogen cyanide (HCN), necessitating supplementary treatment processes or catalytic tolerance to contaminants (Voeten et al., 2024).

Recent studies investigated the integration of Fischer-Tropsch synthesis with renewable energy-driven processes, including high-temperature solid oxide electrolysis cells (SOEC). This method can generate syngas from water and CO_2, significantly diminishing carbon emissions. The solar-driven Fischer-Tropsch pathway combined with solid oxide electrolysis cells can achieve a solar-to-fuels efficiency of around 12.8%, suggesting a viable option for sustainable Fischer-Tropsch fuel production (Lin et al., 2023).

Lifecycle assessment (LCA) indicates that the carbon efficiency of the FT pathway is elevated, generally ranging from 98% to 99% for total liquid products. Kerosene yield efficiency ranges from 60% to 77%, contingent upon process parameters such as chain growth probability and hydrocracking conditions. The methanol-to-kerosene pathway may demonstrate superior kerosene-specific carbon efficiency (60%-90%), yet its overall product efficiency is relatively diminished (74%-92%), rendering FT synthesis competitive (Bube et al., 2024).

Techno-economic evaluations reinforce the viability of FT-derived SAFs, demonstrating that the capital and operational expenditures, although considerable, conform to standard ranges for biomass-to-liquid facilities. FT plants exhibit energy efficiencies exceeding 80%, underscoring their commercial feasibility for extensive applications. The global efficiency is significantly affected by the efficiency of hydrogen production, which varies considerably depending on the employed technology (Boilley et al., 2024).

Ammonia contaminants in the feedstock for FT processes are primarily transformed into organic amines, which are mainly found in the water phase and wax products. This suggests a possible decrease in the complexity and expense related to gas purification, contingent upon the downstream processes' capacity to effectively manage the resultant amines (Voeten et al., 2024).

FT-derived SAFs possess considerable potential for aviation decarbonization owing to their compatibility with current aircraft engines and fuel infrastructure, their capacity to employ diverse renewable feedstocks, and their advantageous environmental performance evidenced by comprehensive LCA analyses. Notwithstanding the obstacles, progress in catalytic technologies, amalgamation with renewable energy sources, and refinement of downstream processes consistently improve their viability and sustainability.

2.6.3 Alcohol-to-Jet

The Alcohol-to-Jet (ATJ) production pathway signifies a promising and progressively feasible method for generating sustainable aviation fuels (SAFs). It predominantly employs biomass-derived alcohols, including ethanol and isobutanol, which can be obtained from diverse renewable feedstocks such as sugarcane, corn, lignocellulosic biomass, and industrial waste streams. Lignocellulosic biomass, including forestry residues, agricultural by-products, and dedicated energy crops, presents significant potential owing to its abundance and reduced environmental impact (Mendieta et al., 2025; Santos et al., 2023).

The ATJ process comprises a sequence of conversion stages, commencing with the fermentation of biomass feedstocks into alcohols. Sugar-based crops such as sugarcane directly produce ethanol, whereas lignocellulosic materials necessitate a more intricate process that includes pretreatment, enzymatic saccharification, and fermentation to generate bioethanol (Mendieta et al., 2025). The generated alcohol is subsequently dehydrated into olefins, including ethylene, via catalytic methods. The olefins are then oligomerized into extended hydrocarbon chains. The resultant hydrocarbons undergo hydrotreatment and isomerization to produce branched paraffinic hydrocarbons, thereby improving fuel quality. The requisite jet fuel fraction is achieved via fractionation, yielding a product that complies with ASTM D7566 standards (Mawhood et al., 2016).

ATJ technology has advanced considerably, with present systems approaching or attaining commercial viability. Ethanol-to-jet and isobutanol-to-jet fuels have received certification under ASTM D7566, permitting their blending with conventional jet fuels. Companies like LanzaJet have notably established commercial-scale facilities, including the Freedom Pines plant, which has been operational since early 2024, demonstrating that the technology has attained elevated Technology Readiness Levels (IEA Bioenergy, 2024). These facilities are

integral to an expanding international initiative aimed at commercializing Sustainable Aviation Fuels (SAFs) and significantly aiding the decarbonization of the aviation industry.

A primary advantage of ATJ fuels is their capacity to serve as drop-in substitutes for conventional Jet-A1 fuels. This indicates that they can presently be mixed up to 50% by volume with petroleum-based jet fuels and utilized in existing aircraft engines and fueling infrastructure without any alterations. This compatibility significantly enhances their integration into commercial aviation. ATJ-SPK (Synthetic Paraffinic Kerosene) has been effectively utilized in both commercial and military aviation, with airlines like Virgin Atlantic performing test flights using ATJ blends to validate their viability (IEA Bioenergy, 2024; Santos et al., 2023).

The ATJ pathway provides significant environmental advantages. Lifecycle assessments demonstrate that ATJ fuels can diminish greenhouse gas emissions by 50% to 75% relative to fossil-derived jet fuels, significantly influenced by the selection of feedstock and energy inputs (IEA Bioenergy, 2024). Ethanol produced from sugarcane, particularly in nations such as Brazil, where mills utilize bagasse for energy, demonstrates notably low carbon intensity. Corn ethanol, although readily accessible, possesses a greater and more contentious carbon footprint owing to the energy-intensive processes involved in its production. Lignocellulosic biomass, as an advanced feedstock, presents significant potential for emissions reduction, contingent upon the utilization of renewable energy inputs and the minimization of land-use impacts (Mendieta et al., 2025; Santos et al., 2023).

Besides diminishing carbon emissions, ATJ fuels also aid in decreasing in-flight emissions of non-CO_2 pollutants. ATJ blends generate reduced particulate emissions and sulfur oxides owing to their diminished aromatic and sulfur content relative to conventional jet fuels. This enhances local air quality near airports and diminishes the formation of contrails and other non-CO_2 climatic impacts. Studies indicate that ATJ-SPK blends can achieve approximately a 50% decrease in soot particle emissions and enhance combustion properties (IEA Bioenergy, 2024).

Notwithstanding these benefits, obstacles persist. The sustainability and accessibility of biomass feedstocks, along with logistical challenges associated with their collection and transportation, present obstacles to scalability. Economic limitations, specifically the elevated capital and operational expenses linked to ATJ conversion processes, impede swift implementation. Resolving these challenges necessitates additional progress in pretreatment technologies, optimized feedstock supply chains, and conducive policy frameworks to promote SAF production (IEA Bioenergy, 2024; Santos et al., 2023).

In conclusion, the Alcohol-to-Jet pathway represents a technologically advanced and environmentally advantageous alternative within sustainable aviation fuel technologies. By utilizing renewable resources and ensuring compatibility with existing aviation infrastructure, it provides a viable approach to diminishing the aviation sector's carbon footprint. Ongoing investment in process optimization, feedstock innovation, and policy support will be crucial for achieving its full potential in fulfilling global climate objectives for aviation.

2.6.4 Biogas-Based Fuel

Biogas-derived fuels constitute a significant pathway for sustainable aviation fuel (SAF), presenting considerable potential for alleviating climate change effects linked to the aviation industry. Biogas predominantly comprises methane (CH_4) and carbon dioxide (CO_2), generated via anaerobic digestion (AD) from diverse biomass feedstocks such as agricultural residues, food waste, municipal solid waste, and energy crops (Weiland, 2009; Allegue & Hinge, 2012).

Anaerobic digestion comprises multiple stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis, which enable the decomposition of organic matter into biogas. This gas mixture, primarily composed of CH_4 and CO_2, can be enhanced to biomethane by eliminating impurities and CO_2 using techniques such as water scrubbing, pressure swing adsorption (PSA), membrane separation, and cryogenic processes (Allegue & Hinge, 2012).

Recent technological advancements indicate that biogas derived from food waste holds considerable potential for sustainable aviation fuel production via biotechnological methods. Zhang et al. (2024) presented an innovative bioprocess employing microorganisms for the

sequential bioconversion of CO_2 and CH_4 sourced from food waste into lipids, which are subsequently upgraded into sustainable aviation fuel (SAF). This method exemplifies a carbon-neutral strategy, markedly diminishing greenhouse gas (GHG) emissions relative to conventional hydrothermal liquefaction pathways. Life cycle assessments (LCA) validate the reduced environmental impacts of bio-based pathways in comparison to traditional thermo-chemical processes (Zhang et al., 2024).

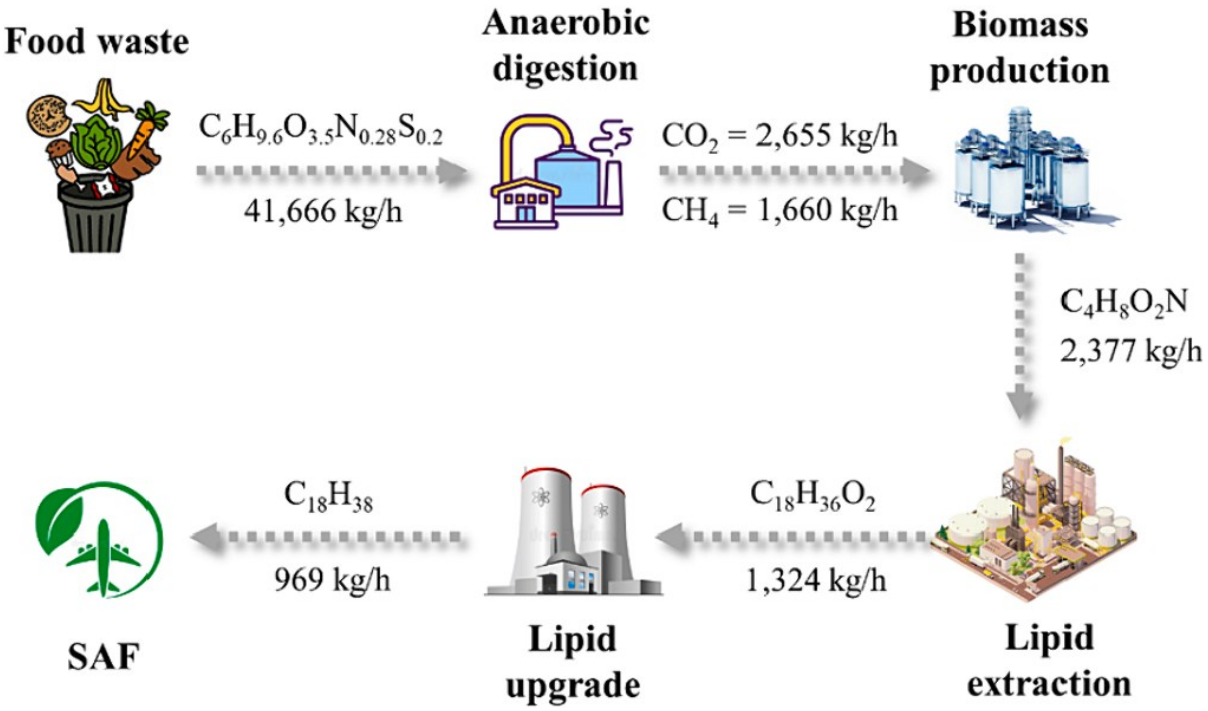

Figure 7. Comparison of GHG emissions for different SAF production pathways (Zhang et al., 2024).

Techno-economic analyses underscore the viability of biogas-derived sustainable aviation fuel, especially from food waste. With suitable economic incentives, including food waste disposal subsidies, the bio-route can attain an internal rate of return (IRR) of up to 38%, highlighting its economic feasibility and appeal for investment and expansion (Zhang et al., 2024).

In terms of technological maturity, biogas-to-SAF pathways are progressing swiftly, attaining Technology Readiness Levels (TRLs) indicative of imminent deployment potential. Conventional biogas production through anaerobic digestion is fully developed, and technologies for upgrading to biomethane have significantly advanced, with numerous commercial facilities in operation worldwide (Allegue & Hinge, 2012). The direct

conversion of biomethane or biogas to sustainable aviation fuel (SAF) is still being optimized, currently positioned at an Integrated lab-scale system or Prototype system in a relevant stage, indicating ongoing pilot-scale validations and nascent commercial demonstrations (Longo et al., 2024).

The environmental effects of biogas-derived fuels, as indicated in the literature, are largely positive, particularly in their capacity to substantially reduce greenhouse gas emissions. The use of food waste for biogas production significantly reduces the carbon footprint, aiding in climate change mitigation and promoting circular economy principles through waste valorization (Bhatia et al., 2023). Moreover, digestate from anaerobic digestion is advantageously repurposed as fertilizer, enhancing nutrient cycling efficiency and mitigating the environmental impacts linked to synthetic fertilizer production (Weiland, 2009).

For aviation applications, the production of Sustainable Aviation Fuel (SAF) from biogas entails the conversion to biomethane, subsequently followed by catalytic processes or biotechnological methods to produce aviation-grade fuels. These fuels exhibit compatibility with current jet engines and infrastructure, diminishing dependence on fossil-derived kerosene and the concomitant emissions of CO_2, particulate matter, and nitrogen oxides (NO_x), thereby enhancing air quality and the environmental sustainability of aviation (Zhang et al., 2024).

In summary, biogas-derived fuels offer a strong and progressively feasible method for generating SAF. Utilizing current anaerobic digestion infrastructure, enhancing bioconversion technologies, and establishing supportive economic frameworks are essential for fully harnessing biogas as a sustainable aviation fuel source.

2.7 Ammonia and Ammonia-Derived Fuels

Ammonia (NH_3) has become a significant contender in the pursuit of sustainable aviation fuels (SAFs), especially regarding the decarbonization of long-haul air travel. Ammonia, as a carbon-free hydrogen carrier, presents significant potential owing to its high hydrogen density, existing global infrastructure, and suitability for both combustion and fuel cell propulsion technologies. It is a storable, transportable fuel that can be generated without

carbon emissions, distinguishing it among alternative fuels being investigated for aviation applications (Valera-Medina et al., 2021).

Ammonia is conventionally synthesized via the Haber-Bosch process, which amalgamates nitrogen (derived from air) with hydrogen at elevated temperatures (400°-500° C) and pressures (100-300 atm) utilizing an iron-based catalyst. The viability of ammonia as an aviation fuel is largely contingent upon the origin of the hydrogen utilized in its production. Two significant pathways are identified. Green ammonia employs renewable electricity, such as that generated from wind or solar sources, to synthesize hydrogen via water electrolysis. Hydrogen is subsequently amalgamated with nitrogen from the atmosphere to produce ammonia. This approach yields a fuel with nearly zero emissions, especially when exclusively powered by renewable sources (Aika & Kobayashi, 2023). Conversely, blue ammonia generates hydrogen from natural gas through steam methane reforming (SMR) or autothermal reforming, while capturing and sequestering the resultant CO_2 emissions via carbon capture and storage (CCS). Although not completely devoid of emissions, blue ammonia provides considerable decreases in life cycle greenhouse gas emissions relative to traditional fossil fuels (Valera-Medina et al., 2021).

Ammonia can be utilized in various propulsion technologies within the aviation sector. It can be ignited in modified gas turbines and internal combustion engines. Despite exhibiting lower flame speeds and a narrower flammability range than traditional jet fuel, advancements in combustion technology and the incorporation of pilot fuels (such as hydrogen or hydrocarbons) are facilitating the mitigation of these challenges (Kobayashi et al., 2019). High-speed propulsion systems, including scramjets, have exhibited robust performance when utilizing ammonia as fuel. Lu et al. (2024) indicated that ammonia scramjets functioning at Mach 9 provide a specific thrust that is 54.5% superior to that of hydrocarbon alternatives. Ammonia is appealing for hypersonic applications; however, issues concerning ignition and combustion stability persist. Advanced propulsion systems are being engineered that integrate solid oxide fuel cells (SOFCs) with gas turbines (GTs), employing ammonia as the principal fuel source. These hybrid systems attain elevated electrical efficiency and negligible carbon emissions, providing a route to electrified, high-performance aircraft propulsion (Wagner & Tingas, 2025).

A significant challenge related to ammonia is its toxicity. Exposure to concentrations of approximately 300 ppm may pose immediate health risks, and leaks could create safety hazards in aircraft or at airport refueling facilities. This requires advancing sophisticated leak detection, ventilation, and storage systems. Furthermore, the harsh scent of ammonia can facilitate early leak detection; however, stringent safety protocols are essential for its safe management in aviation settings (Otto et al., 2023).

Although ammonia combustion does not generate CO_2, it results in the production of nitrogen oxides (NO_x) owing to the fuel's elevated nitrogen content. NO_x emissions are especially problematic at elevated temperatures commonly present in jet engines. Researchers are investigating fuel blending (e.g., with hydrogen or hydrocarbons), low-NO_x combustor designs (e.g., rich-quench-lean or swirl-stabilized combustors), and post-combustion treatments like selective catalytic reduction (SCR) (Otto et al., 2023). Otto et al. (2023) assert that emissions can fluctuate considerably depending on engine operating conditions and fuel-air equivalence ratios. At elevated Mach numbers in scramjets, NO_x emissions escalate significantly with the equivalence ratio, requiring precise optimization.

Ammonia possesses an energy content of 18.6 MJ/kg, which is inferior to that of kerosene; however, its volumetric hydrogen density surpasses that of liquid hydrogen, providing logistical benefits. In contrast to hydrogen, ammonia can be liquefied at moderate pressures (9.9 bar at 25°C) or cryogenically stored at -33.4°C, thereby facilitating storage infrastructure and fuel logistics for aviation (Kobayashi et al., 2019). A significant trade-off, however, is the comparatively low flame speed and ignition temperature of ammonia, which may restrict engine responsiveness. Investigations are currently being conducted to enhance combustion kinetics via catalytic ignition systems (Valera-Medina et al., 2021).

The climate advantages of ammonia are significantly influenced by the method of production. When generated using renewable electricity, green ammonia attains nearly zero well-to-wake greenhouse gas emissions. Life Cycle Assessment results demonstrate significant climate mitigation potential, particularly in long-haul aviation, where battery or hydrogen systems encounter constraints related to weight and volume. Although not carbon-neutral, blue ammonia can diminish lifecycle emissions relative to fossil jet fuels, provided that carbon capture and storage (CCS) systems attain high capture efficiency (Valera-Medina et al., 2021). In addition to greenhouse gas emissions, the utilization of ammonia can prevent

contrail formation and soot emissions, thereby enhancing local air quality and mitigating non-CO_2 climate forcing effects. Nonetheless, NO_x emissions continue to represent a significant challenge that must be mitigated through technological and operational strategies (Wong et al., 2024).

Ammonia represents a novel and technically feasible alternative fuel for aviation, especially for mid to long-term decarbonization strategies. Its production flexibility, high hydrogen density, and carbon-free combustion position it well within future sustainable aviation portfolios. Nevertheless, the successful deployment of ammonia in aviation hinges on overcoming key challenges related to toxicity, NO_x formation, and combustion stability. Continued research into advanced combustion systems, robust safety mechanisms, and efficient ammonia synthesis pathways is crucial to unlock its full potential.

3. Methodology

3.1 Life Cycle Assessment Approach

The Life Cycle Assessment (LCA) completed in this thesis is performed according to the classical method of attributional LCA, where the focus is on estimating the environmental impacts of the production of electro-kerosene, Hydrogen, and Ammonia. Classic attributional LCA is concerned primarily with describing the relevant environmental physical flows of a given product system, and uses average data describing the prevailing technology of the given product system (Finnveden et al., 2009). As such, this form of LCA is ideal when assessing a product system in its entirety, cradle-to-grave (or, in this case, well-to-wake, as with aviation fuels) because it specifically removes all uncertainty in scope, structure, and preset assumptions.

In preparing this thesis, all I had was the LCA scope defined according to the classical frameworks of the international standards ISO 14040 and ISO 14044. As detailed in ISO 14040 (ISO, 2006), the LCA process is divided into four components: goal and scope definition, inventory analysis, impact assessment, and interpretation. Here, the standard provides guidelines on the goal and scope, system boundaries, and the functional unit of the study, insisting on unreproachable coherence and consistency, thereby enhancing reproducibility.

ISO 14044 (ISO, 2006) specifies the requirements and methods necessary for data collection, data processing, allocation of emissions for multi-output processes, and impact category calculation, which means the analysis, interpretation, and impact of life cycle assessment (LCA) and allocation for multi-output processes in this research. Allocation in multi-output processes in this research follows the recommendations in ISO 14044. Therefore, the allocation decisions are clear and justifiable.

The modeling and analysis software is GaBi, developed by Sphera. GaBi software facilitates the collection, organization, analysis, and interpretation of life cycle data. GaBi possesses a comprehensive database and life cycle assessment (LCA) methodologies that encompass both regional and global data, essential for obtaining relevant and accurate LCA outcomes. GaBi's modular design allows for the flexible construction and modification of processes for the production of electro-kerosene, hydrogen, and ammonia. This extensive system modeling encompasses all phases from electricity generation, hydrogen electrolysis, CO_2 capture, and fuel synthesis to finally storing it in Airports. Moreover, GaBi encompasses numerous standard impact assessment methodologies, facilitating the evaluation of results through established environmental impact indicators, particularly Global Warming Potential (GWP) metrics.

3.1.1 Goal and Scope Definition

According to ISO 14040 and 14044, the Goal and Scope Definition is the first and most important step of a Life Cycle Assessment (LCA), as it sets out the framework, direction, and structure of the entire study. The goal definition clearly defines the application purpose of the study, the motivations behind conducting it, and specifies whether the results will be publicly shared with an audience. The scope definition will contain, among others, key issues such as functional unit, system boundaries, allocation rules, impact categories, data needs & assumptions. A proper boundary of these components guarantees the transparency, consistency, and reproducibility of the LCA (ISO, 2006a).

This work is conducted according to the ISO 14040 and 14044 standards, to evaluate environmental impacts from the production of electro-kerosene (also referred to as e-kerosene or Power-to-Liquid kerosene), hydrogen fuel, and Ammonia across their life cycle. The objective is to offer for the first time a comprehensive overview of the greenhouse gas

(GHG) performance of these fuels as well as hotspots from their life cycle perspective, and to assess their potential long-term. alternative compared with conventional jet fuel. The performances of the fuel in terms of the aeroplane decarbonization targets are specifically addressed.

This study is attributional in nature, in other words, based on current technology and datasets that represent conditions for today or the near future. The study uses a well-to-tank (WTT) scope, which includes emissions from fuel production to the distribution and storage in airports. The analysis focuses on the Global Warming Potential over 100 years (GWP100), in kg CO_2-eq., and also analyzes other impact categories, such as marine eutrophication, freshwater eutrophication, and terrestrial acidification.

3.1.2 Functional Unit and System Boundary

According to ISO 14040 and 14044, the functional unit is a measure of the performance of a product system that quantitatively describes said function in relation to which the inputs and outputs are expressed (ISO, 2006a; ISO, 2006b). It standardizes the study outcome, which makes their results comparable across platforms or situations. At the same time, the system boundary defines between which unit processes it is set and has to match with intent of the study in order to hold both for completeness and relevance. ISO suggests that the system boundaries be restricted based on scope, selected impact categories, and it is important to see foreground from background.

In this research, the functional unit is considered in terms of 1 MJ of fuel production. This functional unit gives a realistic and relevant context for comparing the environmental performance of aviation fuels in circumstances that are as close to real-world aviation operations as is practicable, and it will also be shown as g CO_2 eq per MJ to make a comprehensive comparison in more detail.

All material and energy flows in the life cycle inventory (LCI) are originally defined per 1 kg of the final product of each unit process and are later normalised to the functional unit of 1 MJ of fuel. Normalisation enables all upstream processes, electrolysis, CO_2 capture, synthesis, and compression to be expressed on the same output basis. This ensures methodological consistency and allows the results to be directly comparable, thereby

supporting a realistic and operationally relevant comparison between conventional jet fuel and emerging sustainable aviation fuel pathways.

The system boundary of the assessment is set as well-to-tank (WTT), encompassing the entire life cycle of these fuels from the extraction and generation of raw materials (including renewable electricity and water), hydrogen production via electrolysis, CO_2 capture (from direct air capture or industrial sources), synthesis processes (RWGS and FT), transport to the airport, or PSA for nitrogen capture and Haber-Bosch process for ammonia production. This boundary ensures that all upstream and downstream processes relevant to environmental impacts are accounted for. Where applicable, infrastructure and capital goods are excluded in accordance with standard practice in attributional LCA, unless otherwise justified.

3.2 Inventory Data Collection

The inventory analysis phase, as outlined in ISO 14040 and 14044, entails the collection and quantification of all pertinent inputs and outputs for each process encompassed within the specified system boundary (ISO, 2006a; ISO, 2006b). This phase converts the conceptual model of the life cycle into quantifiable flows of energy, materials, and emissions, establishing the fundamental dataset for calculating environmental impacts. An organized and clear inventory is crucial for maintaining the credibility and reproducibility of the entire Life Cycle Assessment (LCA).

This study compiles life cycle inventory (LCI) data for each unit process in the production and utilization chain of electro-kerosene, hydrogen, and ammonia. The inventory encompasses all pertinent input and output flows related to the foreground system, including electricity consumption, water usage, raw material demands, and direct process emissions. Furthermore, background data, including upstream electricity generation, material supply, and infrastructure, are obtained from the GaBi database, which offers regionally and technologically representative datasets.

The foreground system's data collection depends on values documented in peer-reviewed literature, industrial reports, and established LCA studies. The data are processed and normalized to the specified functional unit to ensure uniformity across all life cycle stages.

Special emphasis is placed on guaranteeing that the data accurately reflect contemporary or imminent technological performance standards, with assumptions explicitly articulated in the absence of primary data.

3.2.1 Fossil kerosene inventory

For fossil kerosene (Jet A-1), the upstream processes such as crude oil extraction, refining, and distribution are modeled using GaBi's predefined datasets.

3.2.2 Electro-Kerosene Production Inventory

In this section, the inventory data that is required for e-kerosene modeling in GaBi will be presented for each unit process.

Table 4. Technical parameters for the point source capture (Tanzer, Blok, and Ramírez, 2023)

Inputs	Amount (per 1 kg of CO_2)	Unit
Electricity	0.1	kWh
Heat (Steam)	3	MJ
MEA	0.001	Kg
outputs		
CO_2	1	kg

Table 5. Initial data of hydrogen (H_2) generation from Alkaline water electrolysis and compression

Inputs	Amount (per 1 kg H_2)	Unit	reference
Water [kg]	10	kg/kg H_2	(Koj et al., 2017)
KOH [kg]	0.0019	kg/kg H_2	(Koj et al., 2017)
Electricity [kWh]	50	kWh/kg H_2	(Koj et al., 2017)
Outputs			
H_2 [kg]	1	kg	
O_2 [kg]	8.2	kg/kg H_2	(Sternberg and Bardow, 2016)

Table 6. Potassium hydroxide (KOH) production process data (Ecoinvent Association, 2022)

KOH output [kg]	1
CO_2-eq output [kg]	2.2

Table 7. MEA production process data (Ecoinvent Association, 2022)

MEA output [kg]	1
CO_2-eq output [kg]	2

Table 8. Fischer–Tropsch (FT) Synthesis initial data for 1 kg Synthetic crude (Dry, 2002; Soler et al., 2022)

Stream		Amount per 1 kg of Synthetic crude	Units
Inputs	CO_2	2.99	kg
	H_2	0.397	kg
	Electricity	0.416	kWh
Outputs	Synthetic crude (Wax, Fuel, Gases)	1 (Wax 0.459, Fuel 0.321, Gases 0.22)	kg
	Water	1.17	kg
	Waste heat	7.27	MJ

3.2.3 Hydrogen Production Inventory

In this section, the inventory data that is required for Hydrogen production modelling in GaBi will be presented for each unit process and different types of electrolysis: PEM and SOE.

Table 9. Initial data on hydrogen (H_2) generation from PEM water electrolysis

Inputs	Amount (per 1 kg H_2)	Unit	reference
Water [kg]	9	kg Water/kg H_2	(Soler et al., 2022)
Electricity [kWh]	55.2	kWh/kg H_2	(DOE, 2024)

Outputs			
H_2 [kg]	1	kg	Reference flow
O_2 [kg]	8	kg O_2/kg H_2	(Energiforsk, 2023)

Table 10. Initial data of hydrogen (H_2) generation from (SOEC/HTE) water electrolysis

Inputs	Amount (per 1 kg H_2)	Unit	reference
Water [kg]	9	kg/kg H_2	(Soler et al., 2022)
Electricity [kWh]	35.1	kWh/kg H_2	(ISPT, 2023)
steam	41.1	MJ/kg H_2	(ISPT, 2023)
Outputs			
H_2 [kg]	1	kg	Reference flow
O_2 [kg]	7.8	kg/kg H_2	(ISPT, 2023)

3.2.4 Ammonia Production Inventory

In this section, the inventory data required for Ammonia production modeling in GaBi will be presented for each unit process.

Table 11. Ammonia synthesis reactor (Haber–Bosch)

Inputs	Amount (per 1 kg NH_3)	Unit	reference
H_2 [kg]	0.1775	kg H_2/kg NH_3	(Soler et al., 2022)
N_2 [kg]	0.8235	Kg N_2/kg NH_3	(Soler et al., 2022)
Electricity [kWh]	0.598	kWh/kg NH_3	(Soler et al., 2022)
Outputs			
NH_3 [kg]	1	kg	Reference flow
Heat [Mj]	2.17	MJ/kg NH_3	From the Air mass balance

3.3 GaBi Modeling Procedure

In this chapter, we explain the pathways for each fuel production that is used to model the fuel production in GaBi.

3.3.1 E-FT Kerosene pathway

The e-kerosene production process through the Fischer-Tropsch (FT) method incorporates various unit operations to transform renewable electricity, water, and atmospheric CO_2 into synthetic jet fuel (Figure 8). The system boundary adopts a Well-to-Tank (WTT) methodology, incorporating all upstream and downstream processes, from raw material inputs to the storing of fuel at the airport.

The process commences with Point Source Capture (PSC), wherein industrial CO_2 is sequestered utilizing a chemical sorbent like Monoethanolamine (MEA). The captured CO_2 is subsequently directed to the Reverse Water-Gas Shift (RWGS) reactor, where it reacts with renewable hydrogen to yield carbon monoxide (CO) and water. This step is crucial for transforming CO_2 into an appropriate carbon source for FT synthesis.

Hydrogen is produced through water electrolysis, a process that separates water into hydrogen and oxygen, utilizing renewable electricity. The electrolyzer necessitates water and potassium hydroxide as inputs. A fraction of the hydrogen is utilized in the RWGS process, while the residual hydrogen, in conjunction with CO, generates a syngas mixture that is introduced into the Fischer-Tropsch synthesis reactor.

In the FT reactor, syngas undergoes catalytic conversion into various hydrocarbons, predominantly long-chain waxes, along with lighter gases such as methane and other light hydrocarbons. Residual unreacted CO and H_2 may be recycled, combusted, or vented. The process generates waste heat, which can be partially reclaimed to enhance overall system efficiency.

The substantial hydrocarbon waxes produced from the FT synthesis are directed to a hydrocracking and upgrading unit, where they are decomposed and refined into viable liquid fuels. This process produces synthetic kerosene (e-kerosene) along with byproducts such as diesel-range hydrocarbons and lighter fuels.

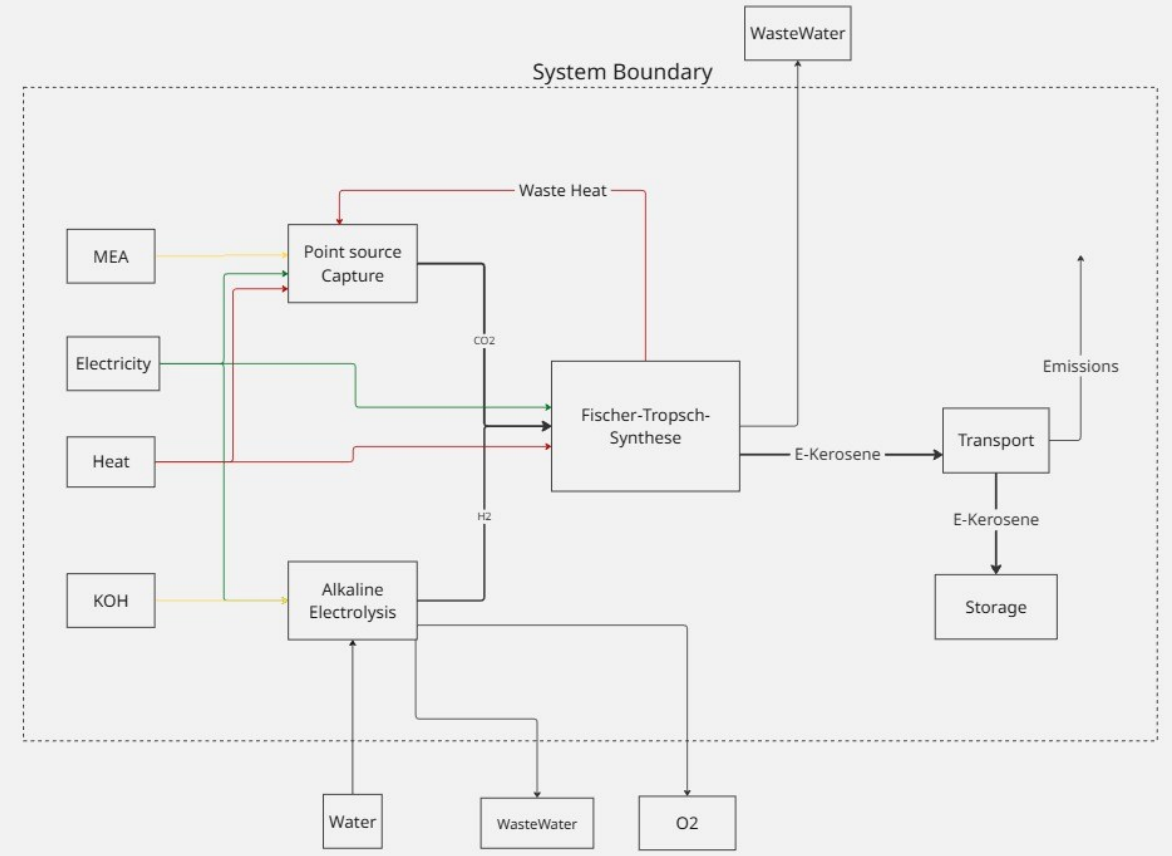

Figure 8. E-FT Kerosene pathway (baseline)

3.3.2 Hydrogen production pathway

This study models hydrogen as a sustainable aviation fuel generated via water electrolysis utilizing renewable electricity (Figure 9). Three technologies are evaluated: alkaline electrolysis (ALK), proton exchange membrane electrolysis (PEM), and solid oxide electrolysis (SOE), as previously detailed in Section 2.4. In GaBi's inventory modeling, all processes are standardized to 1 kg of hydrogen produced, facilitating comparability across pathways.

Post-electrolysis, hydrogen necessitates conditioning prior to its application in aviation. This study assumes compressed hydrogen as the fuel source, which is currently the most viable option.

Hydrogen is then transported to airports, where it is stored and distributed to aircraft refueling systems. In this study, transport by tanker trucks is assumed, in line with common LCA practices.

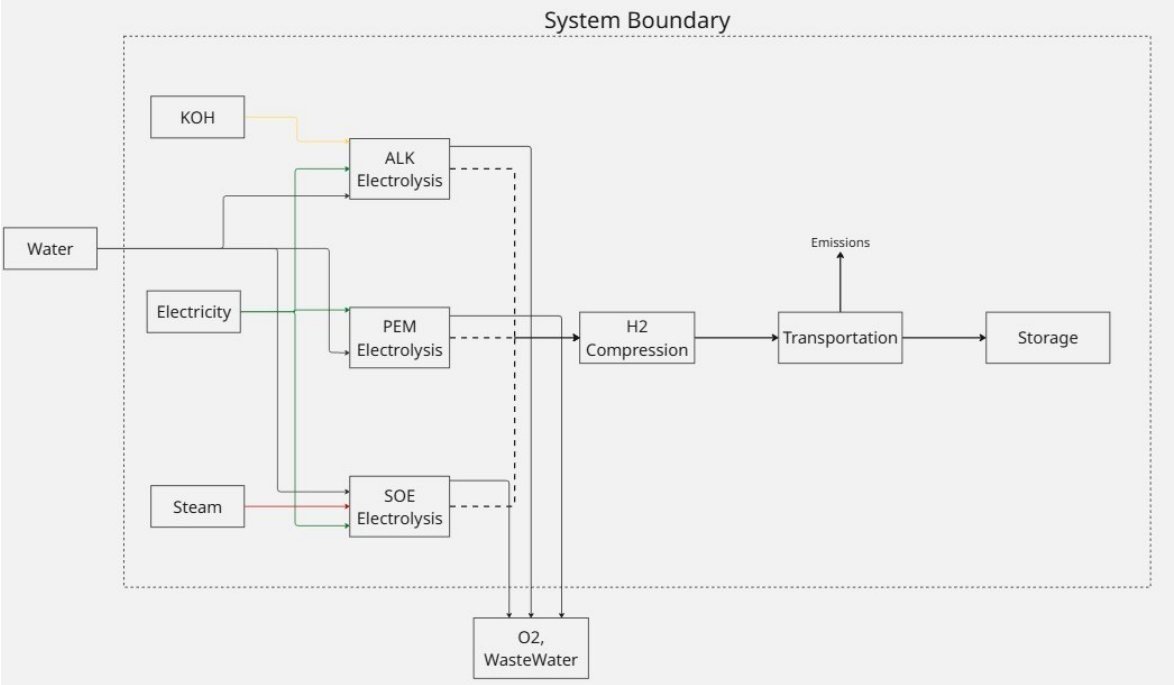

Figure 9. Hydrogen production pathway

3.3.3 Ammonia production pathway

Figure 10 depicts the production pathway for ammonia (NH_3) as a prospective aviation fuel. The process initiates with two fundamental resources, specifically air and water, which are transformed into the required reactants for ammonia synthesis. Nitrogen is extracted from atmospheric air using a pressure swing adsorption (PSA) system. This process necessitates electricity, with oxygen (O_2) produced as a by-product. Simultaneously, hydrogen is produced through alkaline electrolysis, in which water is dissociated into hydrogen and oxygen using electricity and potassium hydroxide (KOH) as an electrolyte. The resultant hydrogen stream is subsequently directed to the synthesis phase.

In the ammonia synthesis reactor, hydrogen and nitrogen react under elevated pressure and temperature, adhering to the Haber-Bosch process. This step results in the production of ammonia, accompanied by the release of heat, which may be either harnessed or regarded as waste, contingent upon the study's boundary parameters. The generated ammonia is then transported to the airport, where energy consumption and transportation-related emissions are incorporated into the assessment.

The system boundary, therefore, encompasses all key upstream processes and transportation, as well as relevant by-products and emissions. The functional unit in this study is defined as 1 Kg of ammonia fuel, enabling comparability with other alternative aviation fuels analysed in this work.

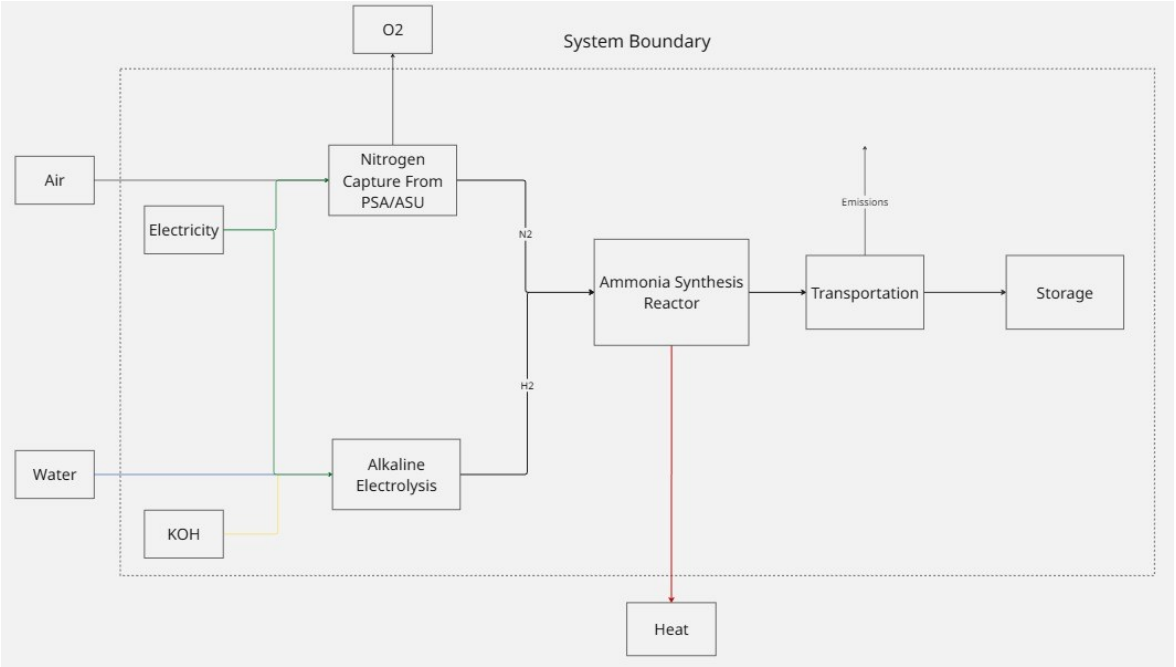

Figure 10. Ammonia production pathway

3.4 Impact Assessment

According to the ISO 14040 and ISO 14044 standards, the impact assessment phase of a Life Cycle Assessment (LCA) is the third major step after goal and scope definition and inventory analysis (ISO, 2006a; ISO, 2006b). This phase, formally called the Life Cycle Impact Assessment (LCIA), evaluates the potential environmental impacts associated with the inventory data collected in the previous stage. The purpose of LCIA is to provide additional information for interpreting the significance of the life cycle inventory (LCI) results by translating elementary flows (e.g., CO_2, CH_4, NO_x, H_2O) into common impact categories such as climate change, acidification, eutrophication, or resource depletion.

In the context of this thesis, the climate change impact category is of central importance, as the research is focused on the contribution of sustainable aviation fuels to global warming. But we are also looking for Freshwater Eutrophication, Marine Eutrophication, and

Terrestrial Acidification. The ISO framework emphasizes that the LCIA phase typically involves three key elements:

Classification: assigning the LCI results (emissions and resource uses) to the relevant impact categories (e.g., greenhouse gases to climate change).

Characterization: converting and aggregating the classified results using characterization factors (e.g., Global Warming Potentials over 100 years, GWP100, expressed in CO_2-equivalents).

Normalization and weighting: comparing results to reference values or applying value choices to aggregate across categories.

The results from this impact assessment form the foundation for Chapter 4, where the outcomes of the modeling are presented, interpreted, and compared across fuel pathways. In particular, the Environmental impacts of the alternative fuels are evaluated relative to the fossil kerosene baseline, highlighting the mitigation potential and trade-offs of each option.

3.4.1 Global Warming Potential (GWP)

The climate change impact category in Life Cycle Assessment (LCA) is generally measured using the Global Warming Potential (GWP) metric, as per ISO 14040 and ISO 14044 standards (ISO, 2006a; ISO, 2006b). The Global Warming Potential (GWP) quantifies the aggregate radiative forcing of a greenhouse gas in comparison to carbon dioxide (CO_2) over a specified time frame, typically 100 years (IPCC, 2021). This facilitates the expression of various gas emissions on a standardized basis in kilograms of CO_2-equivalent (CO_2-eq), thereby allowing for consistent aggregation and comparison across fuel pathways. The 100-year time horizon (GWP100) is the standard employed for long-lived greenhouse gases in ISO-compliant life cycle assessments and international climate policy frameworks.

3.4.2 Additional impact categories

In addition to climate change and non-CO_2 radiative forcing impacts, this study also quantifies other midpoint-level environmental impacts in accordance with the chosen impact assessment method in GaBi. These include freshwater eutrophication, marine eutrophication, and terrestrial acidification. These categories were selected because combustion-related NO_x and upstream emissions from fuel production are known

contributors to acidification and nutrient enrichment processes, and therefore, they provide additional insight beyond global warming alone. The results are based on the ReCiPe 2016 v1.1 Midpoint (H) as implemented in GaBi.

Freshwater eutrophication reflects the potential of emissions such as phosphates, nitrates, and other nutrient-related substances to disturb freshwater ecosystems, leading to algal blooms, oxygen depletion, and biodiversity loss. In aviation fuel pathways, these burdens originate upstream rather than during combustion. The Unit representing this is in g P equivalent.

Marine eutrophication accounts for the release of nitrogen-containing compounds that enter coastal and marine waters, accelerating algal blooms and degrading aquatic ecosystems. The drivers differ slightly from freshwater eutrophication because nitrogen flows (e.g., NO_3^- and NH_4^+) dominate rather than phosphates. As with other non-combustion categories, contributions in aviation fuel pathways are primarily upstream, linked to electricity production, chemical manufacturing, and biomass processes. The Unit representing this is in g N equivalent.

Terrestrial acidification expresses the potential of emitted acidifying compounds, mainly NO_x, SO_2, and NH_3, to acidify soils and forest environments. This leads to nutrient leaching, forest decline, and reduced soil fertility. In the context of aviation fuels, this category captures upstream industrial emissions (from energy and chemical inputs).

4. Results, Interpretation, and Discussion

This chapter presents the results of the modeling, their interpretation, and a thorough discussion of the findings, in accordance with the Life Cycle Assessment (LCA) framework established in ISO 14040 and ISO 14044. The interpretation phase seeks to identify critical issues highlighted by the results, assess the consistency and comprehensiveness of the data, and formulate conclusions that align with the established objectives and parameters of the study. The discourse further contextualizes these findings concerning technological feasibility, environmental significance, and their implications for sustainable aviation.

This chapter integrates numerical findings with qualitative assessment. The aim is to guarantee that the outcomes are both scientifically valid and significant for informing policy, technological advancement, and future investigations into sustainable aviation fuels.

4.1 Results

This chapter presents the life cycle modeling results of the selected aviation fuels. Following the methodological framework described in Chapter 3, baseline inventories were first developed for fossil kerosene (reference), electro-kerosene, hydrogen, and ammonia using GaBi software with a well-to-tank system boundary. CJF is modeled only as a baseline case to provide a reference point, since no scenario variations are applied to fossil-derived fuels. The baseline result for CJF corresponds to 17.13 g CO_2eq/MJ, shown in Table 12, which serves as the benchmark for comparing alternative fuels. Also, other impact categories for CJF are given, which will be the reference for comparison with other fuels.

Table 12. Well-to-Tank results for conventional jet fuel

Impact categories	Unit/MJ	
Climate change	g CO_2 eq.	17.13
Freshwater Eutrophication	g P eq.	1.54E-05
Marine Eutrophication	g N eq.	6.55E-05
Terrestrial Acidification	g SO_2 eq.	2.83E-02

After presenting the baseline results, a set of five scenarios was developed to test the sensitivity of results to key assumptions. These scenarios reflect changes in upstream electricity supply and electrolysis technology, which are common processes across all modeled fuel pathways. By comparing baseline and scenario results, the robustness of the findings and the influence of technological choices on overall environmental impacts can be evaluated.

4.2 Baseline modeling of fuels (Scenario 1)

In this chapter, we present the baseline scenario for each fuel, which includes photovoltaic electricity and alkaline electrolysis.

4.2.1 Electro-kerosene baseline (PV & AEL)

Electro-kerosene was modeled using the Fischer-Tropsch (FT) power-to-liquid pathway, incorporating Point source capture of CO_2, renewable electricity from photovoltaics, and alkaline electrolysis for hydrogen production. The GaBi model covers the full well-to-tank

chain, including electricity generation, CO_2 capture, hydrogen electrolysis, FT synthesis, upgrading, distribution, and final combustion in aircraft engines. Table 22. summarizes the contribution of each process stage to the total CO_2-equivalent emissions per MJ of electro-kerosene.

Table 13. Well-to-tank CO_2 eq results for e-kerosene

Life cycle stage	CO_2 eq (g/MJ)	Share of total (%)
Electricity generation	21.5	94.3
Fuel synthesis (non-electricity)	1.0	4.5
Distribution	0.3	1.2
Total WTT	22.8	100

4.2.2 Hydrogen baseline (PV & AEL)

The hydrogen baseline represents Compressed hydrogen (H_2) produced via alkaline electrolysis powered by renewable electricity from photovoltaic. The model includes electricity generation, water electrolysis, compression and distribution.

Table 14. Well-to-tank CO_2 eq results for Compressed Hydrogen

Life cycle stage	CO_2 eq (g/MJ)	Share of total (%)
Electricity generation	15.2	98.5
Fuel synthesis (non-electricity)	0.1	0.9
Distribution	0.1	0.6
Total WTT	15.4	100

4.2.3 Ammonia baseline (PV & AEL)

Ammonia was modeled through the Haber-Bosch process, with hydrogen supplied from alkaline electrolysis and nitrogen separated from air. The well-to-tank boundary in GaBi includes electricity generation from photovoltaic, hydrogen electrolysis, nitrogen capture, ammonia synthesis, and distribution. Table 24. shows the contribution of each process stage to the total CO_2-equivalent emissions per MJ of ammonia fuel.

Table 15. Well-to-tank CO_2 eq results for Ammonia

Life cycle stage	CO_2 eq (g/MJ)	Share of total (%)
Electricity generation	17.7	83.3
Fuel synthesis (non-electricity)	2.9	13.8
Distribution	0.6	2.9
Total WTT	21.3	100.0

4.2.4 Other impact categories (Scenario 1)

Table 16. Other impact categories for baseline (Scenario 1)

Impact categories	Unit/FU	E-kerosene	Hydrogen	Ammonia
Freshwater Eutrophication	g P eq.	5.22E-05	3.61E-05	5.82E-05
Marine Eutrophication	g N eq.	5.24E-04	3.66E-04	5.41E-04
Terrestrial Acidification	g SO_2 eq.	8.91E-02	4.75E-02	5.88E-02

4.3 Scenario Analysis

In addition to the baseline cases, six scenarios were defined and applied consistently across all fuels to explore how variations in electricity source and electrolysis technology influence life cycle performance. These scenarios are designed as sensitivity analyses rather than alternative baselines, highlighting the impact of specific technological choices:

- Replacing photovoltaic (PV) electricity in the baseline with wind power as the sole renewable source.
- Replacing alkaline electrolysis (AEL) in the baseline with proton exchange membrane (PEM) electrolysis.
- Replacing AEL with solid oxide electrolysis (SOE).

The results of these scenarios are presented in comparative tables for all fuels, followed by a discussion of general trends. This approach ensures that the effect of upstream energy supply and electrolyzer type can be assessed systematically across electro-kerosene, hydrogen, and ammonia fuel pathways.

4.3.1 Scenario 2 – PEM electrolysis and photovoltaic electricity

In the first scenario, the electricity source remains photovoltaic, but the electrolyzer is switched from alkaline to PEM. This change isolates the influence of electrolysis technology on the life-cycle results while holding the renewable electricity source constant, allowing assessment of whether the higher dynamic response and different efficiency profile of PEM leads to a measurable difference relative to the baseline.

Table 17. Life cycle CO_2 emissions and stage contributions for e-kerosene in the PEM & PV

Life cycle stage	CO_2 eq (g/MJ)	Share of total (%)
Electricity generation	27.6	95.7
Fuel synthesis (non-electricity)	1.0	3.4
Distribution	0.3	0.9
Total WTT	28.9	100.0

Table 18. Life cycle CO_2 emissions and stage contributions for Hydrogen in the PEM & PV

Life cycle stage	CO_2 eq (g/MJ)	Share of total (%)
Electricity generation	19.9	99
Fuel synthesis (non-electricity)	0.1	0.5
Distribution	0.1	0.5
Total WTT	20.1	100.0

Table 19. Life cycle CO_2 emissions and stage contributions for Ammonia in the PEM & PV

Life cycle stage	CO_2 eq (g/MJ)	Share of total (%)
Electricity generation	22.7	86.6
Fuel synthesis (non-electricity)	2.9	11.0
Distribution	0.6	2.3
Total WTT	26.2	100.0

Table 20. Other Environmental Impacts of Scenario 2

Impact categories	Unit/FU	E-kerosene	Hydrogen	Ammonia
Freshwater Eutrophication	g P eq	6.37E-05	4.41E-05	6.75E-05
Marine Eutrophication	g N eq	6.62E-04	4.64E-04	6.52E-04
Terrestrial Acidification	g SO_2 eq	1.08E-01	6.06E-02	7.38E-02

4.3.2 Scenario 3 – SOE electrolysis and Photovoltaic electricity

The second scenario retains the same PV electricity as in the baseline but replaces the alkaline electrolyzer with solid oxide electrolysis (SOE). Since SOE operates with higher electrical efficiency through high-temperature steam electrolysis, this scenario is designed to test whether efficiency improvements alone, without changing the electricity source, yield a significant reduction in overall emissions.

Table 21. Life cycle CO_2 emissions and stage contributions for e-kerosene in the SOE & PV

Life cycle stage	CO_2 eq (g/MJ)	Share of total (%)
Electricity generation	15.3	86.7
Fuel synthesis	2.1	11.8
Distribution	0.3	1.5
Total WTT	17.7	100.0

Table 22. Life cycle CO_2 emissions and stage contributions for Hydrogen in the SOE & PV

Life cycle stage	CO_2 eq (g/MJ)	Share of total (%)
Electricity generation	11.2	92.0
Fuel synthesis (non-electricity)	0.9	7.2
Distribution	0.1	0.8
Total WTT	12.2	100.0

Table 23. Life cycle CO_2 emissions and stage contributions for Ammonia in the SOE & PV

Life cycle stage	CO_2 eq (g/MJ)	Share of total (%)
Electricity generation	12.8	74.4
Fuel synthesis (non-electricity)	3.8	22.1
Distribution	0.6	3.6
Total WTT	17.2	100.0

Table 24. Other Environmental Impacts of Scenario 3

Impact categories	Unit/FU	E-kerosene	Hydrogen	Ammonia
Freshwater Eutrophication	g P eq	4.31E-05	2.97E-05	5.09E-05
Marine Eutrophication	g N eq	4.13E-04	2.88E-04	4.51E-04
Terrestrial Acidification	g SO_2 eq	1.10E-01	6.21E-02	7.55E-02

4.3.3 Scenario 4 – Wind electricity and Alkaline electrolysis

In the third scenario, the alkaline electrolyzer is kept unchanged, but the electricity source is replaced with wind power instead of PV. This allows the isolated evaluation of the impact of electricity origin, since wind generally has a lower carbon intensity and a more stable generation profile, making it possible to distinguish the effect of the electricity supply from that of the electrolyzer technology.

Table 25. Life cycle CO_2 emissions and stage contributions for e-kerosene in the Wind and AEL electrolysis

Life cycle stage	CO_2 eq (g/MJ)	Share of total (%)
Electricity generation	6.2	82.8
Fuel synthesis (non-electricity)	1.0	13.7
Distribution	0.3	3.5
Total WTT	7.5	100.0

Table 26. Life cycle CO_2 emissions and stage contributions for Hydrogen in the Wind and AEL electrolysis

Life cycle stage	CO_2 eq (g/MJ)	Share of total (%)
Electricity generation	4.5	95.0
Fuel synthesis (non-electricity)	0.1	3.0
Distribution	0.1	2.0
Total WTT	4.8	100.0

Table 27. Life cycle CO_2 emissions and stage contributions for Ammonia in the Wind and AEL electrolysis

Life cycle stage	CO_2 eq (g/MJ)	Share of total (%)
Electricity generation	5.1	59.1
Fuel synthesis (non-electricity)	2.9	33.9
Distribution	0.6	7.0
Total WTT	8.7	100.0

Table 28. Other Environmental Impacts of Scenario 4

Impact categories	Unit	E-kerosene	Hydrogen	Ammonia
Freshwater Eutrophication	g P eq	2.01E-05	1.27E-05	3.17E-05
Marine Eutrophication	g N eq	1.17E-04	7.19E-05	2.05E-04
Terrestrial Acidification	g SO_2 eq	3.72E-02	9.87E-03	1.60E-02

4.3.4 Scenario 5 – Wind electricity and PEM electrolysis

The fourth scenario introduces a combined change by using wind electricity together with PEM electrolysis. This setting reflects a joint improvement both in the carbon intensity of the power input and in the responsiveness of the electrolysis unit, enabling the examination of how concurrent changes in both parameters collectively influence the life-cycle outcome.

Table 29. Life cycle CO_2 emissions and stage contributions for e-kerosene in the Wind and PEM electrolysis

Life cycle stage	CO_2 eq (g/MJ)	Share of total (%)
Electricity generation	8.0	86.7
Fuel synthesis (non-electricity)	1.0	10.5
Distribution	0.3	2.9
Total WTT	9.3	100.0

Table 30. Life cycle CO_2 emissions and stage contributions for Hydrogen in the Wind and PEM electrolysis

Life cycle stage	CO_2 eq (g/MJ)	Share of total (%)
Electricity generation	5.8	96.8
Fuel synthesis (non-electricity)	0.1	1.6
Distribution	0.1	1.6
Total WTT	6	100.0

Table 31. Life cycle CO_2 emissions and stage contributions for Ammonia in the Wind and PEM electrolysis

Life cycle stage	CO_2 eq (g/MJ)	Share of total (%)
Electricity generation	6.6	65.3
Fuel synthesis (non-electricity)	2.9	28.7
Distribution	0.6	6.0
Total WTT	10.1	100.0

Table 32. Other Environmental Impacts of Scenario 5

Impact categories	Unit	E-kerosene	Hydrogen	Ammonia
Freshwater Eutrophication	g P eq	2.23E-05	1.43E-05	3.35E-05
Marine Eutrophication	g N eq	1.39E-04	8.69E-05	2.23E-04
Terrestrial Acidification	g SO_2 eq	4.09E-02	1.25E-02	1.89E-02

4.3.5 Scenario 6 – Wind electricity and SOE electrolysis

The final scenario combines wind electricity with solid oxide electrolysis. This configuration represents a high-efficiency boundary case, pairing a low-carbon electricity source with the

most efficient electrolysis option considered. It is used to explore the potential lower limit of emissions when both technology and electricity mix are simultaneously optimized relative to the baseline.

Table 33. Life cycle CO_2 emissions and stage contributions for E-kerosene in the Wind and SOE

Life cycle stage	CO_2 eq (g/MJ)	Share of total (%)
Electricity generation	4.4	65.5
Fuel synthesis (non-electricity)	2.1	30.6
Distribution	0.3	3.9
Total WTT	6.8	100.0

Table 34. Life cycle CO_2 emissions and stage contributions for Hydrogen in the Wind and SOE

Life cycle stage	CO_2 eq (g/MJ)	Share of total (%)
Electricity generation	3.3	77.0
Fuel synthesis (non-electricity)	0.9	20.8
Distribution	0.1	2.2
Total WTT	4.2	100.0

Table 35. Life cycle CO_2 emissions and stage contributions for Ammonia in the Wind and SOE

Life cycle stage	CO_2 eq (g/MJ)	Share of total (%)
Electricity generation	3.7	45.7
Fuel synthesis (non-electricity)	3.8	46.7
Distribution	0.6	7.5
Total WTT	8.1	100.0

Table 36. Other Environmental Impacts of Scenario 6

Impact categories	Unit	E-kerosene	Hydrogen	Ammonia
Freshwater Eutrophication	g P eq	2.02E-05	1.28E-05	3.18E-05
Marine Eutrophication	g N eq	1.23E-04	7.55E-05	2.10E-04
Terrestrial Acidification	g SO_2 eq	7.28E-02	3.49E-02	4.47E-02

4.4 Interpretation of the results: comparative analysis

According to ISO 14040 and ISO 14044, the final phase of an LCA consists of (i) presenting the results of the impact assessment in a transparent and reproducible manner, (ii) interpreting the outcomes in relation to the goal and scope of the study, and (iii) identifying key contributions, trade-offs, and uncertainties that may influence the robustness of the conclusions. This chapter, therefore, reports the comparative results of the impact assessment for all fuel pathways and impact categories defined in Chapter 3 and subsequently discusses their relevance in the context of sustainable aviation fuels.

In the first part of this chapter, comparative figures are presented for each midpoint impact category, including climate change, freshwater eutrophication, marine eutrophication, and terrestrial acidification. The results are shown for the baseline cases as well as for the scenario variants where applicable. In the second part, the key differences and drivers behind the results are interpreted, with emphasis on identifying the environmental hotspots and the processes most responsible for variations between fuels.

In accordance with the interpretation phase defined in ISO 14040 and ISO 14044, this section presents the comparative results of the life-cycle impact assessment for the selected aviation fuel pathways. The results are presented by impact category and scenario to ensure a transparent comparison with respect to the goal and scope defined in Chapter 3. For each category, the results are first presented graphically and then briefly interpreted to identify dominant contributors, relative differences between fuels, and scenario-dependent variations. This analysis provides the basis for the subsequent discussion of key findings and uncertainties in Section 5.2.

4.4.1 Climate Change Impacts

Table 37. Climate impact of SAF per Unit of energy (MJ)

Climate change	Unit/MJ	E-Kerosene	Hydrogen	Ammonia	CJF
SOLAR & AEL	g CO_2 eq	22.8	15.4	21.3	
SOLAR & PEM	g CO_2 eq	28.9	20.1	26.2	
SLOAR & SOE	g CO_2 eq	17.7	12.2	26.2	
WIND & AEL	g CO_2 eq	7.5	4.8	17.2	17.13
WIND & PEM	g CO_2 eq	9.3	6.0	8.7	
WIND & SOE	g CO_2 eq	6.8	4.2	10.1	

Table 37 compares the well-to-tank climate impacts of electro-kerosene, hydrogen, and ammonia under different combinations of renewable electricity and electrolysis technologies. The results clearly show that the carbon intensity of the electricity source is the dominant driver of environmental performance. All pathways exhibit substantially lower emissions when powered by wind electricity compared with solar electricity. Among the electrolysis technologies, SOE consistently delivers the lowest impacts due to its higher electrical efficiency.

Across all scenarios, hydrogen shows the lowest climate impacts (4.2–20.1 g CO_2-eq/MJ), followed by ammonia and electro-kerosene. The combination of wind electricity and SOE results in the best overall performance for all fuels, with hydrogen and electro-kerosene achieving 4.2 and 6.8 g CO_2-eq/MJ, respectively. Solar-based systems, particularly for ammonia and PEM configurations, show the highest impacts due to the higher upstream emissions of solar PV electricity.

Even when considering only the well-to-tank stage, all wind-based SAF pathways perform better than the conventional jet fuel (17.13 g CO_2-eq/MJ), highlighting their strong potential for decarbonising aviation. These results underline that the environmental feasibility of SAF production relies primarily on access to low-carbon, high-efficiency electricity pathways.

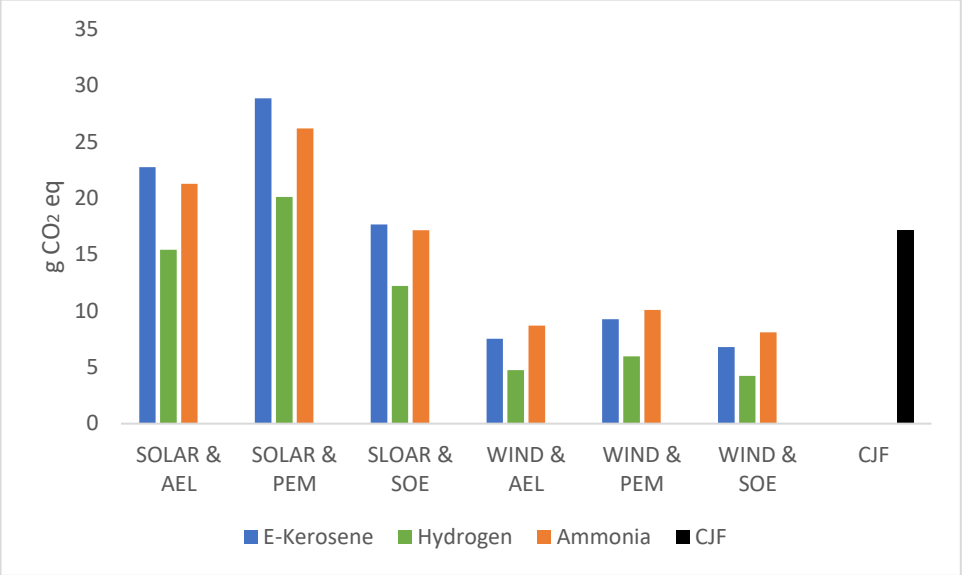

Figure 11. Climate change results for the three fuel pathways per FU

Figure 11 presents the well-to-tank (WTT) climate impacts of electro-kerosene, hydrogen, and ammonia across six electricity-electrolysis configurations, together with the baseline value for conventional jet fuel (CJF). In all solar-based scenarios, emissions remain comparatively high, with Solar + PEM showing the greatest WTT impacts for all three fuels. This is driven by the relatively elevated carbon intensity of photovoltaic electricity and by the higher specific electricity demand of PEM electrolysis. Solar + AEL and Solar + SOE also exhibit higher emissions than their wind-based counterparts, though SOE performs moderately better due to its higher electrical efficiency.

In contrast, wind-powered configurations consistently show substantial reductions in WTT emissions. Across all fuels, Wind + SOE achieves the lowest values, followed closely by Wind + AEL and Wind + PEM, reflecting both the low-carbon intensity of wind electricity and the superior conversion efficiency of high-temperature electrolysis. Hydrogen demonstrates the lowest WTT impacts in every scenario, often falling below 10 g CO_2-eq/MJ, especially in wind-powered pathways. Ammonia exhibits slightly higher emissions due to the additional energy demand of Haber-Bosch synthesis, while electro-kerosene shows the highest emissions among the three SAFs because of multiple synthesis stages (RWGS, FT/MTK upgrading).

The inclusion of the baseline CJF value highlights the significant advantage of renewable-powered electrolysis fuels. All wind-based SAF configurations achieve WTT emissions well below fossil kerosene, even when accounting for the additional processing steps in electro-

kerosene and ammonia pathways. These results reinforce that electricity carbon intensity is the dominant driver of upstream emissions. In addition, differences among electrolysis technologies strongly influence WTT impacts:

- AEL offers robust performance and relatively low energy demand at scale.
- PEM is more electricity-intensive and therefore more sensitive to carbon-intensive grids.
- SOE benefits from high-temperature operation, which significantly reduces electricity consumption and leads to the lowest overall emissions.

Overall, the figure demonstrates that combining low-carbon wind electricity with high-efficiency electrolysis technologies (especially SOE) can reduce WTT emissions across all SAF pathways to levels far below those of fossil-based jet fuel, highlighting their strong potential for decarbonizing upstream aviation fuel production.

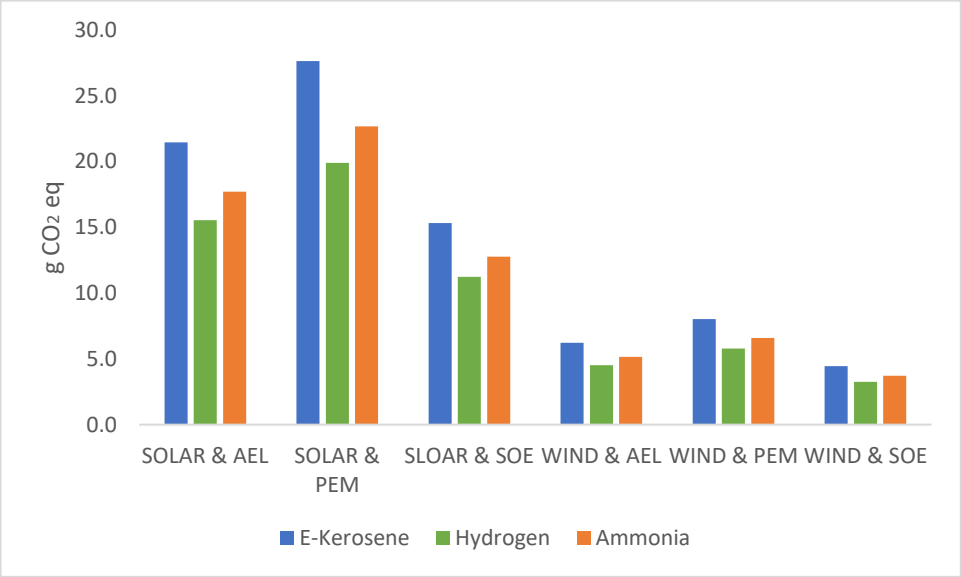

Figure 12. Electricity-related CO_2 emissions (g CO_2-eq/MJ) for e-kerosene, hydrogen, and ammonia

This figure compares the electricity-related CO_2 emissions (g CO_2-eq/MJ fuel) for e-kerosene, hydrogen, and ammonia under different combinations of solar and wind electricity with the three electrolysis technologies. Overall, the results clearly show that wind electricity leads to substantially lower CO_2 emissions for all fuel pathways compared with solar electricity, reflecting the much lower life-cycle carbon intensity of wind power.

Among solar configurations, Solar + PEM shows the highest emissions for all fuels, as PEM electrolysers have higher electricity consumption and more carbon-intensive manufacturing. Solar + AEL and Solar + SOE follow with slightly lower values. Under wind-based scenarios, all fuels see a major reduction, with Wind + SOE producing the lowest emissions due to SOE's high electrical efficiency.

Across fuels, e-kerosene consistently shows higher electricity-related CO_2 burdens due to its energy-intensive synthesis chain (DAC → RWGS → FT), while hydrogen shows the lowest values, and ammonia remains in between. This confirms that electricity sourcing is the dominant driver of upstream CO_2 emissions, and that low-carbon electricity (such as wind) is essential for achieving climate benefits across all SAF pathways.

4.4.2 Freshwater Eutrophication

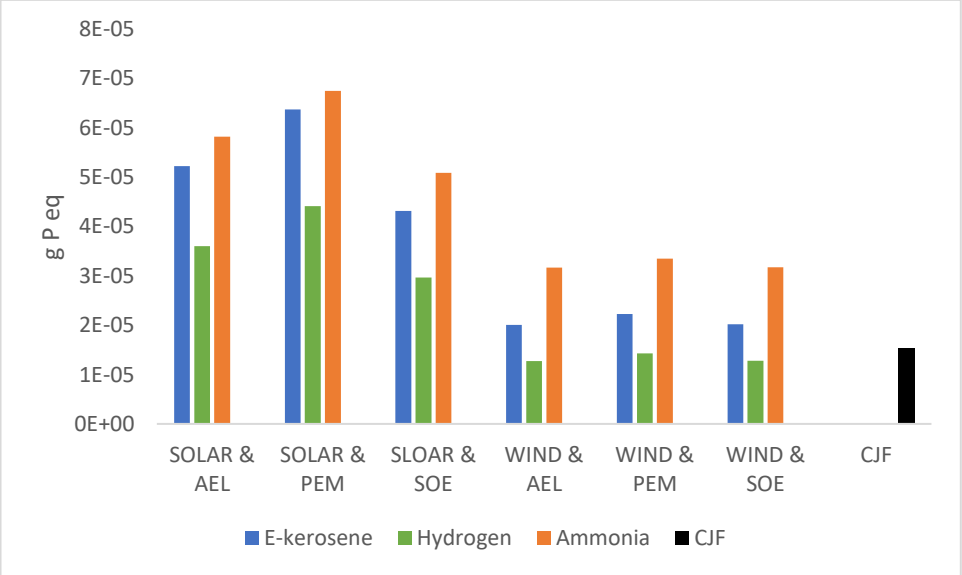

Figure 13. Freshwater eutrophication results for the three fuel pathways

Figure 13 presents the phosphorus depletion (g P-eq.) associated with e-kerosene, hydrogen, and ammonia across six electricity-electrolysis configurations, together with the baseline value for conventional jet fuel (CJF). Across all solar-based scenarios, phosphorus depletion is highest, with values typically ranging from 5.0×10^{-5} to 7.0×10^{-5} g P-eq. depending on the fuel pathway. These elevated impacts are driven primarily by the phosphorus-intensive production of photovoltaic panels.

In comparison, wind-powered systems significantly reduce phosphorus depletion, with values generally in the range of 1.5×10^{-5} to 3.0×10^{-5} g P-eq. This corresponds to a 40-60% reduction relative to the solar-based configurations. For example, ammonia decreases from approximately 7.2×10^{-5} g P-eq. (Solar + PEM) to around 3.0×10^{-5} g P-eq. (Wind + SOE), representing a reduction of approximately 58%.

Electrolyser technology also plays a clear role. PEM electrolysis consistently shows the highest P-eq. impacts, followed by AEL, due to higher electricity consumption and the use of phosphorus-intensive materials. SOE achieves the lowest phosphorus depletion, reducing impacts by an additional 10-20% relative to AEL and PEM systems.

Across all three fuels, hydrogen exhibits the lowest phosphorus depletion, with wind-based hydrogen pathways reaching values around $1.2\text{-}1.5\times10^{-5}$ g P-eq., the smallest among all fuel–technology combinations. E-kerosene displays moderate P-eq. impacts, while ammonia consistently shows the highest values, reflecting the additional material and energy requirements of nitrogen production and the Haber-Bosch synthesis process.

When compared to CJF, which has a baseline phosphorus depletion of approximately 1.5×10^{-5} g P-eq., the results show:

- All solar-based SAF pathways exceed CJF by 250-400%, due to the upstream impacts of photovoltaic systems.
- Wind-powered hydrogen and electro-kerosene fall close to or slightly above CJF, typically 5-30% higher.
- Wind-powered SOE hydrogen approaches CJF the closest, with only a 5-10% difference.
- Ammonia remains above CJF in all cases, though wind + SOE still reduces its P-eq. impacts by about 55-60% compared to solar scenarios.

Overall, phosphorus depletion is primarily driven by the electricity source, with solar pathways producing 2-4 times higher impacts and secondarily by electrolyser choice, with PEM contributing the most and SOE the least. Fuel composition itself plays a smaller role compared to the influence of electricity and electrolysis technology.

4.4.3 Marine Eutrophication

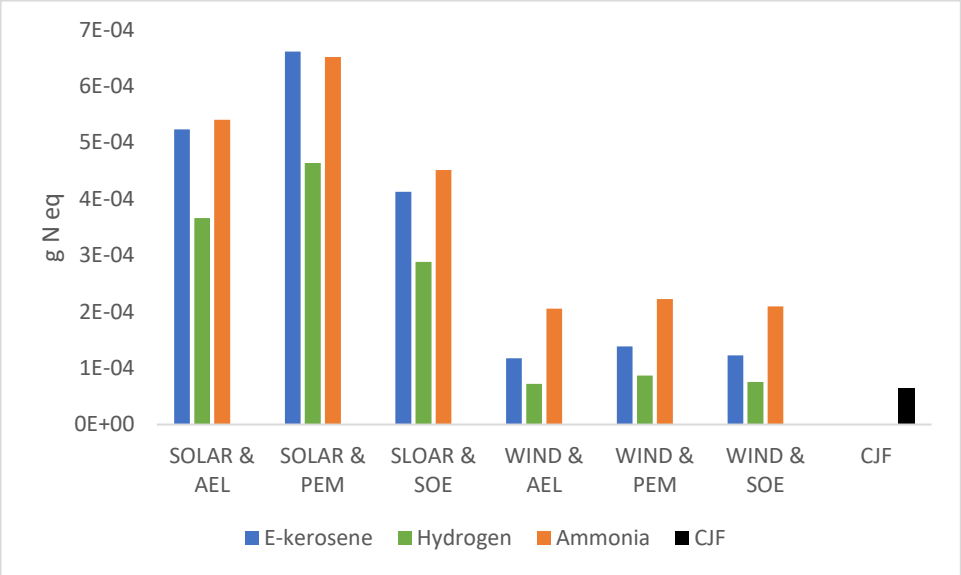

Figure 14. Marine eutrophication results for the three fuel pathways

Figure 14 presents the marine eutrophication potential (g N-eq.) of e-kerosene, hydrogen, and ammonia across all six production pathways, alongside the baseline value for conventional jet fuel (CJF). Solar-based scenarios show the highest eutrophication impacts, with values ranging from approximately 4.0×10^{-4} to 6.5×10^{-4} g N-eq. depending on the fuel. These elevated values result from nitrogen-intensive chemical processes and wastewater emissions associated with photovoltaic panel manufacturing.

Wind-powered configurations substantially reduce eutrophication impacts, yielding values in the range of 1.0×10^{-4} to 2.2×10^{-4} g N-eq. This corresponds to a 55-70% reduction relative to the solar-based scenarios. For example, electro-kerosene decreases from around 6.7×10^{-4} g N-eq. (Solar + PEM) to roughly 1.3×10^{-4} g N-eq. (Wind + PEM), representing a reduction of approximately 80%.

Electrolyser choice also plays a significant role. PEM electrolysis consistently results in the highest eutrophication values, followed by AEL, due to higher energy demand and upstream material requirements. SOE exhibits the lowest impacts among the three technologies, reflecting its higher electrical efficiency and lower material intensity.

Across all fuels and scenarios, hydrogen demonstrates the lowest eutrophication potential, with wind-powered hydrogen pathways reaching values close to 1.0×10^{-4} g N-eq., the smallest among all fuel-technology combinations. E-kerosene shows moderate

eutrophication impacts, while ammonia consistently exhibits the highest values, particularly under Solar + PEM and Solar + AEL due to nitrogen production, catalyst processing, and the energy-intensive Haber-Bosch process.

When compared to conventional jet fuel (CJF), which exhibits a marine eutrophication impact of approximately 1.0×10^{-4} g N-eq., the results show that:

- All solar-based SAF pathways exceed CJF by 300-550%, depending on the fuel and electrolysis configuration.
- Wind-powered hydrogen and electro-kerosene approach or slightly exceed CJF, typically within 10-40% of the CJF baseline.
- Wind + SOE hydrogen most closely aligns with CJF, differing by only 5-10%.
- Ammonia exceeds CJF in all cases, though wind-powered ammonia reduces eutrophication by 60-70% relative to its solar-based variants.

Overall, marine eutrophication impacts are governed primarily by upstream electricity generation and electrolyser technology, rather than fuel composition or combustion. Electricity-intensive processes such as photovoltaic panel production and PEM electrolysis drive the highest impacts, whereas wind-based pathways and SOE systems consistently minimise eutrophication potential.

4.4.4 Terrestrial Acidification

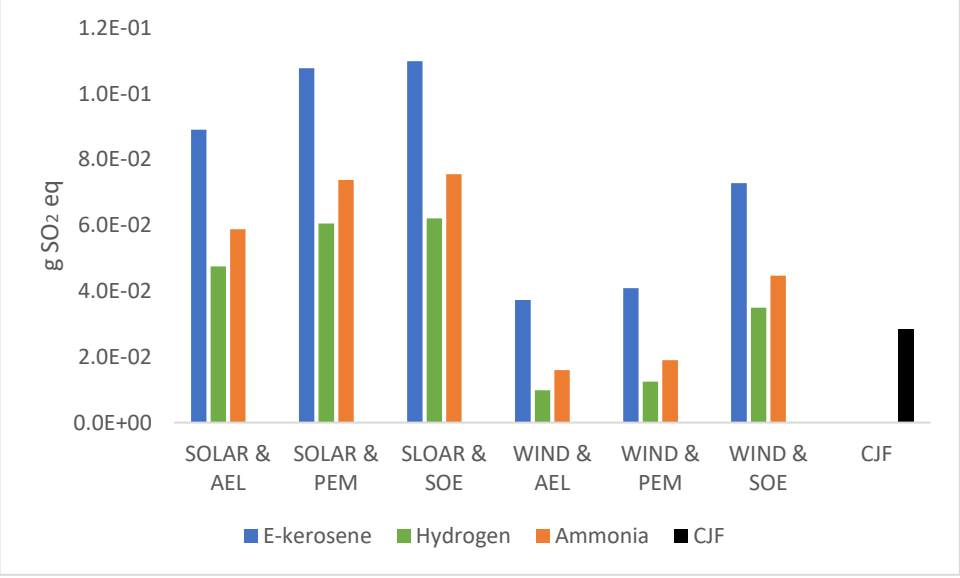

Figure 15. Terrestrial acidification results for the three fuel pathways

Figure 15 presents the terrestrial acidification potential (g SO_2-eq.) associated with the production of e-kerosene, hydrogen, and ammonia under six electricity electrolysis configurations, alongside the baseline value for conventional jet fuel (CJF). Solar-based scenarios consistently exhibit the highest acidification impacts, with values ranging from 0.05 to 0.11 g SO_2-eq., depending on the fuel. These elevated impacts are primarily attributed to the sulfur and nitrogen-intensive upstream processes involved in photovoltaic panel manufacturing, which generate significant SO_2 and NO_x emissions.

Wind-powered pathways substantially reduce acidification impacts, yielding values in the range of 0.01 to 0.04 g SO_2-eq. across all fuels and technologies. This corresponds to a 50-75% reduction relative to the solar-based pathways. For example, electro-kerosene decreases from approximately 0.11 g SO_2-eq. (Solar + SOE) to around 0.035 g SO_2-eq. (Wind + PEM), representing a reduction of nearly 70%.

Fuel pathways differ considerably. E-kerosene consistently shows the highest acidification potential due to the cumulative emissions associated with point source capture (PSC), Reverse Water Gas Shift (RWGS), Fischer-Tropsch (FT) synthesis, compression, and upgrading steps. Ammonia ranks second, as nitrogen production and the energy-intensive Haber-Bosch process contribute to elevated SO_2-eq. emissions. Hydrogen exhibits the lowest acidification impacts across all scenarios, with wind-based hydrogen pathways falling as low as 0.01-0.015 g SO_2-eq., the smallest among all fuel-technology combinations.

Electrolysis technology also plays a significant role. PEM electrolysis results in the highest acidification impacts, driven by catalyst and membrane manufacturing. AEL exhibits moderate impacts, while SOE consistently achieves the lowest values, particularly when paired with wind electricity, owing to its reduced material use and higher electrical efficiency.

Compared to conventional jet fuel (CJF), which exhibits an acidification potential of approximately 0.03 g SO_2-eq., the results indicate that:

- All solar-based SAF pathways exceed CJF, typically by 100-250% depending on the fuel type and electrolysis technology.
- Wind-based hydrogen generally performs better than CJF, achieving 40-65% lower acidification.

- Wind-based electro-kerosene and ammonia approach CJF, generally within 10-40% of CJF's baseline value.
- Wind + SOE hydrogen is the closest to, or slightly lower than, CJF, representing the best-performing pathway among all scenarios.

Overall, terrestrial acidification impacts are driven predominantly by upstream electricity generation and material intensity, particularly the impacts associated with photovoltaic manufacturing and PEM electrolysis. Wind-powered pathways and SOE technology minimise these impacts, while fuel-specific differences reflect the varying material and energy requirements of each production chain.

4.5 Discussion of Key Findings and Uncertainties

The previous section presented the numerical results for all considered impact categories across the three fuel pathways and six scenarios. In this section, the focus shifts from reporting values to interpreting what they mean. The aim is to explain the reasons behind the observed differences between fuels, to identify the dominant processes that drive the impacts, and to clarify how the electricity source, electrolysis technology, and distribution affect environmental performance.

4.5.1 Climate change

The well-to-tank results shown in Figure 11 and Table 37 reveal a consistent ranking of climate change impacts across all production scenarios: hydrogen exhibits the lowest WTT emissions, followed by ammonia, while e-kerosene remains the most carbon-intensive option. This ordering is preserved across all combinations of electricity sources (solar and wind) and electrolysis technologies (AEL, PEM, SOE), indicating that the main drivers of variation are the intrinsic energy and material requirements of each production chain rather than fuel-specific combustion characteristics.

A key outcome of the analysis is that the carbon intensity of electricity overwhelmingly determines the total WTT climate impact. Replacing photovoltaic electricity with wind power yields substantial reductions for all three fuels, typically in the range of 60-70% relative to solar-based configurations. The effect is most pronounced for hydrogen, whose production is dominated by electrolysis and compression; wind-powered hydrogen pathways reduce WTT emissions from approximately 20-22 g CO_2-eq/MJ (Solar + PEM) to 6-7 g CO_2-

eq/MJ (Wind + SOE). Ammonia and e-kerosene similarly benefit from wind electricity, but their relative reductions are moderated by additional synthesis processes, Haber-Bosch for ammonia and PSC/RWGS/FT upgrading for e-kerosene, which introduce fixed energy and material burdens that are not eliminated even under low-carbon electricity.

Across all scenarios, electrolytic hydrogen production emerges as the single largest contributor to WTT climate impacts. This is because hydrogen is a fundamental input to all three fuel pathways, meaning that electrolyser efficiency and electricity demand account for the majority of upstream CO_2 emissions. PEM electrolysis consistently shows the highest WTT impacts (20.1 g CO_2-eq/MJ for hydrogen; 28.9 for e-kerosene; 26.2 for ammonia) due to higher electricity consumption and carbon-intensive stack manufacturing. AEL performs better under identical electricity conditions, while SOE provides the lowest impacts down to 4.2 g CO_2-eq/MJ for hydrogen, because high-temperature operation reduces electricity requirements. These results highlight that improvements in electrolysis efficiency and material sourcing can achieve emissions reductions comparable to switching from solar to wind electricity, making electrolyser technology a critical variable for future SAF production systems.

In all scenarios, e-kerosene exhibits the highest WTT climate impacts, with values ranging from 7-8 g CO_2-eq/MJ under Wind + SOE to 28-30 g CO_2-eq/MJ under Solar + PEM. This reflects its reliance on multiple sequential, energy-intensive conversion steps, including CO_2 capture, RWGS, Fischer-Tropsch synthesis, and final upgrading, which collectively retain significant upstream burdens even when powered by low-carbon electricity. Although point-source CO_2 capture provides a modest avoided-emission credit, it is insufficient to compensate for the pathway's cumulative energy demand. Despite this, e-kerosene offers a major operational advantage as a drop-in fuel compatible with current aircraft engines and airport fuelling infrastructure, making it the most near-term deployable option among the three alternatives.

Because the system boundary of this analysis is limited to WTT, all results reflect only upstream processes and exclude combustion-related climate forcers. Nevertheless, the WTT trends clearly demonstrate that SAF deployment achieves meaningful climate benefits only when integrated with low-carbon electricity systems. The dominance of electricity sourcing over electrolyser type indicates that decarbonising the electricity grid has a greater impact

on the environmental performance of hydrogen, ammonia, and e-kerosene than changes in electrolyser technology. Ultimately, the climate performance of all three fuels is shaped far more by the carbon intensity of their upstream energy inputs than by the molecular characteristics of the fuels themselves.

4.5.2 Other impact categories

Across all non-climate impact categories, hydrogen consistently exhibits the lowest upstream burdens, reflecting the simplicity of its process chain and the absence of CO_2 conversion, nitrogen synthesis, or hydrocarbon upgrading. The relative performance of ammonia and e-kerosene varies by impact category and electricity source, demonstrating that these impacts are driven predominantly by the material, chemical, and energy demands of upstream processes, rather than the properties of the fuels themselves. When compared with conventional jet fuel (CJF), solar-based SAF pathways generally exceed CJF in all categories, while some wind-based pathways approach or fall close to its upstream values.

Freshwater Eutrophication

Hydrogen remains the lowest-impact option in all scenarios, often reaching the closest values to CJF. The highest burdens depend strongly on electricity sourcing. Under solar electricity, e-kerosene tends to show the highest freshwater eutrophication impacts, driven by material-intensive stages such as PSC, RWGS, and FT synthesis, as well as the upstream phosphorus intensity of photovoltaic systems. When wind electricity replaces solar, upstream energy burdens decline substantially, causing the relative influence of Haber-Bosch feedstocks and nitrogen-related precursors to increase, and ammonia becomes the highest-impact pathway. This shift shows that freshwater eutrophication is governed mainly by upstream chemical requirements and background electricity emissions rather than differences in combustion.

Marine Eutrophication

A comparable trend is observed for marine eutrophication. Hydrogen again exhibits the lowest burdens and aligns most closely with CJF. Under solar electricity, e-kerosene becomes the dominant contributor, reflecting eutrophying emissions associated with catalyst fabrication, auxiliary chemicals, and energy-intensive RWGS/FT synthesis. Once wind is introduced, these upstream burdens fall significantly, and ammonia surpasses e-kerosene, as

nitrogen production and Haber-Bosch chemistry remain relatively intensive even under low-carbon electricity. Despite differences in magnitude, all three fuels show substantial reductions moving from solar to wind, confirming that background electricity generation is a major driver of marine eutrophication impacts.

Terrestrial Acidification

Unlike the eutrophication categories, terrestrial acidification is consistently dominated by e-kerosene regardless of the electricity source. This is because acidification is strongly linked to the material and chemical intensity of the synthesis chain itself, especially FT upgrading, PSC sorbents, catalyst production, and intermediate chemical processes. These emissions persist even under wind electricity, meaning that the complexity of the e-kerosene pathway remains the dominant driver. Ammonia exhibits intermediate impacts due to electricity demand and Haber-Bosch processing, while hydrogen again performs best, frequently approaching or falling below CJF. This pattern indicates that terrestrial acidification is influenced more by process complexity than by electricity carbon intensity.

Overall, the non-climate results show that while hydrogen reliably provides the lowest upstream burdens, the relative ranking of ammonia and e-kerosene depends on the impact category and electricity source. Eutrophication impacts are highly sensitive to electricity sourcing, shifting substantially when solar is replaced by wind. In contrast, terrestrial acidification is driven primarily by the depth and complexity of the e-kerosene synthesis chain, which remains material- and emissions-intensive regardless of electricity source.

Compared to CJF, solar-powered SAF pathways consistently exhibit higher impacts, while wind-based pathways, especially hydrogen and, in some categories, ammonia, come closest to matching CJF's upstream performance. Altogether, these patterns reinforce that the environmental performance of SAF pathways is shaped mainly by upstream industrial processes, chemical intensity, and energy systems, not by combustion characteristics. Thus, improving upstream material efficiency and decarbonising electricity supply are critical for reducing non-climate impacts across all sustainable aviation fuel options.

4.5.3 Technological Feasibility and Pathway Considerations

Although life-cycle assessment (LCA) results offer valuable insights into the environmental performance of alternative aviation fuels, their practical implementation is largely contingent upon technological maturity, operational viability, and infrastructure preparedness. The comparative findings of this study emphasise not only the environmental benefits but also key implementation limitations that affect the immediate and long-term viability of each pathway.

Among the electrolysis technologies assessed, Alkaline (AEL) and Proton Exchange Membrane (PEM) electrolysis are the most commercially advanced and extensively implemented. AEL systems are extensively established in large-scale hydrogen production and advantageously offer relatively low capital costs along with demonstrated reliability (Bhandari et al., 2014; Nasser et al., 2022). PEM electrolysers, despite their higher cost, provide greater current densities, a more compact design, and a quicker response to fluctuating renewable electricity, rendering them appropriate for integration with wind or solar power systems (Nasser et al., 2022). Conversely, Solid Oxide Electrolysis (SOE) continues to be in the initial demonstration phase. Despite its prospects for increased electrical efficiency and enhanced thermal integration with industrial heat sources, SOE encounters durability challenges associated with elevated operating temperatures (700–1000 °C) and material deterioration at electrode-electrolyte interfaces (Bhandari et al., 2014). Consequently, although AEL and PEM technologies are viable for immediate deployment in Power-to-Liquid (PtL) or hydrogen production systems, SOE is expected to remain a longer-term alternative, contingent upon substantial advancements in materials and cost reduction.

The hydrogen pathway assessed in this study represents compressed hydrogen storage at approximately 350 bar. However, practical aviation applications will require liquid hydrogen (LH_2) due to the volumetric limitations of compressed gas storage. The liquefaction of hydrogen introduces a considerable additional energy demand, typically around 10 kWh per kg H_2, which corresponds to about 25-30 % of the total energy content of the fuel (Cardella et al., 2017). This additional step would increase the overall life-cycle energy consumption and potentially the GHG emissions of hydrogen-based aviation, particularly if the electricity used for liquefaction is not entirely renewable. Therefore, while hydrogen shows the lowest

global warming potential (GWP) in the present analysis, future assessments incorporating LH_2 storage and distribution requirements may result in higher overall impacts.

Conversely, electro-kerosene (Power-to-Liquid kerosene) is the most viable immediate solution for decarbonizing aviation, as it is a drop-in fuel entirely compatible with current aircraft engines and airport fueling systems. Its physicochemical properties closely resemble those of conventional Jet A-1, facilitating immediate integration without necessitating significant technological modifications. The scalability of e-kerosene production is limited by the substantial energy demands of point source capture (PSC) and Fischer-Tropsch synthesis, in addition to the prevailing cost of renewable electricity. Nonetheless, due to its compatibility with existing infrastructure and regulatory endorsement within the ReFuelEU Aviation framework, e-kerosene is expected to serve a pivotal transitional function in diminishing aviation emissions until hydrogen and ammonia propulsion systems attain greater technical and economic feasibility.

In contrast, ammonia presents considerable long-term potential as a carbon-free fuel, especially as a hydrogen carrier, due to its superior storage and transport capabilities relative to hydrogen. The principal limitation pertains to combustion characteristics, specifically low flame speed and high ignition temperature, resulting in incomplete combustion and increased nitrogen oxide (NO_x) emissions (Alnajideen et al., 2024). Nevertheless, these disadvantages can be alleviated through technological optimization. Innovative engine designs featuring enhanced mixing and combustion regulation, along with the incorporation of selective catalytic reduction (SCR) systems, may significantly reduce NO_x emissions and enhance overall combustion efficiency (Fullonton et al., 2023). Such enhancements could enable ammonia to attain reduced life-cycle greenhouse gas emissions, rendering it a feasible alternative for medium- and long-haul flights, especially when produced from renewable hydrogen.

The LCA results unequivocally illustrate the environmental benefits of sustainable aviation fuels compared to conventional jet fuel; however, the shift to widespread implementation hinges on addressing technological and infrastructural obstacles. Electro-kerosene offers the most immediate solution due to its compatibility and availability, while hydrogen and ammonia serve as long-term alternatives necessitating ongoing advancements in storage, propulsion, and emissions management systems. The interaction among technological

maturity, energy efficiency, and environmental performance will consequently dictate the speed and trajectory of aviation's shift to climate-neutral fuels.

5. Conclusions

This thesis conducted a comparative well-to-tank (WTT) life cycle assessment of three emerging Sustainable Aviation Fuels: electro-kerosene, hydrogen, and ammonia across six electricity-electrolysis configurations. The results clearly demonstrate that electricity carbon intensity and electrolyser efficiency are the main determinants of upstream environmental performance.

In all scenarios, the climate impacts of WTT varied significantly based on the electricity source. Solar-based systems consistently generated the highest emissions, with Solar + PEM attaining WTT values of approximately 29 g CO_2-eq/MJ for electro-kerosene, 20 g CO_2-eq/MJ for hydrogen, and 26 g CO_2-eq/MJ for ammonia. The elevated values result from the greater carbon intensity of photovoltaic electricity and the heightened electricity demand of PEM electrolysis.

Conversely, wind-powered systems significantly diminished emissions. Wind and SOE yielded the lowest well-to-tank (WTT) results, with values reaching 4 g CO_2-eq/MJ for hydrogen, 10 g CO_2-eq/MJ for ammonia, and 7 g CO_2-eq/MJ for electro-kerosene. In comparison to the upstream intensity of conventional jet fuel (17 g CO_2-eq/MJ), these findings indicate a reduction of roughly 40-75% across the three sustainable fuel pathways. This unequivocally illustrates that wind-powered electrolysis can reduce upstream emissions by over fifty percent compared to fossil kerosene, highlighting its significant potential for low-carbon aviation fuel production.

Among the three fuel pathways, hydrogen consistently exhibited the lowest well-to-tank (WTT) impacts, varying from 4 to 20 g CO_2-equivalent per megajoule (MJ), contingent upon the scenario. Ammonia subsequently exhibited values ranging from 9 to 27 g CO_2-eq/MJ, determined by the energy requirements of the Haber-Bosch process. Electro-kerosene exhibited the highest well-to-tank emissions among the sustainable aviation fuels, ranging from approximately 7 to 29 g CO_2-eq/MJ, primarily attributable to supplementary synthesis

processes including reverse water-gas shift and Fischer-Tropsch/Mass Transfer Kinetics upgrading.

Non-climate impact categories exhibited analogous trends. Solar-based systems yielded the highest metrics in freshwater eutrophication, marine eutrophication, terrestrial acidification, and phosphorus depletion. Wind-based scenarios consistently diminished impacts by 40-70%, confirming that the quality of renewable electricity is the predominant environmental factor. Electrolysis technology markedly influenced outcomes: SOE exhibited the least impacts across all categories, PEM demonstrated the greatest due to material intensity and energy requirements, while AEL displayed moderate performance.

Regarding feasibility, electro-kerosene is the most compatible with current aircraft and infrastructure, presenting a pragmatic near-term solution despite its elevated upstream emissions. Hydrogen and ammonia exhibit exceptional long-term decarbonization potential, particularly in wind + SOE configurations where WTT emissions are below 10 g CO_2-eq/MJ; however, both necessitate improvements in storage, combustion systems, and aircraft design.

The findings yield three principal conclusions: The carbon intensity of electricity is the primary factor influencing WTT environmental performance, with wind-based scenarios decreasing emissions by 65-85% relative to solar-based pathways. Electrolysis technology significantly affects emissions, with Solid Oxide Electrolysis (SOE) presenting the minimal impacts and Proton Exchange Membrane (PEM) exhibiting the maximal impacts across all categories. All wind-powered electrolysis methods surpass traditional jet fuel in upstream performance, attaining well-to-tank emissions significantly lower than the conventional jet fuel baseline of 17.13 g CO_2-eq/MJ.

These findings emphasize that the extensive implementation of SAFs must be closely integrated with low-carbon electricity systems and advanced electrolyzer technologies. The strategic prioritization of wind-powered electrolysis and high-efficiency solid oxide electrolysis (SOE) systems can facilitate significant decarbonization in upstream aviation fuel production. The findings offer definitive, data-supported insights that advocate for the progression of climate-neutral aviation routes.

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