Sustainable Aviation Fuel: A History and Future

Ellory Berniard[1] and Jalyn Huang[2#]

[1] Math and Science Academy
[2] Irvine High School
[#] Advisor

ABSTRACT

As a key piece in global connectivity, the aviation industry represents a large part of our world economy and culture. Currently, it faces the substantial challenge of evolving and innovating to meet the International Civil Aviation Organization's goal of net-zero emissions by 2050. This review explores the historical development of aviation fuel and the emergence of Sustainable Aviation Fuel (SAF) as a response to environmental and regulatory demands. Beginning with the early use of tetraethyl lead (TEL) in aviation gasoline, aviation has achieved many great technological milestones and policy shifts, such as the development of high-octane unleaded aviation gasoline. But as the world looks towards a more sustainable future, examining current SAF infrastructure is essential to make improvements in the future. This review covers two primary generations of SAF: biofuels and E-Kerosene. Biofuels offer a short-term solution using biomass-derived hydrocarbons, however it also introduces many concerns over land use, cost, and effectiveness. In contrast, E-Kerosene, derived from carbon capture and renewable energy, presents a long-term solution to these issues. Both approaches rely on the Fischer-Tropsch process to synthesize hydrocarbons identical to those in conventional jet fuel, enabling compatibility with existing engines. While biofuels are a necessary transitional solution, the future of sustainable aviation lies in scaling E-Kerosene production through investment in renewable infrastructure. Understanding the evolution and science behind SAF is essential to achieving a more sustainable future in global air travel.

Introduction

Aviation is a booming industry, connecting people, trade, and cultures across every continent. As the sole form of rapid worldwide transport, the aviation industry contributes $1.1 trillion to the global gross domestic product, carries 4.4 billion passengers and 61.4 million tons of freight per year, and provides millions of people with stable careers in almost every field. Additionally, recent estimates suggest that demand for aviation will continue to increase annually by 4% for the next twenty-five years (Ritchie, 2023) [*Figure 1*].

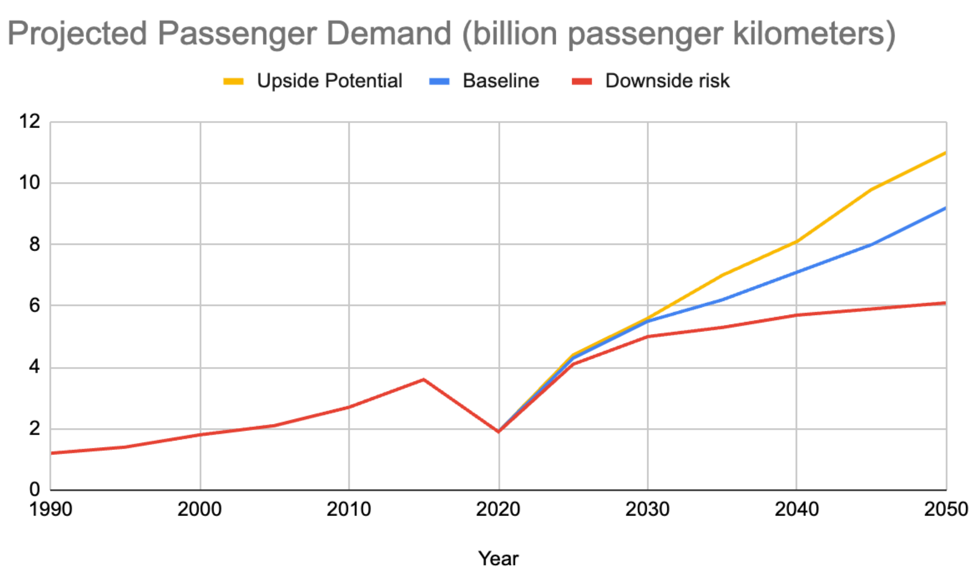

Figure 1. *Global passenger aviation demand: historical and projections.*

While this exceptional growth will greatly benefit the industry's financial state, it also presents the challenging task of accommodating such an evolution within the current infrastructure to meet the International Civil Aviation Organization's (ICAO) goal of net-zero carbon emissions by 2050. Following COVID-19, carbon emissions have extended 90% of their previous peak, and with growing demand, are projected to increase significantly in the future. In order to meet the ICAO's ambitious goal, we must begin to address the source of these emissions: fuel. Jet A and 100LL are the standard for commercial and general aviation aircraft fueling, and since both fuels use combustion to make energy, carbon dioxide is also produced as a byproduct, therefore polluting the atmosphere. Methods for the production of sustainable aviation fuel (SAF) have been in the developmental stage since the early 2000s, starting with the use of biomasses such as oils, fats, wood, and various crops to produce biofuel. As the first generation of SAFs, biofuels currently make up around 2% of global jet fuel usage. Following this is the second generation, E-Kerosene, which utilizes carbon-capture and renewable energy sources like windmills to combine CO_2 and H_2 into a synthetic fuel.

Early Stages of Fuel Development

We can trace the beginnings of general aviation fuel back to 1930, when Jimmy Doolittle first popularized high-octane AVGAS (aviation gasoline). Doolittle was a pilot in the Army reserves when Shell Oil Company hired him as head of the aviation department between WWI and WWII. At the time, automobiles used a four-stroke engine with four stages: intake, compression, combustion, and exhaust. During the compression stroke, the engine compresses a mixture of gasoline and air before igniting it.

Octane and heptane are two important compounds within gasoline due to their opposing qualities. When heptane is placed under pressure, it will spontaneously ignite, while octane will resist igniting. Therefore, a fuel's ability to be compressed a large amount without igniting is reflective of its octane content; higher concentrations of octane will result in more efficient and faster vehicles (Everyday Elements, 2016). Back in Doolittle's time, automobiles used 60-octane gasoline, which is remarkably low compared to the 82-octane fuel commonly used today.

To increase the octane content, TEL (tetraethyl lead) was added to gasoline. Thomas Midley, a chemist at General Motors, discovered that TEL could be used as an octane booster in 1921. General Motors jumped to make this new mixture widely available, marketing it as 'Ethyl' and intentionally avoiding any mention of lead so consumers would purchase it. It became very popular because of its ability to reduce knock, a noise caused when heptane content is too high and ignites inside the compression chamber, causing harmful effects on the engine. However, when the lead in 'Ethyl' exited the engine and condensed into a solid, it ended up heavily polluting the soil and causing health issues for many people (AVweb, 2022a).

While extremely harmful, this innovation led to the United Kingdom's development of aviation alkylate in 1938, which serves as the base stock of all general aviation and jet fuel today. Using alkylation, the base stock was produced by combining light hydrocarbons, and then TEL was added to increase the octane content.

Due to rising public health concerns, TEL was completely banned from automobile gasoline by the Clean Air Act in 1996. However, aviation was exempt from this ban because no suitable octane-booster had been found, and this remains the case today. Since the government had given no incentive or mandate for the removal of lead from AVGAS, 100-octane low lead gasoline (100LL) would remain the standard fuel in America for over 30 years. This greatly benefited fuel companies such as Shell, Chevron, and Phillips because they were able to profit in a relatively closed market with no alternative for 100LL fuel (AVweb, 2022b).

As one could imagine, lead air pollution was no less harmful than the ground pollution from the 1930s, and while there had been several attempts to find a replacement octane-booster by government agencies, no significant progress was made. Instead, GAMI, a small aviation company located in Oklahoma, was the first to certify a high-octane, unleaded fuel called G100UL in September of 2022 (GAMI, 2021). Following this breakthrough, California became the first state to pass a ban on the sale and distribution of leaded aviation gas, which will come into effect in 2031 (Sundeen, 2024).

Sustainable Aviation Fuel

As general aviation takes steps towards a sustainable future, the commercial sector has also brought new fuel innovations to light. Sustainable aviation fuel (SAF) promises to be an important step towards reaching its goal of net zero carbon emissions by 2050. The developmental plan for SAF can be categorized into two 'generations': biofuels and E-Kerosene. Biofuels, as the first generation, have been thoroughly studied and used in the commercial market, while E-Kerosene has yet to see more extensive research and would require updated infrastructure to accommodate on a large scale. That is to say, both generations will serve their purpose (biofuels in the short-term, and E-Kerosene in the long-term) to meet the overarching goal of making our planet a better and less polluted place.

Biofuels: Generation 1

To understand the production pathways used to make biofuels, we must first understand the current fuel technology. Standard jet fuel, Jet-A, is made up of a complex hydrocarbon mixture referred to as refined crude oil. Originating from the remains of ancient marine organisms which were subjected to extreme conditions in the earth's crust, crude oil is the basis of many products today, including medicine, clothes, and fuel. The chemical structure of hydrocarbons used in jet fuel is carbon (C) atoms attached to hydrogen (H) atoms in a specific shape. Hydrocarbons present in crude oil vary greatly in shape due to differences in the ratio of H to C atoms. Through oil refinement processes, about 10% of the hydrocarbon variants found in crude oil can be separated for use in jet fuel (ChemEfy, 2024a).

On a molecular level, biofuel and Jet-A are composed of the same hydrocarbons arranged in the exact same shape [*Figure 2*], and when burned, they both emit similar amounts of carbon dioxide (CO_2).

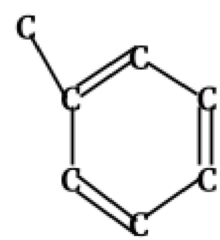

Figure 2. *Chemical structure of Toluene (C_6H_6), one of the hydrocarbons present in both Jet-A fuel and biofuel.*

The distinction between biofuel and Jet-A fuel lies in the source of the H and C elements. SAF is categorized into three different types depending on the source of hydrocarbons: Waste-to-Liquid, Power-to-Liquid, and Biomass-to-Liquid (Revolutionizing Aviation: Understanding the Transformative Power of Power-To-Liquid Fuels, n.d.). Currently, there are eight different pathways approved for the production of Biomass-to-Liquid, each of which uses a feedstock such as fat, biomass, or crops to source hydrocarbons. Biomasses like excess wood and agricultural residues utilize the Fischer-Tropsch, Fischer-Tropsch with Aromatics, synthetic isoparaffins, and hydroprocessed fermented sugars to synthetic isoparaffins pathways to transform cellulose-containing waste into biofuel. Conversion of waste oils and fats into biofuel can be achieved through the Hydrotreated Esters and Fatty Acids and Fats, Oils, and Greases Coprocessing pathways. Finally, the Alcohol-to-Jet and Catalytic Hydrothermolysis Synthesis Kerosene pathways alter non-food crops or sugar crops into biofuel (U.S. Department of Energy, 2024). All of these production pathways are simply different methods for extracting the same hydrocarbon product. For example, the Fischer-Tropsch pathway breaks down solid waste, agricultural waste, or crops as feedstock to make individual H and C building blocks. These building blocks are then synthesized into biofuel.

Since Biomass-to-Liquid production pathways use organisms that naturally convert CO_2 into O_2 as they grow, the CO_2 emitted as biofuel combusts is considered to be balanced at net-zero. On the contrary, Jet-A production involves mining and refining crude oil, a process that increases carbon emissions instead of balancing them out. However, the net-zero label does not account for the land, water, and energy, which would otherwise be used for agriculture, required to grow biomasses. By taking massive amounts of land and water to meet fuel demand, we could exacerbate droughts and inflate land and food prices (Lashof & Denvir, 2023). Additionally, the current infrastructure only allows biofuel to be used in aircrafts as a 50/50 mixture with Jet-A, so although it will serve as a stepping stone to net-zero emissions, biofuels are a short-term solution at best.

E-Kerosene: Generation 2

E-Kerosene, often referred to as Power-to-Liquid (PtL) or E-Fuel, soon emerged as a promising solution to the present challenges of large-scale commercial SAF production. One of the most debated topics regarding the uprising of biofuels to the world stage is food versus fuel. This conflict arose from competing land interests; whether to use agricultural land resources for human consumption or for the production of biofuel (Sustainability Directory, 2025). E-Kerosene provides a similar but alternative pathway to biofuels by greatly limiting the use of these contested resources.

At the heart of E-Kerosene production is the Fischer-Tropsch pathway. Developed by Franz Fischer and Hans Tropsch, this process became prevalent during WWII for fuel synthesis in the absence of conventional oil sources and has recently emerged as a key component in the development of synthetic SAF. Within the Biomass-to-Liquid pathway, Fischer-Tropsch synthesis transforms syngas, a mixture of carbon monoxide (CO) and H, into hydrocarbons using a catalyst. The catalyst, usually small particles of iron or cobalt, helps the CO to bond with itself and loosen the bonds between C and O to allow the insertion of another CO atom. This chain extension process is repeated, resulting in the formation of diverse hydrocarbons [*Figure 3*].

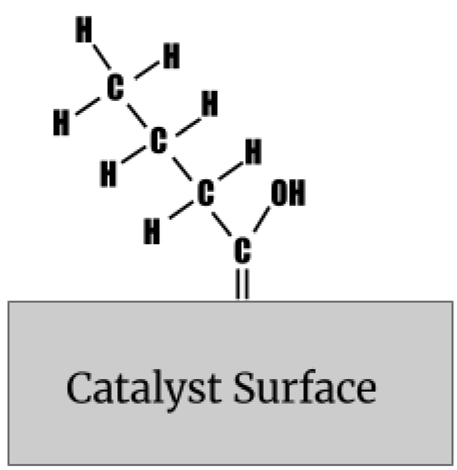

Figure 3. *Molecular diagram of hydrocarbon chain formation on a catalyst from syngas.*

Syngas, one of the most critical components to the Fischer-Tropsch process, can be produced from several sources depending on the intended pathway. Biofuel pathways can utilize feedstocks such as biomass, coal, and natural gas, while E-Kerosene relies on carbon capture and electrolysis of water (H_2O) to produce syngas (Barbosa, 2022). By converting carbon captured from the atmosphere, the CO component of syngas is produced. Water electrolysis involves the separation of H_2O into H and C atoms using an electric current. This electricity can be supplied by various renewable sources, including solar panels, windmills, hydropower, and more. Next, this syngas is fed into Fischer-Tropsch reactors to produce liquid hydrocarbons, a process identical to the production of biofuel (ChemEfy, 2024b). Given its reliance on renewable energy sources and its ability to convert carbon emissions during the production process, E-Kerosene represents an advancement to fuel technology that will surpass biofuel in the future.

Conclusion

Aviation is an essential part of both the global economy and modern life, yet its growing environmental impact cannot be ignored. With increasing amounts of passengers and freight, decarbonizing aviation is vital to the future of our world. Historical reliance on fossil fuels and the long-standing use of TEL demonstrate how deeply embedded environmentally harmful technology is in society. The first generation of SAF fulfills the purpose of a short-term bridge to sustainability but comes with concerns around land use, food supply, and limited production capacity. Biofuel comes with both great potential and tradeoffs of relying on feedstocks.

E-Kerosene represents a transformative next step. By using carbon capture and renewable electricity to synthesize hydrocarbons, it avoids many of the drawbacks of biofuels and holds long-term promise for scalable, truly net-zero aviation. However, infrastructure gaps, high costs, and energy demands remain significant hurdles to its implementation. SAF is proof that innovation and cleaner energy solutions are feasible, however, there is still a great amount of work left to achieve the goal of net-zero by 2050. This study emphasizes the importance of pursuing SAF innovation while acknowledging that current production methods and infrastructure are not yet equipped for large-scale change. Future research should focus on the implementation of government policy to increase adaptivity, challenges of lowering production cost, and other innovations of the future such as battery-powered aircraft.

References

Aviation Fuels of the Future - SAF and other green alternatives. (n.d.). I6.Io. https://www.i6.io/blog/aviation-fuels-of-the-future---saf-and-other-green-alternatives

AVweb. (2022a, August 13). *The Long, Twisted And Slightly Ridiculous Story of Avgas Part 1*. YouTube. https://www.youtube.com/watch?v=9F-WngVMJBQ

AVweb. (2022b, August 13). *The Long, Twisted and Slightly Ridiculous Story of Avgas Part 2*. YouTube. https://www.youtube.com/watch?v=Mvse4Xhzwuk

Barbosa, F. C. (2022). Power to Liquid (PtL) Synthetic Aviation Fuel - A Sustainable Pathway for Jet Fuel Production. *SAE Technical Papers on CD-ROM/SAE Technical Paper Series*. https://doi.org/10.4271/2021-36-0034

ChemEfy. (2024a, February 20). *Renewable Crude Oil? | Fischer Tropsch Process Explained*. Www.youtube.com. https://www.youtube.com/watch?v=I_PimaDNv4c

ChemEfy. (2024b, March 27). *Electro-Crude Oil? | Power To Liquids Explained*. YouTube. https://www.youtube.com/watch?v=NkQN-umIfqU

GAMI. (2021). *G100UL*. G100ul.com. https://g100ul.com/faq

Kimbrough, L. (2022, April 6). *How much does air travel warm the planet? New study gives a figure*. Mongabay Environmental News. https://news.mongabay.com/2022/04/how-much-does-air-travel-warm-the-planet-new-study-gives-a-figure/

Lashof, D., & Denvir, A. (2023). Under New Guidance, “Sustainable” Aviation Fuel in the US Could Be Anything But. *Www.wri.org*. https://www.wri.org/insights/us-sustainable-aviation-fuel-emissions-impacts

Mueller, T., Winter, E., & Grote, U. (2024). Economic impacts of power-to-liquid fuels in aviation: A general equilibrium analysis of production and utilization in germany. *Energy Conversion and Management X*, *23*, 100632–100632. https://doi.org/10.1016/j.ecmx.2024.100632

Perez, S. (2024, September 9). *2024 Facts & Figures: American Aerospace and Defense Remains an Economic Powerhouse*. Aerospace Industries Association; Aerospace Industries Association. https://www.aia-aerospace.org/news/2024-facts-figures-american-aerospace-and-defense-remains-an-economic-powerhouse/

Revolutionizing Aviation: Understanding The Transformative Power of Power-to-Liquid Fuels. (n.d.). 4AIR. https://www.4air.aero/whitepapers/revolutionizing-aviation-understanding-the-transformative-power-of-power-to-liquid-fuels

Ritchie, H. (2023, September 26). *How much does aviation contribute to climate change? How will this change in the future?* Www.sustainabilitybynumbers.com. https://www.sustainabilitybynumbers.com/p/aviation-climate-part-one

SkyNRG. (2024). *The basics of SAF Technology*. SkyNRG. https://skynrg.com/sustainable-aviation-fuel/technology-basics/

Sundeen, M. (2024, September 23). *California Passes Bill to Become First in the Nation to Prohibit the Use of Leaded Aviation Gas – Western Center on Law & Poverty*. Western Center on Law & Poverty. https://wclp.org/avgas-prohibition/

Sustainability Directory. (2025, March 25). *Food Versus Fuel → Term*. Pollution → Sustainability Directory. https://pollution.sustainability-directory.com/term/food-versus-fuel/

U.S. Department of Energy. (2024). *Alternative Fuels Data Center: Sustainable Aviation Fuel*. Afdc.energy.gov. https://afdc.energy.gov/fuels/sustainable-aviation-fuel

Everyday Elements. (2016, July 26). *What Does The Octane Rating Of Gasoline Mean?* Www.youtube.com. https://www.youtube.com/watch?v=1ToBZ74Yhas