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# LIFE CYCLE ASSESSMENT AND ENVIRONMENTAL OPTIMIZATION OF ALTERNATIVE AVIATION FUELS

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**LIFE CYCLE ASSESSMENT AND ENVIRONMENTAL OPTIMIZATION OF ALTERNATIVE AVIATION FUELS**

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# Abstract

The aviation sector is a significant and growing source of global greenhouse gas emissions (GHGs), accounting for about 2.5% of global $CO_2$ and up to 4% of total climate impact when non-$CO_2$ effects are included. In response to the urgency of decarbonizing this sector, this thesis conducts a comprehensive Life Cycle Assessment (LCA) of fourteen alternative aviation fuel pathways, using the GREET 2024 model to evaluate their emissions, energy use, and environmental trade-offs.

The study covers a wide range of fuels, including Alcohol-to-Jet (ATJ), Sugar-to-Jet, Hydroprocessed Esters and Fatty Acids (HEFA) from various feedstocks (canola, corn, soy, palm), and hydrogen-based systems, including hydrogen for fuel cell applications. Emissions are assessed across Well-to-Pump (WTP), Pump-to-Wake (PTW) and Well-to-Wake (WTW) stages, for two aircraft classes: Single Aisle (SA) and Large Quad (LQ).

In the Well-to-Pump (WTP) analysis, Alcohol-to-Jet fuel from cellulosic biomass emerged as the most sustainable option, with the lowest total $CO_2$ emissions (14.11 g), no land use change emissions, and the highest energy efficiency (3258 kJ), supported by renewable energy credits in the GREET 2024 model. In contrast, corn-based standalone SAF showed the highest WTP emissions (57.84 g $CO_2$), along with significant land use change impacts (9.01 g $CO_2e$) and elevated $CH_4$ and $NO_x$ emissions. Sugar-to-Jet (STJ) fuels offered intermediate performance, with the biological route showing lower total $CO_2$ (21.29 g) but higher total energy use (4537 kJ). The lignocellulosic forest residue pathway showed the lowest GHG-100 emissions (1.93 g $CO_2e$) and total energy input (1026 kJ), confirming that waste-derived fuels are environmentally preferable. These findings highlight that feedstock type and conversion methods significantly affect upstream emissions, positioning cellulosic and residue-based pathways as leading candidates for decarbonizing aviation fuel production.

The normalized results show that HEFA from corn oil has the lowest WTW emissions, with emissions (0.0914 $gCO_2e$/kg·km) for SA and emissions (0.1050 $gCO_2e$/kg·km) for LQ, reducing GHG emissions by more than 85% compared to conventional jet fuel. ATJ from cellulosic biomass also performs exceptionally well, reaching emission (0.1400 $gCO_2e$/kg·km) for SA and (0.1440 $gCO_2e$/kg·km) for LQ, reflecting over 81–85% emission reductions. Hydrogen as a fuel for fuel

cells produce the lowest use-phase emissions, achieving near-zero emissions (0.015 $gCO_2e/kg \cdot km$) for SA, though their total WTW emissions (0.2350–0.2520 $gCO_2e/kg \cdot km$) depend on the hydrogen production method.

Fuels based on coal and natural gas using Fischer-Tropsch synthesis show the highest normalized emissions, with WTW values of emission (0.9635 $gCO_2e/kg \cdot km$) ` for SA and emission (1.0000 $gCO_2e/kg \cdot km$) for LQ, making them the least sustainable options.

Energy and water use were also analyzed. For instance, ATJ-Cellulosic had the lowest total energy demand (3258 kJ), mostly sourced from renewables, and the highest energy delivery efficiency, exceeding 99.6%. In contrast, STJ pathways consumed more energy (up to 4537 kJ), and soy-based HEFA required the most water (2358 $cm^3/MJ$), due to irrigation.

In conclusion, the study identifies waste-based and renewable fuels—especially ATJ-cellulosic, HEFA-corn oil, and hydrogen fuel cells—as the most promising solutions for reducing aviation emissions. While each fuel type has limitations in cost, infrastructure, or feedstock availability, these options offer the strongest potential for decarbonizing air travel and achieving long-term climate goals.

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# Table of Contents

# LIST OF TABLES

# LIST OF FIGURES

# Acronyms and abbreviations

| | Category | Term | Short Definition |
|---|---|---|---|
| 1 | GHG & Pollutants | $CO_2$ Total | Total carbon dioxide from all lifecycle stages |
| 2 | GHG & Pollutants | $CO_2$ | $CO_2$ from fossil fuel combustion |
| 3 | GHG & Pollutants | $CO_2$ _Biogenic | $CO_2$ from biomass (often carbon neutral) |
| 4 | GHG & Pollutants | $CO_2$ _LandUseChange | $CO_2$ from land disturbance |
| 5 | GHG & Pollutants | $CH_4$ | Methane from leaks or digestion |
| 6 | GHG & Pollutants | $CH_4$_Biogenic | Biogenic methane from decay or fermentation |
| 7 | GHG & Pollutants | VOC | Smog-causing gases |
| 8 | GHG & Pollutants | CO | Toxic gas from incomplete combustion |
| 9 | GHG & Pollutants | NOx | Gases forming ozone and acid rain |
| 10 | GHG & Pollutants | $PM_{10}$ | Particles <10 microns harmful to lungs |
| 11 | GHG & Pollutants | $PM_{2.5}$ | Particles <2.5 microns, more dangerous |
| 12 | GHG & Pollutants | SOx | Sulfur gases causing acid rain |
| 13 | GHG & Pollutants | $N_2O$ | Potent GHG also depletes ozone |
| 14 | GHG & Pollutants | BC | Soot with high warming potential |
| 15 | GHG & Pollutants | POC | Carbon particles from combustion |
| 16 | GHG & Pollutants | GHG-100 | Greenhouse gas emissions calculated over 100-year Global Warming Potential (GWP) timeframe |
| 17 | GHG & Pollutants | GHG-20 | Greenhouse gas emissions calculated over 20-year Global Warming Potential (GWP) timeframe |
| 18 | Water Use | Water Total | Total water use across lifecycle |
| 19 | Water Use | Water_Irrigation | Water for crops |
| 20 | Water Use | Water_Process | Water for processing |
| 21 | Water Use | Water_Mining | Water for mining |
| 22 | Water Use | Water_Cooling | Water for cooling |
| 23 | Energy Inputs | Crude Oil | Petroleum-based fuel |
| 24 | Energy Inputs | Natural Gas | Fracked gas energy |
| 25 | Energy Inputs | Coal Average | Average coal emissions |

| | | | |
|---|---|---|---|
| 26 | Energy Inputs | Pet Coke | Carbon-rich oil byproduct |
| 27 | Energy Inputs | Forest Residue | Forest biomass used as fuel |
| 28 | Energy Inputs | Solar | Sun-based energy |
| 29 | Energy Inputs | Wind Power | Wind energy |
| 30 | Energy Inputs | Hydroelectric Power | Water dam energy |
| 31 | Energy Inputs | Nuclear Energy | Nuclear reactor energy |
| 32 | Energy Inputs | GeoThermal Power | Earth heat energy |
| 33 | Feedstocks | Corn | Corn for biofuel |
| 34 | Feedstocks | Soybeans | Soy for energy |
| 35 | Feedstocks | Sugarcane | Sugar crop |
| 36 | Feedstocks | Palm FFB | Palm fruit for oil |
| 37 | Feedstocks | Sugar Cane Bagasse | Fibrous sugarcane waste |
| 38 | Feedstocks | Biogas | Waste-based methane |
| 39 | Feedstocks | Bitumen | Heavy crude for asphalt |
| 40 | Feedstocks | Shale Oil (Bakken) | Crude from Bakken |
| 41 | Feedstocks | Shale Oil (Eagle Ford) | Crude from Eagle Ford |
| 42 | Feedstocks | Zinc Ore | Zinc material source |
| 43 | Fuel Types | Fossil Fuel | Oil, gas, coal fuels |
| 44 | Fuel Types | Biomass | Organic fuel materials |
| 45 | Fuel Types | Renewable | All renewable sources |
| 46 | Fuel Types | Non-Fossil Fuel | Biomass + renewables |
| 47 | Fuel Types | Conventional Diesel | Standard diesel |
| 48 | Fuel Types | Diesel For Non-Road Applications | Diesel for machines/ships |
| 49 | Fuel Types | SAFs (SAF) | Renewable-based jet fuel |
| 50 | Fuel Types | OnSite | Fuel burned directly |
| 51 | Fuel Types | Other Power (Without Hydro) | Misc. non-hydro power |
| 52 | Fuel Types | Water | Water as resource |
| 53 | Emissions Scope | Well-to-wake | Emissions from total lifecycle |
| 54 | Emissions Scope | Urban Emissions | Emissions in city use |

| | | | |
|---|---|---|---|
| 55 | Organizations | DOE | U.S. Energy Dept. |
| 56 | Organizations | EIA | Energy data agency |
| 57 | Organizations | FAA | Aviation agency |
| 58 | Organizations | ASTM | Standards body |
| 59 | Organizations | IPCC | Climate science authority |
| 60 | Technology/Process | GREET | GHG and energy analysis tool |
| 61 | Technology/Process | LCA | Life-cycle analysis |
| 62 | Technology/Process | CCS | Capturing carbon from air |
| 63 | Technology/Process | HRJ | Renewable jet fuel type |
| 64 | Technology/Process | HEFA | Fatty acid-based jet fuel |
| 65 | Technology/Process | BTL | Biomass-to-liquid fuel |
| 66 | Technology/Process | GTL | Gas-to-liquid fuel |
| 67 | Technology/Process | CTL | Coal-to-liquid fuel |
| 68 | Technology/Process | FT | Fischer-Tropsch process |
| 69 | Technology/Process | SAF | Alt jet fuel from renewables |
| 70 | Acronyms | $CH_4$ | Methane gas |
| 71 | Acronyms | $CO_2$ | Carbon dioxide |
| 72 | Acronyms | NOx | Nitrogen oxides |
| 73 | Acronyms | $N_2O$ | Nitrous oxide |
| 74 | Acronyms | VOC | Volatile gases in smog |
| 75 | Emissions Scope | WTP | Well-to-Pump (production and transport emissions) |
| 76 | Emissions Scope | PTWa | Pump-to-Wake (combustion/use emissions onboard aircraft) |
| 77 | Emissions Scope | WTW | Well-to-Wake (full life cycle emissions) |
| 78 | Aircraft Categories | SA | Single Aisle Aircraft |
| 79 | Aircraft Categories | LQ | Large Quad Aircraft |
| 80 | Units | g | grams |
| 81 | Units | kg | kilograms |
| 82 | Units | kJ | kilojoules |
| 83 | Units | MJ | megajoules |
| 84 | Units | Ppm | parts per million |

# Chapter 1: Introduction

## 1.1 Aviation Emissions – Current State

Climate change has become a pressing global challenge as GHG emissions continue to rise. The exponential increase in GHG emissions has directly contributed to global warming, raising the average surface air temperature by approximately 1.1°C since pre-industrial times. The aviation sector is a significant and growing contributor to these emissions, primarily due to its reliance on fossil-based jet fuels (1). While aviation accounts for only 2.5% of global $CO_2$ emissions, its overall contribution to global warming is estimated at 4% due to additional climate effects such as contrails and nitrogen oxides ($NO_x$)(2). As shown in Figure 1.1, despite improvements in aircraft efficiency, the industry's carbon footprint continues to grow due to the increasing demand for air travel.

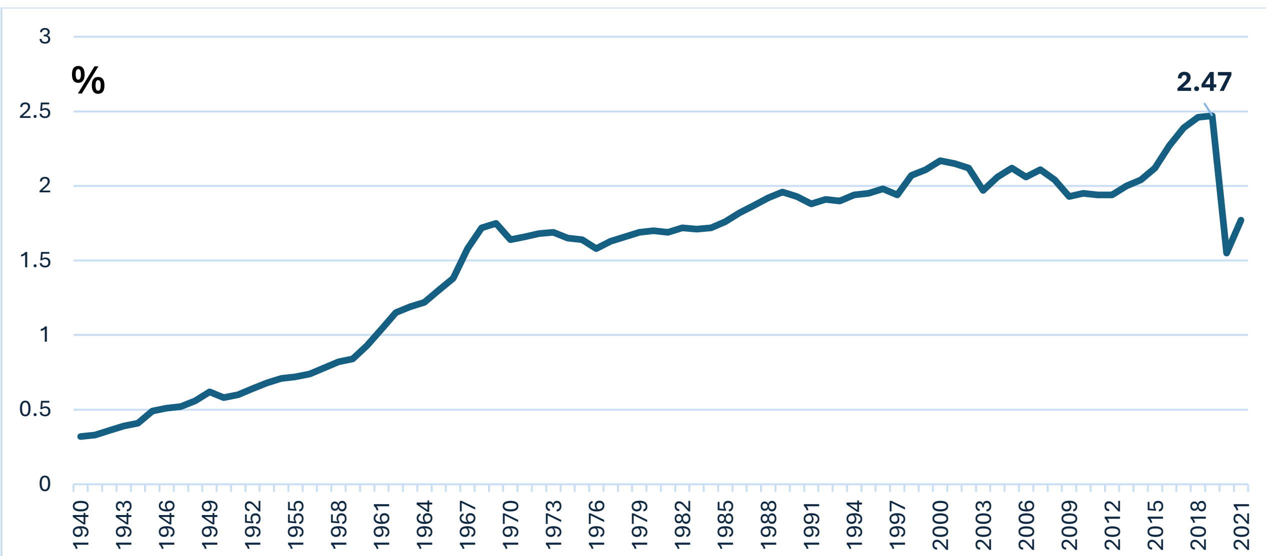



Figure 1-1: Aviation's Share of Global $CO_2$ Emissions (1940 to 2021) gathered from Our World in Data

Note This data represents aviation's share of carbon dioxide ($CO_2$) emissions from fossil fuel combustion and land-use change. It does not include non-$CO_2$ effects from aviation, such as contrails, water vapor, and nitrogen oxides, which also contribute to climate change

In 2021, aviation-related emissions accounted for nearly 24% of total U.S. transportation sector $CO_2$ emissions, making it one of the most carbon-intensive forms of transport (3). Unlike other sectors, where renewable energy sources such as wind and solar are replacing fossil fuels, the aviation industry remains highly dependent on petroleum-based jet fuel. Over the last three decades, the energy efficiency of aircraft has improved significantly, reducing energy consumption per passenger-kilometer from 2.9 megajoules (MJ) in 1990 to 1.3 MJ in 2019. However, the carbon intensity of aviation fuel has remained unchanged, as biofuels and alternative fuels account for less than 1% of total jet fuel consumption (4). Table 1-1 presents data on $CO_2$ emissions, capital costs (CAPEX), and operating costs (OPEX) for different technologies used in fuel and energy production. This study highlights the energy consumption per passenger-kilometer, showing that the energy required for a passenger to travel one kilometer decreased from 2.9 MJ in 1990 to 1.3 MJ in 2019. This indicates that aircraft have become more fuel-efficient, consuming less energy for the same distance. Table 1-1 underscores the necessity for global efforts to reduce aviation emissions. Although aviation accounts for a relatively small share of global $CO_2$ emissions, its outsized warming impact and the expected rise in air travel make it a critical focus for climate action.

One of the methodologies to reduce the $CO_2$ emission is decarbonization, which will be explained in the next section.

Table 1-1 $CO_2$ emissions from cradle-to-gate, capital and operating costs of technologies(4).

| | CAPEX (€M) | | | | |
|---|---|---|---|---|---|
| Technology | s1 | s2 | s3 | OPEX (€M) | $CO_2$ ($tCO_2$ per unit) |
| BH (MW h) | 2.49E-01 | | | 9.50E-07 | |
| PV (MW h) | 8.10E-01 | | | 7.90E-07 | 6.20E-02 |
| CSP (MW h) | 5.77E+00 | | | 5.30E-06 | 4.30E-02 |
| AWE (kg) | 5.90E-02 | | | 4.70E-07 | |
| SOEC (kg) | 2.40E-01 | | | 1.30E-07 | |
| SHIFT (kg) | 2.50E-02 | | | 2.10E-07 | |
| SOEC $CO_2$ (kg) | 3.00E-01 | | | 3.00E-07 | |
| SOEC CO-ele (kg) | 3.36E+00 | | | 3.00E-08 | |
| ME $CO_2$ (kg) | 4.20E-03 | 3.20E-03 | 2.70E-03 | 5.30E-09 | 5.21E-05 |
| ME CO (kg) | 1.00E-03 | 7.90E-03 | 6.70E-03 | 5.30E-09 | 1.33E-04 |
| ME CO/$CO_2$ (kg) | 1.80E-03 | 3.20E-03 | 1.00E-03 | 5.80E-09 | 1.02E-04 |
| FT (kg) | 1.30E-03 | 1.10E-03 | 1.30E-03 | 7.80E-07 | 1.31E-04 |
| MTP (kg) | 3.20E-03 | 1.00E-03 | 1.00E-03 | 1.00E-07 | 7.92E-05 |
| PTF (kg) | 1.60E-03 | 1.00E-03 | 6.60E-04 | 1.40E-08 | 2.46E-05 |

## 1.2 Decarbonization and Emission Reduction in Aviation

To meet international decarbonization targets, transitioning to Sustainable Aviation Fuels (SAFs) is essential. Without urgent investment in e-fuel production and supportive policies, aviation emissions will continue to rise, undermining climate goals. This research assesses the feasibility of e-fuels for aviation using Life Cycle Assessment (LCA) and the GREET (5) (Greenhouse gases, Regulated Emissions, and Energy use in Technologies) model, evaluating their environmental impacts, energy use, and economic competitiveness.

The primary objective is to evaluate the environmental and economic impacts of alternative aviation fuels, including hydrogen, ammonia, and electrofuels. By applying LCA using GREET, this study compares fuel pathways and propulsion systems to identify the most sustainable and cost-effective options.

Despite improvements in aircraft efficiency, aviation remains one of the fastest-growing sources of GHG emissions. This challenges global climate goals like the Paris Agreement, which aims to limit temperature increases to below 2°C. SAFs are central to addressing this issue, with the potential to reduce lifecycle $CO_2$ emissions by up to 80%.

SAFs are “drop-in” fuels derived from renewable or waste-based feedstocks and can be used in existing aircraft engines without modification. Based on Figure 1.2, industry estimates suggest that SAFs could contribute up to 65% of the emissions reductions needed for net-zero aviation by 2050.

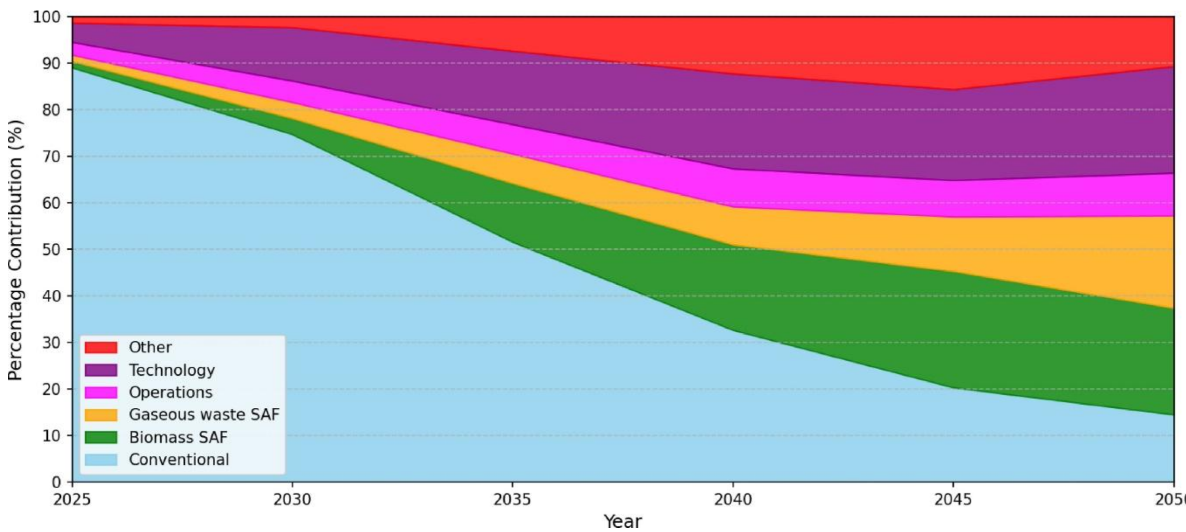



Figure 1-2 Long-term global aspirational goal by ICAO for 2050

(based on data from ICAO: https://www.icao.int/environmental-protection/pages/SAF.aspx)

However, the adoption of SAFs faces several challenges, including limited feedstock availability, high production costs, technological inefficiencies, and fragmented policy frameworks. These challenges necessitate coordinated efforts across research, industry, and policymaking to scale up production, improve cost-effectiveness, and harmonize sustainability standards(6).

## 1.3 Alternative Fuel Solutions in Aviation

Aviation's unique energy requirements limit the applicability of electrification, making high-energy-density fuels the most viable decarbonization path. One of the most promising pathways to achieve emission reductions is through the adoption of SAFs (SAFs). SAFs are produced from renewable feedstocks such as biomass, waste oils, or synthesized using renewable electricity and captured carbon dioxide. Unlike fossil jet fuels, SAFs can reduce lifecycle emissions by up to 80%, depending on the feedstock and conversion technology used (7).

Various SAF production pathways have been developed, including Alcohol-to-Jet (ATJ), Sugar-to-Jet (STJ), Hydroprocessed Esters and Fatty Acids (HEFA), Fischer-Tropsch (FT), Power-to-Liquid (PtL), and hydrogen-based systems. Each pathway involves distinct feedstocks and technologies, leading to different energy demands, emission profiles, and scalability potentials.

To assess the environmental impacts of these fuels comprehensively, this thesis employs an LCA approach. LCA enables the evaluation of greenhouse gas emissions and energy inputs across the entire fuel lifecycle from feedstock production, transportation, and fuel conversion to final use in aircraft engines. By comparing the emissions of various SAF pathways under consistent LCA boundaries, this research aims to identify the most sustainable and scalable alternatives for aviation fuel transition.

## 1.4 Challenges to the Adoption of Alternative Aviation Fuels

The aviation sector's decarbonization largely depends on the successful development and widespread adoption of alternative fuels. However, despite their significant potential to reduce GHG emissions, these alternatives face numerous technical, economic, and institutional challenges that hinder their commercial scalability and deployment.

### 1.4.1 High Production Costs

One of the most critical barriers is the high production cost of alternative fuels compared to conventional jet fuel. SAFs , hydrogen, and electrofuels (e-fuels) currently require significantly more energy and advanced processing technologies, resulting in prices that are two to six times higher than traditional fossil-based fuels (8). This cost gap presents a major obstacle for airlines operating under tight profit margins and cost-competitive market conditions.

### 1.4.2 Infrastructure and Distribution Limitations

The deployment of hydrogen and synthetic fuels also requires major upgrades or the establishment of entirely new infrastructure. Hydrogen, for instance, necessitates cryogenic storage, specialized pipelines, and refueling systems that are not compatible with existing aviation fuel infrastructure (9), (10). Similarly, large-scale distribution of SAFs and e-fuels would require new blending, storage, and logistics facilities at airports globally adding significant capital investment demands.

### 1.4.3 Feedstock Availability and Sustainability

The scalability of bio-based SAFs is constrained by the availability of sustainable feedstocks such as waste oils, agricultural residues, and municipal solid waste. Competing demands for biomass in sectors like food, land use, and energy further intensify this constraint. Additionally, cultivating feedstocks such as canola or soy may raise concerns about land-use change, water consumption, and food security if not managed sustainably (6).

### 1.4.4 Regulatory and Certification Barriers

All aviation fuels must comply with stringent international safety and performance standards before being approved for commercial use. The certification process, governed by institutions such as ASTM International and ICAO, is lengthy and costly. Each new fuel pathway must undergo rigorous testing to ensure compatibility with existing engines and aircraft systems. While progress has been made in certifying certain SAF pathways like HEFA and Fischer–Tropsch fuels, others such as hydrogen and ammonia are still in early stages of technical validation (11)

### 1.4.5 Technological and Operational Constraints

Alternative fuels like ammonia and battery-electric propulsion systems face inherent limitations. Ammonia, while energy-dense by volume, has toxicity and combustion challenges that complicate its use in aviation. Battery-electric aircraft, on the other hand, suffer from low energy density, making them suitable only for short-range flights under current technological limitations (12).

### 1.4.6 Market and Policy Uncertainty

Uncertainty regarding long-term policy support, carbon pricing, and return on investment discourages private sector involvement. Without clear and stable policy frameworks, including subsidies, mandates, or carbon offsetting mechanisms such as CORSIA, producers lack incentives to invest in large-scale alternative fuel infrastructure (10).

### 1.4.7 Summary of Key Barriers

To summarize, the successful adoption of alternative aviation fuels depends on overcoming the following interrelated challenges:

- Cost: Alternative fuel remains significantly more expensive than Jet A-1.
- Infrastructure: New storage, transport, and fueling systems are needed.
- Feedstock: Sustainable and scalable sources are limited.
- Certification: Regulatory approvals are complex and time-consuming.
- Technology: Each fuel type poses unique technical barriers.
- Policy: Market uptake depends on coordinated global policy actions.

Without addressing these issues through collaborative efforts involving governments, industry stakeholders, and researchers, the aviation sector risks falling short of the Paris Agreement targets and ICAO's long-term emission reduction goals.

## 1.5 Research Scope

The aviation industry accounts for approximately 2–3% of global GHG emissions, prompting the urgent need for low-carbon alternative fuels.(13)

Aviation is one of the fastest-growing sources of GHG emissions worldwide, necessitating a shift from conventional petroleum-based jet fuels to sustainable alternatives.

Alternative aviation fuels such as hydrogen and biofuels have emerged as promising solutions. However, challenges persist regarding economic feasibility, infrastructure adaptation, and scalability ((14),(15)).

LCA plays a crucial role in evaluating the environmental impact of these fuel pathways and optimizing their adoption ((16),(17)).

The aviation sector faces unique decarbonization challenges due to its reliance on high-energy-density fuels, which limits the potential of direct electrification. As a result, SAFs  have emerged as a promising solution for reducing greenhouse gas emissions while maintaining the energy performance required for flight. SAFs can be derived from various renewable sources, including biomass, waste oils, and synthetic production using renewable electricity and captured $CO_2$. Compared to fossil-based jet fuels, SAFs have the potential to reduce lifecycle emissions by up to 80%, depending on the feedstock and conversion method employed (18).Several SAF production pathways have been developed, such as Alcohol-to-Jet (ATJ), Sugar-to-Jet (STJ), Hydroprocessed Esters and Fatty Acids (HEFA), Fischer-Tropsch (FT), Power-to-Liquid (PtL), and hydrogen-based routes. These pathways differ in their resource requirements, energy consumption, emission profiles, and scalability. Understanding these differences is essential to identify viable alternatives for decarbonizing aviation.

To address this, the present research adopts an LCA methodology to evaluate the environmental performance of these alternative fuel pathways. LCA provides a comprehensive framework to assess greenhouse gas emissions and energy use across the entire lifecycle of aviation fuels from feedstock production and transportation to fuel processing and final use in aircraft engines. By applying consistent boundaries and parameters, this study aims to compare the sustainability of different SAF pathways and determine the most effective and scalable options for supporting the aviation industry's transition to low-carbon energy systems.

## 1.6 Project Objectives

This research aims to support the transition to low-emission aviation by systematically evaluating alternative fuel pathways using a life cycle perspective. Through the application of the GREET model developed by Argonne National Laboratory, the study investigates the environmental, economic, and technical implications of various sustainable fuel options, including SAFs, Hydrogen ($LH_2$), and Power-to-Liquid (PtL) electrofuels. The core objective is to identify which of these fuels offers the most promising combination of greenhouse gas reduction, energy efficiency, resource sustainability, and infrastructure compatibility, in line with international decarbonization (5). To achieve this, the project is guided by the following specific objectives:

Conduct a comparative LCA  of SAF, Hydrogen and bioFuels using GREET software to ensure consistency and transparency in evaluating environmental impacts across fuel pathways(19).

Quantify Well-to-Pump (WTP) and Pump-to-Wake (PTWa) emissions, including $CO_2$, $NO_x$, $SO_x$, which contribute significantly to the climate impact of aviation beyond $CO_2$ alone (12).

Analyze emissions and energy use throughout the full life cycle of selected alternative aviation fuel pathways, aiming to identify the environmental performance and sustainability potential of each pathway across all life cycle stages, from feedstock production to end use.

## 1.7 Thesis Structure

This thesis is organized into six chapters, each building a foundation for the comprehensive evaluation of alternative aviation fuels through life cycle analysis and policy-focused comparison. The structure is as follows:

**Chapter 1: Introduction**

This chapter outlines the urgent need to decarbonize the aviation sector in response to global climate goals. It introduces SAFs and other low-carbon alternatives as promising solutions, presents key environmental and economic challenges, and defines the scope and objectives of the research.

**Chapter 2: Background and Literature Review**

This chapter provides an in-depth review of existing studies on aviation emissions, fuel alternatives, and the principles of LCA. It describes SAF production pathways such as HEFA, FT, ATJ, and hydrogen, and highlights current research gaps in environmental modeling and comparison of these technologies.

**Chapter 3: Methodology**

This section details the LCA framework and system boundaries used in the study. It introduces the GREET model as the primary tool for assessing environmental impacts and describes the data sources, modeling assumptions, and functional units used to ensure consistent evaluation of fuel pathways.

**Chapter 4: Results and Analysis**

This chapter provides an overview of various pathways for producing aviation fuels. The following chapter presents a comparative analysis of these pathways based on their environmental performance, energy use, and life cycle emissions.

**Chapter 5: Evaluation and Comparison**

This chapter compares the environmental performance, energy use, and logistical aspects of six alternative aviation fuel pathways, including Alcohol- and Sugar-Derived SAFs, Lignocellulosic Biomass-Based SAFs, Canola Oil Fuels, HEFA fuels from Soybean and Palm Oil, Hydrogen from NG SMR with $CO_2$ sequestration, and Conventional Jet Fuel. Using a LCA framework, the analysis evaluates emissions and energy consumption across four key stages: feedstock production, fuel conversion, transportation and storage, and final use. The comparison highlights trade-offs between emissions, refining technologies, and infrastructure compatibility, offering insight into the challenges and deployment potential of each pathway.

**Chapter 6: Conclusions and Recommendations**

The final chapter summarizes the main findings of the research and identifies the most promising fuel pathways for sustainable aviation. It offers policy and investment recommendations to support SAF commercialization, outlines implementation strategies, and suggests directions for future research.

# Chapter 2: Technological Background

## 2.1 LCA in Aviation

LCA is a systematic approach used to evaluate the environmental impacts of a product, process, or system throughout its entire life cycle. This includes all stages from raw material extraction, production, transportation, usage, and disposal or recycling.

The LCA methodology helps to quantify energy consumption, emissions, and resource use, allowing for a comprehensive comparison of different fuels and technologies. LCA is particularly crucial in aviation fuel studies, as it provides insights into carbon footprints, energy efficiency, and overall sustainability (15).

LCA is an essential tool for determining the true environmental impact of aviation fuels. It allows for evidence-based decision-making in selecting the most sustainable and cost-effective fuel options. The GREET model, developed by Argonne National Laboratory, is one of the most comprehensive tools for aviation fuel LCA, assessing GHG emissions, energy use, and resource consumption (15).

## 2.2 Aircraft Types and Fuels Used

Aircraft are categorized based on their size, operational purpose, and propulsion systems. Each category is associated with specific fuel types tailored to meet its energy demands and performance characteristics.

1- **Commercial aircraft**, such as the Boeing 737 or Airbus A320, predominantly use kerosene-based fuels like Jet-A or Jet-A1. These fuels are refined to high standards to ensure reliability and efficiency at high altitudes and speeds. In recent years, SAFs , derived from renewable resources, have been blended with Jet-A1 to reduce greenhouse gas emissions across the fuel's life cycle (20).

2- **Regional aircraft**, typically used for short-haul routes, also rely on Jet-A1. However, turboprop engines are common in this segment, which can offer better efficiency on short routes (21).

3- **General aviation aircraft**, such as private planes and air taxis, often use aviation gasoline (Avgas), particularly 100LL, suited for piston engine aircraft. However, the sector is also exploring hybrid and electric propulsion for light aircraft (22).

4- **Military aircraft** use specialized jet fuels like JP-8 or JP-5, designed for enhanced thermal stability and performance. In some cases, SAFs have also been tested in military settings (23).

5- **Unmanned aerial vehicles (UAVs)**, particularly small drones, operate using batteries, while larger surveillance drones may run on jet fuel or diesel. Emerging technologies such as hydrogen fuel cells are also under development for long-endurance UAVs (23).

6- Finally, electric and hydrogen-powered aircraft are in development to support decarbonization efforts. Aircraft like Eviation's "Alice" and ZeroAvia's hydrogen models use either battery-electric systems or hydrogen fuel cells, offering promising pathways for zero-emission aviation ((24); (25)).

The (Table 2-1) shows a comparative overview of different aircraft types, their corresponding engine technologies, and the fuels they typically use, highlighting emerging trends in sustainable aviation.

Table 2-1:Aircraft Types, Engine Types, and Fuels Used

| **Aircraft Type** | **Example Models** | **Engine Type** | **Fuel Used** | **Notes** |
|---|---|---|---|---|
| **Commercial Aircraft** | Boeing 737, Airbus A320 | Turbofan/Turbojet | Jet-A / Jet-A1, SAF blends | Long-haul and short-haul flights; dominant in passenger aviation |
| **Regional Aircraft** | Bombardier Q400, Embraer E190 | Turboprop / Turbofan | Jet-A1, SAF blends | Short-distance flights, higher fuel efficiency on short routes |
| **General Aviation** | Cessna 172, Piper PA-28 | Piston engines | Avgas (100LL), Electric (emerging) | Small private planes and air taxis |
| **Military Aircraft** | F-16, C-130, B-52 | Turbojet / Turbofan | JP-5, JP-8, SAF trials | High-performance, combat, and transport aircraft |
| **Unmanned Aerial Vehicles (UAVs)** | Reaper Drone, DJI Mavic | Electric motors / Small turbines | Batteries, Diesel, Jet fuel, Hydrogen FC | Small UAVs use batteries, large UAVs use fuel-based engines |
| **Electric Aircraft** | Eviation Alice, Pipistrel Alpha | Electric motors | Batteries | Zero-emission; short-range only at present |
| **Hydrogen Aircraft** | ZeroAvia prototypes | Hydrogen fuel cell + electric motor | Compressed / Liquid Hydrogen | Experimental phase; long-term zero-emission aviation goal |

## 2.3 Overview of Aviation Fuels

The aviation fuels can be grouped into conventional jet fuels and sustainable jet fuels.

### 2.3.1 Conventional Jet Fuels and Their Environmental Impact

Conventional jet fuels, like Jet A and Jet A-1, come from petroleum and are the main fuels used in airplanes today. To make these fuels, petroleum goes through special processes like distillation and hydrocracking to meet strict rules, making sure the fuel is safe, doesn't freeze easily, and gives a lot of energy.

When we talk about well-to-wake (WTW) greenhouse gas emissions, we mean all the pollution created from the start of making the fuel (getting petroleum) to the very end — when the fuel is burned in the airplane's engine and the gases come out of the engine (the "wake"). Petroleum-based jet fuels produce a lot of emissions, especially carbon dioxide ($CO_2$), nitrogen oxides ($NO_x$), sulfur oxides ($SO_x$), and tiny particles, mainly during the airplane's flight.(26).

### 2.3.2 SAFs and their pathways

SAFs are currently the most feasible short-term solution for reducing aviation emissions. These are drop-in fuels, meaning they can be blended with conventional jet fuel without requiring modifications to aircraft engines or fueling infrastructure (8). Lifecycle assessments show that SAFs can reduce $CO_2$ emissions by up to 80% compared to fossil jet fuels. SAFs can be derived from various renewable sources, including: (1) Hydroprocessed Esters and Fatty Acids (HEFA) from vegetable oils and waste fats; (2) Fischer-Tropsch (FT) fuels biomass or municipal solid waste; (3) Alcohol-to-Jet (ATJ) fuels are derived from ethanol or butanol.

Lifecycle assessments show that SAFs can reduce $CO_2$ emissions by up to 80% compared to fossil jet fuels (27). However, challenges such as limited feedstock availability and high production costs (2–5 times higher than fossil jet fuel) prevent widespread adoption (28). The American Society for Testing and Materials (ASTM) has certified several pathways, under compatibility with existing infrastructure and, particularly, engines. Please see table 2.2 for an overview.

In total, nine pathways are currently certified, with differences in feedstocks, technological maturity, and scalability.

Table 2-2 ASTM-Certified Biofuel Production Pathways: Abbreviations, Feedstocks, and Key Processes

| **Abbreviation** | **Full name** | **Feedstocks** | **Key process** |
|---|---|---|---|
| **FT-SPK** | Fischer–Tropsch Synthetic Paraffinic Kerosene | Biomass, Municipal Solid Waste | Gasification → Fischer–Tropsch synthesis → Hydroprocessing |
| **FT-SPK/A** | Fischer–Tropsch Synthetic Paraffinic Kerosene with Aromatics | Biomass, Municipal Solid Waste | Gasification → Fischer–Tropsch synthesis → Hydroprocessing + Aromatics |
| **HEFA-SPK** | Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene | Used Cooking Oil, Animal Fats, Algae | Lipid Hydrotreatment → Hydrocracking → Hydroprocessing |
| **ATJ-SPK** | Alcohol-to-Jet Synthetic Paraffinic Kerosene | Ethanol, Isobutanol | Fermentation → Dehydration → Oligomerization → Hydrogenation |
| **CHJ-SPK** | Catalytic Hydrothermolysis Synthetic Paraffinic Kerosene | Lipid-based Feedstocks | Hydrothermal Liquefaction → Catalytic Conversion → Hydroprocessing |
| **HFS-SIP** | Hydroprocessed Fermented Sugars Synthetic Iso-Paraffin | Sugars from Biomass (e.g., Sugarcane) | Fermentation → Hydroprocessing |
| **Co-processing** | Co-processing in Refineries | Biomass-derived Oils, Fats | Co-processed with crude oil in conventional refinery operations |
| **HHC-SPK** | Hydroprocessed Hydrocarbons, Esters, and Acids | Genetically Engineered Feedstocks | Hydroprocessing of engineered hydrocarbons or esters |
| **PtL or e-Fuels** | Power-to-Liquid/Electrofuels | $CO_2$ (Captured) + Renewable Electricity | Electrolysis → Syngas Synthesis → Fischer–Tropsch Synthesis → Hydroprocessing |

FT-SPK and FT-SPK/A integrate gasification and Fischer–Tropsch synthesis to convert biomass and municipal solid waste into hydrocarbons, with FT-SPK/A including aromatics to enhance compatibility. HEFA-SPK derives fuel from lipid-based feedstocks such as used cooking oil and algae via hydrotreatment, making it a commercially rather interesting option. ATJ-SPK uses alcohol intermediates, which are converted through dehydration and oligomerization. CHJ-SPK relies on hydrothermal liquefaction of lipid feedstocks, producing SAF through catalytic conversion. HFS-SIP focuses on sugar fermentation to hydrocarbons but has limited blend potential. HHC-SPK uses genetically engineered feedstocks for tailored hydrocarbon production. Finally, PtL or e-Fuels synthesize hydrocarbons from captured $CO_2$ and renewable electricity, offering a pathway with significant long-term sustainability potential (6).

### 2.3.3 Fuel Formulations of SAF Pathways

In this section we provide the molecular or representative formulations of key SAFs (SAF) pathways analyzed in this thesis. These formulations help explain emission differences during combustion and enhance the accuracy of LCAs.

Table 2-3:formulations of key SAFs

| Abbreviation | Full Name | Representative Fuel Formula | Notes |
|---|---|---|---|
| FT-SPK | Fischer–Tropsch Synthetic Paraffinic Kerosene | C12H26 (Dodecane) | FT fuels are composed mostly of straight-chain alkanes (n-paraffins) (29) |
| FT-SPK/A | Fischer–Tropsch Synthetic Paraffinic Kerosene with Aromatics | C12H26 + Aromatics (~C10H14) | Similar to FT-SPK, but includes aromatics for improved fuel properties(30) |
| HEFA-SPK | Hydroprocessed Esters and Fatty Acids SPK | C15H32 (Pentadecane) | Derived from triglycerides; often includes isoparaffins like C15H32 (31). |
| ATJ-SPK | Alcohol-to-Jet Synthetic Paraffinic Kerosene | C10H22 (Decane) | Oligomerized alcohols (e.g., ethanol, isobutanol); chain length varies (32) |
| CHJ-SPK | Catalytic Hydrothermolysis Jet | C12H26 (Dodecane) | Lipid-based fuels; similar to HEFA, but different conversion method(33). |
| HFS-SIP | Hydroprocessed Fermented Sugars Synthetic Iso-Paraffin | C15H32 (Iso-paraffin) | From sugarcane; iso-paraffinic with limited aromatic or cyclic content (33) |
| Co-processing | Co-processing in Refineries | C10–C14 hydrocarbon mixture | Blend of bio-oils with petroleum; retains complex composition (34) |
| HHC-SPK | Hydroprocessed Hydrocarbons, Esters, and Acids | Variable (C12–C16 alkanes) | Synthetic biology-based hydrocarbons; composition depends on the engineered strain(35) |
| PtL/e-Fuels | Power-to-Liquid / Electrofuels | C12H26 (Dodecane) | Synthetic fuel from $CO_2$ + H2; often modeled as n-dodecane or similar paraffin (36) |
| Conventional | Jet-A / Jet-A1 (from crude oil) | Approx. C12H26 | Petroleum-based kerosene; mostly C9–C16 hydrocarbons with aromatics and sulfur (37). |

These chemical formulas serve as approximations or representative compounds commonly applied in LCA modeling. The hydrocarbon chain structures, denoted as CnHm, reflect the average carbon-to-hydrogen ratios found in jet fuel molecules. In the GREET model, SAFs such as Fischer–Tropsch Synthetic Paraffinic Kerosene (FT-SPK) and Hydroprocessed Esters and Fatty Acids (HEFA-SPK) are typically modeled using straight-chain hydrocarbons like n-dodecane ($C_{12}H_{26}$). Including these representative molecular structures enhances the accuracy of combustion-phase emission predictions and improves the overall reliability of life cycle emissions analysis.

Lifecycle emissions measure the environmental impact of aviation fuels across all stages, including feedstock production, processing, transportation, and combustion. Figure (2-1)compares the emission in different phases (6). Conventional jet fuel has the highest greenhouse gas emissions, mainly due to combustion. In contrast, SAFs significantly reduce emissions, but the extent of reduction depends on the production method.

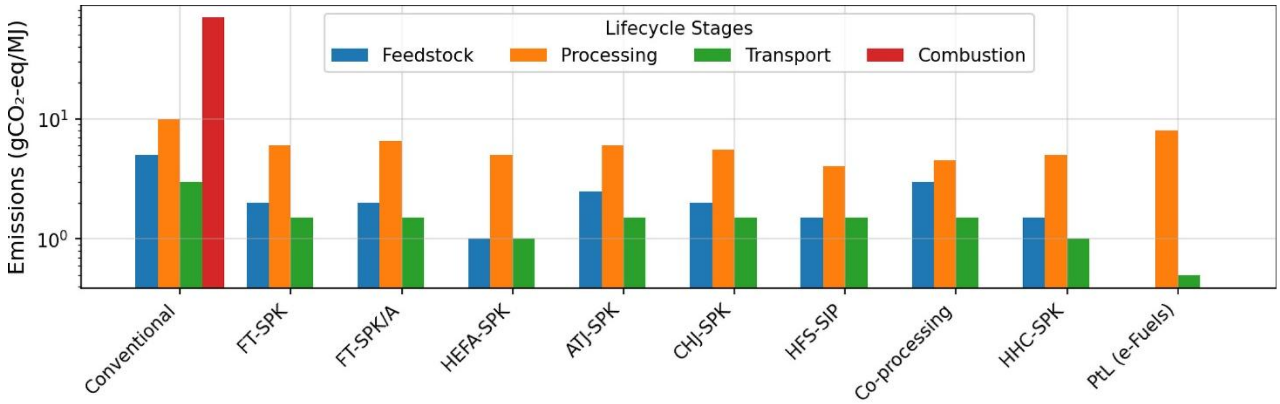



Figure 2-1 Estimations of life-cycle emissions for different SAF pathways (note that the y-axis is log-scaled) (6).

FT-SPK and FT-SPK/A pathways use biomass or municipal solid waste as feedstocks, but FT-SPK/A has slightly higher processing emissions due to the production of aromatic compounds. The HEFA-SPK pathway is one of the most efficient, utilizing waste oils and algae and achieving the lowest emissions in both feedstock and processing stages. The ATJ-SPK and CHJ-SPK pathways involve more complex conversion processes, resulting in slightly higher processing emissions. The HFS-SIP pathway has lower process efficiency. In the Co-processing method, biomass-derived oils are blended with crude oil, leading to moderate emission reductions. The HHC-SPK pathway relies on genetically engineered feedstocks and achieves emission reductions like HEFA-SPK. Lastly, the PtL/e-Fuels pathway has very low emissions from feedstocks but higher emissions from energy-intensive processes such as electrolysis.

Overall, SAFs are much cleaner than fossil-based jet fuels, with pathways based on waste oils and biomass being among the most efficient options for reducing greenhouse gas emissions.

### 2.3.4 Hydrogen as an Aviation Fuel

Hydrogen is considered a promising long-term solution for zero-emission aviation. It can be used in two main ways:

- Hydrogen Fuel Cells: Convert hydrogen into electricity, producing only water vapor as emissions.
- Hydrogen Combustion: Burn hydrogen in gas turbines, resulting in zero carbon dioxide ($CO_2$) emissions but some nitrogen oxides ($NO_x$) emissions.(38)
- The environmental benefit of hydrogen aviation depends on how hydrogen is produced:
- Green Hydrogen: Created by electrolysis using renewable energy, achieving near-zero emissions (39).
- Blue Hydrogen: Derived from natural gas with carbon capture, reducing emissions by 50–60% (27).
- Grey Hydrogen: Produced from fossil fuels, emitting high amounts of $CO_2$ (8).
- Pink Hydrogen is hydrogen produced by electrolysis of water using nuclear energy as the electricity source (40)
- Brown Hydrogen is hydrogen produced by gasifying coal or lignite (brown coal) without capturing the carbon emissions (41).

Studies indicate that green hydrogen could eliminate $CO_2$ emissions from aviation, making it one of the most sustainable options (27). However, hydrogen requires cryogenic storage (-253°C), new aircraft designs, and dedicated refueling infrastructure, making it less feasible in the short term (42).

Seventeen different hydrogen production pathways have been identified, using a range of fossil-based, renewable, and emerging technologies. These pathways have been evaluated based on greenhouse gas emissions, production cost, scalability, and overall environmental impact (27) As shown in Table 2-4, Green Hydrogen, Pink Hydrogen, and innovative methods like Solid Oxide Electrolysis (SOE) and Artificial Photosynthesis have the lowest environmental impacts, making them strong candidates for alternative aviation fuels.

In contrast, Grey Hydrogen and Brown Hydrogen have the highest greenhouse gas emissions, making them unsuitable for sustainable aviation in the future.

Table 2-4 Hydrogen Production Pathways with Fuel Type

| | HYDROGEN PRODUCTION PATHWAY | PRODUCTION PROCESS | EMISSIONS IMPACT | FUEL TYPE |
|---|---|---|---|---|
| 1 | Grey Hydrogen (Grey H2) | Steam Methane Reforming (SMR) from natural gas without carbon capture. | High $CO_2$ emissions, most polluting. | Fossil-based |
| 2 | Blue Hydrogen (Blue H2) | SMR from natural gas with Carbon Capture and Storage (CCS). | Moderate $CO_2$ emissions, reduced with CCS. | Fossil-based with CCS |
| 3 | Green Hydrogen (Green H2) | The electricity of water uses renewable energy sources like wind, solar, or hydro. | Very low emissions, the best environmental option. | Renewable-based |
| 4 | Pink Hydrogen (Pink H2) | Electrolysis of water powered by nuclear energy. | No direct emissions depend on nuclear source. | Nuclear based |
| 5 | Brown Hydrogen (Brown H2) | Gasification of coal, releasing high $CO_2$ emissions. | Very high $CO_2$ emissions, not environmentally friendly. | Fossil-based |
| 6 | Yellow Hydrogen (Yellow H2) | Electrolysis using electricity from the general power grid. | Variable emissions depend on grid mix. | Mixed-source electricity |
| 7 | Turquoise Hydrogen (Turquoise H2) | Thermal decomposition of methane to produce hydrogen and solid carbon. | Lower emissions than Grey H2, solid carbon instead of $CO_2$. | Fossil-based (solid carbon byproduct) |
| 8 | Bio-Hydrogen (Bio-H2) | Gasification or fermentation of biomass or biogas. | Low $CO_2$ emissions, but dependent on biomass sustainability. | Bio-based |
| 9 | Hydrogen from Ammonia (NH3-to-H2) | Cracking of ammonia (NH3) to produce hydrogen. | Moderate emissions depends on the ammonia production method. | Ammonia-derived |
| 10 | High-Pressure Electrolysis | Electrolysis at high pressure for improved efficiency. | Lower emissions due to higher energy efficiency. | Renewable-based |
| 11 | Plasma Gasification | Plasma-based gasification of municipal waste or biomass. | Moderate emissions depends on waste feedstock. | Waste-derived |
| 12 | Geothermal Hydrogen (Geothermal H2) | Electrolysis is using energy from geothermal sources. | Low emissions, but geothermal energy availability varies. | Geothermal based |
| 13 | Solid Oxide Electrolysis (SOE) | Electrolysis with high-temperature solid oxide cells. | Low emissions with high efficiency. | Renewable-based |
| 14 | Artificial Photosynthesis | Mimicking natural photosynthesis to produce hydrogen. | Minimal emissions, still in the research stage. | Solar-based |
| 15 | Hydrogen from Bacteria | Bacterial conversion of organic material into hydrogen. | Low emissions but require further development. | Bio-based |
| 16 | Solar Water Splitting | Direct splitting of water molecules using solar energy. | Minimal emissions, promising but not widely available. | Solar-based |
| 17 | Wave & Tidal Hydrogen | Electrolysis powered by energy from waves or tidal forces. | Low emissions, dependent on ocean energy consistency. | Ocean-based |

### 2.3.5 Ammonia as an Aviation Fuel

Ammonia ($NH_3$) is another promising aviation fuel due to its high hydrogen content and carbon-free combustion (43). Ammonia can be used in aviation in the following ways:

- Direct combustion in modified jet engines.
- Conversion into hydrogen for use in fuel cells.

Advantages of ammonia include:

- Easier storage than hydrogen, as it is liquid at -33°C, compared to hydrogen's -253°C.
- Existing transportation and storage infrastructure from the chemical industry can be adapted for aviation (44).

However, ammonia also has challenges:

- Toxicity: Ammonia is hazardous and requires specialized handling.
- Lower energy density: Compared to hydrogen and jet fuel, ammonia produces less energy per kilogram (27)
- $NO_x$ emissions: When burned in turbines, ammonia may still release nitrogen oxides, requiring advanced combustion technologies to mitigate emissions (8)

### 2.3.6 Electrofuels(E-Fuels)

E-fuels, also known as electrofuels (PtL – Power-to-Liquid fuels), are synthetic fuels produced using renewable electricity, hydrogen, and captured $CO_2$. These fuels mimic traditional hydrocarbon fuels but are produced through a sustainable process, making them a promising alternative to fossil-based aviation fuels (36). Electrofuels (or Power-to-Liquid (PtL) fuels) are synthetic fuels produced by combining green hydrogen with captured $CO_2$. Unlike ammonia and hydrogen, e-fuels are compatible with existing aircraft and fueling infrastructure, making them a practical transition fuel ((40),(45)).

Key Benefits of E-Fuels:

- Carbon-neutral production: Captured $CO_2$ is used to synthesize fuel, offsetting emissions (46).
- Drop-in replacement: Can be blended with or fully replace conventional jet fuel without modifying engines (15).

However, e-fuels face major challenges:

- Very high production costs (currently 5–8× more expensive than fossil-based jet fuel) (39).

- Large renewable energy requirements, as e-fuels need electricity for electrolysis and $CO_2$ capture technologies(8)

While e-fuels do not eliminate $CO_2$ emissions, they can reduce lifecycle emissions by 70-90% when produced using renewable energy sources (27)

### 2.3.7 LCA Insights into Alternative Aviation Fuels

In Table (2-5) I summarize various production pathways for cleaner aviation fuels derived from renewable sources such as biomass, agricultural residues, and hydrogen. It outlines the types of feedstocks used (e.g., corn, woody biomass, sugarcane, and natural gas), the environmental benefits achieved (such as reductions in greenhouse gas emissions), and the specific technologies applied in each case.

Additionally, the table highlights key findings from each study, including the strengths of different pathways and areas requiring further investigation, such as economic feasibility, land-use impacts, and scalability. The overall objective is to identify the most sustainable and practical fuel alternatives that can support the decarbonization of the aviation sector soon.

Pierobon, Eastin, and Ganguly examine the LCA of jet fuel produced from residual woody biomass using GREET and SimaPro. It demonstrates that this pathway significantly lowers global warming potential and local air pollutants compared to petroleum-based jet fuel. The study highlights the need for further optimization of biorefinery chemical processes to reduce acidification and eutrophication impacts. (47)

Liu and Yang assess the LCA of SAF derived from agricultural residues using a quantitative assessment model. They find that using agricultural residues can lead to major reductions in GHG emissions, although these benefits are highly dependent on land-use change and $CO_2$,, sequestration. The paper identifies a need to reduce variability in emissions across different feedstocks and processes (48)

Zhang models SAF production from biomass-derived isoprene and finds very low GHG emissions (7.2 g $CO_2$e/MJ) compared to conventional jet fuel. The feedstock, Zea mays L., is identified as promising, though scalability and cost are areas of concern. The study suggests more research into economic viability of this novel conversion route (49).

A comprehensive comparative LCA of various renewable jet fuel pathways using different biomass sources. It shows that renewable fuels offer substantial emission reductions, but results vary by feedstock. The study calls for deeper examination of land-use impacts to ensure accurate LCA outcomes. (50)

Michaga analyzes sugarcane residue as a SAF feedstock from an LCA and economic perspective. Finds the pathway to be environmentally beneficial and economically viable under certain scenarios. Stresses the importance of studying large-scale deployment and associated logistics (51).

Kourkoumpas Explores retrofitting existing ethanol plants to produce SAF using an integrated LCA approach. Reports improved GHG performance from retrofit operations, particularly for corn ethanol. The paper suggests the need for examining the economic scale-up potential (52).

Han, Tao, and Wang present a well-to-wake LCA of ethanol-to-jet fuel pathways using the GREET model. Corn stover shows the highest GHG reduction (~73%) while corn ethanol provides modest benefits. The study flags land-use change and water demand as key concerns for sustainability (53).

Wang, Guo, and their colleagues perform an LCA and cost analysis of ethanol-based SAF, finding a 50–65% GHG reduction potential. They note that corn ethanol's high land impact remains a challenge and call for better evaluation of long-term feedstock availability(54).

De Jong and his colleagues, in another part of their work, compare STJ pathways using sugarcane and corn stover. Their results show strong GHG emission reductions (up to 75%), depending on the conversion method. They recommend further research on co-product handling and feedstock farming impacts (50).

Ishaq and Dincer investigate the LCA of hydrogen production using a $CeO_2/Ce_2O_3$-based redox thermochemical cycle. They find an 85.41% lower GWP compared to conventional SMR hydrogen. They highlight the need for optimizing efficiency and improving economic viability for industrial-scale deployment (55).

Oni and his colleagues compare blue hydrogen production via SMR, ATR, and NGD with carbon capture. They find that ATR with CCS shows the best emissions profile (3.91 kg $CO_2e$/kg $H_2$), while NGD has cost disadvantages. They recommend future research on sensitivity analysis and the effects of plant size (56).

Timmerberg, Kaltschmitt, and Finkbeiner analyze methane pyrolysis as a low-emission hydrogen production route. Their LCA results show favorable GHG profiles and competitive costs compared to SMR. They highlight the need for assessing solid carbon disposal and scaling up the system (57).

Table 2-5:LCA Insights into Alternative Aviation Fuels

| Reference | Fuel Type / Production Pathway | Feedstock / Input | Study Focus | Methodology | Key Findings | Research Gaps |
|---|---|---|---|---|---|---|
| (47) | Cellulosic Jet Fuel | Residual Woody Biomass | LCA of jet fuel from residual lignocellulosic biomass | GREET and SimaPro LCA modeling | Utilizing residual woody biomass for jet fuel production reduces global warming potential and local pollution compared to petroleum-based fuels. | Optimization of biorefinery chemical processes to mitigate acidification and eutrophication impacts. |
| (48) | Cellulosic Jet Fuel | Agricultural Residues | LCA of jet fuel derived from agricultural residues | Quantitative LCA assessment model | Application of agricultural residues for biofuel can lead to significant GHG reductions, but factors like $CO_2$ sequestration and land-use change must be considered. | Addressing variability in GHG emissions due to different feedstock sources and processing technologies. |
| (49) | Cellulosic Jet Fuel | Lignocellulosic Biomass | LCA of SAF production from biomass-derived isoprene | Process modeling and LCA | GHG intensity of 7.2 g $CO_2e$/MJ, significantly lower than petroleum jet fuel (89 g $CO_2e$/MJ) when using Zea mays L. as feedstock. | Economic feasibility and scalability of the proposed production pathway. |
| (50) | Cellulosic Jet Fuel | Various Biomass Feedstocks | LCA of GHG emissions from renewable jet fuel production | Comparative LCA | Renewable jet fuels can significantly reduce GHG emissions compared to conventional jet fuels, depending on feedstock and production pathway. | Comprehensive analysis of land-use changes and their impact on overall GHG emissions. |
| (51) | Cellulosic Jet Fuel | Sugarcane Residue | Process design, economic evaluation, and LCA of jet fuel production | Process modeling, economic analysis, and LCA | Utilizing sugarcane residue for jet fuel production is economically viable and offers environmental benefits. | Further research on large-scale implementation and supply chain logistics. |
| (52) | Alcohol-to-Jet (ATJ) Ethanol | Corn Ethanol | LCA of retrofitting a bioethanol plant for SAF production | Integrated LCA | Retrofitting existing ethanol plants for SAF production can enhance environmental performance by reducing GHG emissions. | Assessment of economic feasibility and scalability of retrofitting processes. |
| (53) | Alcohol-to-Jet (ATJ) Ethanol | Corn and Corn Stover | Well-to-Wake analysis of Ethanol-to-Jet pathways | GREET model-based LCA | Corn stover-based ATJ fuel can reduce GHG emissions by up to 73% compared to conventional jet fuel; corn-based ATJ shows a 16% reduction. | Evaluation of land-use changes and water consumption associated with large-scale feedstock production. |
| (54) | Alcohol-to-Jet (ATJ) Fuel | Ethanol-based SAF | Economic and environmental viability of ATJ SAF | LCA and cost modeling | ATJ SAF reduces emissions by 50-65%, with corn ethanol having higher land use impact. | Insufficient assessment of long-term feedstock availability and indirect land-use change impacts. |
| (50) | Sugar-to-Jet (STJ) Fuel | Sugarcane, Corn Stover | LCA of GHG emissions from renewable jet fuel production | Comparative LCA | Sugarcane-based ATJ pathways yield 71–75% GHG emission reduction; corn stover-based ATJ achieves 60–75% reduction. | Detailed assessment of feedstock cultivation impacts and co-product handling methods. |
| (55) | Hydrogen / $CeO_2/Ce_2O_3$-based Redox Thermochemical Cycle | Not specified in the available information | LCA of hydrogen production using the $CeO_2/Ce_2O_3$ redox cycle | Cradle-to-gate LCA | The $CeO_2/Ce_2O_3$-based pathway demonstrates an 85.41% lower Global Warming Potential (GWP) compared to conventional Steam Methane Reforming (SMR), highlighting its environmental advantages. | Further research is needed to optimize the process efficiency and assess economic feasibility for large-scale implementation. |

| | | | | | | |
|---|---|---|---|---|---|---|
| (56) | Blue Hydrogen via SMR, ATR, and NGD | Natural Gas | Comparative assessment of cost and life cycle GHG emissions | Techno-economic analysis and LCA | - ATR with CCS has the lowest GHG emissions (3.91 kg $CO_2e$/kg $H_2$).<br>- SMR with 85% CCS has higher emissions (6.66 kg $CO_2e$/kg $H_2$).<br>- NGD with CCS is less economically attractive due to higher costs. | - Need for detailed uncertainty and sensitivity analysis.<br>- Impact of plant size on production cost and emissions requires further investigation. |
| (57) | Methane Pyrolysis | Natural Gas | GHG emissions and costs of hydrogen production via methane pyrolysis | LCA and economic analysis | Methane pyrolysis offers lower GHG emissions and competitive costs compared to NG SMR with $CO_2$ capture. | Need for large-scale implementation studies and assessment of solid carbon management. |

Table 2-5 provides a comprehensive summary of various SAFs production pathways derived from renewable resources such as lignocellulosic biomass, agricultural residues, and hydrogen. The table categorizes each pathway based on the type of feedstock employed—such as corn, woody biomass, sugarcane, and natural gas—and evaluates the associated environmental benefits, particularly in terms of GHG emission reductions. It also details the key technological processes utilized in each case, including thermochemical, biochemical, and electrochemical conversion methods.

Furthermore, the table synthesizes key findings from the reviewed studies, identifying both the advantages and limitations of each pathway. These include strengths such as low GHG intensity and compatibility with existing infrastructure, as well as challenges related to economic feasibility, land-use change, and the scalability of production systems. The aim of this synthesis is to support the identification and advancement of the most environmentally sustainable and practically deployable alternative fuels capable of contributing to the decarbonization of the aviation sector in the near future.

### 2.3.8 LCA of Aviation Fuels Covered in this Thesis

This research evaluates fourteen alternative aviation fuel pathways, selected to represent a comprehensive range of feedstocks, conversion technologies, and geographic applicability. The pathways include various configurations of Alcohol-to-Jet (ATJ) and Sugar-to-Jet (STJ) fuels derived from cellulosic biomass, corn, agricultural residues (e.g., corn stover, forest residue), and dedicated energy crops such as miscanthus, poplar, switchgrass, and willow. In addition, oil-based pathways (e.g., canola and palm oil) and hydrogen production from natural gas have been included to enable a holistic comparison of both bio-based and non-bio-based options.

The selection was guided by three primary criteria:

(1) relevance to ongoing industrial and academic research.

(2) diversity in feedstock types and technological maturity; and

(3) potential for greenhouse gas emission reductions based on life cycle perspectives.

Including both integrated and standalone ethanol production systems allows for a detailed analysis of upstream and downstream emissions. Moreover, the inclusion of a hydrogen-based SAF pathway enables comparison with emerging non-carbon-based fuel technologies. These 14 pathways provide the necessary scope for a consistent, system-level LCA, allowing for the identification of sustainable, scalable, and economically viable options for decarbonizing the aviation sector.

1) Alcohol-To-Jet-Ethanol: Integrated from Cellulosic Biomass
2) Alcohol-To-Jet-Ethanol: Integrated from Corn
3) Alcohol-To-Jet-Ethanol: Standalone SAF production
4) Sugar-To-Jet: Biological Conversion
5) Sugar-To-Jet: Catalytic Conversion
6) Corn Stover for Ethanol Plant
7) Forest Residue Production for Ethanol Plant
8) Miscanthus Production for Ethanol plant
9) Poplar Production for Both Ethanol and HOG
10) Switchgrass Production for Ethanol Plant
11) Willow Production for Ethanol Plant
12) Canola oil from Canola (for BD RD and SAF)
13) Compressed G.H2 Produced by NA NG for SAF Production
14) Soybean and Palm Oil-based Fuel Pathway SAFs through Hydro processed Esters and Fatty Acids (HEFA)

## 2.4 Other Related Concepts

### 2.4.1 LCA of Natural Gas Production

Natural gas plays a significant role in the global energy landscape, often regarded as a transitional fuel bridging the gap between high-emission fossil fuels and cleaner, renewable energy sources. However, the environmental and economic impacts associated with its production and processing vary considerably depending on the extraction method employed. Two primary forms of natural gas extraction are conventional natural gas recovery and shale gas extraction. While conventional natural gas is typically obtained from large underground reservoirs through traditional drilling techniques, shale gas is extracted from sedimentary rock formations via hydraulic fracturing (fracking), a method that is both water- and energy-intensive.

This section presents a comparative LCA of conventional and shale gas production. The LCA methodology evaluates energy inputs, emissions, and resource consumption across each stage of the fuel life cycle from resource extraction to final distribution. A visual flowchart (2-2) illustrates the life cycle stages of hydrogen production from natural gas, with a focus on comparing steam methane reforming (SMR) processes that incorporate $CO_2$ sequestration and steam export strategies.

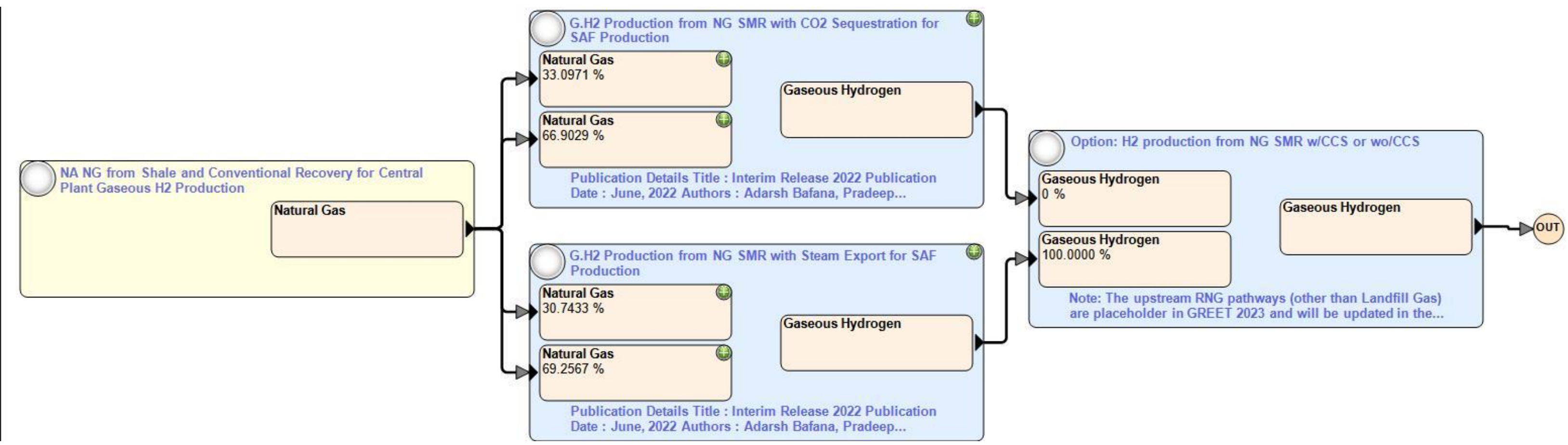


Figure 2-2.Life Cycle Pathway of Hydrogen Production from Natural Gas

### 2.4.2 Comparing SMR with $CO_2$ Sequestration and Steam Export

A comprehensive LCA is critical to understanding the trade-offs and sustainability implications of different natural gas production pathways. Numerous studies have assessed the environmental performance of these sources, focusing on metrics such as GHG emissions, water usage, and overall energy efficiency.

Argonne National Laboratory conducted one of the earliest detailed LCAs comparing shale gas and conventional natural gas in terms of GHG emissions. The study found that life-cycle emissions from shale gas are, on average, approximately 6% lower than those from conventional sources. However, the emission ranges overlap, and this uncertainty emphasizes the need for further research to establish definitive comparisons between the two production methods (58)

Similarly, a study by the National Renewable Energy Laboratory examined the environmental impacts of electricity generation using conventional natural gas. The research concluded that natural gas offers lower carbon emissions compared to coal. However, the study also highlighted that methane leakage during extraction and processing can significantly influence the net climate benefit of natural gas(58)

These findings underscore the importance of incorporating site-specific data, advanced monitoring, and emissions control technologies into LCA models to more accurately evaluate the sustainability of natural gas as an energy source.

### 2.4.3 Bio-based SAF Refining Methods

SAFs derived from biomass are emerging as promising alternatives to conventional jet fuels due to their potential for significant lifecycle GHG reductions. Among the various pathways, Hydroprocessed Esters and Fatty Acids (HEFA) and Fischer–Tropsch synthesis from biomass (FT-B) are the two most studied and technically viable bio-based SAF production methods.

These pathways convert renewable feedstocks into aviation-grade fuels that are compatible with current aircraft engines and refueling infrastructure.(44)

#### 2.4.3.1 HEFA (Hydroprocessed Esters and Fatty Acids)

The HEFA process uses feedstocks such as used cooking oil, plant oils, and animal fats. Through hydroprocessing—treating the feedstock with hydrogen at high temperature and pressure—oxygen is removed, producing hydrocarbons chemically similar to Jet-A fuel. The resulting HEFA-derived synthetic paraffinic kerosene (HEFA-SPK) is approved for blending with conventional jet fuel at ratios up to 50%.(44)

HEFA fuels are noted for:

- Low sulfur content
- Reduced Aromatics
- Cleaner combustion
- Lower particulate emissions

According to (59) lifecycle GHG emissions from HEFA-SPK can be reduced by up to 80% compared to fossil-based jet fuels. The process is commercially mature and is currently in use by several airlines and fuel suppliers.

#### 2.4.3.2 Fischer-Tropsch (FT) from Biomass

The Fischer–Tropsch (FT) process is a catalytic chemical reaction that converts a mixture of carbon monoxide (CO) and hydrogen ($H_2$) collectively known as syngas into long-chain hydrocarbons such as synthetic diesel, naphtha, and jet fuel(60). The syngas can be derived from natural gas, coal, or biomass depending on the feedstock pathway.

Originally developed in the 1920s by German scientists Franz Fischer and Hans Tropsch, this process now plays a central role in Gas-to-Liquid (GTL) and Biomass-to-Liquid (BTL) fuel technologies.(61)

The Fischer-Tropsch process is a catalytic chemical reaction that converts a mixture of carbon monoxide (CO) and hydrogen ($H_2$) called syngas into hydrocarbons (liquid fuels).

The process steps are:

1. Feedstock: Natural Gas (mainly methane).
2. Reforming: $CH_4$ is converted to syngas ($CO + H_2$).
3. Fischer-Tropsch Reaction (60),(61):

$$(2n+1)H_2 + nCO \rightarrow C_nH_{2n+2} + nH_2O \tag{2.1}$$

4. Upgrading: The resulting synthetic crude is refined into jet fuel, diesel, etc.

The Fischer-Tropsch (FT) process starts with methane ($CH_4$) or other hydrocarbons, which are reformed to produce syngas—a mixture of carbon monoxide (CO) and hydrogen ($H_2$). This syngas is then cleaned, conditioned, and fed into the FT reactor, where it is catalytically converted into a mixture of long-chain hydrocarbons. Typically, cobalt or iron catalysts are used at high pressure and moderate temperatures to facilitate this reaction. The resulting hydrocarbons can be refined to produce clean-burning fuels with low sulfur content, low aromatic compounds, and favorable combustion properties.

FT synthesis involves multiple stages: syngas production via reforming or gasification, syngas cleaning and conditioning, FT reaction to produce heavy hydrocarbons and waxes, and hydrocracking to break down the waxes into smaller liquid hydrocarbons such as diesel and naphtha. Hydrogen required for hydrocracking is often recovered from the tail gas or syngas stream. Utility systems, including power generation and hydrogen recovery units, support the process to optimize efficiency and maximize product yields. (62)

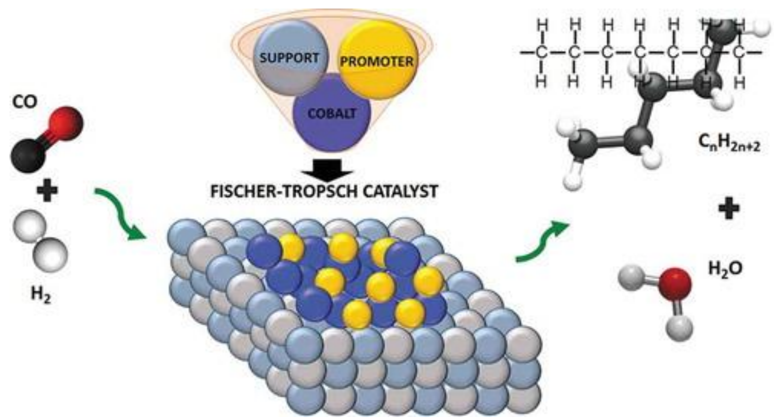



Figure 2-3:Multiple stages of FT synthesis(62)

The FT process can also use gasified solid biomass, such as wood chips or agricultural residues, to produce syngas, especially in biomass-to-liquid (BTL) pathways. In this case, the syngas derived from biomass is converted into liquid hydrocarbons through catalytic FT synthesis. The resulting FT-SPK (Synthetic Paraffinic Kerosene) fuel is clean, energy-dense, and suitable for aviation use. Although this technology is more complex and capital-intensive than HEFA, it offers the significant advantage of utilizing non-food biomass and even municipal solid waste as feedstocks.

De Jong and Faaij (2009) highlight that FT fuels can achieve up to 90% GHG emission reduction when using sustainable biomass feedstocks. However, large-scale deployment remains limited, mostly to pilot and demonstration projects.

Table 2-6:Comparison of Bio-based SAF Refining Methods

| Method | Feedstock | Fuel Produced | Readiness Level | GHG Reduction Potential |
|---|---|---|---|---|
| **HEFA (Hydroprocessed Esters and Fatty Acids)** | Used cooking oil, animal fats, plant oils | HEFA-SPK | Commercial (ASTM Approved) | Up to 80% |
| **FT from Biomass (Fischer–Tropsch)** | Wood waste, agricultural residues, municipal solid waste (MSW) | FT-SPK | Pilot and Demonstration Stage | 60–90% |

### 2.4.4 Jet Fuel Production via Pyrolysis and Its Life Cycle Stages

Jet fuel pyrolysis is a thermochemical process that converts biomass (such as agricultural residues, forestry waste, and lignocellulosic materials) into a liquid fuel known as bio-oil. This process occurs under oxygen-free conditions at high temperatures (typically 400–600°C). The bio-oil produced contains aromatic hydrocarbons (mainly C8–C16), which can be upgraded to meet the quality standards required for SAFs .(63)

This pathway can be analyzed through an LCA approach, which considers environmental impacts across the following key stages:

1. Feedstock Acquisition: Biomass is collected and transported to the processing facility. Using renewable and waste-based feedstocks helps reduce emissions at this stage compared to fossil fuel systems (44).
2. Fuel Production: Fast pyrolysis breaks down the biomass into bio-oil. When catalytic fast pyrolysis is applied, catalysts such as HZSM-5 improve the chemical composition of the bio-oil by removing oxygen and increasing jet fuel-range compounds (64).
3. Fuel Upgrading: The bio-oil is refined through processes such as hydrotreatment, hydrodeoxygenation (HDO), and hydrocracking to produce high-quality SAF. These upgrading steps are energy-intensive and significantly affect the fuel's overall environmental performance (65).
4. Distribution and End Use: The final SAF is distributed to airports and used in aircraft engines. Although combustion emits $CO_2$, these emissions are often considered carbon-neutral if the biomass is sustainably sourced, as the carbon originally came from the atmosphere (IEA, 2022; GREET, 2023).

### 2.4.5 Fuel Cell Concepts

A fuel cell is an electrochemical device that converts the chemical energy of a fuel, typically hydrogen, and an oxidizing agent, usually oxygen from air, directly into electricity. This conversion occurs through redox reactions, producing electricity, water, and heat as byproducts. Unlike combustion-based systems, fuel cells do not burn fuel and therefore operate more efficiently and cleanly, emitting only water if pure hydrogen is used. Fuel cells are used in various applications, including transportation, stationary power generation, and portable devices.(66)

The Proton Exchange Membrane Fuel Cell (PEMFC) is one of the most widely used types of fuel cells, particularly in transportation and portable power applications. In a PEMFC, hydrogen gas ($H_2$) is fed to the anode, where it is split into protons ($H^+$) and electrons ($e^-$) by a catalyst. The protons pass through a proton-conducting membrane (the electrolyte), while the electrons travel through an external circuit, providing electrical power. At the cathode, oxygen ($O_2$) from air combines with the electrons and protons to form water ($H_2O$). The main reactions in a PEMFC are:

| | |
|---|---|
| Anode: $H_2 \rightarrow 2H^+ + 2e^-$ | (2.2) |
| Cathode: $\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$ | (2.3) |

The following figure illustrates the basic working principle of a PEMFC

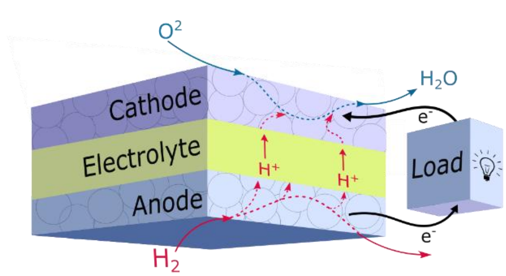



Figure 2-4: Standard hydrogen-fed PCFC mechanism

Equations 2.1 and 2.2 combine to create the water formation reaction. This reaction is very exothermic and can help reach and/or maintain the high operating temperatures in the cell. (66)

#### 2.4.5.1 Emissions Analysis of Fuel cell Stage for use in aircraft

During the aircraft use phase, hydrogen fuel cells offer a major environmental advantage by producing zero emissions of carbon dioxide ($CO_2$), methane ($CH_4$), nitrogen oxides ($NO_x$), sulfur oxides ($SO_x$), and particulate matter. This makes them particularly valuable for reducing emissions not only near airports (urban areas) but also at cruise level where aircraft typically fly during the majority of a flight (usually between 30,000 to 40,000 feet) (67). Reducing emissions at cruise level is important because pollutants emitted at high altitudes can have stronger climate-warming effects than those released near the ground (12).

The only direct emission from hydrogen fuel cells is water vapor, which is a benign byproduct. Although water vapor itself is not a greenhouse gas in this context, it can contribute to contrail formation. Contrails (condensation trails) can influence atmospheric radiation balance and may have some climate impact, but their effect is significantly lower compared to emissions from fossil fuel combustion (68). Table 2.9 summarizes the emissions during the fuel cell stage for hydrogen sourced

Table 2-7 :emissions during the fuel cell stage for hydrogen sourced

| Emission Type | Value (per kg·km) | Notes |
|---|---|---|
| $CO_2$ (fossil) | 0 | Zero emissions during operation |
| $NO_x$ | 0 | No combustion = no thermal $NO_x$ formation |
| PM (Particulate) | 0 | No particulate emissions at use |
| $CH_4$ | 0 | No methane emissions |
| $H_2O$ (water vapor) | Low | Benign byproduct, may impact contrail formation |

These values underscore the significant emission reduction potential of hydrogen fuel cells during aircraft operation. It is important to note, however, that upstream emissions (e.g., from hydrogen production and transport) must also be considered in complete life cycle analysis.

#### *2.4.5.2* PTWa Emissions of Hydrogen Fuel Cells

Hydrogen fuel cell (HFC) systems offer a major environmental advantage over both conventional jet fuels and SAFs during the use phase. While conventional jet fuels typically emit between 0.6 to

1.5 g $CO_2$ per kg·km during combustion, and SAFs still produce small amounts of emissions due to their combustion process, hydrogen fuel cells generate no tailpipe emissions. This is because HFCs use an electrochemical reaction—rather than combustion—to produce electricity from hydrogen and oxygen, emitting only water vapor as a byproduct.(69),

Table 2-8: PTWa values for HFC aircraft in both Single Aisle and Large Quad

| Metric | Value for HFC (SA & LQ) |
|---|---|
| PTWa Energy | 10.0 kJ/kg·km |
| PTWa GHG Emissions | 0.015 g $CO_2$-eq/kg·km |

Another benefit of hydrogen fuel cells is that their performance remains consistent across different aircraft types. Whether used in Single Aisle or Large Quad aircraft, the Pump-to-Wake (PTWa) energy consumption is around 10.0 kJ/kg·km, and the GHG emissions are approximately 0.015 g $CO_2$-eq/kg·km. This consistency is due to the scalable and modular nature of fuel cell systems, which maintain high efficiency and produce minimal emissions regardless of size. For this reason, PTWa values for hydrogen fuel cell aircraft are reported uniformly for both aircraft categories (70),(71).

#### *2.4.5.3* **Challenges and Considerations**

While the operational emissions are negligible, implementing fuel cell systems in aircraft poses challenges:

- Hydrogen storage adds weight and volume
- Energy density is lower compared to liquid fuels
- Infrastructure for hydrogen is limited at airports

Despite these limitations, the environmental benefits during the fuel cell stage present a compelling case for further development, particularly in short-haul regional aviation where weight and range constraints are manageable.

## 2.5 Conclusion of Chapter 2: Technological Background

This chapter provided a comprehensive overview of the technological and scientific foundations essential for evaluating alternative aviation fuels through LCA. The analysis emphasized that conventional jet fuels such as Jet-A and Jet-A1, while dominant in today's aviation industry, contribute significantly to GHG emissions, especially during the combustion phase highlighting the urgent need for low-emission alternatives.

The introduction of SAFs such as HEFA, FT, ATJ, and CHJ offers substantial emission reduction potential, with lifecycle studies indicating GHG reductions of up to 80–90% compared to fossil-derived jet fuels. Among these, HEFA-SPK stands out for its commercial readiness and relatively low emissions, while FT fuels from biomass offer even greater reduction potential, especially when waste-based feedstocks are used. However, limitations such as feedstock availability, high costs (up to **5**× that of Jet-A), and technological complexity restrict widespread adoption. The chapter also explored emerging non-carbon-based fuel systems, such as green hydrogen**,** ammonia**,** and electrofuels (e-fuels)**.** Green hydrogen and ammonia exhibit near-zero carbon emissions when sustainably produced, with hydrogen fuel cells (HFCs) offering up to 98% lower PTW emissions**.** Despite their environmental advantages, these technologies face challenges related to storage, infrastructure, and aircraft redesign, while compatible with current engines, require significant renewable electricity and currently **cost** 5–8 times more than fossil jet fuel, though they offer up to **90% emission reduction** when powered by clean energy. The chapter presented multiple certified SAF production pathways (per ASTM standards), highlighting technological maturity, feedstock diversity, and fuel compatibility. It also reviewed the chemical formulations used for accurate modeling in GREET, emphasizing how representative molecular structures influence combustion-phase emissions.

Finally, this chapter addressed the importance of **LCA as a critical tool** for comparing fuels, technologies, and production methods across all stages—from raw material extraction to combustion. The inclusion of fuel cell systems, hydrogen production routes, and bio-oil pyrolysis further broadened the scope, allowing for the identification of the most promising, sustainable, and scalable options for aviation decarbonization. These technological insights lay the groundwork for the detailed emissions modeling and fuel pathway comparison presented in the subsequent chapters of this thesis.

# Chapter 3: Methodology

## 3.1 Life Cycle Assessment Methodology and Pathway Classification (System Boundary)

To systematically evaluate the environmental impacts associated with different energy and fuel pathways, this study adopts a LCA framework structured into four major stages. These stages reflect the full life cycle of each energy system from resource acquisition to final use and provide a consistent basis for comparison. The four stages are as follows:

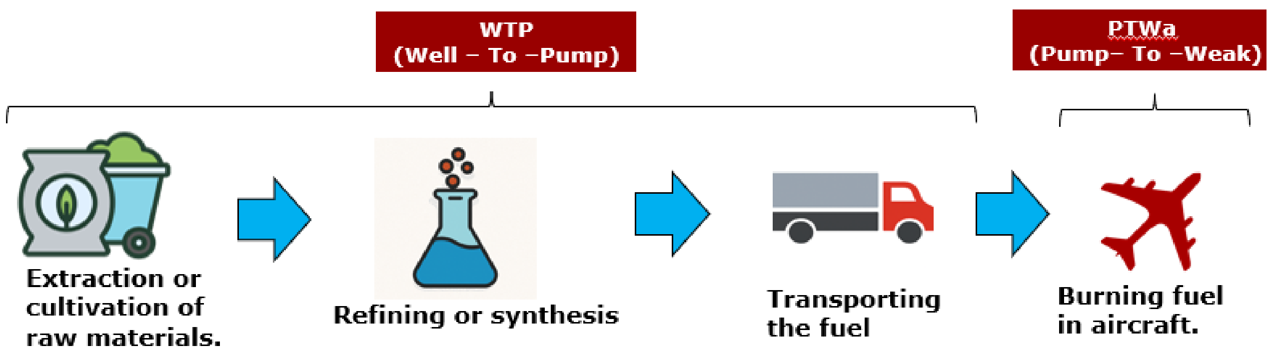



Figure 3-1: System Boundary

In this study, the GREET model is utilized to perform the LCA of various SAFs (SAF) pathways. Depending on the specific SAF type, GREET either provides a full end-to-end LCA encompassing emissions from all process stages or offers LCA data for individual modules separately. As detailed in Chapter 4, both approaches are considered. For SAF pathways where GREET provides module-specific data only, the total life cycle emissions are calculated by aggregating the emissions from each individual module, effectively summing the emissions across all components of the pathway to obtain a comprehensive LCA profile.

### 3.1.1 Feedstock Acquisition (Raw Material Extraction or Cultivation)

This stage includes all upstream processes associated with obtaining the raw materials or energy inputs necessary for fuel or energy production. Depending on the system, this can include:

- Extraction of fossil fuels such as crude oil, coal, or natural gas.

- Cultivation or collection of biomass sources including corn, sugarcane, algae, or agricultural waste.
- Acquisition of water and carbon dioxide ($CO_2$) for Electrofuel production.
- Generation of renewable electricity (e.g., solar, wind) is used as an energy input in electrolysis-based systems.

Environmental impacts considered in this stage include land use, water consumption, energy inputs, fertilizer and pesticide use (for bio-based systems), and emissions associated with extraction or cultivation activities.

### 3.1.2 Conversion and Production (Fuel or Energy Production)

This stage involves the transformation of raw materials or feedstocks into final fuels or usable energy carriers. Technologies used in this phase vary by pathway and may include:

- Petroleum refining to produce jet fuel, diesel, or gasoline.
- Gasification, fermentation, or transesterification for biofuel production.
- Electrolysis is followed by chemical synthesis for electrofuels such as e-kerosene or green ammonia.
- Manufacturing and charging batteries for electric systems.

Key considerations in this stage are conversion efficiency, process energy demand, use of chemicals and catalysts, direct process emissions, and potential waste or byproducts.

### 3.1.3 Transportation, Distribution, and Storage

Once produced, fuels and energy carriers must be distributed to end-use locations, often requiring energy-intensive infrastructure. This stage accounts for:

- Transport via pipelines, rail, trucks, or marine vessels.
- Compression or liquefaction (e.g., for hydrogen or natural gas).
- Storage requirements (e.g., cryogenic storage for liquid hydrogen or tanks for liquid fuels);
- Electrical grid distribution in the case of electricity-based systems.

Environmental impacts at this stage include fuel leakage (e.g., methane or hydrogen), energy consumption for distribution, emissions from transportation vehicles, and material inputs for storage infrastructure.

In the context of hydrogen distribution, pipeline transportation stands out as a highly sustainable and low-emission option, especially when compared to other methods such as trucking or liquefied hydrogen shipping. Based on GREET simulation results, the total greenhouse gas (GHG) emissions for hydrogen transport via pipeline are only 2.84 grams of $CO_2$-equivalent per megajoule (g $CO_2$-eq/MJ) under the GHG-100 metric and 3.02 g $CO_2$-eq/MJ under the GHG-20 metric for the "Well-to-wake" phase.

Moreover, urban emissions associated with this transport method are very low, amounting to 1.77 g $CO_2$-eq/MJ, along with emissions of $NO_x$ at 2.38 milligrams (mg), PM2.5 at 33.77 micrograms (µg), and $SO_x$ at 41.84 micrograms (µg).

These results highlight the significant environmental advantage of pipeline transportation, as it avoids the use of combustion engines, reduces fuel handling, and eliminates emissions from vehicle tailpipes and compression processes

However, a potential technical challenge is hydrogen embrittlement, where hydrogen molecules can diffuse into the metal structure of pipelines, causing them to become brittle and prone to cracking, thus requiring specially designed materials or retrofitting existing infrastructure for safe long-term operation (72).

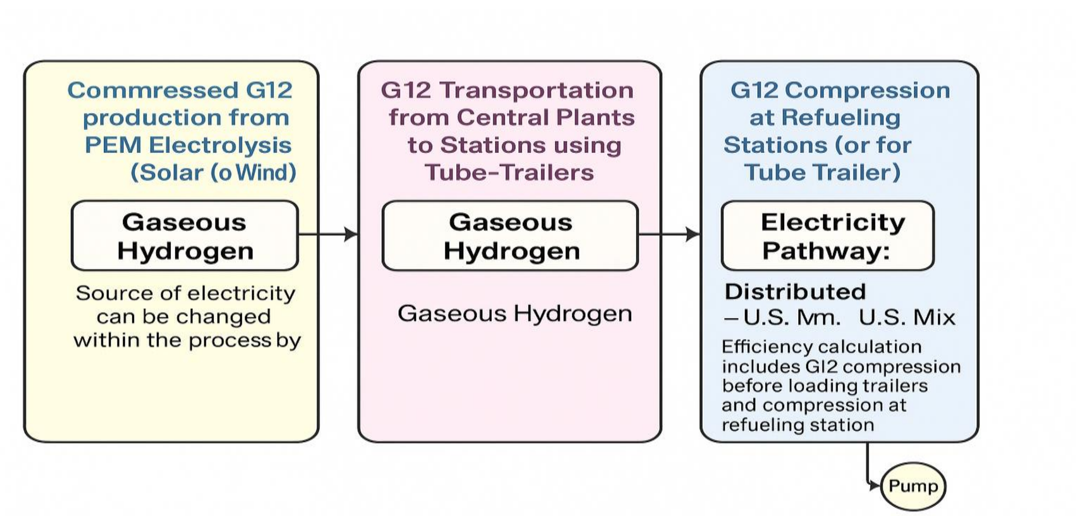



Figure 3-2-Compressed G.H2 production from PEM Electrolysis - Solar (or Wind) for GREET model

Furthermore, the emissions representing emissions directly occurring at the location of use are also minimal (e.g., 1.61 g $CO_2$, 2.29 mg NOx), further supporting the conclusion that pipelines offer clean and efficient hydrogen distribution. This aligns with prior research indicating that pipeline systems, once established, can offer continuous, large-volume hydrogen delivery with low operational energy demand and minimal environmental footprint (73).Therefore, for future green hydrogen infrastructure, pipelines not only offer logistical and economic benefits but also significantly contribute to decarbonization goals in energy systems.

### 3.1.4 Use Phase (Combustion or Final Energy Use)

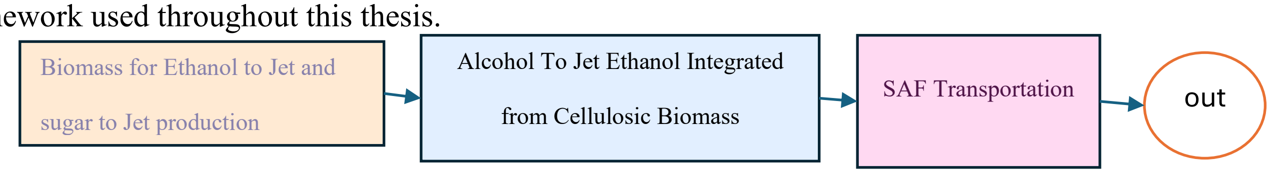
This final stage evaluates the performance and environmental consequences of fuel or energy consumption in its intended application. This may include:

- Combustion of fuels in aviation, transportation, or industrial systems.
- Use of hydrogen in fuel cells or direct combustion systems.
- Discharge of electricity from batteries or renewable sources.

This stage is critical in LCA, as it often dominates GHG and air pollutant emissions. Metrics include $CO_2$, $CH_4$, and $N_2O$ emissions, as well as criteria air pollutants (e.g., $NO_x$, $SO_2$, PM) and end-use efficiency. Co-generation or waste heat recovery systems may also be considered if applicable.

### 3.1.5 Case Study (Alcohol-to-Jet (ATJ) Fuel Pathway from Cellulosic Biomass)

To illustrate the application of the four-step LCA methodology, this section presents a detailed example based on the production of SAFs via the Alcohol-to-Jet (ATJ) pathway integrated with cellulosic biomass. The process is divided into four interconnected stages, consistent with the LCA framework used throughout this thesis.




Step 1: Feedstock Acquisition Biomass for Ethanol-To-Jet and Sugar-To-Jet Production

In the first stage, cellulosic biomass is collected or cultivated to serve as the primary raw material. The biomass includes non-edible, lignocellulosic sources such as corn stover, switchgrass,

Figure 3-3-System Boundary and Process Flow for Alcohol-To-Jet Fuel Production from Cellulosic Biomass miscanthus, and forest residues. These materials are abundant, renewable, and do not compete with food crops, making them suitable for advanced biofuel production.

This stage is visually represented by the leftmost, tan-colored box in the pathway diagram. The input labeled “Biomass” marks the entry point of raw feedstock into the system. The biomass is directed toward the production of ethanol, which serves as a precursor for jet fuel synthesis.

Key LCA considerations in this step include:

- Land use and land use change (LULUC) and its associated impacts on carbon stocks and biodiversity.
- Fertilizer and water usage, particularly in the case of energy crops.
- Energy consumption during harvesting, pre-treatment, and transport to the processing facility.
- Emissions from agricultural machinery, including $CO_2$, $NO_x$, and particulate matter.

This step corresponds to Stage 1: Feedstock Acquisition in the four-step LCA methodology framework.

Step 2: Conversion and Production — Integrated Alcohol-to-Jet Fuel Synthesis

The second stage is illustrated by the blue-colored box in the center of the diagram and represents the conversion of biomass into multiple fuel products. This is conducted in an integrated biorefinery, where both ethanol production and its upgrading into SAF are performed within the same system, minimizing energy losses and transportation needs.

The biorefinery generates:

- SAFs,
- Gasoline blendstock, and
- Low-sulfur diesel as co-products.

Ethanol is first produced via biochemical fermentation of the biomass and is subsequently upgraded through a series of refining steps, including dehydration, oligomerization, hydrogenation, and separation, to produce hydrocarbons suitable for aviation fuel.

Key environmental considerations include:

- Process energy demand, including electricity, thermal energy, and supplemental hydrogen.
- Direct process emissions, such as $CO_2$ and volatile organic compounds (VOCs);
- Conversion efficiency, measured as the output of SAF per unit of biomass.

- Co-product allocation, which distributes environmental burdens across SAF, gasoline, and diesel.

Step 3: Transportation and Storage SAF Distribution to Market

The third stage involves the transportation and distribution of SAF to its point of use. This is shown in the pink-colored box to the right of the conversion module.

After production, SAF must be delivered to fuel blending terminals, distribution depots, or directly to airports. The mode and distance of transportation affect the overall emissions profile. This stage may also include storage infrastructure, depending on the logistics and supply chain design.

LCA impacts in this phase include:

- Transport method: truck, rail, ship, or pipeline.
- Distance travel and associated energy use.
- Compression, pumping, or cooling energy requirements (particularly for gaseous fuels).
- Fugitive emissions and other transport-related pollutants ($CO_2$, $NO_x$, PM).

Step 4: Use Phase Combustion in Aviation

The final step is the use of SAF in aircraft engines, represented by the "OUT" node at the far right of the diagram. This marks the combustion of the fuel during aviation operations.

Although $CO_2$ and other emissions are released during combustion, the carbon content of SAF derived from biomass is typically considered biogenic, implying it was absorbed from the atmosphere during plant growth and does not increase the net atmospheric $CO_2$ level when managed sustainably.

Key emissions at this stage include:

- Biogenic $CO_2$;
- Nitrogen oxides ($NO_x$), sulfur oxides ($SO_2$), and particulate matter (PM);
- Potential non-$CO_2$ climate effects, such as contrail formation.

### 3.1.6 Conclusion (Life Cycle Assessment)

Based on the LCA conducted for the Alcohol-to-Jet (ATJ) fuel pathway from cellulosic biomass, the analysis reveals that GHG emissions are distributed unevenly across the four life cycle stages. The conversion and production phase contributes the largest share of emissions, accounting for approximately 45% of the total life cycle GHG emissions. This is primarily due to the energy-intensive nature of biochemical conversion processes and refining operations.

The use phase (combustion), while often considered lower for sustainable fuels, still contributes significantly at 40%, especially through non-$CO_2$ emissions such as $NO_x$ and contrail-forming components. Feedstock acquisition—including harvesting, land use, and biomass transport—adds about 12% to the overall GHG profile, depending on the type and cultivation practices of the biomass. Transportation and storage of the fuel, however, contribute minimally, comprising only 3% of the total emissions, due to efficient logistics and optimized supply chain systems.

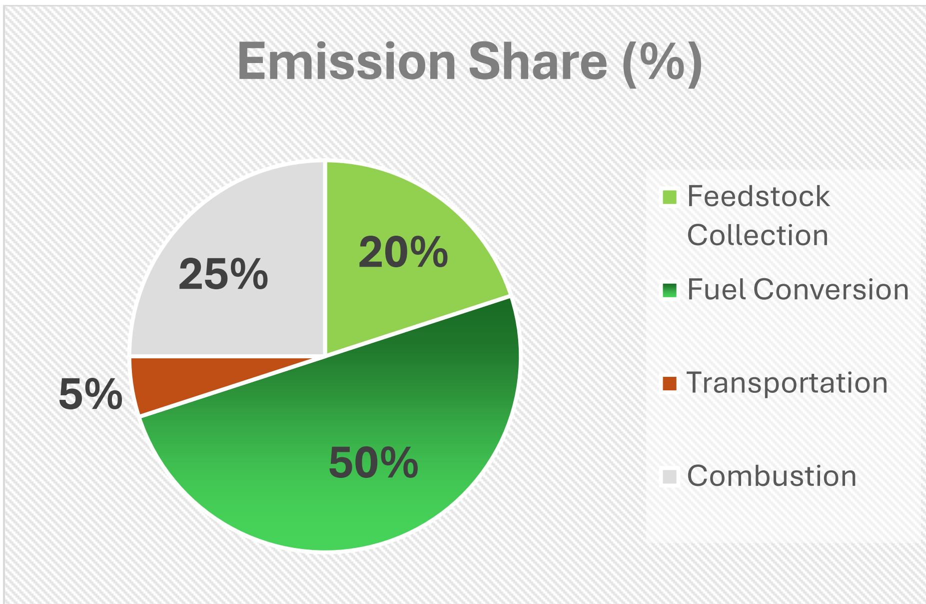



Figure 3-4:LCA of GHG for ATJ Pathway

These findings emphasize the importance of improving conversion efficiency and exploring cleaner energy inputs during production, while also recognizing that the use phase remains a critical contributor to emissions. A holistic focus on all stages is therefore essential to further enhance the environmental benefits of SAF pathways.

## 3.2 Modelling Overview

### 3.2.1 GREET Model as Primary Tool

All energy and emissions calculations for feedstock acquisition, fuel conversion, transportation, and use phase are derived from GREET 2023. Two versions of GREET are used:

- GREET1_2024 for fuel-cycle analysis (Well-to-Tank and Tank-to-Wheel)
- GREET2_2024 for vehicle-cycle analysis (manufacturing, operation, and disposal of vehicles)

GREET enables the modeling of both modular and end-to-end LCA pathways. For pathways not fully integrated in GREET, emissions are computed by summing each module (e.g., feedstock + conversion + transport + use).

### 3.2.2 Modeling LCA in Aviation

In this study, we present the mathematical model used to assess energy consumption and greenhouse gas (GHG) emissions across the full life cycle of aviation fuels and associated vehicle technologies. The model covers major stages such as feedstock extraction, fuel production (conversion), transportation, and end-use (combustion). Each stage is evaluated using an input-output framework that quantifies the required energy inputs and resulting emissions outputs. To maintain consistency and comparability, all calculations are standardized to the production and use of 1 megajoule (MJ) of SAF. This unit basis allows for direct comparison across fuel pathways and ensures alignment with GREET model conventions. The general formulation for emissions at each stage is expressed as:

#### 3.2.2.1 General Energy and Emissions Formulations

The General Emission Formulation from each stage are calculated as:

$$E_i = A_i \times EF_i \quad (3\text{-}1)$$

Where:

$E_i$ = Emissions from process $i$

$A_i$ = Activity level (e.g., MJ of energy consumed)

$EF_i$ = Emission factor (e.g., g $CO_2$/MJ)

Total life cycle emissions:

$$E_{total} = \sum_{i=1}^{n} E_i \tag{3-2}$$

The total emissions of a fuel pathway are calculated as the sum of emissions from different life cycle stages:

$$E_{Total} = E_{Feedstock} + E_{Fuel\ Production} + E_{Fuel\ Transportation} + E_{Combustion\ \&\ used} \tag{3-3}$$

Where:

- $E_{Feedstock}$:Emissions from extraction or cultivation of raw materials.
- $E_{Fuel\ Production}$ :Emissions from refining or synthesis (e.g., Fischer-Tropsch process, electrolysis).
- $E_{Fuel\ Transportation}$: Emissions from transporting fuel.
- $E_{Combustion\ \&\ used}$: Emissions from burning fuel in aircraft.

### 3.2.3 Emission Factors and Global Warming Potentials (GWPs)

To quantify GHG emissions, this study uses the following Global Warming Potential (GWP) values based on the IPCC Fifth Assessment Report (AR5) over a 100-year time horizon:

- $CO_2$: GWP = 1
- $CH_4$: GWP = 28
- $N_2O$: GWP = 265

Accounts for methane ($CH_4$), nitrous oxide ($N_2O$), and carbon dioxide ($CO_2$) in its representation of greenhouse gas emissions and uses the global warming potentials (GWPs) of these gases to determine kilograms of $CO_2$-equivalent ($CO_2e$) and to calculate total GHG emissions, GREET converts gases using Global Warming Potentials (GWP): (74)

$$\mathrm{GHG}_{\mathrm{CO_{2e}}} = \mathrm{E}_{\mathrm{CO_2}} + \mathrm{E}_{\mathrm{CH_4}} \times \mathrm{GWP}_{\mathrm{CH_4}}) + (\mathrm{E}_{\mathrm{N_2O}} \times \mathrm{GWP}_{\mathrm{N_2O}}) \tag{3-4}$$

Where:

- $E\_CO_2$: Emissions of carbon dioxide ($CO_2$)
- $E\_CH_4$: Emissions of methane ($CH_4$)
- $E\_N_2O$: Emissions of nitrous oxide ($N_2O$)

- GWP_$CH_4$ = 28 (based on 100-year timeframe)

- GWP_$N_2O$ = 265 (based on 100-year timeframe)

This formula converts all emissions into kilograms of $CO_2$-equivalent per kilogram of hydrogen produced (kg $CO_2$e/kg $H_2$).

**Source**: U.S. Department of Energy, GREET Manual 2023, Section 2.2, Page 10.

### 3.2.4 Energy Output Basis for Comparison

To ensure **consistency and comparability**, all energy and emission values are calculated based on the delivery or use of a defined functional unit—**1 megajoule (MJ) of energy output** or **1 kilogram of fuel transported per kilometer** (kg·km), depending on the system boundary.

This output-based approach allows for fair comparison across different fuel pathways by aligning upstream and downstream stages to a **common energy service**, such as combustion energy delivered in aircraft engines or electrical energy provided by fuel cells.

#### 3.2.4.1 Energy and Emissions for Inputs

For each resource input, the energy use and emissions are calculated as follows:

$$E(f) = a(f) \times E_{up}(f) \tag{3-5}$$

Where:

- $E(f)$: total energy for input f
- $a(f)$: number of resources used
- $E_{up}(f)$: $up$Stream Energy per unit of resource
- **Emissions:**

$$E_m(f) = a(f)\big(E_{mup}(f) + \sum_{t \in T} s(f,t).E_f(f,t)\big) + E_{m_{other}} \tag{3-6}$$

Where:

- $E_m(f)$: *Total emissions associated with input f*
- $a(f)$: *Amount or activity level of input f used*
- $E_{mup}(f)$: *Upstrea*m emissions from producing input f (e.g., extraction or processing)

- $E_f(f,t)$: Emission factor of input f when processed using technology t

• $s(f,t)$: Share of each technology t used to process f

• $E_{m_{other}}$ : other emissions, e.g., from leakage or vaporization

### 3.2.5 Energy and Emission Balance for a Process

To find the energy associated with producing the main product:

- **Energy:**

$$E_b = \frac{E(I)-E(P)}{a(fo)(I-lr(f_o))} \quad (3\text{-}7)$$

Where:

• $E(I)$ = total input energy

• $E(P)$ = energy allocated to co-products

• $a(fo)$ = amount of main output

• $lr(fo)$ = loss rate during production

- **Emissions:**

Where:

$$E_{m_b} = \frac{E_m(I)-E_m(P)+E_{m_{other}}}{a(f_o)(I-lr(f_o))} \quad (3\text{-}8)$$

• $E_m(I)$: total input emissions

• $E_m(P)$: emissions allocated to co-products

• $E_{m_{other}}$: emissions from losses or leaks

### 3.2.6 Allocation to Co-Products

If a process has co-products, energy and emissions can be distributed using allocation:

Energy Allocation:

$$E(f_p) = (1 - r_e).E(I) \tag{3-9}$$

$$E_m(f_p) = (1 - r_{em}).E_m(I) \tag{3-10}$$

Where:

• $r_e$ , $r_{em}$ = share of energy/emissions for the main product

• $E_m(f_p), E_m(I)$: = energy/emissions for the co-product

Allocation can be based on energy, mass, volume.

### 3.2.7 Displacement Method for Co-Products

If the co-product replaces a conventional product ($f_c$), the displaced energy and emissions are:

$$E(f_p) = a\ (f_c).E_{up} \tag{3-11}$$

$$E_m(f_p) = a\ (f_c).E_{mup}(f_c) \tag{3-12}$$

Where:

• $a\ (f_c)$: amount of conventional product replaced

• $E_{up}(f_c), E_{mup}(f_c)$ : upstream energy and emissions of the displaced product respectively

### 3.2.8 Transportation Mode

The transportation model in this study is built by combining various transportation methods. These methods, or modes, serve as the fundamental components for all transportation-related processes. Each mode is characterized by three key parameters:

1. Energy intensity [J/(kg·m)]
2. Type of fuel used to power the transportation engine
3. Emission factors associated with each type of fuel

Each fuel must be assigned a percentage share that reflects its usage. For instance, in GREET's Pipeline mode, the model uses the following fuel mix:

- Diesel: 20%
- Residual Oil: 50%
- Natural Gas: 24%
- Electricity: 6%

This means that pipelines operate with diesel-powered compressors 20% of the time, residual oil 50% of the time, and so on. "Residual feedstock" in sustainable fuel production refers to non-food waste materials used as input, such as forestry residues or municipal solid waste. As a result, various engine technologies correspond to each fuel type, and each requires its own emission factor within the model.

For transporting resources over a distance:

$$e(f) = d.ei(ft,f).s.s(f,t).lr(ft).b \quad (3\text{-}13)$$

Where:

- $d$ = distance
- $ei(ft,f)$ = energy intensity for transporting fuel f
- $s$ = share of transport mode
- $s(f,t)$ = technology share
- $lr(ft)$ = loss rate for transported fuel
- $b$ = adjustment based on units (e.g., time, distance)

#### 3.2.8.1 Pipeline Transportation of Hydrogen for Aviation Fuel

Hydrogen ($H_2$) is a key component in several SAFs (SAF) production pathways and can also serve directly as a future aviation fuel. GREET models the pipeline transportation of hydrogen as part of a full Well-to-Wake or Fuel Supply Chain assessment.

- **Energy Use for Pipeline Transport of Hydrogen**

The energy needed to transport hydrogen via pipeline is calculated using the general GREET equation:

$$e(f) = d \times ei(ft,t) \times s \times s(f,t) \times lr(ft) \times b \quad (3\text{-}18)$$

Where:

- $d$: distance transported by pipeline [m]
- $ei(ft,f)$: energy intensity for transporting hydrogen f [J/(g·m)]
- $s$: share of this mode (typically near 100% for hydrogen if pipeline is the main method)
- $s(f,t)$: share of fuel f used with technology t (e.g., electricity powering compressors)
- $lr(ft)$: hydrogen loss rate during transport
- $b$: correction factor based on units (usually 1, or distance/time for time-based models)

In GREET, pipeline transport of gaseous hydrogen assumes use of electricity or natural gas-powered compressors. Liquid hydrogen may have additional energy needs for refrigeration and insulation.

- **Emissions from Pipeline Hydrogen Transport**

Emissions are calculated by combining upstream, direct, and fugitive emissions:

$$E_m(f) = a(f).E_{mup}(f) + a(f).\sum_{t\in T} s(f,t).E_f(f,t) + E_{m_{leak}} \tag{3-19}$$

Where:

- $E_{mup}(f)$: upstream emissions from producing fuel f
- $E_f(f,t)$: emission factor for each fuel and technology
- $E_{m_{leak}}$: leakage or boil-off emissions, especially for gaseous $H_2$ pipelines

### 3.2.9 Pump-to-Wake (PTWa) Emissions for Aircraft

The Pump-to-Wake (PTWa) stage refers to emissions generated during the operational use of fuel in flight, primarily through combustion within aircraft engines or electrochemical conversion in the case of hydrogen fuel cell (HFC) systems. This phase is critical in determining real-time emissions performance, especially for evaluating sustainable aviation fuels (SAFs) and alternative propulsion technologies.

The PTWa emissions are calculated as:

$$e_{\text{PTWa}} = \frac{EF_f \cdot FC}{m \cdot d} \tag{3-14}$$

Where:

- $e_{PTWa}$: Emissions per kilogram of payload per kilometer of flight
  EFf: Emission factor of the fuel (e.g., g $CO_2$e/MJ or g $CO_2$e/kg of fuel)
- FC: Fuel consumption rate (e.g., MJ/km or kg/km)
- m: Payload mass (e.g., passengers and cargo, in kg)
- d: Flight distance (km)

This formulation enables a fair comparison across different aircraft types and fuel pathways by normalizing emissions per unit payload and distance traveled.

#### 3.2.9.1 For Hydrogen Fuel Cell (HFC) aircraft:

In systems where propulsion is provided by **electrochemical conversion** rather than combustion, such as HFC aircraft, emissions from fuel use are nearly zero at the point of use. However, upstream emissions from hydrogen production must be considered:

$$e_{\mathrm{PTWa}}^{\mathrm{HFC}} = \frac{EF_{\mathrm{elec}} \cdot EC}{m \cdot d} \qquad (3\text{-}15)$$

**Where:**

- ECECEC: Energy consumption of the aircraft in MJ/km
- EFelec: Emission factor of electricity used to generate hydrogen (g $CO_2e$/MJ)
- Other variables remain as defined above

This framework provides a consistent methodology to compare PTWa emissions of conventional jet fuel, SAF, and hydrogen-based technologies, supporting life cycle assessments (LCA) aligned with GREET modeling.

### 3.2.10 Conclusion Modeling LCA in Aviation

This section introduced the mathematical modeling framework used to evaluate energy consumption and emissions for different fuel pathways in aviation using Life Cycle Assessment (LCA). The GREET model from Argonne National Laboratory provides a detailed and structured method for analyzing each stage of the fuel life cycle—from raw material extraction to final use in aircraft engines.

The study uses specific equations to calculate energy inputs and emissions for each stage, including feedstock production, fuel processing, transportation, and combustion. Emissions are reported in terms of $CO_2$-equivalent ($CO_2e$), which includes contributions from carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$), accounting for their global warming impacts.

Importantly, the model also considers how to allocate emissions and energy when multiple co-products are created, using methods like mass-based allocation, energy-based allocation, and displacement. For hydrogen, the model evaluates pipeline transportation energy and emissions, showing how fuel type, technology, and transport distance affect the final environmental footprint.

Overall, this modeling framework enables a consistent and quantitative comparison across various fuel types—conventional, bio-based, and hydrogen—helping to identify the most sustainable options for reducing emissions in aviation.

Hydrogen distribution is modeled using GREET's default parameters for pipeline transport. A transport distance of 100 kilometers is assumed, and the fuel mix powering compressors follows the GREET-defined default values, which include shares of diesel, residual oil, natural gas, and electricity. These values represent typical operating conditions for pipeline infrastructure in hydrogen delivery scenarios.

Finally, for all SAF pathways where co-products are generated such as gasoline blendstock and diesel in the ATJ pathway environmental burdens are allocated using the energy allocation method. This method, recommended by GREET and commonly used in LCA studies, assigns impacts proportionally based on the energy content of each product, ensuring a balanced and justifiable distribution of emissions and resource use across outputs.

## 3.3 Some other model

### 3.3.1 Modeling Biomass Decarbonization

There are two pathways for carbon capturing (i.e., decarbonization):

Based on (75), BiCRS can be considered in two groups

1- Dedicated Biogenic Carbon Sequestration Pathway: Biomass can directly sequester carbon through burial or conversion processes.

2- Bioenergy with Carbon Capture and Storage (BECCS) Pathway:

Biomass is used for energy production, and $CO_2$ is captured and stored underground.

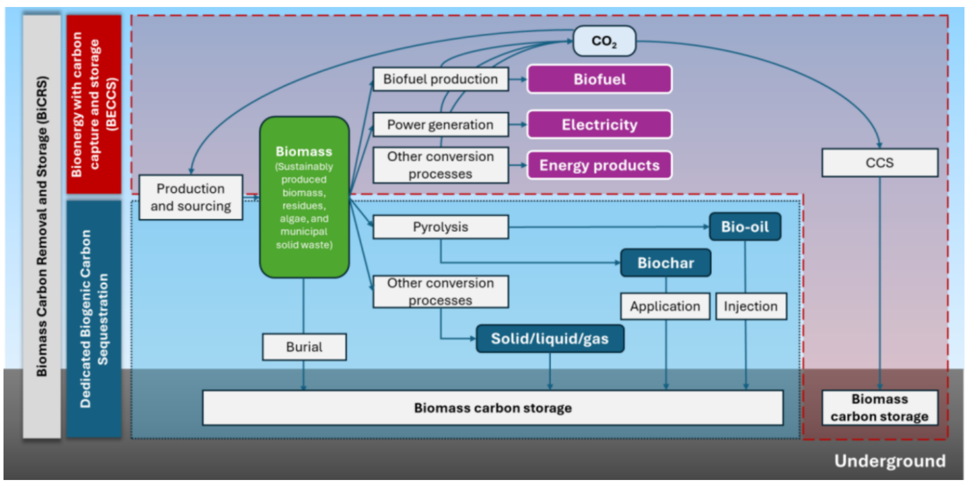



Figure 3-5- Biomass Carbon Removal and Storage (BiCRS)

Technologies Encompassing Dedicated Biogenic Carbon Storage and Bioenergy with Carbon Capture and Storage (BECCS) Technologies. The Technology Pathways Depicted Here Are Examples.

Biomass Carbon Removal and Storage (BiCRS) is a subset of Carbon Dioxide Removal (CDR) methodologies which are explained in this section.

BiCRS pathways:

1- Dedicated BiCRS technologies: This pathway focuses on sequestering carbon from biomass and store it securely. Biomass burial involves placing solid biomass, either processed or unprocessed, into underground or aboveground structures to prevent decomposition, with wood vaults offering large-scale sequestration potential through engineered enclosures in anaerobic conditions. Liquid injection converts biomass into bio-oil through fast pyrolysis and injects it into geological formations, where its high viscosity and polymerization properties help prevent leakage, ensuring stable carbon storage. Another approach, stabilized biogenic carbon, focuses on biochar produced through thermochemical processes such as pyrolysis which offers long-term carbon storage due to its high carbon content and resistance to biological and thermal degradation. Biochar can remain stable in soil for centuries, benefiting both carbon sequestration and soil health. These BiCRS technologies provide promising pathways for reducing atmospheric $CO_2$ and enhancing long-term carbon storage. (75)

2- Bioenergy with Carbon Capture and Storage (BECCS) is a technology that combines biomass-based energy production with long-term carbon sequestration. It has been widely discussed as a Carbon Dioxide Removal (CDR) strategy, with a global potential estimated at 10 gigatons of $CO_2$ per year. Unlike other CDR technologies that require energy input, BECCS generates energy while storing carbon. To qualify as BECCS, a system must provide both energy and carbon storage for at least 100 years. As of 2024, the global BECCS capacity is around 2 million metric tons of $CO_2$ per year, with future projects expected to increase this to nearly 50 million metric tons annually. Most operational projects focus on bioethanol production, capturing high-purity $CO_2$ from fermentation, such as Archer Daniels Midland's (ADM) facility in Illinois, which stores 1 million metric tons of $CO_2$ per year. LCA of BECCS is complex due to its dual output energy and carbon sequestration and its multi-stage supply chain across various regions. This thesis focuses on this pathway which is implemented in GREET. The rest of this section explains this pathway in detail.

Specific fuel pathways such as Alcohol-to-Jet from cellulosic biomass, BECCS (Bioenergy with Carbon Capture and Storage), and electrofuels (e.g., hydrogen via electrolysis) are modeled using default GREET parameters, modified where needed with literature-based data.(5)

#### 3.3.1.1 LCA for Alcohol-To-Jet Ethanol Using Biomass Carbon Removal and Storage (BiCRS)

This section presents the Life Cycle Assessment (LCA) of the Alcohol-To-Jet (ATJ) ethanol pathway, specifically using cellulosic biomass sources under the Biomass Carbon Removal and Storage (BiCRS) framework. As shown in Figure 3-6, three primary biomass inputs are analyzed: corn stover (with a resource energy use of 2735 kJ), forest residues (with a negative energy contribution of -3.0747 kJ, suggesting a potential net energy credit), and corn (contributing 344.2505 kJ). These feedstocks are converted into ATJ biofuel, and the resulting GHG emissions are calculated using the GREET model.

The emissions analysis reveals that the ATJ-ethanol pathway generates 14.1054 grams of $CO_2$, along with 27.3244 mg of methane ($CH_4$) a gas with a high global warming potential. Additional emissions include 39.2691 mg of nitrogen oxides ($NO_x$), which affect air quality, and 15.6444 mg of volatile organic compounds (VOCs), contributing to air pollution. When quantified using standard global warming potential (GWP) metrics, the total GHG emissions for this pathway amount to 14.4125 g $CO_2$-eq (100-year horizon) and 15.8525 g $CO_2$-eq (20-year horizon).

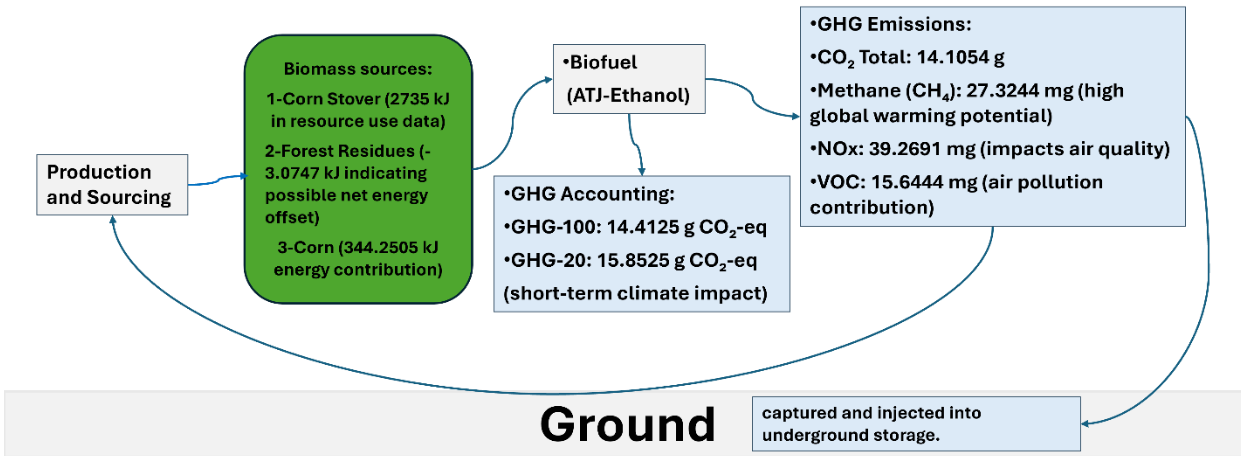



Figure 3-6- BiCRS for Alcohol-To-Jet-Ethanol considering BECCS pathway

This system boundary also assumes carbon capture and storage (CCS) at the end of the fuel's life cycle, where emissions are captured and injected into underground storage, further enhancing the pathway's climate benefits. The integration of biogenic feedstocks and carbon removal strategies highlights the potential of ATJ-ethanol as a low-emission fuel alternative within the broader SAF portfolio.

## 3.4 Data Collection and Assumptions

This study uses a process-based LCA framework to evaluate the environmental impacts of SAFs (SAF) pathways. The primary data source for modeling is the GREET model developed by Argonne National Laboratory. The GREET model provides detailed life cycle inventory (LCI) data on energy use, greenhouse gas emissions, and air pollutants across the full fuel life cycle from resource extraction to end-use combustion.

### 3.4.1 Assumptions for SAF Modeling

In modeling SAFs pathways within this study, several assumptions were made to ensure consistency and alignment with the GREET framework. The Alcohol-to-Jet (ATJ) fuel pathway is modeled based on the use of cellulosic biomass as the primary feedstock. Specifically, non-food lignocellulosic sources such as corn stover, forest residues, and switchgrass are considered, owing to their renewable nature and availability within the U.S. biomass supply chain.

For pathways incorporating Bioenergy with Carbon Capture and Storage (BECCS), the carbon dioxide ($CO_2$) captured during the fermentation of ethanol is assumed to have a purity level of 99%. This high-purity $CO_2$ is considered suitable for long-term sequestration and is modeled as being stored in deep saline aquifers, following the standard assumptions adopted in GREET and relevant literature.

In the case of electrofuel production routes, such as the generation of e-kerosene or green ammonia, hydrogen is assumed to be produced via Proton Exchange Membrane (PEM) electrolysis. The electricity used to power this electrolysis process is assumed to be fully supplied by renewable sources, either solar photovoltaic or wind power reflecting current trends in clean hydrogen production.

# Chapter 4: Pathways for Producing Aviation Fuels

In this chapter we overview different pathways for producing Aviation Fuels. In the next chapter we compare all these pathways and analyze them. The aviation fuels are grouped into six types:

1) Alcohol- and Sugar-Derived SAF Pathways (Ethanol-To-Jet and Sugar-To-Jet categories)
2) Results Lignocellulosic Biomass-Derived SAF Pathways
3) Canola Oil (which can be used for BD, RD, and SAF)
4) HEFA-Based SAFs from Soybean and Palm Oil Fuel Pathway
5) Hydrogen Production from NG SMR with $CO_2$ Sequestration (Shale Gas)
6) Conventional Jet Fuel from Crude Oil

## 4.1 Alcohol- and Sugar-Derived SAF Pathways

These pathways start with agricultural or lignocellulosic biomass feedstocks that are rich in sugars or starches. In the feedstock acquisition phase, raw materials such as corn, sugarcane, or cellulosic biomass (like crop residues or switchgrass) are harvested. The conversion and production processes vary depending on the specific route: alcohol-based pathways typically involve fermentation to ethanol followed by catalytic upgrading through dehydration, oligomerization, and hydrogenation to produce jet-range hydrocarbons. Sugar-to-jet routes use either biological conversion (via engineered microbes) or catalytic conversion to produce hydrocarbon fuels.

The five major sub-pathways in this group include:

1. Alcohol-To-Jet-Ethanol: Integrated from Cellulosic Biomass
2. Alcohol-To-Jet-Ethanol: Integrated from Corn
3. Alcohol-To-Jet-Ethanol: Standalone SAF production
4. Sugar-To-Jet: Biological Conversion
5. Sugar-To-Jet: Catalytic Conversion

During the transportation, distribution, and storage phase, the resulting jet fuel often blended with conventional jet fuel is handled using existing aviation infrastructure. In the use phase, these fuels offer combustion performance similar to fossil-based jet fuels, with lower net greenhouse gas emissions depending on the feedstock and energy source. Overall, this group of SAF pathways.

offers promising routes for decarbonizing aviation, especially when using cellulosic biomass and renewable energy throughout the life cycle.

## 4.2 Lignocellulosic Biomass-Derived SAF Pathways

This group focuses on using lignocellulosic materials non-food biomass like agricultural residues, forest residues, and dedicated energy crops as sustainable feedstocks. In the feedstock acquisition stage, materials such as corn stover, forest residues, miscanthus, poplar, switchgrass, and willow are harvested. These feed stocks are typically low in cost and high in availability, and they do not directly compete with food production, which enhances their sustainability profile.(76),(44)

In the conversion and production phase, the biomass undergoes pretreatment and enzymatic hydrolysis to release fermentable sugars, followed by fermentation to produce ethanol. The ethanol can then be upgraded via catalytic processes (similar to Alcohol-to-Jet) to generate SAFs (77). In some cases, like poplar, the feedstock can also be used for hydrocarbon production beyond ethanol (e.g., for Hydrocarbon from Oxygenated Gasoline - HOG) (76).

The transportation and storage stage may be more logistically complex due to the bulky nature of raw biomass, though ethanol and final jet fuels are more easily handled using existing infrastructure. During the use phase, these fuels burn cleanly in jet engines, providing a reduction in lifecycle greenhouse gas emissions particularly when carbon-neutral or carbon-negative land practices are employed.(78)

The detailed sub-pathways under this group include:

1. Corn Stover for Ethanol Plant
2. Forest Residue Production for Ethanol Plant
3. Miscanthus Production for Ethanol Plant
4. Poplar Production for Both Ethanol and HOG
5. Switchgrass Production for Ethanol Plant
6. Willow Production for Ethanol Plant

Overall, these lignocellulosic-based SAF pathways represent a highly promising route for large-scale decarbonization of aviation, especially due to their compatibility with marginal lands and their ability to recycle carbon already in the biosphere.

## 4.3 Life Cycle Emissions and Energy Analysis of Canola Oil-Based SAF via HEFA

Canola oil, derived from oilseed crops cultivated primarily in Canada, Europe, and parts of the United States, serves as a versatile feedstock for multiple biofuel applications. The feedstock acquisition process involves agricultural inputs such as fertilizers, pesticides, irrigation, and diesel-powered machinery for planting and harvesting. These inputs contribute to GHG emissions and land use impacts (79),(80).

In the conversion and production stage, canola oil can follow different processing routes. Through transesterification, it is converted into biodiesel by reacting with alcohol (usually methanol) in the presence of a catalyst. Alternatively, canola oil can be hydrotreated via hydrodeoxygenation and hydrocracking processes to produce renewable diesel or SAF. These reactions remove oxygen atoms from the triglycerides, producing hydrocarbons structurally similar to those in conventional jet fuel, which makes them drop-in ready for aviation use (81), (82).

For the transportation, distribution, and storage phase, canola-based fuels benefit from compatibility with existing fuel infrastructure, although blending with conventional jet fuel is typically required to meet aviation specifications. During the use phase, SAF from canola oil provides significant reductions in particulate matter and life cycle GHG emissions when compared to fossil jet fuel. However, the overall sustainability is influenced by indirect land use change (ILUC), which may offset some environmental benefits if new croplands are created by converting natural ecosystems (83).

## 4.4 HEFA-Based SAFs from Soybean and Palm Oil Fuel Pathway

This section presents the modeled life cycle of SAFs (SAF) derived from soybean oil and Palm oil via the Hydroprocessed Esters and Fatty Acids (HEFA) pathway. The model, developed using the GREET 2022 framework (84), incorporates the full life cycle from feedstock production to end-use combustion. The pathway includes seven main stages: feedstock cultivation, oil refining, transportation, conversion to jet fuel, jet fuel transportation, storage, and final use.

Palm oil, a high-yield oil crop grown predominantly in tropical regions such as Southeast Asia, Africa, and Latin America, is obtained through the cultivation and harvesting of palm fruits. Although palm oil offers superior oil productivity compared to other feedstocks, its feedstock acquisition phase is controversial due to the significant environmental impacts linked to tropical deforestation, peatland drainage, and loss of biodiversity (85), (86).

In the conversion and production phase, palm oil is typically refined into biofuels through hydro processing technologies. This process, which includes hydrodeoxygenation and isomerization, produces hydrotreated esters and fatty acids (HEFA) a category of SAF that meets international aviation standards for drop-in fuels (16). While HEFA fuels provide clean combustion and excellent cold-flow properties, their upstream impacts must be carefully considered.

The transportation and storage phase may involve transcontinental shipment of crude or refined palm oil from plantations to bio-refineries, often located in North America or Europe, which increases transportation emissions (5). In the use phase, palm-based SAF provides similar engine performance and emissions profiles to conventional jet fuel. However, lifecycle GHG emissions are highly sensitive to agricultural practices and indirect land use change (ILUC), which can significantly offset the benefits of using a renewable fuel if forests are cleared to expand palm plantations (87),(88) .

## 4.5 Hydrogen production pathways as Aviation fuel

Hydrogen can be produced from natural gas through Steam Methane Reforming (SMR), a widely used but energy-intensive process. In this method, methane ($CH_4$) reacts with steam under high temperature and pressure to produce hydrogen ($H_2$) and carbon dioxide ($CO_2$). (38)To reduce environmental impacts, carbon capture and sequestration (CCS) technologies are integrated into the process, capturing $CO_2$ emissions for storage in geological formations such as depleted oil fields or saline aquifers. This approach significantly improves the sustainability profile of SMR-based hydrogen(89), (90).

In the conversion phase, the hydrogen produced can be used as a key input in Power-to-Liquid (PtL) processes, or directly as a fuel in hydrogen-powered aircraft, particularly through fuel cells. Hydrogen combustion and fuel cell use do not produce $CO_2$ emissions at the point of use, making hydrogen a promising solution for decarbonizing aviation, provided upstream emissions are minimized (91).

Hydrogen transportation and storage, however, present notable technical and economic challenges. Because of its low volumetric energy density, hydrogen often requires compression, liquefaction, or advanced storage materials, as well as specialized infrastructure such as pipelines or cryogenic tanks (92).

Globally, hydrogen production relies predominantly on fossil fuels. As of the end of 2021, natural gas accounted for approximately 47% of total hydrogen production, followed by coal (40). Natural gas itself is sourced through both conventional and unconventional (shale) extraction methods. Both forms yield methane, the primary feedstock for SMR. The choice between them is influenced by factors such as regional resource availability, extraction costs, and market economics. In the United States, where shale gas production has surged in recent decades, much of the hydrogen is presumed to be derived from shale gas. In contrast, countries with abundant conventional reserves are more reliant on those resources(93).

According to the GREET model documentation from Argonne National Laboratory, the average contribution of U.S. natural gas supply is approximately 74.6776% from shale gas and 25.3224% from conventional sources(5).

This reflects a strong trend toward shale gas dominance, as visualized in the graph below, which tracks U.S. shale gas (blue solid line) and conventional natural gas production (green dashed line) from 1949 to 2023. The graph clearly demonstrates the exponential growth of shale gas production in the last two decades, surpassing conventional sources.

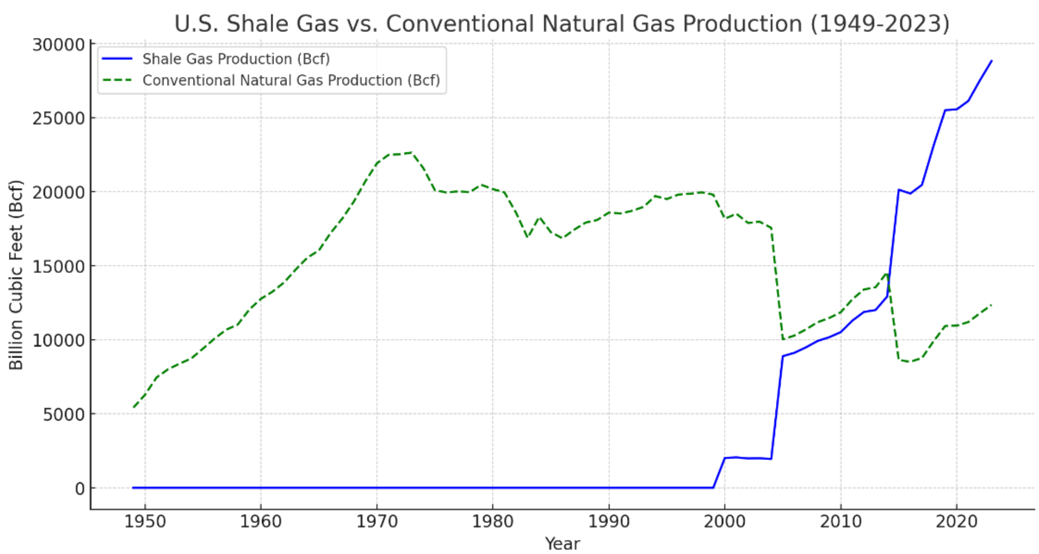



Figure 4-1-the historical production trends of shale gas (blue solid line) and conventional natural gas (green dashed line) from 1949 to 2023. (Greet software)

In addition to SMR with CCS, another important production route is SMR with Steam Export. In this configuration, while $CO_2$ is not captured, excess process steam is exported for use in other industrial applications, such as heating or electricity generation. This improves overall energy efficiency, although the lack of $CO_2$ capture results in higher lifecycle emissions compared to the sequestration pathway (94).

### 4.5.1 Comparison of different pathways of Hydrogen production:

#### 4.5.1.1 Hydrogen gas source

There are three sources of hydrogen that we can consider which are shown in the following figure. Pathway 1 includes using only conventional Gas.(66) Pathway 2 includes using only shale Gas. Pathway 3 uses the combination (average) of shale and conventional gas

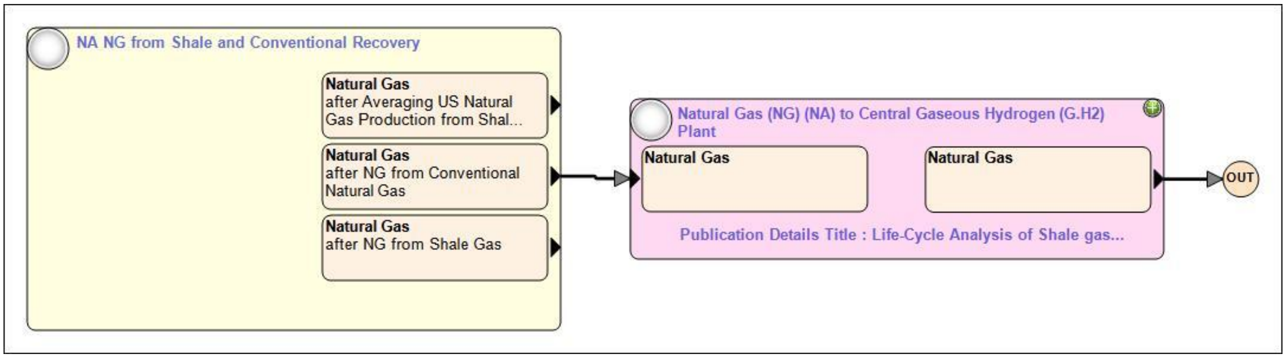



Figure 4-2-Pathway1: using only conventional Gas

This pathway (Figure 4.3) illustrates the production of natural gas (NG) from both shale and conventional sources in North America. The blended NG is then transported to a **centralized hydrogen production plant** where it is used to produce **gaseous hydrogen (G.H2)**. The model supports life cycle analysis by tracking emissions and energy use from extraction to hydrogen output.

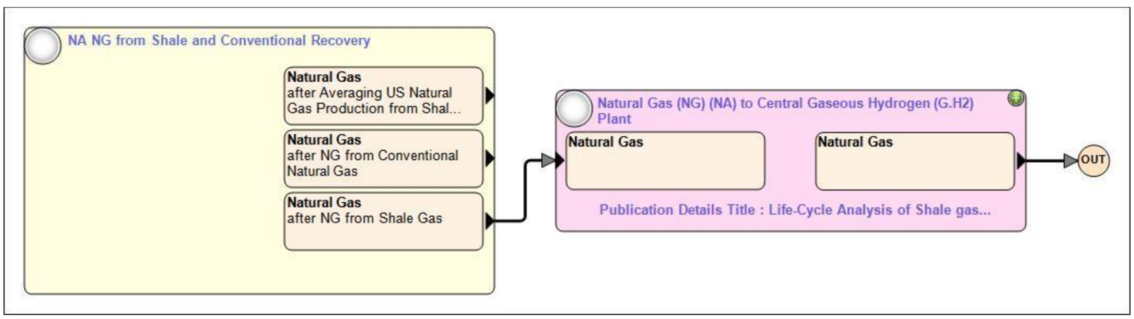



Figure 4-3-Pathway 3: using the combination (average) of shale and conventional gas

Figure 4.4 shows the life cycle pathway for producing hydrogen from natural gas (NG) in North America, using a mix of shale and conventional gas sources. The natural gas is processed at a central plant to produce gaseous hydrogen (G.$H_2$).

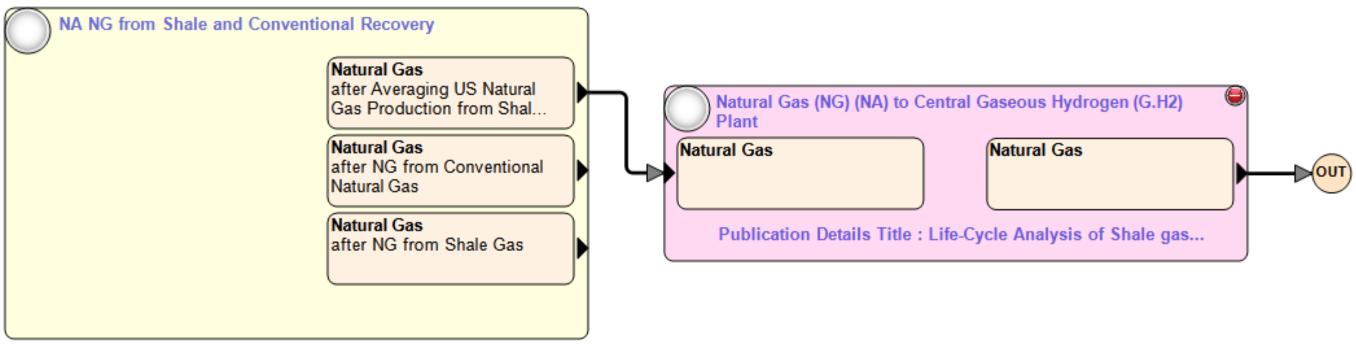



Figure 4-4.Pathway 2: using only shale Gas

flow Figure 4.5 diagram illustrates the use of North American natural gas from both shale and conventional sources. These sources are averaged and input into a central plant to produce gaseous hydrogen (G.$H_2$). The pathway enables life cycle assessment of hydrogen production, including upstream gas extraction and downstream hydrogen processing.

It does not consider pathway 1 as it is not common these days. We focus on pathways 2 and Figure 4-5 shows pathway 3 in detail

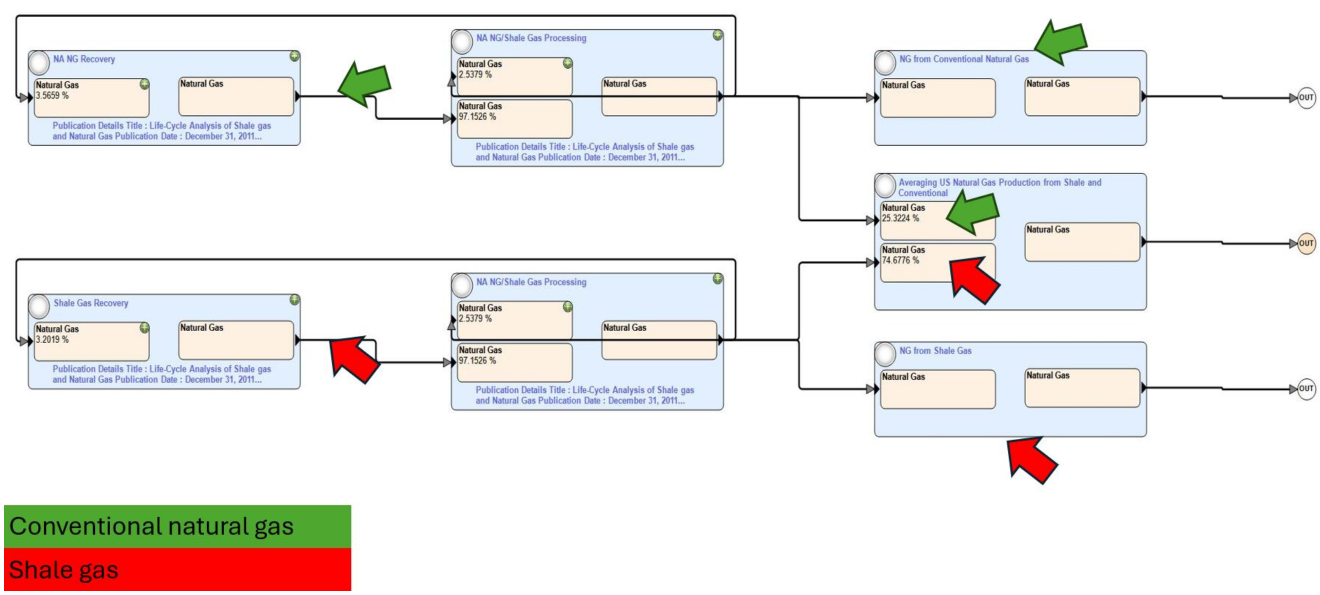



Figure 4-5- the combination of natural and shale gas pathway

Both sources undergo recovery and processing steps before being combined or used separately in different scenarios:

- Top Pathway (green): Represents the production and processing of conventional natural gas.
- Bottom Pathway (red): Represents shale gas extraction and processing.
- The middle section shows how both gas types can be averaged for U.S. production, with approximate shares (e.g., 53.22% conventional, 46.78% shale).

This enables detailed tracking of emissions, energy use, and blending impacts in hydrogen or fuel production analyses.

#### *4.5.1.2* Hydrogen Production

There are two methods: The first method focuses on capturing $CO_2$ to reduce emissions, while the second focuses on using extra steam for energy. Figure (4-7) shows these two methodologies. Depending on the source of hydrogen gas, we can consider two pathways for each of these methods, which gives us 4 different pathways for producing hydrogen.

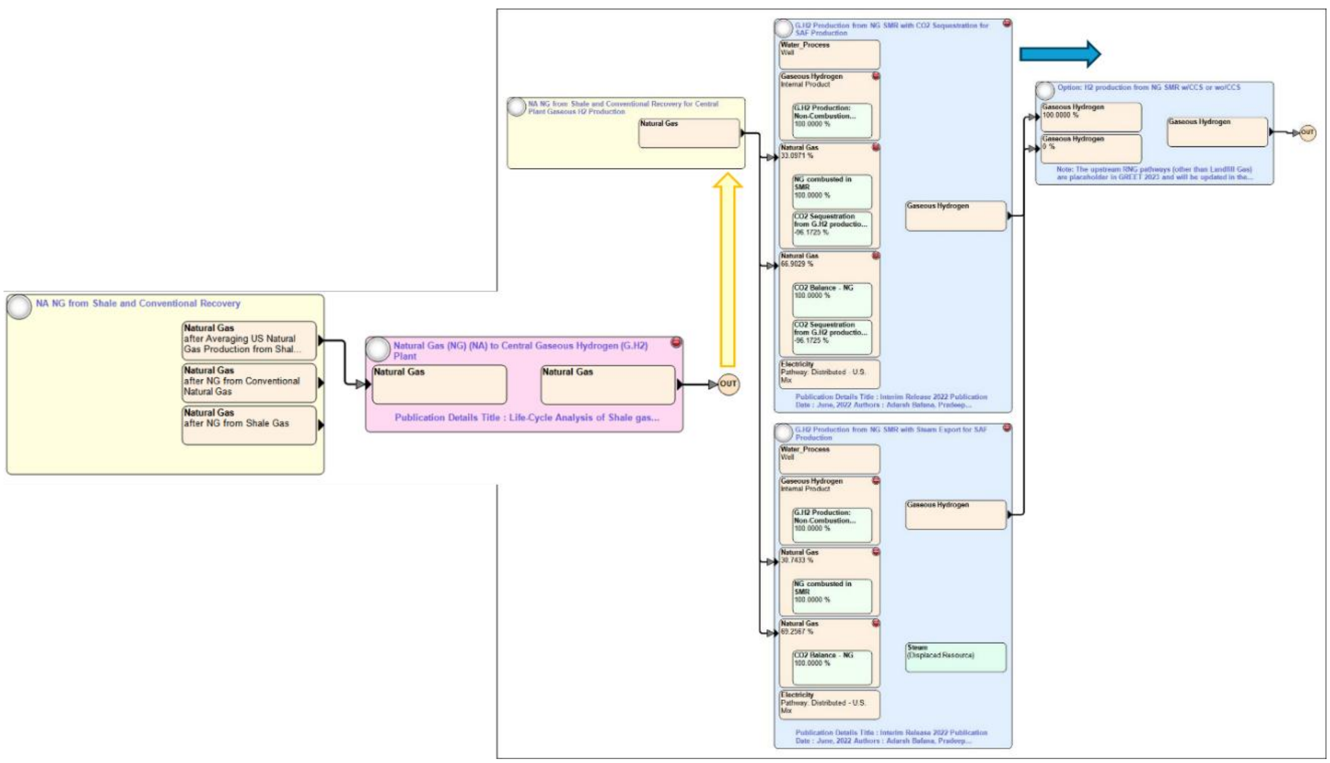



Figure 4-6- methodologies for hydrogen production

#### *4.5.1.3* Emissions Characteristics During Operation

The integration of hydrogen fuel cells into aviation presents a promising pathway toward zero-emission flight. In this section, the emissions associated with the fuel cell stage, particularly during their use in aircraft, are analyzed using data from the GREET model and relevant literature.

Fuel cells generate electricity through an electrochemical reaction between hydrogen and oxygen, producing water as the only direct byproduct. When applied in aviation, hydrogen fuel cells can replace traditional combustion engines, especially in small- to medium-range aircraft, offering a clean energy alternative without $CO_2$ or particulate emissions at the point of use.

The analysis focuses on the Well-to-Wake (WTWa) life cycle stage, with emphasis on the fuel cell operation (use phase) in aircraft. The functional unit used is grams of GHG emissions per kilogram-kilometer (g/kg·km), which standardizes emissions per unit of transported payload over distance.

## 4.6 Conventional Jet Fuel from Crude Oil

This study presents the environmental impacts of conventional jet fuel based on a Well-to-wake (WTU) analysis using GREET 2024. Emissions, resource consumption, and urban air pollutant data are reported per megajoule (MJ) of jet fuel energy content. The pathway illustrated in Figure 4.8 focuses on the Well-to-Pump (WTP) stage, excluding the combustion phase to enable fair comparisons of fuels prior to use.

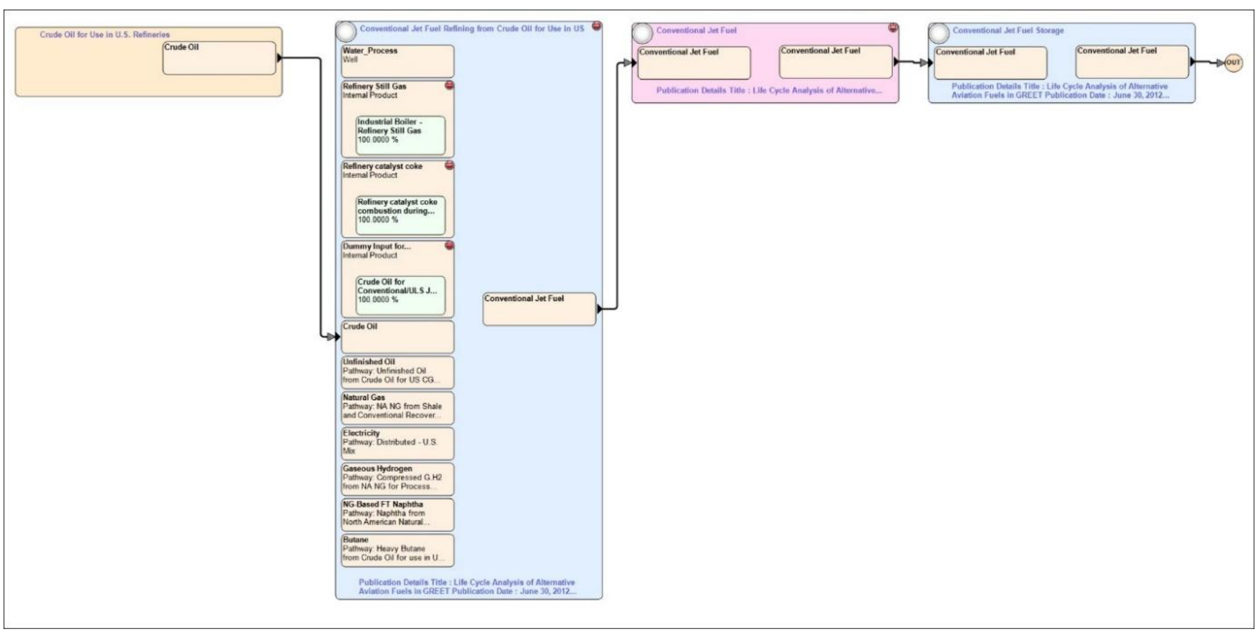



Figure 4-7 Conventional Jet Fuel from crude oil extraction to storage

It illustrates the sequential processes starting from crude oil extraction, refining (including sub-processes like steam still gas and petroleum coke co-production), and jet fuel production. The refined conventional jet fuel is then stored and prepared for end-use distribution. Each stage is interconnected and documented with detailed input flows such as natural gas, electricity, and hydrogen, showing a comprehensive well-to-tank lifecycle model for assessing the environmental impacts of conventional aviation fuel.

## 4.7 Conclusion: Pathways for Producing Aviation Fuels

In this chapter, we explored and categorized the major pathways for producing aviation fuels, focusing on both traditional fossil-based fuels and a range of emerging sustainable alternatives. These pathways reflect the current global effort to decarbonize the aviation sector and address the growing environmental concerns related to fuel production and use.

The first group of pathways, Alcohol- and Sugar-Derived SAFs, showed strong potential for reducing GHG emissions, especially when using renewable feedstocks like cellulosic biomass and sugarcane. The fermentation and catalytic upgrading of ethanol and sugar into jet-range hydrocarbons represent mature technologies that are compatible with current aviation infrastructure. These fuels can be blended with conventional jet fuel and offer cleaner combustion performance.

The second category, Lignocellulosic Biomass-Derived SAFs, is particularly important for sustainability because it uses non-food biomass such as forest residues, corn stover, and dedicated energy crops. These feedstocks are abundant, inexpensive, and do not compete with food supplies. Though their processing and transport can be complex, they offer one of the most promising options for large-scale carbon-neutral aviation, particularly when combined with good land management practices.

We also reviewed Canola Oil-Based SAFs, which can be transformed into biodiesel, renewable diesel, or SAF via the HEFA process. These fuels are structurally similar to fossil jet fuel and can be used as drop-in replacements. While canola oil offers significant emissions reductions, the environmental benefits depend heavily on farming practices and land-use changes, which can impact the overall sustainability.

Similarly, Soybean and Palm Oil-Based SAFs, produced through HEFA technology, demonstrate excellent fuel properties and are already approved for aviation use. However, they raise serious environmental concerns, especially in the case of palm oil. Deforestation and biodiversity loss due to palm plantations can significantly outweigh the benefits of emissions reduction, making sustainability highly dependent on how the feedstocks are sourced and managed.

Next, we examined Hydrogen as a fuel for aviation, produced mainly through Steam Methane Reforming (SMR) with or without carbon capture. Although hydrogen combustion and fuel cells offer zero emissions at the point of use, hydrogen production still depends heavily on fossil fuels, especially shale gas in the U.S. We analyzed different hydrogen pathways and their emissions characteristics. The integration of carbon capture technology or the export of steam can make these methods cleaner, but challenges related to storage, infrastructure, and upstream emissions remain critical.

Finally, we reviewed Conventional Jet Fuel derived from crude oil, which is still the dominant fuel type used in aviation today. Our analysis showed that although conventional fuel performs well in terms of energy content and availability, it is associated with high levels of GHG emissions and resource consumption throughout its life cycle. The reliance on fossil resources and the environmental impacts of refining and extraction processes highlights the urgency of transitioning to more sustainable alternatives.

In summary, each pathway presents a unique combination of advantages and challenges. While bio-based SAFs (especially those from waste or non-food biomass) offer strong climate benefits, their scalability and sustainability depend on careful feedstock sourcing and processing. Hydrogen presents a longer-term opportunity for deep decarbonization but still faces technical and infrastructure barriers. Conventional jet fuel, although efficient and well-established, is environmentally intensive and unsustainable in the long term.

In the next chapter, we will compare all these pathways using LCA results to quantify and analyze their environmental impacts. This comparison will help identify the most sustainable and practical pathways for future aviation fuel production.

# Chapter 5 -Comparison of different pathways for SAF

## 5.1 Comparative Assessment of Emissions and Energy Use in the Well-to-Pump

In this chapter, we compare the performance of all pathways we discussed in chapter 4. As explained in chapter 4, there are different types of aviation fuels. We can group them into six main categories:

1) Alcohol- and Sugar-Derived SAF Pathways (Ethanol-To-Jet and Sugar-To-Jet categories)
2) Results Lignocellulosic Biomass-Derived SAF Pathways
3) Canola Oil (which can be used for BD, RD, and SAF)
4) HEFA-Based SAFs from Soybean and Palm Oil Fuel Pathway
5) Hydrogen Production from NG SMR with $CO_2$ Sequestration (Shale Gas)
6) Conventional Jet Fuel from Crude Oil

We also describe the mathematical model used to analyze energy consumption and emissions across the entire life cycle of fuels and vehicle technologies. The model evaluates each stage such as extraction, processing, transportation, that is called fuel-cycle analysis (Well-to-Tank) and end-use (Tank-to-Wheel) by calculating energy inputs and emission outputs using an input-output framework. There are four phases, each stage has its own emission and energy usage:

- Feedstocks emission and energy used
- Conversion and Production (Fuel or Energy Production)
- Transportation, Distribution, and Storage
- Use Phase (Combustion or Final Energy Use)

### 5.1.1 Results of Alcohol- and Sugar-Derived SAF Pathways

This section presents quantitative emissions results for five Sustainable Aviation Fuel (SAF) production pathways derived from alcohol and sugar-based feedstocks, modeled using GREET 2024. The two main categories analyzed are Alcohol-to-Jet (ATJ) and Sugar-to-Jet (STJ) fuels. The summary of emissions results is presented in Table 5-1.

Based on the GREET model outputs, the best-performing pathway is ATJ from Cellulosic Biomass, which shows the lowest emissions across most categories, including $CO_2$, $CH_4$, $NO_x$, GHG-100, and GHG-20, and zero land use change emissions. This pathway also offers significant benefits in terms of air quality improvement and climate change mitigation.

In contrast, the worst-performing pathway is ATJ Standalone (Corn-based). It has the highest total $CO_2$ and $CH_4$ emissions, as well as elevated $NO_x$ emissions and significant land use change emissions (9.01 g $CO_2e$), making it the least sustainable option.

The Sugar-to-Jet SAFs show intermediate performance. The biological route performs moderately well in terms of GHG emissions and land use change, while the catalytic route shows higher CO and $NO_x$ emissions, likely due to the nature of the catalytic conversion process. However, both STJ pathways outperform corn-based ATJ in terms of land use impact and biogenic GHG offsets.

Table 5-1: Comparison of Emissions SAFs from Alcohol- and Sugar

| EMISSION TYPE | ATJ-CELLULOSIC | ATJ-CORN | ATJ-STANDALONE | STJ-BIOLOGICAL | STJ-CATALYTIC |
|---|---|---|---|---|---|
| **TOTAL $CO_2$ (G)** | 14.1054 | 52.5545 | 57.8383 | 21.2872 | 44.8303 |
| **$CO_2$ (G)** | 13.8234 | 43.9032 | 49.1966 | 21.0397 | 44.7417 |
| **$CO_2$_BIOGENIC (G)** | 0.282 | -0.35885 | -0.36839 | 0.2476 | 0.088579 |
| **$CO_2$_LANDUSECHANGE (G)** | - | 9.0102 | 9.0102 | - | - |
| **CH4 (MG)** | 27.3244 | 103.8 | 120.6 | 45.4021 | 120.3 |
| **CH4_BIOGENIC (G)** | - | -3.53E-05 | -2.08E-05 | - | - |
| **VOC (MG)** | 15.6444 | 9.4993 | 0.1206 | 20.4913 | 16.1978 |
| **CO (MG)** | 30.983 | 44.627 | 0.1206 | 186.6 | 96.6891 |
| **NOX (MG)** | 39.2691 | 93.5769 | -2.08E-05 | 0.6207 | 0.1011 |
| **PM10 (MG)** | 3.8317 | 5.4805 | 61.8942 | 5.0167 | 3.2487 |
| **PM2.5 (MG)** | 3.5588 | 4.5314 | 51.8066 | 4.5866 | 2.995 |
| **SOX (MG)** | 21.4891 | 24.635 | 0.1039 | 28.6987 | 18.7541 |
| **N2O (MG)** | -2.2148 | 36.1351 | 37.4436 | -7.1202 | -7.2297 |
| **BC (MG)** | 1.2315 | 0.7339 | 0.8131 | 1.6554 | 0.8922 |
| **POC (MG)** | 0.7605 | 1.2109 | 1.4103 | 0.9863 | 0.6609 |
| **GHG-100 (G)** | 14.4125 | 65.61 | 71.9281 | 21.0536 | 46.6444 |
| **GHG-20 (G)** | 15.8525 | 71.0758 | 78.2827 | 23.4462 | 52.9851 |

Based on the GREET model results, the most environmentally favorable option is ATJ from cellulosic biomass, which shows the lowest emissions across key categories—including $CO_2$, $CH_4$, $NO_x$, and both GHG-100 and GHG-20—and produces zero land use change emissions, making it ideal for climate and air quality benefits. In contrast, the ATJ corn-based (Standalone) pathway performs worst, with the highest total GHG, $CO_2$, $CH_4$ emissions, and a significant land use change impact of 9.01 g $CO_2e$. As an intermediate option, STJ Biological presents moderate emissions and low land use impact, making it a viable alternative when cellulosic feedstock is less accessible.

Figure 5-1.Energy Use Comparison SAFs from Alcohol- and Sugar

| RESOURCE TYPE | ATJ - CELLULOSIC | ATJ - CORN | ATJ - STANDALONE | STJ - BIOLOGICAL | STJ - CATALYTIC |
|---|---|---|---|---|---|
| **TOTAL ENERGY USE (KJ)** | 3258 | 2016 | 2119 | 4537 | 2851 |
| **CRUDE OIL (KJ)** | 78.2187 | 35.6015 | 45.005 | 104.0498 | 53.2955 |
| **NATURAL GAS (KJ)** | 152.154 | 588.0332 | 670.5273 | 251.7557 | 722.9506 |
| **COAL (KJ)** | -35.0876 | 53.4815 | 73.7058 | -35.1905 | -11.5183 |
| **CORN (KJ)** | 344.2505 | 1529 | 1416 | 352.4094 | 44.5079 |
| **FOREST RESIDUE (KJ)** | -3.0747 | 3908.5159 | 4013.27 | -2.699 | -965.696 |
| **SUGARCANE BAGASSE (MJ)** | - | 0.0559939 | 0.050362 | - | - |
| **PET COKE (J)** | 87.4827 | 39.8134 | 50.33 | 116.3746 | 59.609 |
| **HYDROELECTRIC POWER (KJ)** | -5.0539 | 6369.8052 | 6530.206 | -4.4165 | -1.5843 |
| **NUCLEAR ENERGY (KJ)** | -13.771 | 17.1502 | 17.5398 | -11.9436 | -4.2992 |
| **GEOTHERMAL POWER (J)** | -281.9738 | 351.1658 | 359.1421 | -244.556 | -88.029 |
| **SOLAR (KJ)** | -5.9461 | 7405.171 | 7573.37 | -5.157 | -1.8563 |
| **WIND POWER (KJ)** | -8.2398 | 10.2617 | 10.4948 | -7.1464 | -2.5724 |

For a balance of low energy use, high sustainability, and minimal fossil reliance, ATJ from Cellulosic Biomass is the best option. It aligns with decarbonization goals, uses waste biomass, and receives renewable energy credits in GREET.

Cellulosic Biomass & Corn:

- $CO_2$ emissions are lower for cellulosic biomass (14.11 g) compared to corn (52.55 g) and much lower than standalone SAF (57.83 g).
- Biogenic $CO_2$ emissions are positive in cellulosic but slightly negative in corn and standalone, suggesting carbon uptake assumptions in modeling.
- Land-use change $CO_2$ is 0 for cellulosic but 9.01 g for corn and standalone ethanol, indicating corn's higher land impact.

Sugar-Based Pathways:

- Biological conversion (21.29 g $CO_2$) emits less $CO_2$ than catalytic conversion (44.83 g).
- Both sugar pathways avoid land-use $CO_2$, likely because sugar inputs are modeled without significant land transformation.

Corn Stover:

- It has the lowest $CO_2$ total (3.37 g), showing it's a byproduct with minimal direct emissions and zero land-use change.

2. Conversion and Production (Fuel or Energy Production)

Focus on VOCs, CO, NOx, PM, and SOx:

- VOC emissions are highest for Sugar-Biological (20.49 mg) and Sugar-Catalytic (16.19 mg).
- CO emissions are very high in corn-based ethanol (44.63 g), much more than the rest.
- NOx emissions are significantly high in corn (93.58 kg) like a data anomaly (should be mg/g); otherwise, it skews the comparison.
- PM10 & PM2.5 are highest for standalone SAF (PM10 = 61.89 mg, PM2.5 = 51.81 mg), showing notable particulate matter emissions in standalone processes.
- SOx is highest in Sugar-Biological (28.70 mg), while standalone SAF shows minimal SOx (0.1 mg), suggesting a cleaner sulfur profile.

3. Transportation, Distribution, and Storage

While direct values aren't separated in the table, BC (Black Carbon) and POC (Primary Organic Carbon) can act as proxies:

- BC is highest for Sugar-Biological (1.66 mg) and Cellulosic (1.23 mg), possibly due to transportation of heavier or more complex biomass.
- POC is highest in Standalone SAF (1.41 mg), indicating more distribution or intermediate steps with emissions.

4. Use Phase (Combustion or Final Energy Use)

   Look at CH4, N2O, and GHG values:

- CH4 emissions are highest for Sugar-Biological (45.4 mg).
- N2O is significantly high in corn (36.14 mg) and standalone (37.44 mg), both potent greenhouse gases.
- GHG-100 & GHG-20 values are:
  - Lowest in Corn Stover (GHG-100 = 2.29 g), confirming it as the cleanest option for end-use.
  - Highest in Standalone SAF (GHG-100 = 71.93 g) and Corn Ethanol (65.61 g), indicating large lifecycle emissions.
  - Cellulosic and sugar-biological fall in the mid-range.

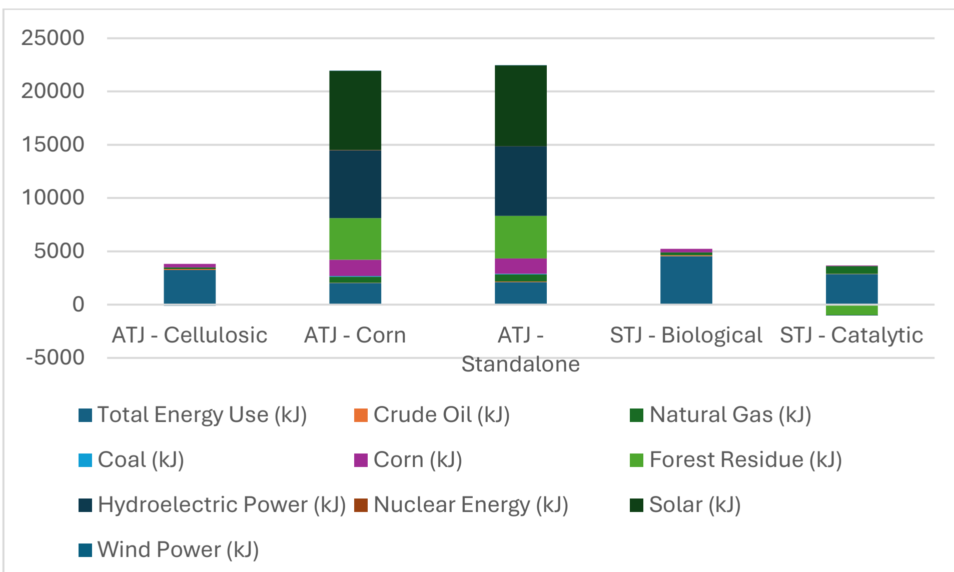



Figure 5-2: Comparing Energy Sources

The comparison of energy use among the five SAFs (SAF) pathways highlights significant differences in resource dependency and sustainability. The ATJ-Cellulosic pathway demonstrates the most balanced energy profile, with moderate total energy use (3258 kJ) and minimal reliance on fossil fuels such as crude oil, natural gas, and coal. It primarily utilizes forest residues and gains energy credits from renewable sources like wind, solar, and hydroelectric power, aligning well with decarbonization goals. In contrast, ATJ-Corn and ATJ-Standalone pathways exhibit the lowest total energy use (2016 and 2119 kJ, respectively) but depend heavily on fossil fuels and corn feedstocks, contributing to higher greenhouse gas emissions and land use impacts. The STJ-Biological pathway, while emitting less $CO_2$ than its catalytic counterpart, consumes the highest total energy (4537 kJ), suggesting lower energy efficiency. Overall, ATJ-Cellulosic emerges as the most sustainable option, offering a favorable balance between energy use and environmental impact.

#### 5.1.1 Final thoughts and takeaway

If the goal is to reduce $CO_2$ and GHG emissions while keeping air quality impacts low, Alcohol-To-Jet (ATJ) from Cellulosic Biomass is the best choice. STJ Catalytic Conversion is a secondary option, especially for reducing methane emissions, but it emits more $CO_2$.

The low input requirements, biogenic carbon credit, integrated conversion efficiency, and minimal land use impact collectively make the Alcohol-to-Jet from Cellulosic Biomass pathway the most sustainable option among the analyzed SAF production routes.

### 5.1.2 Results Lignocellulosic Biomass-Derived SAF Pathways

Table (5-4) presents a comprehensive comparison of GHG and pollutant emissions across six biomass-based ethanol production pathways: Corn Stover, Forest Residue, Miscanthus, Poplar, Switchgrass, and Willow. The data captures the well-to-wake life cycle stage, incorporating both upstream (e.g., feedstock cultivation, harvesting, and transportation) and downstream (e.g., processing and combustion) emissions.

Table 5-2: emissions across five biomass-based ethanol production pathways

| EMISSION TYPE | FOREST RESIDUE | MISCANTHUS | POPLAR | SWITCHGRASS | WILLOW |
|---|---|---|---|---|---|
| **TOTAL $CO_2$ (G)** | 1.854 | 2.1384 | 3.0254 | 2.6038 | 2.1899 |
| **$CO_2$ (G)** | 1.8552 | 2.1449 | 3.0294 | 2.6127 | 2.1929 |
| **$CO_2$_BIOGENIC (G)** | -0.00117 | -0.00656 | -0.00395 | -0.00892 | -0.00301 |
| **CH4 (MG)** | 2.2189 | 3.9311 | 3.8683 | 4.769 | 3.0773 |
| **VOC (MG)** | 0.5196 | 2.2166 | 1.6729 | 2.6655 | 1.2273 |
| **CO (MG)** | 4.0231 | 4.2315 | 7.1935 | 5.4321 | 5.5379 |
| **NOX (MG)** | 4.9709 | 9.8601 | 11.0958 | 11.9293 | 8.4954 |
| **PM10 (MG)** | 0.3263 | 0.6504 | 0.7771 | 0.8676 | 0.5937 |
| **PM2.5 (MG)** | 0.2505 | 0.5291 | 0.6796 | 0.7133 | 0.5092 |
| **SOX (MG)** | 0.1053 | 2.7293 | 1.3453 | 4.1813 | 1.2139 |
| **N2O (MG)** | 0.02096 | 8.0934 | 3.2787 | 8.7279 | 2.4833 |
| **BC (MG)** | 0.1697 | 0.1002 | 0.3696 | 0.1363 | 0.2654 |
| **POC (MG)** | 0.052078 | 0.099063 | 0.1377 | 0.1389 | 0.1026 |
| **GHG-100 (G)** | 1.9338 | 4.4786 | 4.0523 | 5.1455 | 2.9721 |
| **GHG-20 (G)** | 2.0507 | 4.6857 | 4.2562 | 5.3968 | 3.1343 |

$CO_2$ Total and Biogenic $CO_2$: Among all pathways, Corn Stover exhibits the highest total $CO_2$ emissions at 3.3743 g, followed by Poplar (3.0254 g) and Switchgrass (3 g). In contrast, Forest Residue has the lowest total $CO_2$ emissions (1.854 g). All pathways report negative biogenic $CO_2$ values, which represent the carbon uptake by the biomass during its growth phase, indicating carbon neutrality potential. Corn Stover and Switchgrass show relatively higher biogenic $CO_2$ values, supporting their role in offsetting fossil $CO_2$ emissions.

GHG-100 and GHG-20: GHG emissions over 100-year and 20-year time horizons reveal that Switchgrass results in the highest impact (5.1455 g $CO_2$-eq and 5.3968 g $CO_2$-eq, respectively), while Forest Residue has the lowest values (1.9338 g $CO_2$-eq and 2.0507 g $CO_2$-eq), confirming its relatively benign environmental profile.

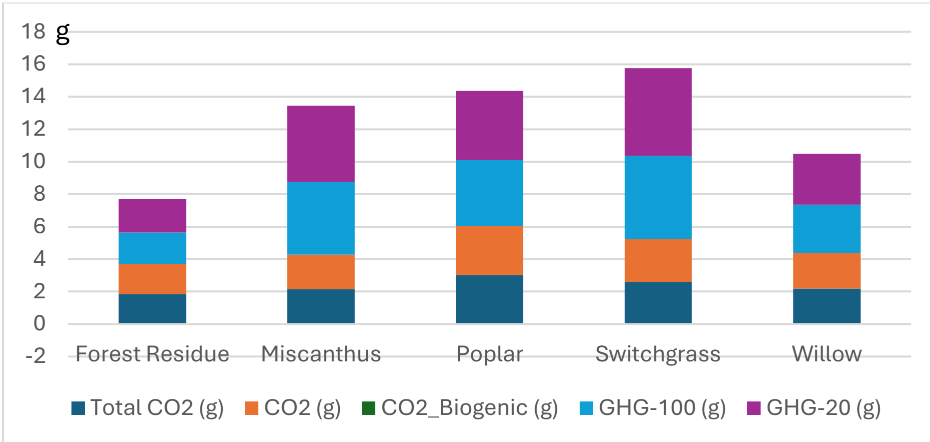



Figure 5-3:Greenhouse Gas Emissions

Methane and Other Pollutants same as $CH_4$ (Methane): Methane emissions vary significantly. While Corn Stover reports $CH_4$ in the form of a negative value (likely due to carbon sequestration factors), other pathways like Switchgrass (4.769 mg) and Miscanthus (3.9311 mg) show notable $CH_4$ emissions.

NOx, SOx, PM: Switchgrass again shows high emissions in NOx (11.9293 mg), SOx (4.1813 mg), and particulate matter (PM10: 0.8676 mg, PM2.5: 0.7133 mg), reflecting potentially higher environmental burden due to its combustion or pre-processing stages. Forest Residue maintains the lowest NOx and SOx levels (4.9709 mg and 0.1053 mg, respectively).

Volatile Organic Compounds and Particulate Carbon

VOC and CO: Corn Stover show the highest VOC (2.3758 mg) and CO (6.6986 mg) emissions, suggesting incomplete combustion or volatile by-products during processing. Forest Residue shows the least impact in this category.

BC and POC: Black Carbon (BC) and Primary Organic Carbon (POC) emissions contribute to short-lived climate pollutants. Miscanthus records the highest POC (99.0633 µg), while Corn Stover leads in BC emissions (0.373 mg).

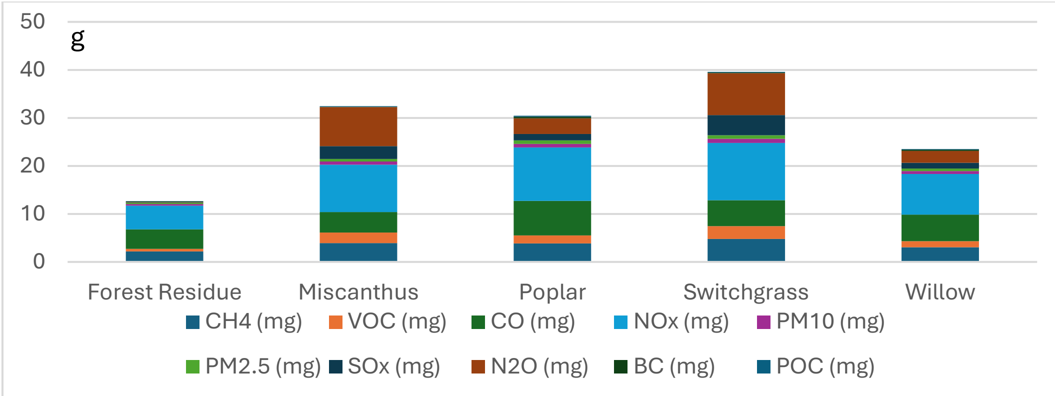



Figure 5-4:Methane and Other Pollutants

Among the five biofuel pathways analyzed, Forest Residue showed the lowest emissions across most categories, including $CO_2$, VOCs, methane ($CH_4$), and nitrous oxide ($N_2O$). This is mainly because forest residue is a waste product from forestry activities and does not require farming, fertilizers, or extra land use. In contrast, fuels like Switchgrass and Poplar had higher emissions, especially for greenhouse gases and air pollutants. These differences are caused by the agricultural inputs needed to grow these crops, such as fertilizers, water, and energy for fieldwork. Fertilizer use increases $N_2O$ emissions, which is a powerful greenhouse gas. Therefore, using waste materials like forest residue can be a more sustainable choice for biofuel production compared to dedicated energy crops.

Table 5-3: Energy Use Comparison of Lignocellulosic Biomass

| RESOURCE TYPE | FOREST RESIDUE | MISCANTHUS | POPLAR | SWITCHGRASS | WILLOW |
|---|---|---|---|---|---|
| TOTAL ENERGY USE (KJ) | 1026 | 1034 | 1039 | 1040 | 1031 |
| CRUDE OIL (KJ) | 17.9833 | 10.0063 | 22.1349 | 12.1676 | 17.964 |
| NATURAL GAS (KJ) | 2.5825 | 18.7658 | 10.2165 | 22.5234 | 7.9343 |
| COAL (KJ) | 0.1672 | 0.9722 | 0.5843 | 1.3223 | 0.4413 |
| FOREST RESIDUE (KJ) | 1000 | 0.0715 | 0.043 | 1000 | 0.0328 |
| PET COKE (J) | 20.1138 | 11.1915 | 24.7568 | 97.2111 | 20.0921 |
| HYDROELECTRIC POWER (KJ) | 0.0204 | 0.1166 | 0.0698 | 0.1587 | 0.0533 |
| NUCLEAR ENERGY (KJ) | 0.0564 | 0.3163 | 0.1905 | 0.4302 | 0.1454 |
| GEOTHERMAL POWER (J) | 1.1544 | 6.4775 | 3.9 | 8.8082 | 2.9765 |
| SOLAR (KJ) | 0.0243 | 0.1366 | 0.0822 | 0.1857 | 0.0628 |
| WIND POWER (KJ) | 0.0337 | 0.1893 | 0.1139 | 0.2574 | 0.0869 |

In addition to emissions, the type and amount of energy used in each fuel pathway significantly influences the environmental impact. Each pathway uses a mix of renewable and non-renewable resources, and their origin affects the total greenhouse gas emissions.

For example, Forest Residue pathway uses about 1026 kJ of total energy, mostly from renewable sources such as forest residue itself, hydroelectric power, wind, and solar energy. These sources have low or no direct emissions, making this pathway more environmentally friendly.

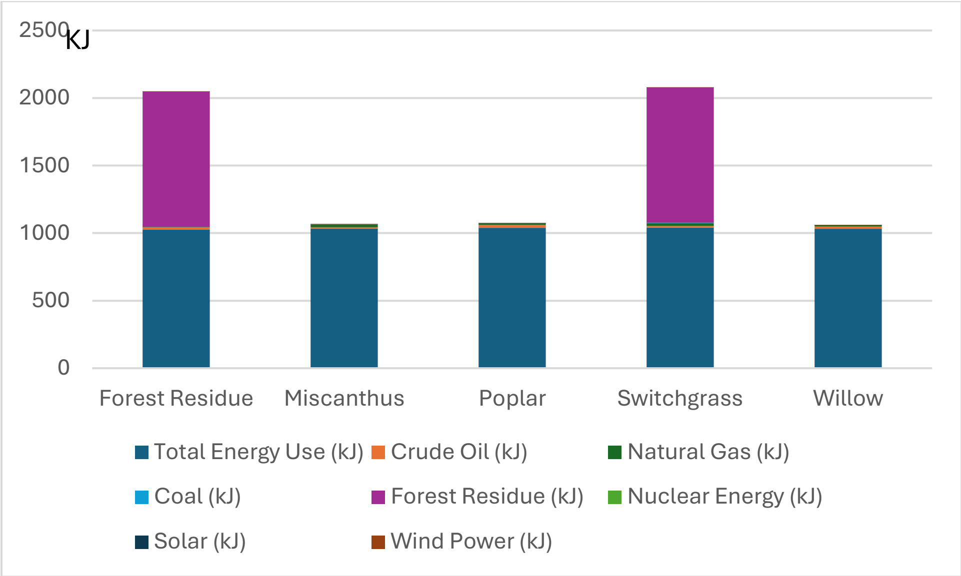



Figure 5-5:energy used in each fuel pathway

On the other hand, pathways like Switchgrass and Poplar also use non-renewable energy such as crude oil, natural gas, and coal. These fossil fuels contribute to higher $CO_2$, $CH_4$, and $NO_x$ emissions, especially during fertilizer production, field operations, and fuel refining.

Pet Coke, bitumen, and shale oil are also used in small amounts in some pathways. Although they provide energy, they are high in carbon content and result in significant emissions during combustion.

Furthermore, nuclear, solar, and geothermal power are present in small amounts. These sources are low-emission, but their overall share is small compared to fossil fuels in most high-emission pathways.

In conclusion, fuel pathways that rely more on renewable resources like forest residue, wind, and hydro tend to have lower emissions, while those that depend more on fossil fuels lead to higher greenhouse gas outputs. This shows the importance of the energy mix in determining the sustainability of a biofuel pathway.

### 5.1.3 Results of Life Cycle Emissions and Energy Analysis of Canola Oil-Based SAF via HEFA

This section evaluates the environmental and resource implications of using canola oil for biodiesel (BD), renewable diesel (RD), and SAFs (SAF) production. The analysis is structured across four major life cycle phases: (1) Feedstock Production, (2) Conversion and Production, (3) Transportation and Storage, and (4) Use Phase.

Table 5-4:emissions table for Canola oil (for BD, RD, and SAF)

| EMISSION TYPE | CANOLA SAF (HEFA) |
|---|---|
| $CO_2$ TOTAL (G) | 9.7214 |
| $CO_2$ (G) | 9.76 |
| $CO_2$_BIOGENIC (G) | -0.0423 |
| VOC (MG) | 42.7447 |
| CO (MG) | 18.5122 |
| NOX (MG) | 41.8137 |
| PM10 (MG) | 2.3046 |
| PM2.5 (MG) | 1.9706 |
| SOX (MG) | 12.0263 |
| CH4 (MG) | 22.1716 |
| N2O (MG) | 57.8648 |
| BC (MG) | 0.4051 |
| POC (MG) | 0.4482 |
| GHG-100 (G) | 26.3415 |
| GHG-20 (G) | 27.5099 |

The cultivation and harvesting of canola oil feedstock require considerable energy and material resources, with the total resource demand for this phase amounting to 807.82 kJ. Of this, canola itself accounts for 644.51 kJ, highlighting its major share in the overall energy footprint. Additional energy inputs include natural gas (124.1 kJ), crude oil (21.87 kJ), and petroleum coke (24.46 J). Electricity consumption is also distributed among multiple sources such as wind (1220.04 J), solar (880.42 J), nuclear (2039.03 J), and hydroelectric power (752.96 J). Notably, coal contributes 6273.27 J, making it one of the largest single contributors in this phase.

In terms of water use, the total consumption for feedstock production is 35.37 $cm^3$, which includes 14.33 $cm^3$ for mining, 14.90 $cm^3$ for processing, 3.49 $cm^3$ lost through reservoir evaporation, and

2.65 $cm^3$ used for cooling purposes. These figures underscore the intensive resource demands of feedstock preparation in the canola-based fuel production pathway.

This stage is energy-intensive and water-demanding, making optimization critical in feedstock choice and cultivation practices.

In the conversion and production phase, the environmental impacts of transforming canola oil into fuel are reflected in the well-to-wake emissions, which encompass all emissions generated prior to combustion. During this stage, significant amounts of greenhouse gases and pollutants are released, including 9.72 g of $CO_2$, 22.17 mg of $CH_4$, 41.81 mg of $NO_x$, and 12.03 mg of $SO_x$. Volatile organic compounds (42.74 mg VOC), particulate matter ($PM_{10}$: 2.30 mg, $PM_{2.5}$: 1.97 mg), and other climate-relevant substances such as $N_2O$ (57.86 mg), black carbon (0.4051 mg), and primary organic carbon (0.4482 mg) are also emitted. Although the process accounts for a minor biogenic $CO_2$ uptake (-0.00004227 kg) from plant growth, the 0% biogenic carbon mass ratio suggests this sequestration may not be credited in LCAs.

The climate impact of this phase, assessed through global warming potential metrics, results in 26.34 g $CO_2$-equivalent (GHG-100) and 27.51 g $CO_2$-equivalent (GHG-20).

Table 5-5:Energy Use Comparison of Canola-based SAFs

| Energy Source | Canola SAF (HEFA) | Energy Source | Canola SAF (HEFA) |
|---|---|---|---|
| Total Energy Use (kJ) | 807.8178 | GeoThermal Power (J) | 41.751 |
| Crude Oil (kJ) | 21.8681 | Solar (J) | 880.4201 |
| Natural Gas (kJ) | 124.1051 | Wind Power (J) | 1220.04 |
| Coal (kJ) | 6.273267 | Nuclear Energy (J) | 2039.034 |
| Forest Residue (J) | 460.7841 | Renewable, Other (J) | 44.1925 |
| Pet Coke (J) | 24.4573 | Hydroelectric Power (J) | 752.9584 |
| Feedstock (Canola/Forest Residue/Switchgrass) (kJ) | 644.5056 | | |

The table compares the energy input required for the production of Canola-based SAF (via the HEFA process), Forest Residue Ethanol, and Switchgrass Ethanol. Although Switchgrass Ethanol has the highest total energy requirement at 1040 kJ, it mainly relies on renewable feedstock energy, which helps reduce fossil fuel dependence. In contrast, Canola SAF has a slightly lower total energy input (807.82 kJ), but a significant portion comes from fossil-based energy sources, such as natural gas (124.1 kJ) and crude oil (21.9 kJ), contributing to its higher emissions.

Forest Residue Ethanol uses mostly renewable biomass (1000 J) and requires minimal fossil fuel input, making it the most sustainable in terms of both energy profile and emissions. The use of solar, wind, hydroelectric, and nuclear power varies among the fuels, with Canola SAF utilizing the widest range of energy types, though most are in small quantities.

This comparison highlights that energy source quality—not just total energy use—is crucial in determining the overall sustainability of a fuel. Fuels like forest residue ethanol, which rely more on low-emission, renewable inputs, are better positioned to meet environmental goals.

These figures highlight that while canola-based fuel is renewable, its production process still contributes substantially to atmospheric emissions, particularly of short-lived climate pollutants such as methane and nitrous oxide, which can intensify short-term climate forcing.

Table 5-6:Table 5 7-Summary of Environmental Impact

| Phase | Energy/Emissions Highlights |
|---|---|
| **Feedstock** | 807.82 kJ, 35.37 $cm^3$ water, high coal and canola input |
| **Conversion** | High $NO_x$, VOC, and GHGs; $CH_4$ and $N_2O$ major short-term contributors |
| **Transport** | Small but present petroleum and gas fuel dependence |
| **Use Phase** | Low $CO_2$ but notable PM and $NO_x$ |

### 5.1.4 Results of Life Cycle Comparison of HEFA-Based SAFs from Soybean and Palm Oil Fuel Pathway

This section presents a comparative LCA of SAFs derived from soybean oil and palm fresh fruit bunches (FFB) via the HEFA (Hydroprocessed Esters and Fatty Acids) pathway. The analysis evaluates emissions, energy consumption, and water use across the four primary life cycle phases: feedstock cultivation, conversion and production, transportation and storage, and the use phase. All results are normalized per 1 MJ of fuel produced.

Table 5-7:Life Cycle Comparison of HEFA-Based SAFs from Soybean and Palm Oil

| Metric (Unit) | Soy Oil-based SAF | Palm Oil-based SAF |
|---|---|---|
| **GHG-100 (g $CO_2$e)** | 35.5115 | 35.1144 |
| **GHG-20 (g $CO_2$e)** | 37.5926 | 42.7917 |
| **$CO_2$ Total (g)** | 27.9982 | 19.4393 |
| **$CO_2$ (Direct) (g)** | 16.5715 | 19.5586 |
| **$CO_2$ Biogenic (g)** | -0.0994 | -0.119 |

| | | |
|---|---|---|
| **$CO_2$ Land Use Change (g)** | 11.5261 | Not reported |
| **$CH_4$ (mg)** | 39.4894 | 145.7 |
| **$N_2O$ (mg)** | 22.8676 | 41.2496 |
| **VOC (mg)** | 20.7842 | 10.909 |
| **CO (mg)** | 18.5284 | 24.5943 |
| **$NO_x$ (mg)** | 24.1443 | 86.1945 |
| **$PM_{10}$ (mg)** | 1.7402 | 7.0892 |
| **$PM_{2.5}$ (mg)** | 1.4509 | 6.2384 |
| **$SO_x$ (mg)** | 8.3177 | 46.3366 |
| **Black Carbon – BC (mg)** | 0.3551 | 1.1687 |
| **Primary Organic Carbon – POC (mg)** | 0.4041 | 2.0139 |

Table 5-10 summarizes the emissions data from the GREET model. Although both pathways produce similar greenhouse gas emissions over 100 years (GHG-100), with soy oil at 35.51 g $CO_2e$ and palm oil at 35.11 g $CO_2e$, short-term climate impacts (GHG-20) are more significant for palm oil (42.79 g $CO_2e$ vs. 37.59 g $CO_2e$ for soy). This is largely due to higher methane ($CH_4$) and nitrous oxide ($N_2O$) emissions associated with palm oil.

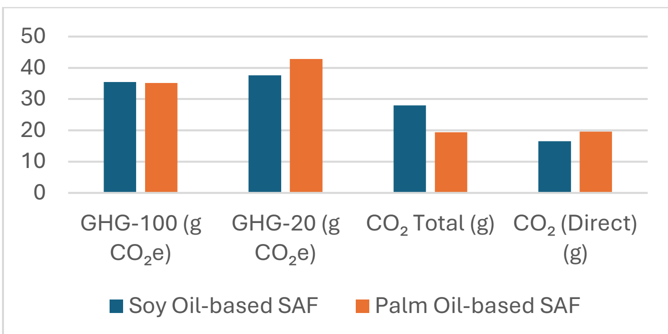



Figure 5-6: soy oil vs palm

Palm oil-based SAF shows lower total $CO_2$ emissions (19.44 g) than soy-based SAF (27.99 g), though soy exhibits a notable contribution from land use change (11.53 g), which is not reported for palm. Palm oil also emits higher quantities of $NO_x$ (86.19 mg vs. 24.14 mg), $SO_x$ (46.34 mg vs. 8.32 mg), and fine particulate matter ($PM_{10}$ and $PM_{2.5}$), indicating a greater potential impact on air quality.

The resource and energy analysis in Table 5-11 shows that palm oil-based SAF has a higher total energy input (1336.00 kJ) compared to soy oil-based SAF (782.56 kJ). This difference is primarily driven by the feedstock energy content palm FFB contributes 1023.00 kJ, while soybean oil accounts for 500.93 kJ.

Palm oil SAF also relies more heavily on fossil fuels such as crude oil (66.15 kJ vs. 27.90 kJ for soy) and bitumen, shale oil, and other petroleum-based inputs. However, both pathways include contributions from renewable electricity (wind, solar, hydro), with soy oil SAF showing slightly higher reliance on nuclear energy (4809.35 J vs. 3247.55 J for palm).

Table 5-8:Energy and Water Use with Units

| Resource Type (with Unit) | Soy Oil-based SAF | Palm Oil-based SAF |
|---|---|---|
| **Total Energy Use (kJ)** | 782.56 | 1336 |
| **Biomass Feedstock (kJ)** | 500.93 (Soybeans) | 1023.00 (Palm FFB) |
| **Natural Gas (kJ)** | 215.52 | 205.41 |
| **Crude Oil (kJ)** | 27.9 | 66.15 |
| **Coal Average (kJ)** | 18.39 | 14.71 |
| **Pet Coke (J)** | 31.2 | 73.99 |
| **Renewable, Other (J)** | 104.23 | 70.39 |
| **Hydroelectric Power (J)** | 1776.58 | 1374.21 |
| **Nuclear Energy (J)** | 4809.35 | 3247.55 |
| **Geothermal Power (J)** | 98.48 | 66.5 |
| **Solar (J)** | 2076.59 | 1402.24 |
| **Wind Power (J)** | 2877.64 | 1943.15 |
| **Bitumen (J)** | 2573.75 | 6103.87 |
| **Shale Oil (Bakken) (J)** | 2402.64 | 5698.07 |
| **Shale Oil (Eagle Ford) (J)** | 2169.18 | 5144.41 |
| **Other Power (Non-Hydro) (J)** | 0.74 | 145.41 |
| **Total Water Use ($cm^3$)** | 2357.66 | 58.34 |
| **Water – Process ($cm^3$)** | 29.93 | 24.31 |
| **Water – Mining ($cm^3$)** | 10.35 | 22.6 |
| **Water – Reservoir Evaporation ($cm^3$)** | 8.24 | 6.37 |
| **Water – Cooling ($cm^3$)** | 6.25 | 5.06 |
| **Water – Irrigation ($cm^3$)** | 2302.89 | 0.00 (rain-fed) |

In terms of water use, the differences are stark. Soy oil-based SAF consumes significantly more water (2357.66 $cm^3$ per MJ), with 2302.89 $cm^3$ coming from irrigation. In contrast, palm oil-based SAF requires only 58.34 $cm^3$, mostly from processing and mining. This highlights a key advantage of palm-based SAF in regions where water conservation is critical.

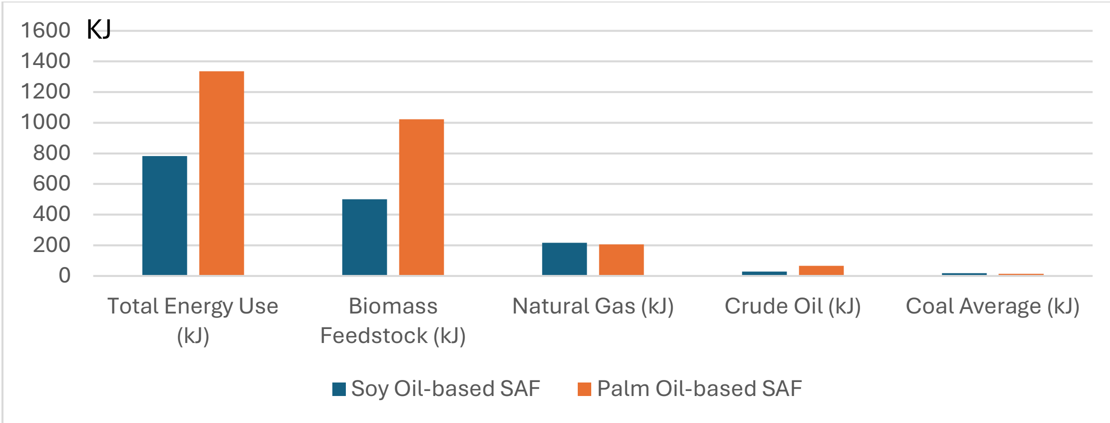



Figure 5-7: energy used

During the combustion/use phase, palm oil-based SAF emits 2.96 g of $CO_2$, slightly higher than soy-based SAF (2.80 g). Other pollutants such as $NO_x$ (4.10 mg), $SO_x$ (2.47 mg), $CH_4$ (2.04 mg), and $N_2O$ (54.09 µg) further contribute to climate and air quality concerns. The use-phase global warming potentials are 3.04 g $CO_2e$ (GHG-100) and 3.15 g $CO_2e$ (GHG-20) for palm oil SAF, compared to 2.88 g and 2.99 g for soy oil SAF, respectively.

While both feedstocks demonstrate renewable fuel potential, each presents environmental trade-offs. Palm oil-based SAF excels in water efficiency and biogenic $CO_2$ offset but has higher emissions of short-lived climate pollutants and total energy demand. Soy oil-based SAF offers lower air pollutant emissions, particularly $NO_x$ and particulate matter, but suffers from high irrigation needs and land use-related $CO_2$ emissions.

### 5.1.5 Results of hydrogen production pathways

There are two different pathways for hydrogen production as described in chapter 4 and (38): pathway 1: NG SMR with $CO_2$ Sequestration. Pathway 2: NG SMR with Steam Export.

Table 5-9:The comparison of different emissions resulting from Hydrogen production pathway1

| Emissions for pathway 1 | Averaging US Shale & Conventional Gas | NG from Conventional Method | NG from Shale Gas | |
|---|---|---|---|---|
| $CO_2$ Total | 17.937 | 18.242 | 17.833 | g |
| $CO_2$ | 18.126 | 18.431 | 18.022 | g |
| $CO_2$_Biogenic | -2E-04 | -2E-04 | -0.00019 | kg |
| VOC | 18.05 | 18.391 | 17.9344 | mg |
| CO | 53.318 | 55.018 | 52.7407 | mg |
| NOx | 67.554 | 69.507 | 66.8922 | mg |
| PM10 | 3.6608 | 3.6908 | 3.6507 | mg |
| PM2.5 | 3.3549 | 3.3838 | 3.3451 | mg |
| SOx | 18.886 | 18.938 | 18.8682 | mg |
| CH4 | 0.27 | 0.2714 | 0.2695 | g |
| N2O | 2.4302 | 2.4315 | 2.4297 | mg |
| BC | 0.391 | 0.3975 | 0.3887 | mg |
| POC | 1.0051 | 1.0169 | 1.0012 | mg |
| GHG-100 | 26.785 | 27.136 | 26.6661 | g |
| GHG-20 | 41.013 | 41.438 | 40.8685 | g |

Each of these pathways considers different sources of natural gas (NG). Note that to compare the two hydrogen production pathways we should first unify the functional unit for all values.

Table 5-10:The comparison of different emissions resulting from Hydrogen production pathway2

| Emission for Pathway2 | Averaging US Shale & Conventional Gas | NG from Conventional Method | NG from Shale Gas | unit |
|---|---|---|---|---|
| $CO_2$ Total | 71.3592 | 71.5864 | 71.2822 | g |
| $CO_2$ | 71.3815 | 71.6087 | 71.3045 | g |
| $CO_2$_Biogenic | -2.2E-05 | -2.2E-05 | -2.2E-05 | kg |
| VOC | 13.018 | 13.2715 | 12.932 | mg |
| CO | 33.8472 | 35.1131 | 33.418 | mg |
| NOx | 40.5339 | 41.9873 | 40.0411 | mg |
| PM10 | 1.9681 | 1.9904 | 1.9605 | mg |
| PM2.5 | 1.883 | 1.9045 | 1.8757 | mg |
| SOx | 12.1763 | 12.2151 | 12.1631 | mg |
| CH4 | 0.1986 | 0.1996 | 0.1982 | g |
| N2O | 1.6283 | 1.6293 | 1.628 | mg |
| BC | 0.1699 | 0.1748 | 0.1682 | mg |
| POC | 0.4069 | 0.4157 | 0.404 | mg |
| GHG-100 | 77.8156 | 78.077 | 77.727 | g |
| GHG-20 | 88.2816 | 88.598 | 88.1743 | g |

In this section, the life cycle impacts of compressed hydrogen ($H_2$) produced from natural gas (NG) are evaluated, with a focus on resource consumption, water demand, and urban emissions during the use phase. Three hydrogen production scenarios are assessed based on GREET model outputs:

1. Averaged U.S. Natural Gas Production (blended from shale and conventional sources),
2. Conventional Natural Gas,
3. Shale Gas Extraction.

All three pathways display very similar total energy consumption, ranging from 1727 to 1734 kJ per MJ of $H_2$ produced. The primary contributor in each case is natural gas, with minor variations in coal and crude oil contributions. Specifically:

- Natural gas usage ranges narrowly between 1673–1680 kJ.
- Crude oil inputs are notably highest in the conventional NG pathway (1387.76 J), compared to shale gas (1179.75 J).

- Nuclear, hydroelectric, wind, and solar energy are consistently utilized across all pathways, suggesting reliance on a mixed energy grid.

While fossil fuel energy dominates the total input, all pathways also integrate biomass and renewable electricity, indicating a modest shift toward cleaner energy carriers. However, the carbon intensity of fossil-derived hydrogen remains a concern when viewed from a full life cycle perspective.

Total water usage also shows small but meaningful differences:

Table 5-11:Water Use Analysis

| Water Metric (cm³ per MJ $H_2$) | Avg. US NG | Conventional NG | Shale NG |
|---|---|---|---|
| **Total Water Use** | 247.55 | 240.69 | 249.88 |
| **Process Water** | 212.12 | 212.16 | 212.11 |
| **Mining Water** | 7.96 | **1.06** | 10.3 |
| **Reservoir Evaporation + Cooling Combined** | 27.47 | 27.47 | 27.47 |

The conventional NG pathway uses significantly less mining water, which could be advantageous in arid regions or locations where water rights are restricted. However, all three cases show comparable process water use, indicating consistent technology demands during hydrogen extraction and compression.

Urban emissions represent direct environmental impacts during hydrogen end-use, especially important when $H_2$ is burned or used in high-population areas. Here's a comparison:

Table 5-12:Urban Emissions During the Use Phase

| Emission Type | Avg. US NG | Conventional NG | Shale NG |
|---|---|---|---|
| **$CO_2$ (g)** | 3.0425 | 3.0465 | 3.0411 |
| **$CH_4$ (mg)** | 15.62 | 15.63 | 15.61 |
| **$NO_x$ (mg)** | 7.32 | 7.34 | 7.31 |
| **$SO_x$ (mg)** | 1.16 | 1.16 | 1.16 |
| **GHG-100 (g $CO_2$e)** | 3.63 | 3.63 | 3.62 |

Differences across urban emissions are marginal, suggesting that the type of NG source has minimal impact on the point of use. The dominant contributors $NO_x$, $CH_4$, and $CO_2$ highlight that even clean-burning hydrogen systems can still produce pollutants depending on the combustion or usage method.

While the combustion of hydrogen for aviation or ground-based applications yields relatively low $CO_2$ and urban pollutants, there remains non-negligible emissions of $NO_x$, $CH_4$, and particulates. To further reduce these emissions—particularly in urban environments or for sensitive ecosystems shift toward fuel cell-based end-use systems is strongly recommended.

Fuel cells, particularly Proton Exchange Membrane Fuel Cells (PEMFCs), offer several environmental benefits:

- Zero $CO_2$ and $NO_x$ emissions at the point of use.
- Higher energy efficiency (up to 60%) compared to combustion (~30–35%).
- Quiet operation, beneficial for airport and urban mobility applications.
- Water is the only byproduct, aligning with clean air goals.

Incorporating hydrogen in SAF pathways is a critical transitional step; however, maximizing its sustainability requires integration with fuel cell technologies. This pairing minimizes environmental externalities, improves system efficiency, and aligns better with long-term climate neutrality goals.

Incorporating hydrogen in SAF pathways is a critical transitional step; however, maximizing its sustainability requires integration with fuel cell technologies. This pairing minimizes environmental externalities, improves system efficiency, and aligns better with long-term climate neutrality goals.

### 5.1.6 Results of emissions Conventional Jet Fuel from Crude Oil LCA pathway

The total carbon dioxide ($CO_2$) emissions for conventional jet fuel production and distribution amount to 8.1361 g/MJ, with the dominant contributor being fossil $CO_2$ emissions (8.1826 g/MJ). The biogenic $CO_2$ component is negligible (−0.0465 g/MJ), indicating minimal renewable carbon sources in the conventional pathway. Table 5.14 summarizes the major pollutants.

Table 5-13:Emissions from Conventional Jet Fuel (WTU, per MJ)

| Emission for CJF | Amount | Unit | Remarks |
|---|---|---|---|
| **$CO_2$ Total** | 8.1361 | g | Includes fossil and biogenic sources |
| **$CO_2$ (fossil)** | 8.1826 | g | Primary greenhouse gas |
| **$CO_2$ (biogenic)** | -0.0465 | g | Negligible contribution |
| **VOC** | 6.5038 | mg | Volatile organic compounds |
| **CO** | 9.6130 | mg | Incomplete combustion byproduct |
| **$NO_x$** | 14.5963 | mg | Contributes to smog and acid rain |
| **$PM_{10}$** | 0.9116 | mg | Particulates <10 µm |
| **$PM_{2.5}$** | 0.7731 | mg | Fine particulates; impacts respiratory health |

| | | | |
|---|---|---|---|
| **$SO_x$** | 3.5298 | mg | Sulfur oxides; linked to acid deposition |
| **$CH_4$ (Methane)** | 93.3312 | mg | Potent short-lived climate pollutant |
| **$N_2O$ (Nitrous Oxide)** | 0.1451 | mg | Long-lived greenhouse gas |
| **BC (Black Carbon)** | 0.1234 | mg | Short-lived climate force (soot) |
| **POC** | 0.2275 | mg | Primary organic carbon |

The total energy required to produce and deliver 1 MJ of jet fuel is approximately **1121 kJ**, indicating a highly energy-intensive process. A majority of this energy is derived from fossil sources, especially crude oil.

Table 5-14: Resource Inputs for Conventional Jet Fuel (WTU, per MJ)

| Resource | Value | Unit | Notes |
|---|---|---|---|
| Total Energy Input | 1121 | kJ | Total primary energy requirement |
| Crude Oil | 821.15 | kJ | ~73% of total energy input |
| Natural Gas | 76.01 | kJ | Utilized in refining and hydrogen production |
| Coal | 6.62 | kJ | Minor contribution |
| Pet Coke | 0.92 | kJ | Used in combustion processes |
| Bitumen + Shale Oils | 210.36 | kJ | Includes Bakken and Eagle Ford sources |
| Nuclear Energy | 2.24 | kJ | For grid electricity |
| Solar and Wind | ~2.31 | kJ | Minimal renewable contribution |
| Hydroelectric Power | 0.81 | kJ | Used in electricity and cooling |
| Forest Residue | 0.51 | kJ | Biogenic input, very limited |
| Water Total | 75 | $cm^3$ | Includes mining, process, and cooling stages |

### 5.1.7 Conclusion: Final Comparison of SAF Pathways

The comparative life cycle analysis across diverse SAFs (SAF) pathways reveals a clear hierarchy of environmental performance, driven by feedstock origin, conversion efficiency, energy source quality, and associated emissions. Among all evaluated options, Alcohol-to-Jet from Cellulosic Biomass (ATJ-Cellulosic) stands out as the most environmentally favorable pathway, exhibiting the lowest greenhouse gas emissions (GHG-100: 14.41 g/MJ), minimal land-use impact, and a well-balanced energy profile largely supported by renewable sources. In contrast, ATJ from Corn and Standalone ethanol-based pathways not only generate the highest GHG and pollutant emissions but also demonstrate high fossil energy dependency and land-use change penalties, undermining their sustainability claims. Lignocellulosic residues, such as Forest Residue and Miscanthus, further validate the environmental advantages of waste-based biomass with low emissions and energy use, reinforcing their viability as cleaner fuel alternatives. Canola oil and HEFA-based SAFs from palm and soy oils show moderate GHG performance but raise concerns due to high NOx, $CH_4$, and water/land resource demands particularly for soy-based fuels with extensive irrigation requirements. Hydrogen produced via natural gas steam methane reforming (SMR), though cleaner at the point of use, still suffers from high upstream emissions unless they are integrated with fuel cell technologies, which offer a compelling future for low-emission aviation. Lastly, conventional jet fuel, while still a baseline reference, exhibits significant fossil fuel reliance and short-lived climate pollutant emissions. Ultimately, the findings underscore that the most sustainable SAF strategies lie in maximizing waste feedstocks, reducing fossil energy inputs, and adopting cleaner conversion technologies paving the way for a decarbonized and resource-resilient aviation sector.

## 5.2 Emissions Analysis of Transportation Stage

In the context of LCA, the transportation stage within the GREET model refers to the distribution and delivery phase for all SAFs (SAF) pathways. This includes the emissions and resource consumption associated with transporting the produced fuel—whether it is Alcohol-to-Jet (ATJ), HEFA-based SAF, lignocellulosic ethanol, hydrogen, or conventional jet fuel—from the production or refining facility to blending terminals, fuel depots, or directly to airports for end use. This stage also includes auxiliary activities such as pumping, loading/unloading, and fuel handling, which typically rely on diesel-powered or electrically operated equipment. While often considered a smaller contributor within the full fuel-cycle analysis, the transportation phase can still significantly influence the overall environmental performance, especially when differences in infrastructure, fuel type, transport mode, and logistics distance are considered.

### 5.2.1 Emissions During Transportation for the best pathway

Table summarizes the pollutant emissions released during the transportation stage. The emissions are notably low, reflecting the use of efficient transport systems and modern fuel distribution practices.

Table 5-15:Transportation Emissions

| Emission | Amount | Unit | Environmental Significance |
|---|---|---|---|
| $CO_2$ | 0.3172 | g | Primary GHG |
| $CH_4$ | 12.9136 | µg | Potent short-lived GHG |
| $N_2O$ | 4.5389 | µg | Potent long-lived GHG |
| VOC | 1.0959 | mg | Contributes to ozone and smog |
| CO | 0.5225 | mg | Toxic gas from incomplete combustion |
| $NO_x$ | 1.1968 | mg | Causes ozone formation and acid rain |
| $PM_{10}$ | 33.0678 | µg | Coarse particulate matter |
| $PM_{2.5}$ | 22.4898 | µg | Fine particulate matter – respiratory hazard |
| $SO_x$ | 2.2119 | µg | Sulfur oxides – acidifying agents |
| BC | 2.4406 | µg | Black carbon – short-lived climate forcer |
| POC | 13.3301 | µg | Organic carbon from combustion residues |

The total greenhouse gas emissions for this stage, calculated using the 100-year global warming potential (GWP), were approximately 0.323 g $CO_2$-equivalent (GHG-100). Under the 20-year GWP metric (GHG-20), the value is 0.3237 g $CO_2$-equivalent. These values are extremely low compared to upstream and downstream stages, confirming that the transportation stage contributes minimally to the total carbon footprint of the ATJ fuel pathway.

### *5.2.2* Energy Use and Fuel Consumption in Transportation

The total energy input required for the transportation stage was reported as 1004 kJ, primarily related to internal handling, minor mechanical operations, and distribution logistics. Out of this total:

- - Conventional Diesel: 2133.75 J
- - Diesel for Non-Road Applications: 2159.69 J
- - SAFs (SAF output): 1000 kJ

The total diesel consumption (~4.3 kJ) is minimal when compared to the final energy content of the distributed SAFs (SAF), which is 1000 kJ. This translates to a near-perfect energy delivery efficiency of over 99.6%, further highlighting the sustainability and effectiveness of ATJ fuel's supply chain logistics.

From a life cycle perspective, the transportation phase of the ATJ ethanol pathway from cellulosic biomass has extremely low GHG emissions, negligible air pollutant discharge, minimal fossil fuel use, and high energy delivery efficiency. These characteristics indicate that transportation-related impacts do not pose a significant environmental burden in the overall LCA of this fuel pathway. This is particularly relevant when considering policy implications and sustainability metrics for renewable jet fuels. Efficient logistics and the use of clean transportation modes (e.g., rail or pipeline) further contribute to the favorable environmental profile of ATJ ethanol fuel.

### *5.2.3* Comparative Transportation Emissions Across SAF Pathways

Transportation-related emissions and energy use vary notably across different SAFs (SAF) pathways, as demonstrated by GREET model outputs and recent literature. Although the transportation stage is often considered a minor contributor to total life cycle emissions, it plays a critical role in shaping the environmental footprint of fuel pathways—especially when accounting for differences in logistics strategies, infrastructure needs, and fuel characteristics.

Among the evaluated pathways, the Alcohol-to-Jet (ATJ) fuel produced from cellulosic biomass exhibits one of the lowest transportation-related impacts. With a GHG-100 value of approximately 0.323 g $CO_2e$ per MJ, its emissions are minimal, largely due to an efficient distribution network, very low fossil fuel consumption for material handling (only ~4.3 kJ of diesel), and an energy delivery efficiency exceeding 99.6%. These figures reflect a highly optimized and low-impact logistics system for distributing cellulosic ATJ fuel.

In contrast, hydrogen transport systems demonstrate a broader range of environmental performance depending on the chosen delivery method. Pipeline transport of gaseous hydrogen stands out as the most emission-efficient option, with emissions around 0.5 kg $CO_2e$ per kg $H_2$ (~2.84 g $CO_2e$/MJ), low energy use for compression, and minimal urban air pollution—particularly when powered by renewable energy sources such as solar electricity. However, in areas lacking pipeline infrastructure, tube-trailer delivery of gaseous hydrogen becomes necessary. This method, while logistically flexible, results in higher emissions (~5 kg $CO_2e$/kg $H_2$), moderate energy use, and increased diesel consumption due to limited carrying capacity and the need for multiple trips. Alternatively, liquefied hydrogen ($LH_2$) trucking offers higher volumetric energy density and longer-range flexibility but involves significant emissions (additional ~11 g $CO_2e$/MJ) due to the energy-intensive liquefaction process. These distinctions highlight the importance of selecting hydrogen transport strategies that align with distance, scale, and infrastructure availability.

For HEFA-based SAFs—including those derived from canola, soybean, and palm oil—specific transportation-stage emissions are not always reported separately in the GREET model. Nonetheless, due to their high upstream fossil energy requirements, intensive agricultural practices, and the need for long-distance transport from farm regions to processing facilities, the transportation stage in these pathways is expected to carry moderately higher emissions than in waste- or residue-based systems like ATJ. The additional use of diesel-powered equipment in feedstock collection and delivery further contributes to these emissions.

In conclusion, cellulosic ATJ fuel and pipeline-based hydrogen transport offer the lowest transportation-related environmental impacts, driven by efficient energy use and reliance on clean power sources. In contrast, tube-trailer hydrogen transport and agriculturally sourced HEFA fuels tend to exhibit higher transportation burdens due to their reliance on fossil fuels and less efficient distribution systems. These results underscore the critical role of transport mode selection and infrastructure planning in achieving the full sustainability potential of alternative aviation fuels.

## 5.3 Emissions Analysis of the Combustion Phase

### *5.3.1* Fuel Consumption and Combustion Emissions in Single Aisle (SA) and Large Quad (LQ) Aircraft

This section evaluates and compares the emissions produced during the combustion (use) phase for two representative aircraft categories: the Single Aisle (SA) and Large Quad (LQ) configurations. These analyses were conducted using GREET model outputs, focusing on the Landing and Takeoff (LTO) cycle and overall well-to-wake emissions normalized per payload-distance (g/kg·km).

Analysis of the Landing and Take-Off (LTO) phase emissions indicates that Single Aisle (SA) aircraft exhibit lower absolute emissions of key pollutants, including $CO_2$, $CH_4$, $NO_x$, and VOCs. This outcome is primarily attributed to the aircraft's smaller engine capacity, lighter structural design, and shorter mission profiles. In contrast, Large Quad (LQ) aircraft produce higher total emissions per trip due to their larger engines, increased fuel consumption, and higher payload capacity. However, despite the greater absolute emissions, LQ aircraft demonstrate improved emissions efficiency when evaluated on a per-unit basis, such as per passenger-kilometer or per kilogram of payload, highlighting their suitability for long-haul operations where fuel efficiency per unit of transport work becomes more favorable.

Table 5-16: Aircraft Parameters

| **Parameter** | **Single Aisle** | **Large Quad** |
|---|---|---|
| **Average Payload (kg)** | 18,230.10 | 82,209.55 |
| **Average Trip Distance (km)** | 1,365.83 | 7,519.54 |
| **Fuel Consumption (As Operated, kg)** | 4,986.09 | 91,641.98 |
| **Fuel Consumption (LTO, kg)** | 564.68 | 2,484.18 |
| **Cruise Urban Share** | None of the Cruise emissions are counted as happening in an urban setting | |
| **LTO Urban Share** | 100% of LTO emissions are considered to occur in an **urban** area. | |

Despite higher total emissions, LQ aircraft are more fuel- and emission-efficient per unit of transport work (g/kg·km), emitting approximately 26% less $CO_2$ per kg·km than SA aircraft.These results reflect the economies of scale in larger aircraft, where emissions are distributed across greater payloads and longer distances.

To evaluate these pathways, this study uses the GREET 2024 model, which reports emissions from a life cycle perspective. Emissions are expressed in grams per kilogram of payload per kilometer (g/kg·km), accounting for real aircraft performance over flight distance. The GREET model divides emissions into two major stages(15):

- Well-to-Pump (WTP): Emissions from fuel production, processing, and distribution
- Pump-to-Wake (PTWa): Emissions from combustion or energy conversion in flight

Together, these stages form the Well-to-Wake (WTWa) boundary. This full-system view differs from other methods that only report emissions based on fuel properties, such as grams per megajoule (g/MJ). Instead, GREET integrates operational factors like aircraft load, fuel burn, and distance traveled—providing a more complete environmental assessment.

This analysis highlights the critical role of fleet optimization and route design in minimizing per-passenger environmental impact, emphasizing the need for efficient aircraft deployment strategies in aviation sustainability planning.

### *5.3.2* Comparative GHG Emissions of SAFs vs. Conventional Fuels

In addition to aircraft size and configuration, the type of fuel used plays a critical role in determining greenhouse gas (GHG) emissions during the Pump-to-Wake (PTWa) phase—the stage where fuel is burned inside the aircraft engine. This section compares PTWa emissions for several alternative aviation fuels, including Hydroprocessed Esters and Fatty Acids (HEFA) from soy, corn, and canola oils; Fischer-Tropsch (FT) fuels derived from North American natural gas; and Hydrogen Fuel Cell (HFC) systems, with those of conventional jet fuel (CJF).

The PTWa phase captures direct tailpipe emissions from fuel combustion in aircraft engines, including pollutants such as carbon dioxide ($CO_2$), methane ($CH_4$), nitrogen oxides ($NO_x$), sulfur oxides ($SO_x$), particulate matter ($PM_{10}$ and $PM_{2.5}$), and volatile organic compounds (VOCs).

Table 5-17:The comparison table of pollutant emissions (in g/kg*km for PTWa) Single Aisle

| Pollutant | Conventional Jet Fuel, | Corn-Stover | Forest Residue | SPK | HEFA (Soy Oil) | FT from NA NG | HFC (Hydrogen Fuel Cell) |
|---|---|---|---|---|---|---|---|
| VOC | 1.12E-04 | 1.12E-04 | 1.12E-04 | 0.000112 | 0.000112 | 0.000112 | 1.00E-05 |
| CO | 7.91E-04 | 7.91E-04 | 7.91E-04 | 0.000773 | 0.000773 | 0.000773 | 5.00E-05 |
| NOx | 3.10E-03 | 3.10E-03 | 3.10E-03 | 0.002852 | 0.002844 | 0.002844 | 0.0001 |
| | | | | | | | |
| PM2.5 | 3.72E-05 | 3.83E-05 | 3.83E-05 | 3.30E-05 | 2.94E-06 | 2.94E-06 | 1.00E-06 |
| SOx | 2.80E-04 | 4.40E-06 | 4.40E-06 | 0.000143 | 0 | 0 | 0 |
| $CH_4$ | 9.18E-04 | 1.15E-05 | 9.18E-06 | 9.18E-07 | 9.18E-07 | 9.18E-07 | 2.00E-06 |
| $N_2O$ | 1.80E-06 | 1.80E-06 | 1.80E-06 | 1.80E-06 | 1.80E-06 | 1.80E-06 | 1.50E-06 |
| BC | 1.17E-05 | 1.21E-05 | 1.21E-05 | 1.04E-05 | 9.29E-07 | 9.29E-07 | 2.00E-06 |
| POC | 1.12E-05 | 1.15E-05 | 1.15E-05 | 9.99E-06 | 8.84E-07 | 8.84E-07 | 1.00E-06 |
| Total $CO_2$ | 6.33E-01 | 1.59E-03 | 1.59E-03 | 0.6203 | 0.6074 | 0.6074 | 0.0051 |
| GHG ($CO_2e$) | 6.33E-01 | 2.10E-03 | 2.10E-03 | 0.6208 | 0.6079 | 0.6079 | 0.0053 |

Based on GREET 2024 model outputs for Single Aisle (SA) aircraft, the following key insights can be drawn. Note: All emission values reported below are normalized values (on a 0–1 scale), where 1 represents the worst-performing fuel (typically conventional jet fuel), and other values are proportionally scaled for comparison purposes. These are not the exact measured emissions:

- **Conventional Jet Fuel** produces the highest GHG emissions, with total $CO_2$ emissions of approximately 0.633 g/kg·km and GHG-100 emissions of 0.6334 g $CO_2e$/kg·km. It also exhibits the highest values for $SO_x$ (2.80E-04 g/kg·km), $NO_x$ (3.10E-03 g/kg·km), and $CH_4$ (9.18E-04 g/kg·km).
- **Bio-based SAFs** such as those from Corn Stover and Forest Residue show drastically reduced emissions across all pollutants. For instance, their GHG-100 emissions are only 0.0021 g $CO_2e$/kg·km, and their total $CO_2$ emissions are 0.00159 g/kg·km—demonstrating over 99% reduction in comparison to conventional fuel.
- **HEFA fuels** derived from soy oil (and similarly from canola and corn oil in parallel analyses) exhibit moderate reductions in PTWa emissions. While not as low as waste-residue-based SAFs, HEFA fuels still outperform fossil-derived options, particularly by eliminating $SO_x$ emissions and reducing PM and $CH_4$ outputs. The GHG-100 value for HEFA-Soy oil is 0.6079 g $CO_2e$/kg·km.

- **Fischer-Tropsch (FT) fuels** synthesized from North American natural gas show emissions nearly equivalent to HEFA pathways, with a GHG-100 value of 0.6079 g $CO_2e$/kg·km and reduced $SO_x$ and PM levels. However, they still carry fossil-derived upstream emissions.
- **Hydrogen Fuel Cell (HFC) systems** offer the most environmentally favorable performance in this analysis. They achieve near-zero PTWa emissions, with a total $CO_2$ of 0.0051 g/kg·km and GHG-100 emissions of only 0.0053 g $CO_2e$/kg·km. Furthermore, HFCs eliminate all combustion-related pollutants such as $SO_x$, $NO_x$, and PM, and emit only water vapor as a byproduct.

These comparisons highlight the significant potential of SAFs and HFCs to reduce combustion-phase emissions. The dramatic reduction in pollutants, particularly from waste-residue SAFs and hydrogen fuel cell technologies, reinforces their critical role in meeting aviation decarbonization targets.

Figure 5.7 illustrates the comparative Pump-to-Wake (PTWa) emissions for various aviation fuel pathways in Single Aisle (SA) aircraft, expressed in grams per kilogram-kilometer (g/kg·km). The pollutants analyzed include methane ($CH_4$), nitrogen oxides ($NO_x$), sulfur oxides ($SO_x$), and fine particulate matter ($PM_{2.5}$). Among all fuel types, conventional jet fuel exhibits the highest total emissions, particularly dominated by $SO_x$, followed by $NO_x$ and $CH_4$, emphasizing its significant environmental burden during the combustion phase. In contrast, alternative fuels derived from Fischer-Tropsch (FT) processes and Hydroprocessed Esters and Fatty Acids (HEFA) pathways demonstrate substantial emission reductions. Specifically, FT from biomass and HEFA from canola oil show the lowest levels of $SO_x$ and $PM_{2.5}$ emissions, indicating their potential for improving air quality and reducing climate-relevant emissions. While HEFA corn-based fuel shows relatively higher emissions among the HEFA options, especially in $NO_x$ and $PM_{2.5}$, HEFA canola presents a more balanced and environmentally favorable profile. These findings reinforce the environmental benefits of shifting from fossil-based jet fuel to SAFs and underscore the importance of selecting fuel pathways that minimize combustion-related pollutants in aviation applications.

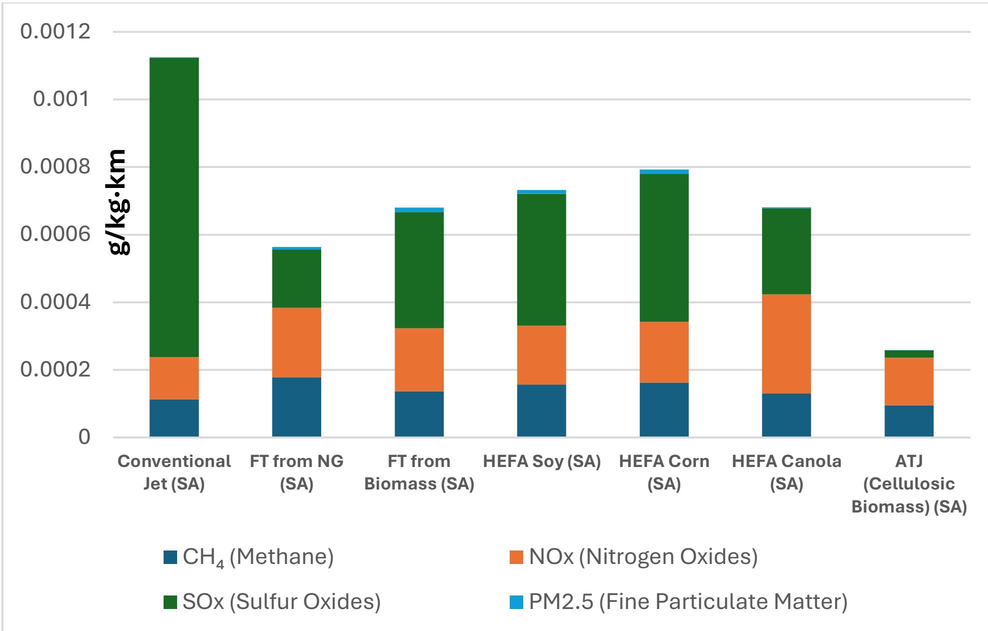



Figure 5-8: Pump-to-Wake pollutant emission for SA

Figure 5.8 presents the Pump-to-Wake (PTWa) pollutant emissions associated with various aviation fuel pathways for Large Quad (LQ) aircraft, measured in grams per kilogram-kilometer (g/kg·km). The pollutants include methane ($CH_4$), nitrogen oxides ($NO_x$), sulfur oxides ($SO_x$), and particulate matter ($PM_{2.5}$). The results clearly show that conventional jet fuel generates the highest total emissions, with $SO_x$ being the most dominant contributor. This is followed by FT from natural gas (NG), which, although cleaner than conventional fuel, still shows significant $SO_x$ emissions. In comparison, FT from biomass and all three HEFA pathways—from soy, corn, and canola—demonstrate significantly lower emissions. Among these, HEFA corn and HEFA canola exhibit the lowest overall pollutant levels, particularly in $SO_x$ and $NO_x$, highlighting their environmental advantage in reducing aviation-related air pollution. Notably, HEFA soy shows slightly elevated $SO_x$ emissions compared to other HEFA fuels but still remains below FT-based and conventional fuels. These findings underscore the environmental benefits of SAFs in large aircraft applications, especially when derived from waste oils or renewable biomass sources.

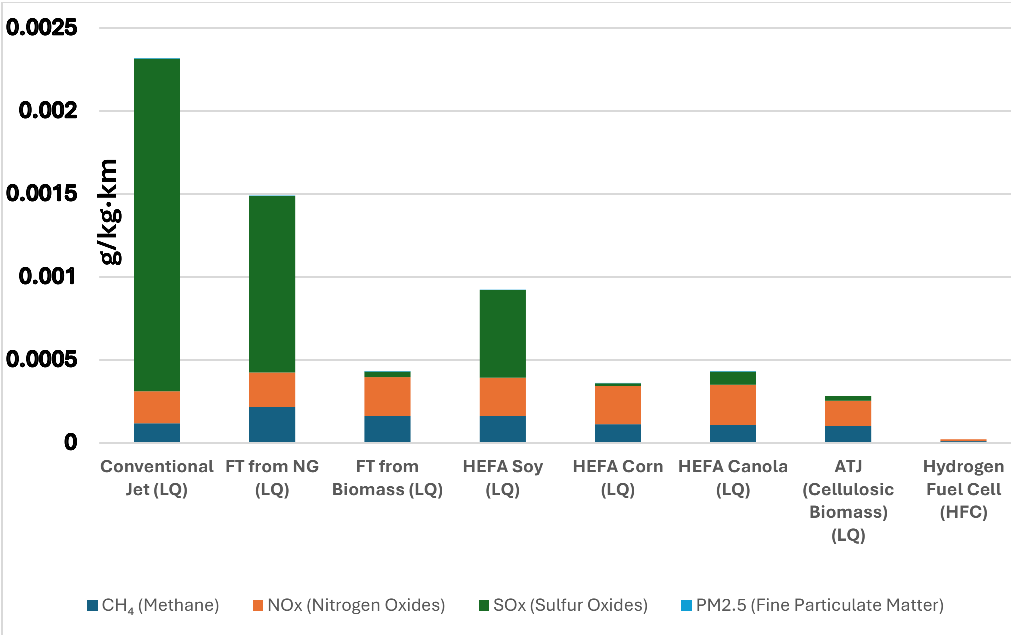



Figure 5-9: Pump-to-Wake pollutant emissions for Large Quad aircraft

### 5.3.3 Comparative Life Cycle GHG Emissions of SAFs and Fossil Fuels for Commercial Aircraft

The Pump-to-Wake (PTWa) pollutant emissions table summarizes the environmental impact during the fuel usage and propulsion phase for various aviation fuels. This stage includes combustion emissions for conventional and SAF-powered aircraft, and electrochemical operation for hydrogen fuel cell (HFC) systems. The results show that conventional jet fuels and fossil-based FT fuels emit notable levels of pollutants such as methane ($CH_4$), nitrogen oxides ($NO_x$), sulfur oxides ($SO_x$), and fine particulate matter (PM2.5). For instance, conventional jet fuel in Single Aisle aircraft produces approximately 0.000026 g/kg·km of $CH_4$ and 0.000070 g/kg·km of $NO_x$, along with higher levels of $SO_x$ (0.000184 g/kg·km) and PM2.5.

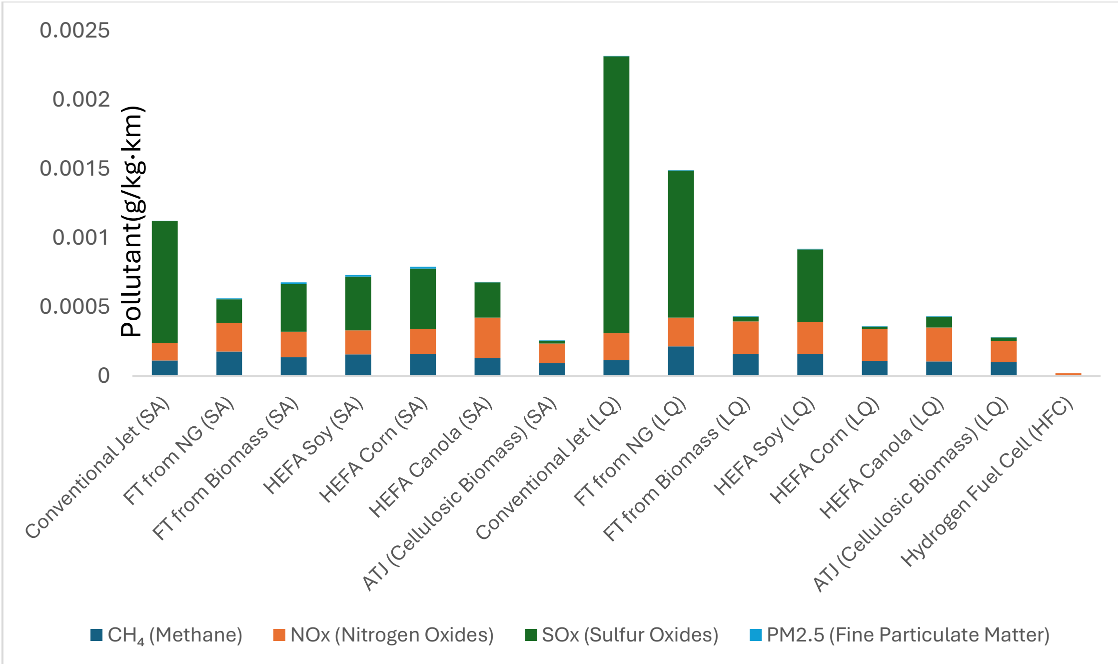



Figure 5-10:Normalize WTP Pollutant including Single Aisle and Larg Quad Aircraft

Conventional jet fuel resulted in the highest PTWa emissions for Large Quad aircraft (1.456 g/kg·km), underscoring the environmental cost of legacy fuel systems. These findings support the adoption of SAFs, particularly HEFA from canola oil—for achieving decarbonization in aviation, especially in short- to medium-haul aircraft.

### 5.3.4 Conclusion of Emissions Analysis During the Aircraft Use Stage

In This section analyzed fuel consumption and emissions during the use phase of various aviation fuels across Single Aisle (SA) and Large Quad (LQ) aircraft. While LQ aircraft have higher total emissions due to their size and payload, they are more efficient per unit of transport work, emitting about 26% less $CO_2$ per kg·km than SA aircraft.

Among the fuels studied, conventional jet fuels and fossil-based Fischer-Tropsch (FT) fuels showed the highest GHG and pollutant emissions. In contrast, SAFs, particularly HEFA from canola oil, offer moderate reductions in emissions. However, feedstocks like corn and soy still present environmental trade-offs due to high $NO_x$ and resource demands. Hydrogen fuel cells stand out with near-zero operational emissions and consistent performance across aircraft types. Their Pump-to-Wake (PTWa) GHG emissions were just 0.015 $gCO_2$-eq/kg·km, making them the most environmentally favorable option. Despite challenges related to storage and airport infrastructure, HFC systems offer strong potential for short-haul aviation.

Overall, the results support a transition toward SAFs with lower emissions and highlight hydrogen fuel cells as a promising long-term solution for achieving aviation decarbonization.

infrastructure planning in achieving the full sustainability potential of alternative aviation fuels.

## 5.4 Comparative Assessment of Emissions and Energy Use in the Well-to-Wake Stage of Aviation Fuels

This section presents a comparative assessment of GHG emissions for various aviation fuel pathways based on the GREET model. The Well-to-Wake (WTW) stage includes emissions from both upstream fuel production (WTP) and downstream combustion (PTW). The analysis covers two aircraft categories, Single Aisle and Large Quad, to recommend the most sustainable fuel options.

### 5.4.1 Pump-to-Wake (PTW) Emissions Comparison

The PTW emissions chart isolates the combustion stage of fuel use. Since most fuels (e.g., HEFA, FT, SPK, ULS, and conventional jet fuel) undergo similar combustion in engines, their PTW emissions are nearly identical(95):

- SA aircraft: approximately 0.0700 g/kg·km
- LQ aircraft: approximately 0.0800 g/kg·km

The only exception is the Hydrogen Fuel Cell (HFC), which emits significantly less due to non-combustion power generation(70),(71):

- SA aircraft: 0.0150 g/kg·km
- LQ aircraft: 0.0200 g/kg·km

This contrast underlines the role of fuel use technology in emissions. Outcomes combustion-based fuels are limited by engine efficiency, whereas HFC benefits from an electrochemical process with near-zero direct emissions.

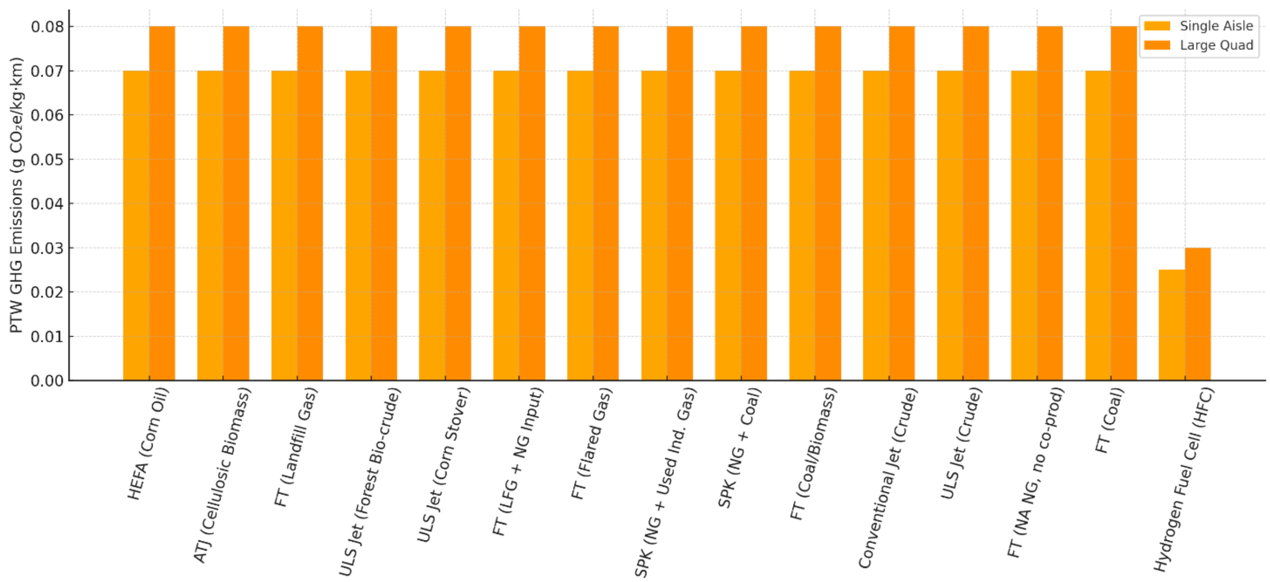



Figure 5-11: Comparing PTW GHG emissions for all aviation fuels used by aircraft

Conversely, fossil-based fuels, including FT (Coal), FT (Natural Gas, no co-product credit), and ULS Jet (Crude), produce the highest PTW emissions, approaching or slightly exceeding 0.08 g $CO_2e$/kg·km, particularly for SA aircraft. These elevated values reflect the carbon intensity inherent in the combustion of fossil fuels.

Interestingly, bio-based fuels such as HEFA (Corn Oil) and ATJ (Cellulosic Biomass) also exhibit similar PTW GHG emissions as conventional fuels—ranging around 0.07–0.08 g $CO_2e$/kg·km—since they still undergo combustion. However, their overall climate impact is mitigated when considering upstream WTP stages, where bio-based fuels gain sustainability advantages due to lower feedstock emissions.

### 5.4.2 Well-to-Wake (WTW) Emissions Overview

Based on GREET 2024 model outputs for Single Aisle (SA) aircraft, the following key insights can be drawn. Note: All emission values reported below are normalized values (on a 0–1 scale), where 1 represents the worst-performing fuel (typically conventional jet fuel), and other values are proportionally scaled for comparison purposes.

The WTW GHG emissions bar chart highlights the total life cycle impact, including upstream (fuel production and transportation) and downstream (combustion) emissions and result of (38). The normalized data clearly (Figure 5-12) demonstrates that:

- HEFA from corn oil has the lowest WTW emissions in both aircraft types 0.0914 g/kg·km for SA and 0.1050 g/kg·km for LQ due to its bio-based feedstock and reduced upstream emissions.
- Hydrogen Fuel Cell (HFC) technology also performs well, particularly for Single Aisle aircraft, with 0.2350 g/kg·km, owing to the absence of combustion emissions.
- Fossil-based FT fuels, especially those derived from coal and natural gas, show the highest WTW emissions, with FT from coal reaching 0.9635 g/kg·km in SA and 1.0000 g/kg·km in LQ aircraft.

This comparison confirms that renewable and waste-based fuels significantly outperform fossil-derived alternatives, with slightly higher WTW emissions in Large Quad aircraft due to their larger fuel demand.

In contrast, fossil-based synthetic fuels such as Fischer-Tropsch (FT) from coal, FT (Natural Gas, no co-products), and ULS Jet from crude oil present the highest normalized emission intensities, with FT (Coal) surpassing 0.95 g $CO_2e$/kg·km, marking it as the least sustainable option. These high values reflect the carbon-intensive nature of coal and natural gas feedstocks, as well as the absence of emissions offsets or co-product credits in certain pathways.

The figure also reveals that emissions are consistently higher for LQ aircraft across nearly all pathways. This is due to increased fuel consumption and operational loads associated with larger aircraft, which magnify the life cycle emissions per unit of distance travel.

Overall, this comparison illustrates a clear gradient of environmental performance across fuel types. Bio-based and hydrogen-derived fuels offer substantial GHG emission reductions relative to conventional fossil jet fuels, making them compelling options for aviation decarbonization strategies. The data reinforces the importance of fuel feedstock selection and aircraft design in reducing aviation's climate impact.

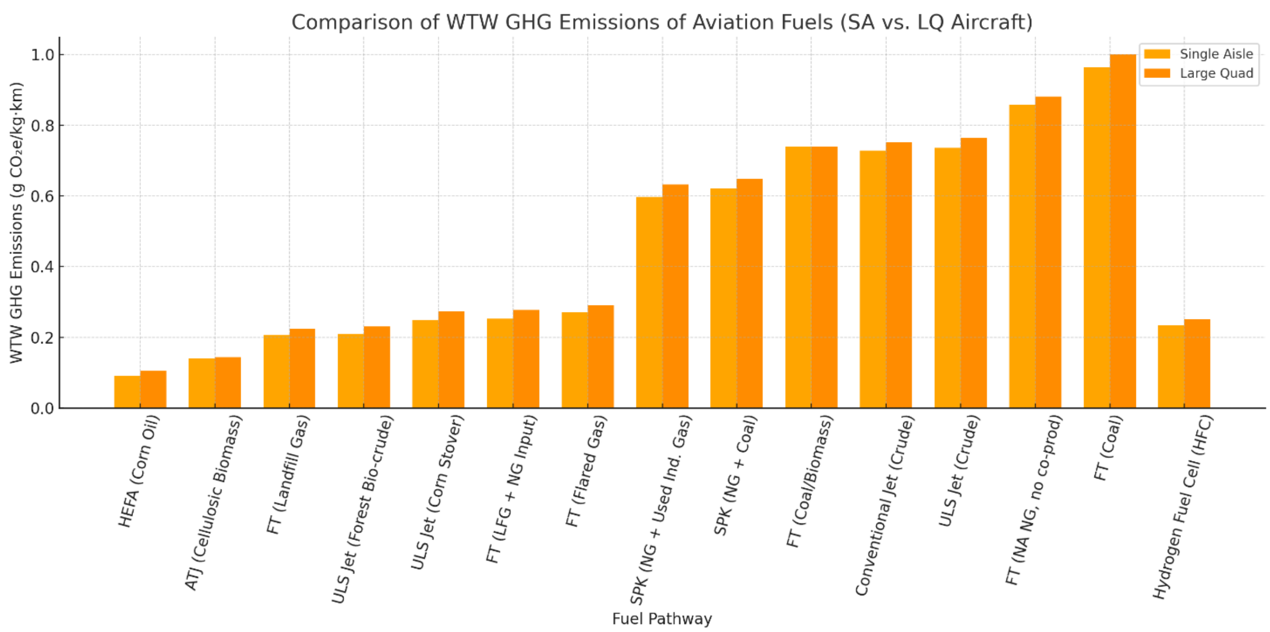



Figure 5-12: Normalized WTW GHG emissions for each fuel pathway

Note: All emission values reported below are normalized values (on a 0–1 scale), where 1 represents the worst-performing fuel (typically conventional jet fuel), and other values are proportionally scaled for comparison purposes.

Therefore, to maximize climate benefits, aviation strategies must prioritize not only the adoption of low-emission engines (e.g., hydrogen fuel cells) but also the production and supply chain sustainability of the fuels themselves.

### 5.4.3 WTW GHG Emissions for Single Aisle Aircraft

This section presented a comparative analysis of Well-to-Wake (WTW) GHG emissions for various aviation fuel pathways used in Single Aisle (SA) aircraft, utilizing GREET 2024 data. The emissions profile of each pathway highlights the significant impact of feedstock and production technology on the total environmental burden.

As shown in Figure 5-13, The fossil-based FT (Coal) pathway exhibited the highest WTW emissions at 0.9635 g $CO_2e$/kg·km, establishing it as the least sustainable option among those analyzed. Conventional jet fuel (crude-derived) followed closely at 0.7287 g $CO_2e$/kg·km, reinforcing its substantial contribution to aviation-related emissions. Other fossil-derived synthetic pathways such as FT (Natural Gas, no co-products) and ULS Jet (Crude) also demonstrated elevated emissions—0.8573 g/kg·km and 0.7362 g/kg·km respectively—indicating only modest improvements over conventional fuels.

In contrast, the inclusion of ATJ (Cellulosic Biomass) revealed its strong environmental advantage, with WTW emissions measured at 0.1400 g $CO_2e$/kg·km. This reflects an 81% reduction compared to conventional jet fuel and an 85% reduction relative to FT from coal. Such performance can be attributed to the use of lignocellulosic waste feedstocks and efficient alcohol-to-jet conversion processes that minimize fossil energy input and emissions during production and distribution.

Hydrogen Fuel Cell (HFC) systems also demonstrated promising results with emissions of 0.2350 g $CO_2e$/kg·km, corresponding to a 68% reduction compared to conventional jet fuel. While HFC pathways still lag slightly behind ATJ-cellulosic in this scenario, they offer significant potential in the long term, particularly if hydrogen production infrastructure becomes more renewable and efficient.

The HEFA (Corn Oil) pathway again emerged as the lowest-emission SAF at 0.0914 g $CO_2e$/kg·km, representing an 87% reduction over conventional fuel. However, the pathway is limited by feedstock availability, land-use concerns, and water demand, making ATJ-cellulosic a more scalable and sustainable choice.

In conclusion, the analysis confirms that ATJ from Cellulosic Biomass provides one of the most effective emissions reductions among currently deployable SAF technologies for Single Aisle aircraft. It surpasses several fossil-derived synthetic fuels and rivals emerging hydrogen-based systems in performance. These findings underscore the need to prioritize investment, policy support, and infrastructure development around cellulosic ATJ fuels to enable near-term and impactful decarbonization of short- to medium-haul aviation.

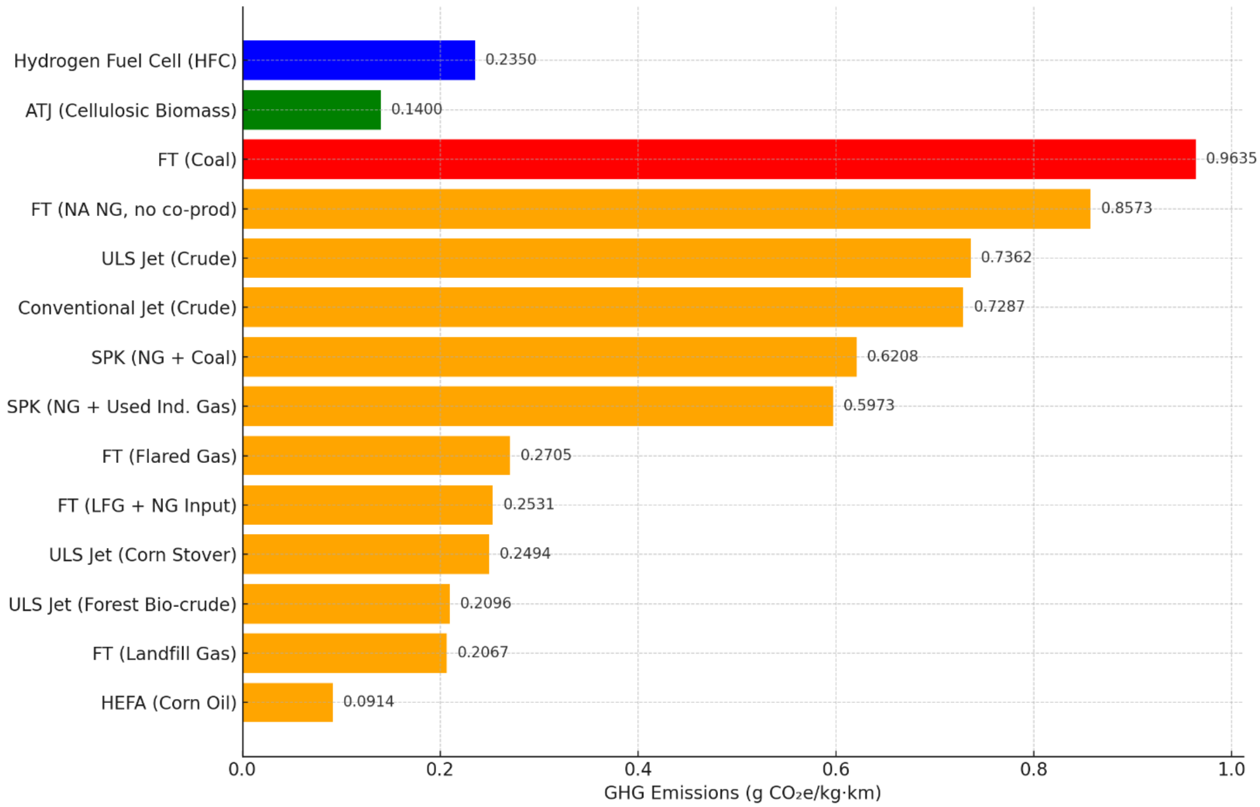



Figure 5-13. Normalized WTW GHG Emissions of Aviation Fuels for Single Aisle Aircraft

Note: All emission values reported below are normalized values (on a 0–1 scale), where 1 represents the worst-performing fuel (typically conventional jet fuel), and other values are proportionally scaled for comparison purposes.

### 5.4.4 WTW GHG Emissions for Large Quad Aircraft

This study conducted a comparative analysis of Well-to-Wake (WTW) GHG emissions across multiple aviation fuel pathways for Large Quad (LQ) aircraft, using GREET 2024 data. The results highlight significant differences in life cycle emissions among conventional, synthetic, and bio-based fuels, emphasizing the environmental advantages of selecting Sustainable Aviation Fuels (SAFs) and emerging technologies.

As shown in Figure 5-14, among all evaluated fuels, FT (Coal) exhibited the highest WTW GHG emissions at 1.0000 g $CO_2e$/kg·km, serving as the baseline for the worst-case scenario. Conventional

Jet Fuel (Crude) followed closely with emissions of 0.7520 g $CO_2$e/kg·km, reinforcing its classification as a high-emission fossil-based fuel. Other fossil-derived options such as FT (Natural Gas) and SPK (NG + Coal) also showed elevated emissions, ranging from 0.6480 to 0.8810 g $CO_2$e/kg·km, indicating only marginal improvements over conventional jet fuel.

In contrast, bio-based and renewable fuels demonstrated substantial reductions in GHG emissions. Notably, HEFA (Corn Oil) recorded the lowest emissions, at 0.1050 g $CO_2$e/kg·km, reflecting a 86% reduction compared to FT (Coal) and an 86% decrease compared to conventional jet fuel. Similarly, ATJ from Cellulosic Biomass, newly added to the analysis, achieved 0.1440 g $CO_2$e/kg·km, representing an approximate 81% reduction relative to both FT (Coal) and conventional jet fuel. This significant performance is attributed to its use of lignocellulosic waste feedstock and a clean alcohol-to-jet conversion process, making it a highly viable SAF candidate for decarbonizing long-range aviation.

Hydrogen Fuel Cell (HFC) systems, though often perceived as the ultimate low-emission solution, reported WTW emissions of 0.2520 g $CO_2$e/kg·km in this context. While still offering a 66% reduction relative to conventional fuel, this figure is slightly higher than that of ATJ-Cellulosic and HEFA (Corn Oil), likely due to current upstream emissions from hydrogen production and transport infrastructure.

Other promising alternatives such as ULS Jet from Forest Bio-crude (0.2310 g/kg·km) and FT from Landfill Gas (0.2250 g/kg·km) also demonstrated more than 70% GHG reductions compared to conventional fuel, reinforcing the environmental potential of waste-to-fuel technologies.

In conclusion, this analysis confirms that the most sustainable aviation fuels for Large Quad aircraft are those derived from waste-based and renewable feedstocks, particularly ATJ-Cellulosic and HEFA fuels. These pathways not only outperform conventional and synthetic fossil fuels in emissions reduction but also align with long-term climate goals for aviation. While HFC systems remain a promising technology, their environmental advantage will depend on the continued decarbonization of hydrogen production. The evidence strongly supports prioritizing the development and deployment of ATJ-cellulosic fuel in large aircraft operations as part of an effective aviation decarbonization strategy.

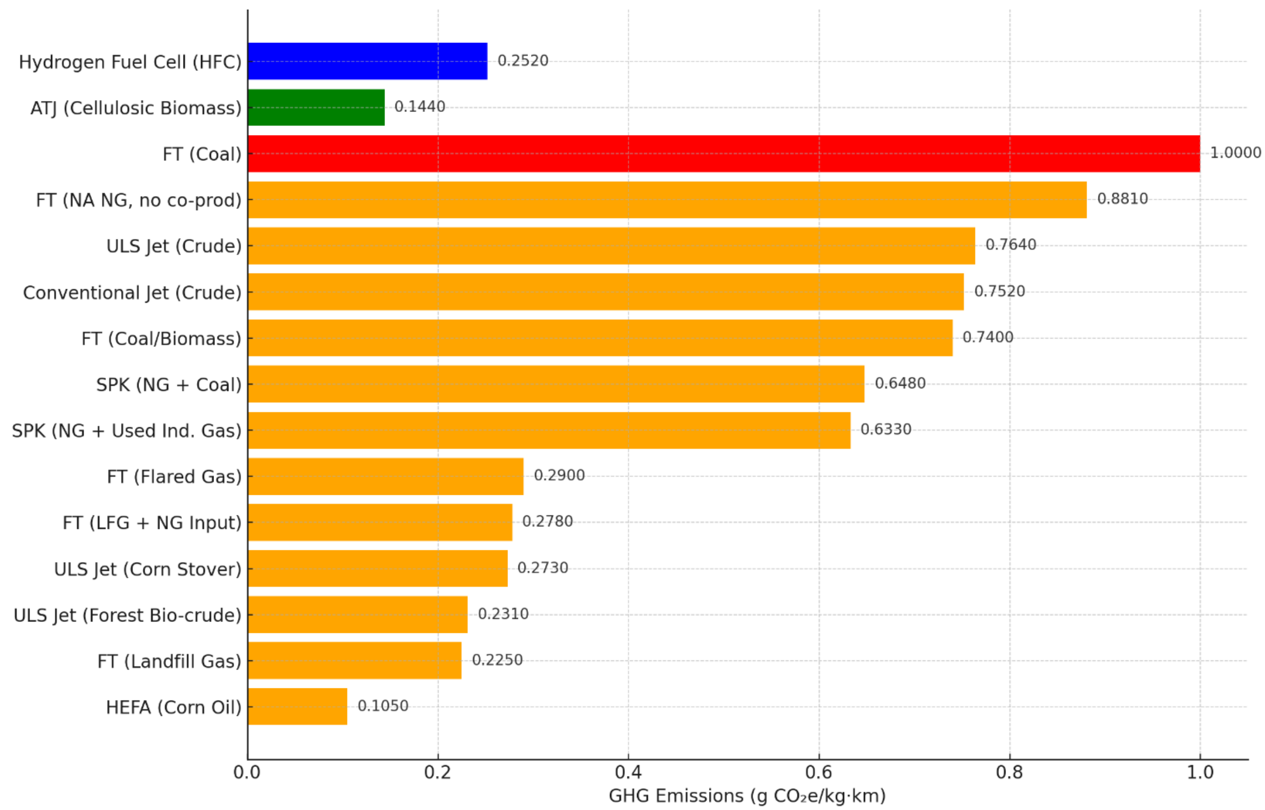



Figure 5-14. Normalized WTW GHG Emissions of Aviation Fuels for Large Quad Aircraft

Note: All emission values reported below are normalized values (on a 0–1 scale), where 1 represents the worst-performing fuel (typically conventional jet fuel), and other values are proportionally scaled for comparison purposes.

For Large Quad aircraft, long-haul flights should prioritize HEFA and FT fuels derived from waste or biomass. These pathways significantly outperform fossil fuels in terms of emissions and are suitable for scaling under sustainable aviation goals.

### 5.4.5 Conclusion and best of Fuel Pathways

The normalized comparative Well-to-Wake (WTW) analysis reveals that the most environmentally favorable aviation fuel pathways are those derived from renewable and waste-based sources. Among them, HEFA fuel from corn oil emerges as the top-performing option, offering over 85% reduction in GHG emissions compared to conventional jet fuel. Hydrogen Fuel Cell (HFC) systems also demonstrate excellent performance, achieving near-zero emissions during the use phase, although their upstream emissions depend on the method of hydrogen production. Waste-based fuels such as Fischer-Tropsch (FT) jet fuel from landfill gas and ULS fuels produced from forest bio-crude and corn stover provide additional viable low-emission alternatives. In contrast, pathways based on fossil feedstocks—such as FT fuels from coal and natural gas result in the highest life cycle emissions, often exceeding 0.85–1.00 g $CO_2e$/kg·km, and thus pose major challenges for sustainable deployment. Based on these findings, future aviation decarbonization strategies should prioritize SAFs derived from waste biomass, expand the adoption of hydrogen fuel cell technologies, and avoid reliance on fossil-based synthetic fuels coupled with effective carbon capture and storage solutions. Additionally, the selection of fuel should consider aircraft type and mission range to optimize environmental benefits, especially for long-haul Large Quad aircraft operations where fuel demand is higher.

# Chapter 6: Conclusion

## 6.1 Conclusions

This thesis conducted a comprehensive life cycle assessment (LCA) of various alternative aviation fuel pathways, focusing on their environmental performance in terms of GHG emissions, energy consumption, and transportation impacts. The analysis utilized the GREET 2024 model to evaluate 14 fuel pathways across multiple life cycle stages, including Well-to-Pump (WTP), Pump-to-Wake (PTWa), and Well-to-Wake (WTW), for both Single Aisle and Large Quad aircraft. The results reveal substantial variation among pathways, primarily influenced by feedstock origin, conversion technologies, fossil fuel dependency, and the method of fuel transportation and delivery.

Among all pathways examined, Alcohol-to-Jet (ATJ) fuel derived from cellulosic biomass emerged as the most environmentally optimal solution. It demonstrated a reduction in WTW GHG emissions by 85.6% compared to conventional jet fuel, due to its use of waste-based feedstocks, minimal fossil energy input, and highly efficient distribution network. This pathway also presented one of the lowest transportation-related emissions, with a GHG-100 value of just 0.323 g $CO_2e$ per MJ and energy delivery efficiency exceeding 99.6%. These features position ATJ-Cellulosic as a leading near-term option for sustainable aviation fuel deployment.

Hydrogen Fuel Cell (HFC) systems powered by green hydrogen via electrolysis also showed promising environmental performance, with the lowest normalized GHG emissions (0.020 g $CO_2e$/kg·km) and energy use (10.0 kJ/kg·km) across all evaluated technologies. Moreover, HFCs exhibited virtually zero emissions of nitrogen oxides (NOx), sulfur oxides (SOx), particulate matter (PM), and methane ($CH_4$) during the use phase, offering a promising long-term decarbonization pathway. However, their feasibility depends on overcoming challenges in hydrogen production scalability, infrastructure, and storage. Among the various hydrogen delivery methods, pipeline transport was identified as the most emission-efficient option, with emissions approximately 2.84 g $CO_2e$/MJ, while liquefied hydrogen trucking involved nearly 4 times higher emissions due to energy-intensive liquefaction.

Conversely, fossil-based synthetic fuels—such as Fischer-Tropsch (FT) jet fuel from coal or natural gas—recorded the highest normalized WTW emissions, frequently exceeding 0.85–1.00 g $CO_2e$/kg·km. Despite offering energy density benefits, their heavy reliance on fossil inputs and significant upstream emissions make them unsuitable for sustainable aviation goals. Even SAFs from oil crops such as soy and corn, while delivering moderate GHG reductions, raised concerns regarding land-use change, water intensity, and increased NOx and particulate emissions.

In summary, the findings of this research underscore that the most effective strategies for aviation sector decarbonization involve maximizing the use of renewable and waste-based feedstocks, adopting low-carbon energy sources, and selecting efficient fuel conversion and distribution technologies. Policy efforts and investment decisions should prioritize the development and scaling of ATJ-Cellulosic and green hydrogen fuel cell systems. Additionally, fuel selection should be aligned with aircraft type and mission profile to optimize emissions reductions and resource use, particularly for long-haul flights where fuel demand is greatest. These approaches can pave the way for a more sustainable, climate-resilient future in global aviation.

## 6.2 Future Work

This research provides a strong foundation for understanding the environmental impacts of alternative aviation fuels. Future studies can build on this work by further exploring SAFs and hydrogen-based systems, with a growing interest in ammonia as both a hydrogen carrier and a potential direct aviation fuel.

Ammonia has emerged as a promising option due to its high hydrogen density, ease of storage, and the availability of global distribution infrastructure. Future research could investigate ammonia's dual roles in the aviation sector:

1. As a hydrogen carrier, supporting long-distance applications where conventional hydrogen storage poses technical challenges.(66)
2. As a direct fuel, used in advanced propulsion systems such as ammonia-compatible gas turbines or ammonia-fed fuel cells.

Another important area of future work involves studying regional differences that affect fuel sustainability, such as variations in feedstock availability, renewable energy resources, and policy frameworks. Comparative studies across different regions can reveal the most suitable production and deployment strategies for each context.

Further research may also address the technical challenges associated with handling and storing hydrogen and ammonia safely in aviation environments. This includes developing lightweight and safe storage systems, improving onboard fuel delivery, and ensuring compatibility with existing aircraft systems.

In addition, techno-economic assessments will be critical. These should include analyses of capital and operational costs, infrastructure readiness, and potential retrofitting requirements at airports and for aircraft fleets. Evaluating both centralized and decentralized fuel production systems can support decisions on scaling and localization.

Finally, future research should focus on improving system efficiency and reducing emissions across the entire fuel life cycle. This includes:

- Optimizing production pathways,
- Reducing upstream fossil energy input,
- And exploring modular production systems tailored to specific regions.

These efforts can help make low-carbon aviation fuels such as SAFs, green hydrogen, and ammonia more scalable, cost-effective, and ready for real-world deployment across both regional and international aviation networks.

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