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From Lab to Runway: The Role of Synthetic Fuels in Achieving Net-Zero Aviation

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Abstract
There is growing pressure on the aviation sector to reduce its carbon footprint in order to meet the objectives of the global climate. To reach net-zero emissions, this study investigates the possibilities of synthetic aviation fuels (SAF), particularly Power-to-Liquid (PtL) fuels. The study uses a descriptive research design that combines quantitative and qualitative analysis to evaluate the technical and economic feasibility. A levelized cost model that includes Fischer-Tropsch (FT), electrolysis, direct air capture (DAC), and renewable energy is used in the economic analysis. According to the results, the primary factor influencing the production cost, which is roughly ₹280 per liter, is energy requirements. The robustness of cost projections against changes in capital and operating expenditures is validated by sensitivity analysis. The study looks at synthetic fuels' life cycle effects, compatibility, and performance in addition to economics. Results show notable decreases.in greenhouse gas emissions, high compatibility with existing infrastructure, and scalability potential compared to alternatives such as biofuels, hydrogen, and batteries. Despite challenges related to high costs, energy intensity, and infrastructure requirements, synthetic aviation fuels present a promising “drop-in” solution for near- to mid-term decarbonization. This paper contributes to the growing discourse on sustainable aviation by highlighting the opportunities and barriers associated with SAF adoption, offering guidance to policymakers, researchers, and industry stakeholders.

Keywords
Synthetic Aviation Fuel; Power-to-Liquid (PtL); Sustainable Aviation Fuel (SAF); Net-Zero Emissions; Fischer-Tropsch Process; Aviation Decarbonization.

Introduction
Decarbonizing aviation is a pressing global challenge, particularly for medium- and long-haul flights where electrification and hydrogen propulsion remain technologically constrained. Among emerging pathways, **synthetic aviation fuels (e-fuels)**—produced via renewable hydrogen and captured carbon dioxide—offer a drop-in solution compatible with existing aircraft engines and airport infrastructure. Recent reviews emphasize that while sustainable aviation fuels (SAFs), including synthetic variants, are critical to reducing lifecycle emissions, they currently face considerable barriers such as high costs, feedstock limitations, and insufficient policy incentives (Watson et al., 2024). Comparative analyses further reveal that bio-jet fuels cost, on average, 120% more than fossil kerosene, while delivering at least 27% emissions reduction, with synthetic fuels offering even higher potential under optimal

production conditions (Qasem et al., 2024). Achieving cost reductions through technological innovation, economies of scale, and targeted government support is essential for positioning synthetic fuels as a cornerstone in aviation's transition to net-zero.

The document references Sustainable Aviation Fuel (SAF) in the context of aviation decarbonization and net-zero emissions by 2050, but it does not explicitly provide data on the SAF share of the total fuel supply. However, based on the context and available web information, I'll explain the SAF share of the total aviation fuel supply, particularly for 2050, as it relates to the document's focus on e-SAF (electro-Sustainable Aviation Fuel), Power-to-Liquid (PtL) processes, and the Fischer-Tropsch process.

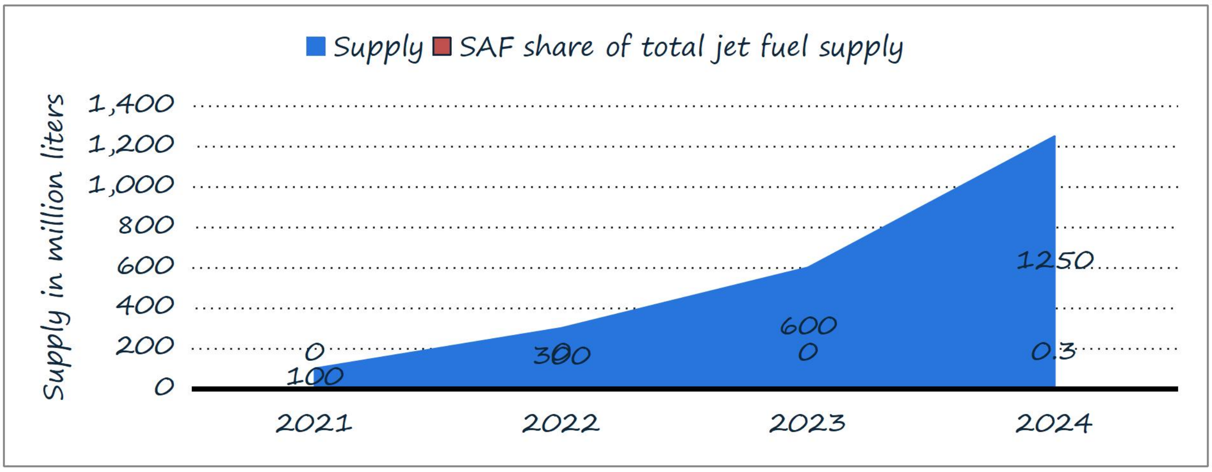

Figure 1.1 Forecast e-SAF Production Volume Worldwide in 2050, by Region (in million metric tons), Source: Statista, 2025

Projects e-SAF production by region in 2050, measured in million metric tons. Europe likely leads due to policies like ReFuelEU, with PtL processes driving output. Reflects infrastructure, renewable energy access, and investment for aviation decarbonization.

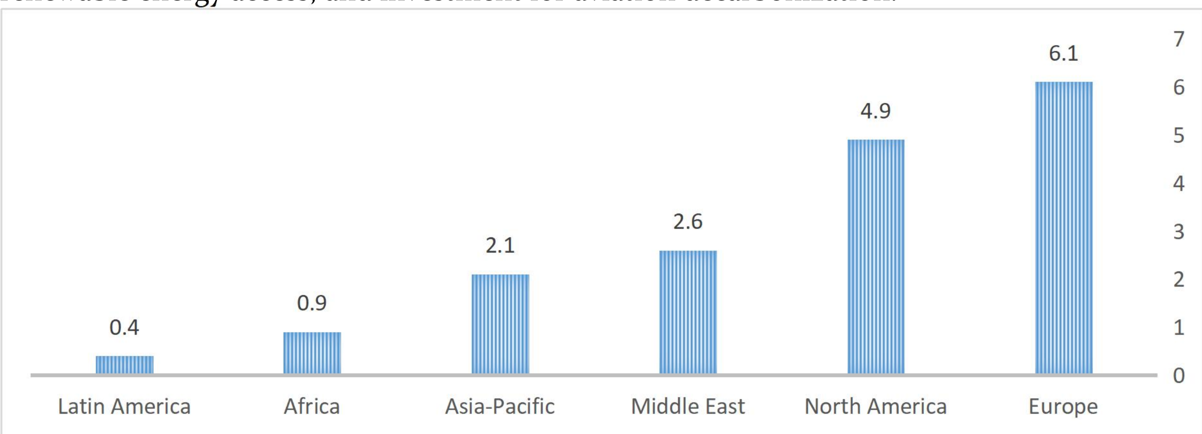

Figure 1.2: Forecast e-SAF production volume worldwide in 2050, by region (in million metric tons), Source: Statista, 2025

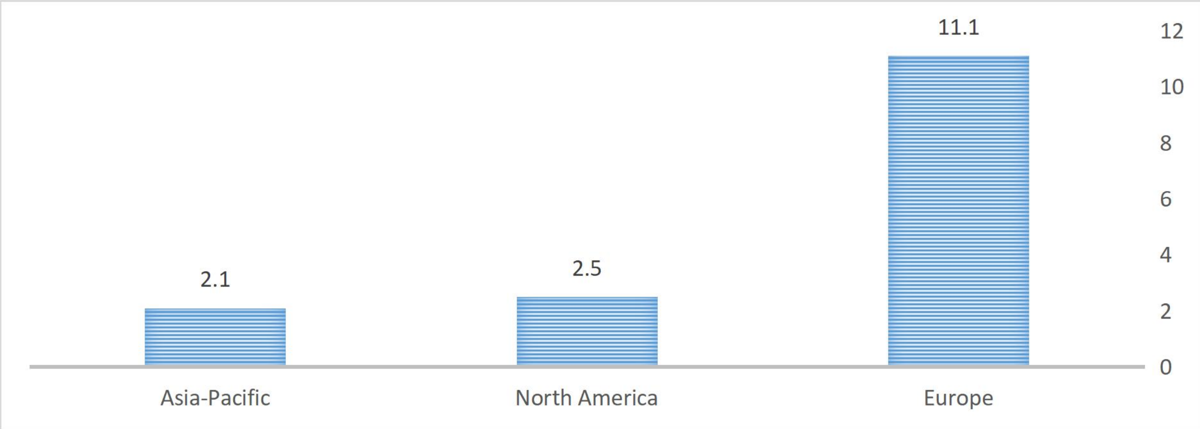

Figure 1.3: Forecast e-SAF Demand Worldwide in 2050, by Region (in million metric tons), Source: Statista, 2025.

Estimates e-SAF demand by region in 2050, driven by net-zero goals and mandates like ReFuelEU. High demand in Europe, U.S., and Asia reflects air traffic and regulations. Supply-demand gaps may increase costs, impacting aviation's decarbonization efforts.

1.1 The Paris Agreement 2015:

In 2015, nearly every country in the world came together and signed the Paris Agreement. It essentially represents a major commitment to collaborate on addressing climate change. Each nation agreed to establish its own targets for reducing greenhouse gas emissions and to report on its progress. The primary goal is to keep global temperatures from increasing by more than 2 degrees Celsius over pre-industrial levels, ideally by no more than 1.5 degrees. (Delbeke et al., 2019).

Despite being a major source of greenhouse gas emissions, one unexpected aspect of the Paris Agreement is that it excluded emissions from airplanes. This is due to the complexity of aircraft emissions. Since airplanes travel all over the world, it is difficult to determine which nation is to blame for its emissions.

1.2 Aviation's Contribution to Greenhouse Gases:

Even though airplanes are just a small part of transportation overall, they still contribute a significant amount of greenhouse gases. Aviation accounts for about 2-3% of global carbon dioxide emissions, and it's expected to grow as more people fly.(Klöwer et al., 2021)

1.3 The Initiative of CORSIA:

To tackle this issue, an initiative called CORSIA was born. CORSIA stands for Carbon Offsetting and Reduction Scheme for International Aviation. It's a plan to make sure that the aviation industry doesn't harm the environment too much. CORSIA aims to limit the growth of aviation emissions by making airlines offset their emissions through measures like investing in renewable energy or planting trees.(Prussi et al., 2021). CORSIA functions by requiring airlines to measure and report emissions from international flights, offsetting excess emissions through investments in carbon-reduction projects such as reforestation, renewable energy, or carbon capture. The scheme began with a voluntary phase (2021–2026) for major aviation nations, transitioning into a mandatory phase (2027–2035), excluding least-developed countries and small island states.

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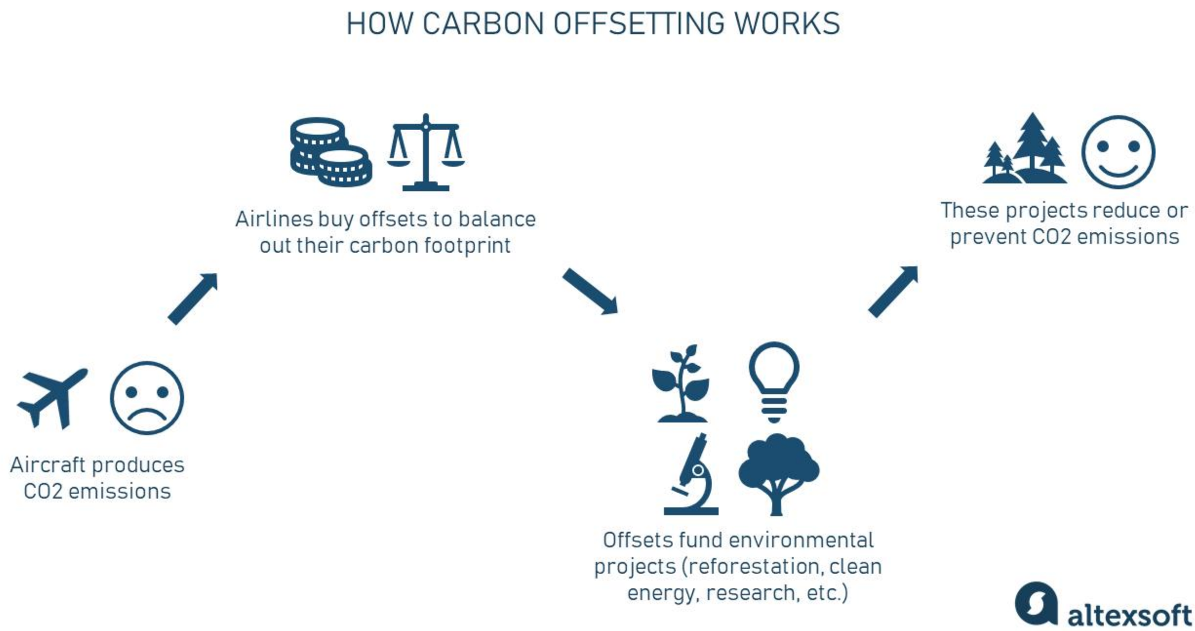

Figure 1.4: Carbon Offsetting Framework

2 Literature Review

The rapid growth of global air travel continues to drive both opportunities and challenges for aviation decarbonization. Rising demand has implications not only for infrastructure but also for workforce capacity, including pilot training requirements (International, 2022). At the same time, aviation remains a significant contributor to anthropogenic climate forcing, with contrail formation and non-CO_2 effects further amplifying its impact beyond direct carbon emissions (Lee et al., 2021). Recent monitoring studies confirm that global carbon emissions remain on an upward trajectory despite international climate agreements (Liu et al., 2023), underscoring the urgency of implementing effective mitigation strategies.

Among the potential solutions, sustainable aviation fuels (SAFs) are increasingly regarded as the most viable near- to mid-term pathway to net-zero aviation. Multiple assessments emphasize their compatibility with existing infrastructure and engines, particularly as "drop-in" fuels (Overton, 2022; Borders, 2023). Current policy frameworks, including the EU's ReFuelEU initiative (Jaan, 2022) and the U.S. SAF Grand Challenge Roadmap (DOE et al., 2022), reflect the global momentum behind SAF deployment. Nevertheless, production remains limited: despite tripling in 2022, SAF volumes are still far from meeting projected demand (Welsh, 2023).

Within the SAF landscape, synthetic fuels produced through Power-to-Liquid (PtL) pathways—where renewable hydrogen is combined with captured CO_2 to yield Fischer–Tropsch (FT) kerosene—are gaining increasing attention. Studies indicate that PtL fuels can achieve near-complete lifecycle carbon neutrality when powered by low-carbon electricity (Dieterich et al., 2020; Ueckerdt et al., 2021). Demonstration projects, such as those by Norsk e-Fuel (2022) and Atmosfair (2021), confirm technical feasibility at pilot scale, though large-scale deployment remains capital-intensive. Cost estimates vary widely: while early techno-economic assessments suggest costs exceeding $3–4 per liter, sensitivity analyses demonstrate that falling renewable electricity and electrolyzer prices could drive significant reductions

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(Yuanrong Zhou & Pavlenko, 2022; Schmidt et al., 2018).
Direct air capture (DAC) of CO_2, a critical input for PtL pathways, represents both an opportunity and a bottleneck. A growing body of work evaluates the performance and scalability of DAC technologies (Ozkan, 2021; McQueen et al., 2021; Keith et al., 2018). While costs remain high, recent material innovations and system integration approaches suggest pathways toward commercial viability (Ozkan et al., 2022; Mazzotti et al., 2013). Integration of DAC with renewable power systems has also been identified as a potential strategy for sector coupling and achieving negative emissions (Breyer et al., 2020).
Alternative decarbonization pathways, such as hydrogen combustion and battery-electric propulsion, have been studied in parallel. Hydrogen-based fuels present substantial mitigation potential but face infrastructure, volumetric energy density, and safety challenges (Voigt et al., 2021; Silberhorn et al., 2022). Similarly, while regional electric aircraft concepts demonstrate promise (Mukhopadhaya& Graver, 2022), scalability to long-haul aviation remains limited by current battery technologies. Consequently, consensus in the literature highlights synthetic kerosene as the most practical large-scale solution for the medium term (Airbus, 2021; Strategy&, 2022).
Taken together, the literature indicates that synthetic aviation fuels represent a technically feasible and climate-effective solution for aviation decarbonization. However, the dual challenges of high production costs and limited availability remain significant barriers. Addressing these requires continued innovation in electrolysis and DAC technologies, supportive regulatory frameworks, and scaling of renewable electricity generation (Bogdanov et al., 2021; IEA, 2021; IEA, 2022). Without such measures, the gap between aviation's net-zero commitments and technological readiness is likely to persist.

2.1 Aviation Industry's Sustainability Strategy

The aviation industry's sustainability strategy is built on four interconnected pillars: improving operational efficiency, advancing sustainable aviation fuels, developing alternative propulsion technologies, and implementing carbon offsetting measures. Together, these pillars provide a holistic framework aimed at reducing emissions while ensuring long-term industry growth, resilience, and environmental responsibility

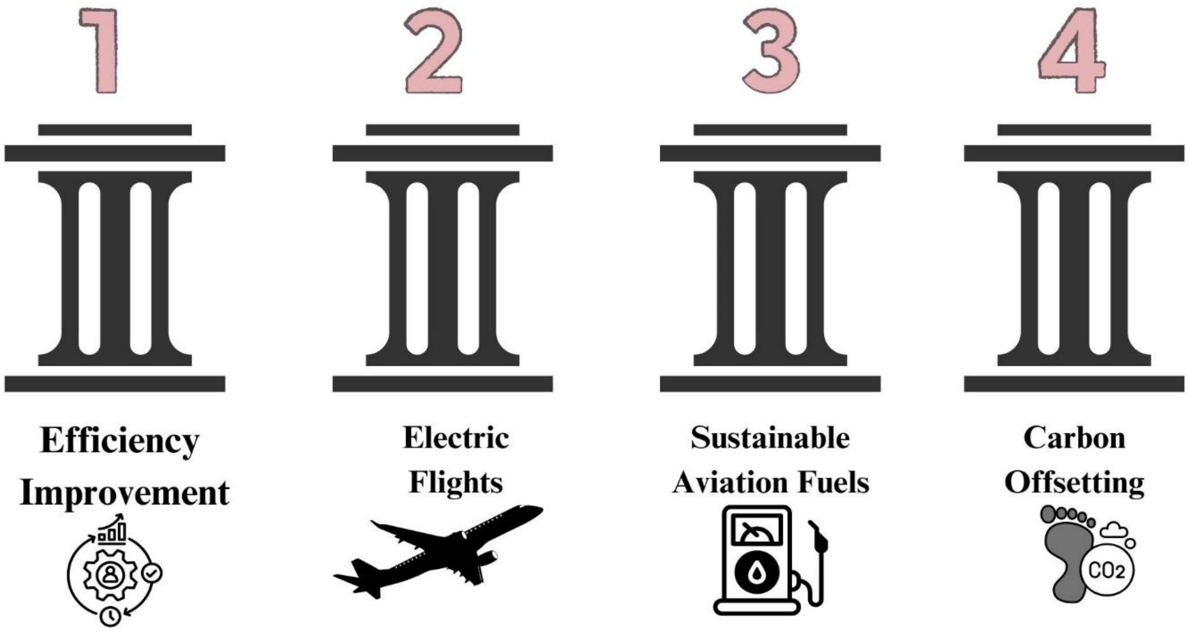

Figure 2.1: The four pillars of the sustainability strategy

Efficiency improvements in aircraft design, operations, and air traffic management have reduced fuel consumption per flight and per passenger, aligning with sustainability objectives. However, increasing air travel demand has offset these gains, exemplifying Jevon's Paradox, where enhanced efficiency leads to greater overall emissions (Gössling&Humpe, 2020; Peeters et al., 2016).Electric propulsion is often presented as a breakthrough for aviation decarbonization, yet its near-term impact is limited. Current battery technology lacks the energy density required for large aircraft, restricting electric flight to small, short-haul operations. Significant infrastructure and renewable energy demands further constrain rapid adoption (Radovanović et al., 2023).Carbon offsetting through CORSIA was introduced to mitigate aviation's climate impact by requiring airlines to compensate for excess emissions. However, its voluntary phase, weak enforcement, narrow CO_2 scope, and reliance on low-cost offsets limit effectiveness, raising doubts about its capacity to drive genuine emission reductions (Gössling& Mayer, 2023).

2.2 Sustainable Aviation Fuels (SAF):

SAF, derived from renewable sources such as biomass, waste oils, and synthetic processes, offers a way to significantly reduce the carbon footprint of aviation. By promoting the production and use of SAF, the industry aims to transition away from fossil fuels and toward more sustainable alternatives.

<u>THE OVERVIEW OF SUSTAINABLE AVIATION FUELS</u>

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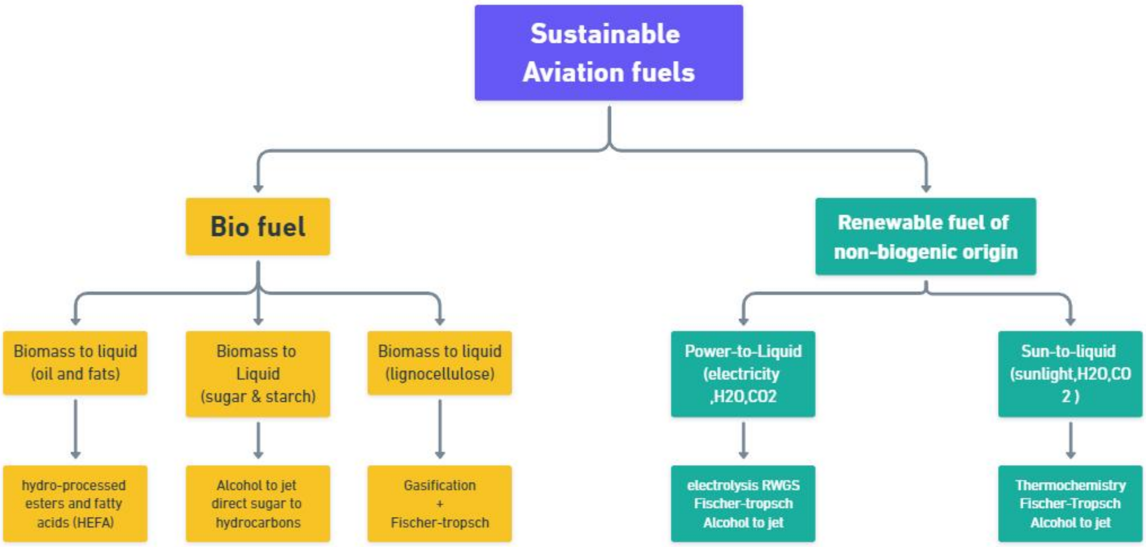

Figure 2.2: Types of SAFs

Aviation biofuels, produced from plant oils, animal fats, and waste materials, provide significant reductions in lifecycle emissions compared to fossil jet fuels (Rathore et al., 2024). Common variants include hydroprocessed esters and fatty acids (HEFA), hydrotreated vegetable oil (HVO), and bioethanol, all of which are compatible with existing engines (Mawhood et al., 2016). Gasification of lignocellulosic biomass offers another pathway, converting agricultural residues and wood into syngas for biofuel production (Qasim et al., 2021). Beyond biomass, renewable fuels of non-biogenic origin such as power-to-liquids (PtL) present scalable alternatives. Compared with batteries and hydrogen, synthetic fuels show greater promise for long-haul aviation (Bicer & Dincer, 2017).

2.3 Hydrogen

Hydrogen production from electricity is simple through electrolysis and today with 70 % already quite efficient. Hydrogen-powered aircraft have already been built and have been flown successfully. Hydrogen is a tested technology in aviation that will work. It makes sense to look again at this concept with new ideas to limit investment and avoid bulky aircraft.

While hydrogen is a clean energy carrier, storing and transporting it pose challenges. Hydrogen has a low energy density by volume, requiring large storage tanks or high compression, which adds weight to the aircraft. There are also safety concerns associated with hydrogen due to its flammability. Developing a hydrogen infrastructure for aviation is a significant challenge.

High energy density(weight) Low energy density (volume)

120MJ 44MJ 8MJ 32MJ

Figure 2.3: Hydrogen Property

Synthetic fuels, with high energy density and drop-in compatibility, can be produced from renewable electricity, industrial byproducts, or captured CO_2, enabling seamless integration

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into aviation infrastructure (Agusdinata et al., 2022). Power-to-liquids (PtL) technology further advances this pathway by converting electricity, water, and CO_2 into jet-fuel-equivalent hydrocarbons via Fischer–Tropsch or methanol synthesis, offering a scalable, long-term solution for aviation decarbonization (Bauckhage et al., 2020).

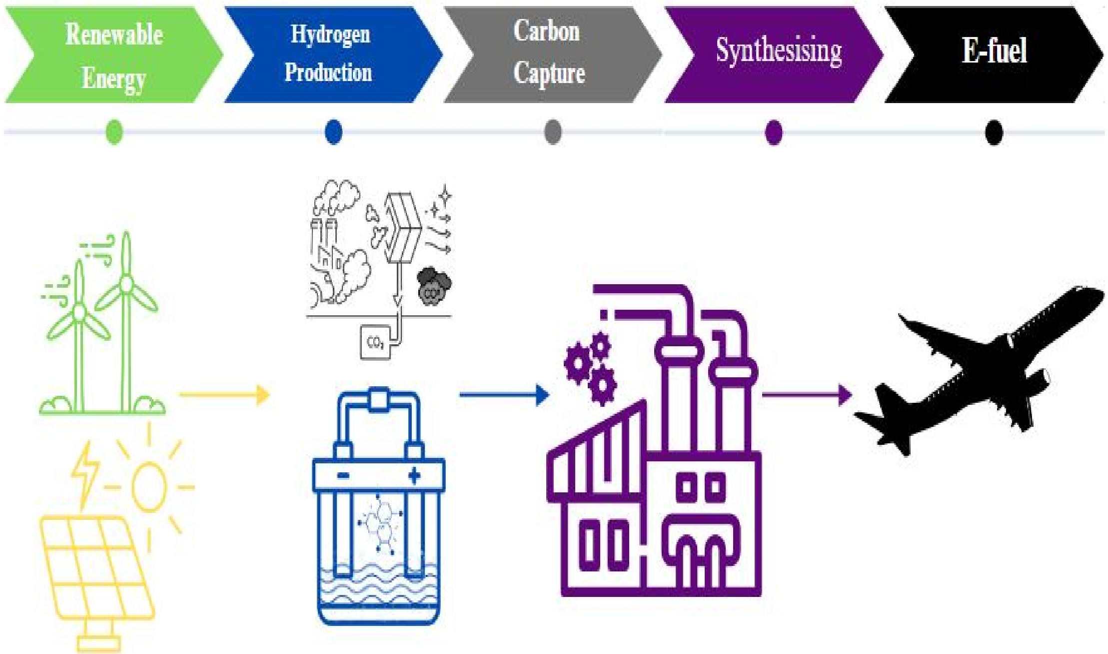

Figure 2.4: Synthetic hydrocarbon fuel production layout

3 Methodology

Fischer-Tropsch Pathway: Fischer-Tropsch (FT) synthesis is crucial in PtL processes, converting hydrogen and carbon monoxide (derived from CO2) into liquid hydrocarbon fuels. This pathway is well-established, with approval for use in civil aviation. Fischer-Tropsch synthesis requires a specific ratio of hydrogen to carbon monoxide, and in PtL processes, CO2 is combined with a fraction of the hydrogen stream from water electrolysis to produce synthesis gas.There are two primary methods to produce synthetic hydrocarbon fuels: Fischer-Tropsch (FT) synthesis and methanol synthesis.

3.1 Methanol (MeOH) Synthesis:

Process: Methanol synthesis involves the catalytic conversion of synthesis gas (hydrogen and carbon monoxide) into methanol. Methanol can serve as a liquid fuel or as a precursor for the production of other hydrocarbon fuels.
Feedstock: Similar to Fischer-Tropsch synthesis, methanol synthesis requires a source of hydrogen and carbon monoxide. These can be derived from renewable sources, such as water electrolysis for hydrogen and CO2 capture for carbon monoxide.
Advantages: Methanol is a versatile chemical that can be used not only as a fuel but also as a feedstock for the production of various chemicals and materials. It has a high-octane rating and can be blended with gasoline or used as a standalone fuel in some applications.

3.2 Fischer-Tropsch (FT) synthesis:

The Fischer-Tropsch (FT) pathway is a well-established method for producing liquid hydrocarbon fuels. Traditionally, Fischer-Tropsch fuels have been derived from natural gas and coal reserves. However, with advancements in technology and growing concerns about climate change, there's increasing interest in producing Fischer-Tropsch fuels from renewable sources. In the FT synthesis process, hydrogen and carbon monoxide are combined in a specific ratio, typically around 2:1, to form synthesis gas (syngas). This syngas can be obtained from various sources. In the context of power-to-liquids (PtL) technology, a fraction of the hydrogen stream produced from water electrolysis is reacted with carbon dioxide (CO_2) to obtain carbon monoxide (CO) via the reverse water-gas shift reaction (RWGS(Batteiger et al., n.d.)). This CO, along with additional hydrogen, serves as the feedstock for Fischer-Tropsch synthesis.

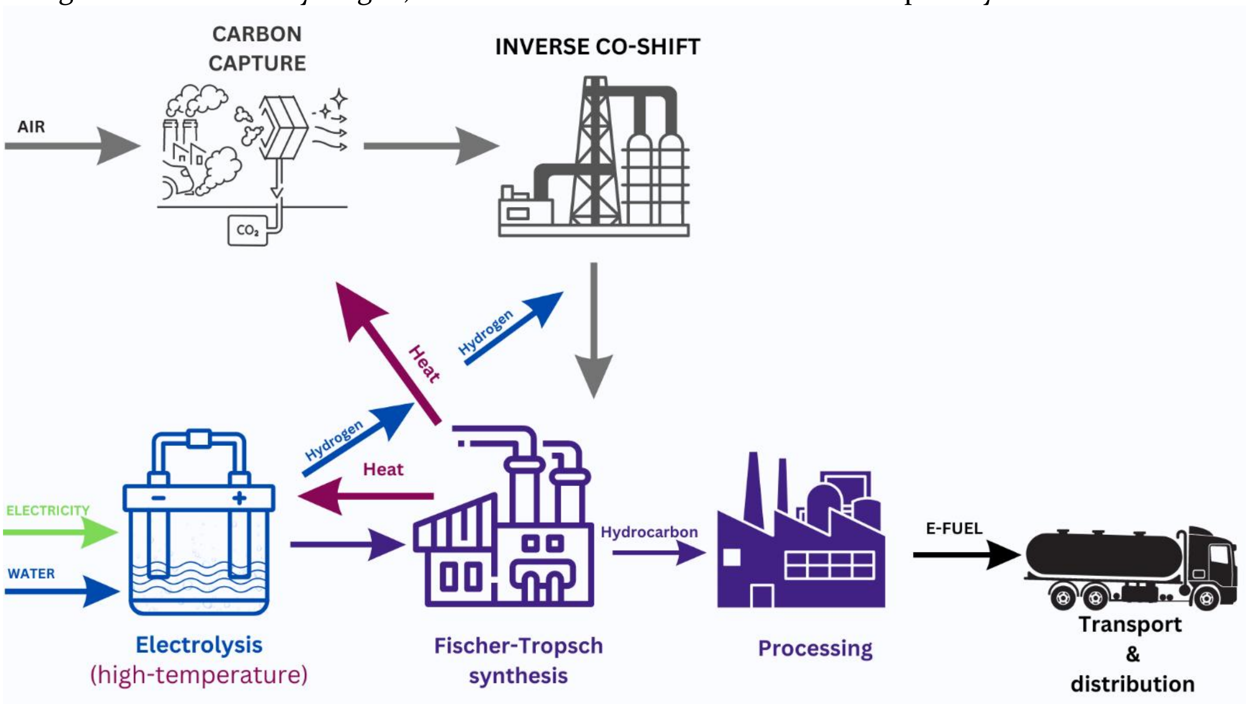

Figure2.4: E-fuel production via Fischer-Tropsch pathway (high-temperature electrolysis)

3.3 Levelized Cost Economic Model

This section delves into the levelized cost economic model applied to the production of e-fuel from renewable sources. The methodology employed is established in the literature and involves calculating the levelized costs of energy (LCOE), CO_2 (LCODAC), and hydrogen (LCOH), culminating in the determination of the levelized cost of e-fuel (LCOe-fuel).

The equations utilized for this analysis take into account various factors such as capital expenditure (Capex), operational expenditure (Opex), and the opportunity cost of capital (r). Each equation represents the levelized cost for a specific component of the production process, ultimately contributing to the overall cost of e-fuel production.

Levelized Cost of Energy (LCOE):

LCOE=∑t=oN (1+r)t(CapexEquity,t +Opext +Debtt) ÷Total kWh

Levelized Cost of Hydrogen (LCOH):

=∑ =o(, + +)(1+) ÷Total H2

Levelized Cost of CO_2 (LCODAC):

=∑ =o(, + +)(1+) ÷Total CO_2

Levelized Cost of FT (LCOFT):

− =∑ =o(, + +)(1+) ÷Total e-fuel

Levelized Cost of e-fuel (LCOe-fuel):

LCOe–fuel=∑t=oN (1+r)t(CapexEquity,t +Opext +Debtt) ÷Total e-fuel+cLCOH×LCOH+cLCODAC×LCODAC+cLCOE×LCOE

The below table presents a concise overview of the nomenclature and corresponding conversion factors employed in the calculation of LCOe-fuel:

Table 3.1 Nomenclature and Conversion Factors

Acronym	Description	Conversion Factor (₹/UNIT)
cLOCDAC	Conversion factor of LCODAC	3.6₹/Kg
cLCOE	Conversion factor of LCOE	27.5₹/kWh
cLOCH	Conversion factor of LCOH	0.5₹/kg

3.4 PV System

A photovoltaic (PV) system is chosen as the renewable energy source for electricity production. The chosen PV plant size is 1 MW, with each kW producing an average of 1700 kWh of energy annually. The annual production of the PV system is set at 1,700,000 kWh annually.

3.5 The DAC plant

The size of the Direct Air Capture (DAC) system is determined based on the required amount of synthetic fuel. The DAC plant captures CO2 from the air using a solvent, requiring significant energy for air handling, solvent loading, and CO2 release. The amount of CO2 required for producing 1 liter of e-fuel is specified.

3.6 Electrolysis Plant:

Hydrogen production involves extracting hydrogen from water through electrolysis. The plant size is calculated based on the amount of e-fuel produced, with 9 liters of water required to produce 1 kg of hydrogen. The power requirement for such a plant is provided.

3.7 E-fuel Production Plant

The production of e-fuel involves transforming syngas into liquid carriers, typically using a cobalt catalyst. The annual production of e-fuel is estimated and set at 40,000 liters. Operating cost assumptions are made, and data are aligned with literature findings.

3.8 Input data

General Data

total operating days	280
life period	25 years

Realization time	1 year
The opportunity cost of capital	6%
equity capital-debt capital	40%-50%
debt period	10 years
debt interest rate	4%
annual plant yield loss	0.80%

Photovoltaic System	
Plant Power	1 MW
kWh Produced per Year	17,00,000
kWh Produced in 25 Years	3,86,59,590
Capex	₹ 13,37,85,000
Opex (per year)	₹ 80,71,100
Opportunity Cost of Capital	6%
Useful Life	25 years
Direct Air Capture Plant	
kg Produced per Year	1,44,000
kg Produced in 25 Years	32,74,695
Capex	₹ 93,75,632
Opex (per year)	₹ 5,62,594
Opportunity Cost of Capital	6%
Useful Life	25 years
Electrolysis Plant	
Plant Power	267 kW
H2 Produced per Year	20,000 kg
H2 Produced in 25 Years	454,819 kg
Capex	₹ 4,16,67,068
Opex (per year)	₹ 25,03,139
Opportunity Cost of Capital	6%
Useful Life	25 years
E-fuel Production Plan (FT)	
E-fuel Products per Year	40,000 l
E-fuel Produced in 25 Years	916,650 l

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Capex	₹ 62,45,300
Opex (per year)	₹ 3,74,628
Opportunity Cost of Capital	6%
Useful Life	25 years

Analysis and Discussion

The cost analysis in the baseline scenario involves the calculation of e-fuel production costs using equations and the input data provided in the table. In addition to the costs associated with the Fischer-Tropsch (FT) process, the cost of e-fuel includes the levelized costs of energy (LCOE), hydrogen (LCOH), and CO_2 capture (LCODAC), which are multiplied by the respective conversion factors of 27.5 kWh, 0.5 kg, and 3.6 kg.
The following results are obtained:

PV(opext)	₹ 10,31,75,745.89
pv(costs)	₹ 23,69,60,745.89
LCOE	₹ 6.13/kWh

DAC(opext)	₹ 71,91,839.47
DAC(costs)	₹ 1,65,67,471.47
LCODAC	₹ 5.06/kg

H(opext)	₹ 3,19,98,517.35
H(costs)	₹ 7,36,65,585.35
LCOH	₹ 161.97/kg

FT(opext)	[illegible]
FT(costs)	₹ 1,10,34,303.15
LCOFT	₹ 12.04/l

PV	DAC	Electrolysis	FT
6.13	5.06	161.97	12.04
168.575	18.216	80.985	12.04

Multiplication by the respective conversion factors:

LCOe-fuel	₹279.816

The cost of e-fuel is approximately ₹280/l, with the majority of the cost attributed to energy, which accounts for 60% of the total cost. The remaining components include the cost of hydrogen (29%), CO_2 (7%), and the FT process (4%).
It's important to note that within the operational expenditure (opex) costs of individual plants, the energy required for specific processing was not included. Instead, it was only considered in

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the levelized cost of an e-fuel unit. Specifically, the total energy for each process, encompassing CO2 capture via the Direct Air Capture (DAC) process, hydrogen production via the electrolysis process, and e-fuel production via the FT process, is accounted for solely in the final LCOe-fuel formula.

4.1 Sensitivity Analysis:

To evaluate the robustness of the baseline scenario and understand the effects of individual variables on e-fuel production costs, we conduct a sensitivity analysis. In this analysis, we vary key parameters within a specified range to assess their impact on the overall cost of e-fuel production.

Variables Considered:
Capital Expenditure (Capex) of Each Individual Plant: Variation: ± 10%
Operational Expenditure (Opex) of Each Individual Plant: Variation: ± 10%

Variable	Baseline Value	Variations	Variations	New value	New value	COST	COST	LCOE	LCOE
Capex (PV)	₹ 13,37,85,000	10%	-10%	₹ 14,71,63,500	₹ 12,04,06,500	₹ 25,03,39,245.89	₹ 22,35,82,245.89	₹ 6.48	₹ 5.78
Capex(DAC)	₹ 93,75,632	10%	-10%	₹ 1,03,13,195	₹ 84,38,069	₹ 1,75,05,034.67	₹ 1,56,29,908.27	₹ 5.35	₹ 4.77
Capex(H2)	₹ 4,16,67,068	10%	-10%	₹ 4,58,33,775	₹ 4,12,50,397	₹ 7,78,32,292.15	₹ 7,32,48,914.67	₹ 171.13	₹ 161.05
Capex(FT)	₹ 62,45,300	10%	-10%	₹ 68,69,830	₹ 61,82,847	₹ 1,16,58,833.15	₹ 1,09,71,850.15	₹ 12.72	₹ 11.97

Variable	Baseline Value	Variations	Variations	New value	New value
Opex(PV)	₹ 80,71,100	10%	-10%	₹ 88,78,210	₹ 72,63,990
Opex(DAC)	₹ 5,62,594	10%	-10%	₹ 6,18,853	₹ 5,06,335
Opex(H2)	₹ 25,03,139	10%	-10%	₹ 27,53,453	₹ 22,52,825
Opex(FT)	₹ 3,74,628	10%	-10%	₹ 4,12,091	₹ 3,37,165

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(OPEXt)	(OPEXt)	COST	COST	LCOE	LCOE
₹ 11,34,93,320.48	₹ 9,28,58,171.30	₹ 24,72,78,320.48	₹ 22,66,43,171.30	₹ 6.40	₹ 6
₹ 79,11,023.42	₹ 64,72,655.53	₹ 1,72,86,655.42	₹ 1,58,48,287.53	₹ 5.28	₹ 4.84
₹ 3,51,98,369.09	₹ 2,87,98,665.62	₹ 7,68,65,437.09	₹ 7,04,65,733.62	₹ 169.00	₹ 154.93
₹ 52,67,903.47	₹ 43,10,102.84	₹ 1,15,13,203.47	₹ 1,05,55,402.84	₹ 12.56	₹ 11.52

Capex Variation: When capex is increased by 10%, the e-fuel production cost rises slightly compared to the baseline scenario. Conversely, a 10% reduction in capex leads to a slight decrease in production cost. These findings suggest that capital expenditure has a modest impact on overall production costs.

Opex Variation: Changes in operational expenditure also have a minor effect on e-fuel production costs. A 10% increase in opex results in a slight cost increase, while a 10% decrease leads to a marginal cost reduction. This indicates that operational efficiency plays a relatively minor role in determining production costs.

Comparison with Baseline Scenario:

Overall, the variations in capex and opex examined in the sensitivity analysis have only a modest impact on e-fuel production costs. The observed changes are within a narrow range of ₹270-₹290 per liter, suggesting that the project's economic feasibility is relatively resilient to fluctuations in expenditure.

4.2 Assessment of E-Fuel Compatibility:

E-fuel, especially fully synthetic jet fuel, presents a promising alternative to conventional jet

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fuel, offering potential benefits such as reduced emissions and improved air quality. However, its compatibility with existing aircraft is a critical factor in determining its feasibility for widespread adoption.

4.3 Current Standards and Blending Ratios:

Pathway	Standard	Max. Blend Rate	Aromatic Content	Fleet Compatibility
FT-SPK	ASTM D7566 Annex A1	50%	< 0.5%	Only in blends
FT-SPK/A	ASTM D7566 Annex A4	50%	< 20%	Potentially fully compatible
ATJ-SPK	ASTM D7566 Annex A5	50%	< 0.5%	Only in blends
Finished Blends with Conventional Jet Fuel	ASTM D7566		8 – 25%	Fully compatible
Co-refining of FT Synthetic Crude	ASTM D1655 Annex A1.2.2	5% (co-feeding ratio)	Not defined	Fully compatible
SASOL Fully Synthetic Fuel	ASTM D1655 DEF STAN 91-91	100%	8 – 25%	Fully compatible
Methanol Pathway	Future Target	50 – 100%	Subject to pathway design	Potentially fully compatible
Fully Synthetic Jet Fuel	Future Target	100%	Few%	Fully compatible
100% SPK Jet Fuel	Future Target	100%	Well below 1%	Compatible with advanced aircraft

The provided data and standards indicate varying levels of compatibility for different types of synthetic jet fuels. For instance, FT-SPK/A (Fischer-Tropsch Synthetic Paraffinic Kerosene with aromatics) has a maximum blending rate of 50% and is potentially fully compatible with existing aircraft fleets. On the other hand, 100% SPK jet fuel is not compatible with many existing aircraft but offers significant long-term benefits.

Regulatory Approval and Infrastructure Adaptation:
The approval of fully synthetic jet fuels for use in aviation is a crucial step toward achieving fleet-wide compatibility. Initial flights using fully synthetic jet fuel have already taken place, demonstrating progress in this area. However, existing approvals are limited to specific facilities, and more general specifications are needed to ensure fleet-wide compatibility.

4.4 Challenges and Considerations:

One key challenge in integrating e-fuel into current aircraft fleets is the need to ensure that it meets regulatory standards and aircraft manufacturer specifications. This includes considerations such as fuel properties, engine compatibility, and potential modifications to aircraft fuel systems.

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Outlook and Transition Planning:
While fully synthetic jet fuel offers significant advantages, a transition period may be required to address infrastructure challenges and ensure a smooth integration process. During this period, separate fuel infrastructures may be necessary at airports to accommodate the use of e-fuel alongside conventional fuels.

4.5 Life Cycle Analysis (LCA) of E-Fuel:

The Life Cycle Analysis (LCA) of E-Fuel provides a comprehensive assessment of the environmental impact associated with the production, distribution, and utilization of e-fuel. By examining inputs, outputs, and emissions across different stages of the e-fuel life cycle, we gain valuable insights into its sustainability and potential for reducing greenhouse gas (GHG) emissions.
Inputs:
CO_2 Feedstock: -70.9 g per MJ of e-fuel
Outputs:
Medium-Pressure (M.P.) Steam: 0.39 MJ per MJ of e-fuel
GHG Emissions (gCO2e per MJ of E-Fuel):
CO_2 Feedstock: 3.63 g
M.P. Steam: -31.7 to -32.1 g (negative indicates net reduction)
E-Fuel Production Emissions (FT Emissions): 0.83 to 0.84 g
Transmission and Distribution (T&D) Emissions: 0.31 g
Vehicle Emissions: 70.1 g
Well-to-Wheel (WTW) Emissions:
WTW Emissions: -24.6 to -25 gCO2e per MJ of e-fuel (negative indicates reduction compared to conventional jet fuel)
GHG Reduction Relative to Petroleum Jet Fuel:129% to 130%
Key Findings:

- Negative Emissions: The production of medium-pressure steam results in negative emissions, indicating a net reduction in GHG emissions associated with steam production.
- GHG Reduction: When considering the entire life cycle, e-fuel achieves a significant reduction in GHG emissions compared to conventional petroleum jet fuel, with a reduction of 129% to 130% relative to petroleum jet fuel.
- Contributors to Emissions: The main contributors to GHG emissions in the e-fuel life cycle include vehicle emissions and emissions associated with electricity consumption and CO_2 feedstock.

CONCLUSION & RECOMMENDATIONS
The emergence of Power-to-Liquid (PtL) fuels from solar and wind power represents a promising avenue for sustainable aviation fuel supply. While PtL fuels have yet to achieve large-scale production, recent advancements in research-scale demonstration projects and the establishment of commercial production plants mark the beginning of a transformative phase in PtL upscaling and market deployment.
Strengths:
PtL fuels offer several advantages. They utilize renewable electricity from sources like solar and wind power, providing a sustainable alternative for aviation fuel. Their production involves scalable carbon sources such as CO_2 extraction from air, resulting in near-zero well-to-wake

greenhouse gas (GHG) emissions. Additionally, PtL fuels require reduced water and land compared to biofuels and exhibit reduced toxicity. Importantly, they possess a "drop-in" capability, meaning they are compatible with the existing aircraft fleet.

Opportunities:

There are significant opportunities associated with the use of PtL fuels. They enable emission reduction through cleaner fuel combustion, leading to reduced particulate matter and SOx emissions, which can improve local air quality and high-altitude climate impact. PtL production also supports renewable energy infrastructure development, providing economic benefits for regions with wind and solar power potential. Furthermore, PtL fuels can provide grid ancillary services and help establish hydrogen value chains.

Challenges/Weaknesses:

Despite their advantages, PtL fuels face several challenges. High production costs compared to current jet fuel prices present a significant barrier. Additionally, there are limitations in conversion efficiency and a high overall energy demand, requiring substantial amounts of renewable electricity. Rapid scale-up is necessary to meet aviation fuel demand, but limited availability and capacity of CO2 extraction from air technologies pose challenges. Moreover, while PtL fuels can reduce emissions, particulate matter and NOx emissions from combustion are not completely eliminated.

Potential Concerns/Threats:

There are potential concerns associated with the widespread adoption of PtL fuels. The availability of PtL fuels for conventional aircraft propulsion systems may relax the pressure to innovate with new aircraft concepts. There is also the risk of "lock-in" effects with established technologies and non-renewable electricity, hindering efforts to decarbonize. Concerns about land use and local population acceptance may arise, as well as dependency on point source CO2 from industrial facilities.

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