ICEAIST-25
M.A.M. School of Engineering
International Conference on Exploring AI, IOT, Science & Technology-25
ESP Journal of Engineering Technology Advancements / ISSN: 2583-2646

Original article

Critical Analysis Of Sustainable Aviation Fuel For Zero Emission Aircraft

Mr.V.P.Joseph Arun[1], Jithendraa P[2], Jothibasu A[3], Kalaiyarasan S[4],
[1] Assistant proferser,Department of Aeronautical Engineering,M.A.M College of Engineering, Trichy,Tamil Nadu,India,
[2,3,4] UG scholar, M.A.M College of Engineering,Trichy,Tamil Nadu,India.

Abstract:*Aviation has always been a paradox of technology turned into tradition. On one side, it makes continents smaller and supports worldwide commerce while bringing cultures together; on the distance end, aviation contributes to nearly 2–3% of global CO_2 emissions, with that number projected to rise as other industries decarbonize. Zero-emission aircraft is no longer a futurepipe dream — it is a must, driven by global sustainability ambitions aligned with international goals (such as the Paris Agreement or ICAO 2050 net-zero pledge). In this context, SAF is the fastest real solution for reduction of carbon emissions that does not leave a large global fleet on the ground, it is also the fastest to be deployed at an industrial scale. Yet answering the knotty question of how fast it can make that leap from novelty to mainstream — and developing solutions to scientific, economic, regulatory and infrastructural barriers that stand in the way — has proved elusive.In this paper we critically evaluate SAF, considering chemistry of SAF, and production pathways for sustainable supply of SAF; fuel properties in-flight and emissions (assessing the environmental impact of volume based properties such as aromaticity) the back-of-the-envelope costs for alternative technology drop-ins related to PDL, if high aromatic fuels were mandated; growth inhibition by fleet blend uptake where retrofit/re-engine U replacement is differentiated from first-engine-in-the-next aircraft uptake; impact on engine durability during in-flight, with data culled from precursor generic fuels studies like that of Soto et al. It begins by unpacking the variety of places SAF can come from — waste oils, algae and power-to-liquid synthetic processes — and wonders whether they can scale given feedstock constraints. Applied to life cycle assessment (LCA) the LMA can go far beyond tailpipe emissions for upstream energy inputs, land-uses damages while also considering other than CO_2 climate effects, e.g. contrail formation. When comparing to economics, the relative cost position of SAF vs Jet A-1 cost Some governments and institutions already play a significant role by subsidizing SAF, as the cost of producing SAF exceeds that of traditional Jet A-1 An examination of subsidies, carbon pricing mechanisms, and other commercial incentives that can help to close the gaps between SAF and traditional Jet A-1 are also covered later.It also covers technology readiness and points out the "drop-in" nature of SAF with existing aircraft engines and its compatibility with next-generation propulsion systems – specifically, hydrogen fuel cells and electric-hybrid configurations. It examines the present policy landscape—contrasting regional strategies such as THE EU's blending mandates against the U.S. tax credit approach—and calls for global goals to avoid the danger of incrementalist progress.The paper also identifies research frontiers in R&D (e.g., genetically modified microalgal strains, AI-optimized production and carbon capture-to-fuel pathways), which could support the transformation of SAF from bridge solution to flying sustainability by the end of the century. But nor does the analysis shy away from discussing some critical challenges: How much can cleaner jet fuel really compete with food production for the same feedstocks, and how can supply be ramped up in time to provide for world aviation demand while 2050 draws ever closer?But those results truly say, while SAF alone can't get the aviation industry to fully zero emissions, it is the critical bridge that keeps the industry progressing until alternative propulsion technologies are more mature. Producing green skies will require more than technological breakthroughs — it will require an extraordinary coming together of governments, industry, science and passengers. This paper attempts to provide an evidence-based, holistic perspective on SAF — cutting through the hype, and ensuring that aspiration and realism meet as we chart a course to the zero emissions in aviation.*

Keywords: *Sustainable Aviation Fuel, Zero Emission Aircraft, Green Aviation, Carbon Neutral Aviation, Alternative Fuels, Renewable Energy In Aviation, Biofuels, Synthetic Fuels, Hydrogen Fuel, Lifecycle Emissions, Aviation Decarbonization, Climate Change Mitigation, Net Zero Aviation, Sustainable Transportation, Future Of Aviation*

I. INTRODUCTION

Life as we know it today has been stitched on to the spine of aviation, producing an age that can zip quickly around the world, produce worldwide trade and adapt cross-cultural exchange. But it is also one of the fastest-growing sources of emissions and accounts for around 2–3% of global CO_2 emissions plus significant non-CO_2 climate impacts. By now, the climate is creeping over airplanes' deck-glass as a result of international agreements and net-zero commitments that are snaring aviation in a noose to hold its emissions steady if not bring them downward, and more gravitating toward sustainable propulsion. Electric and hydrogen aircraft are the HuffPost reasons given, though those can offer significant (technical, infrastructural, economic) challenges to anything beyond highly restricted ongoing use (e.g. no high-energy-density fuel for extended-range flights).

In that regard, it is undeniable that Sustainable Aviation Fuel (SAF) has quickly risen to the top as the best short and medium term option. SAFE is made using renewable or waste-based feedstocks and is designed to be a “drop-in” replacement for conventional jet fuel, enabling use with existing aircraft and infrastructure without changes in equipment. SAF can be blended at different levels with conventional jet fuel and can reduce life cycle greenhouse gas emissions by up to 80% depending on the feedstock and process used, so constitutes an important part of the aviation sector´s decarbonization strategy.

Hardly the straight story as to the SAF version of the narrative. Regrettably, the limited production capacity, production cost, competition with feedstocks and environmental performance of methylphenol have also given rise to serious doubts on the scalability and long-term sustainability of methylphenol (and the approach in general). As aviation demand continues to rise · on a global scale, the challenge is not only that SAFs be available in sufficient quantities, but also that their deployment advances true zero- · emitting aspirations — and not, as in too many other industries, short-term compliance.

Through a critical lens, this paper reviews SAF pathways as the chemistry and sustainability of future ZE aviation are considered including the economic and technological challenges, policy and regulatory frameworks, innovation and the 2050 roadmap. Balancing optimism and realism, it aims to bring little bit of light to the question of whether SAF is the future of fuel — or just a small detour on the road to an even bigger revolution in aviation.

II. SAF AND ZERO EMISSION CRUCIBLE

For more than a century, aviation has been a celebration of human striving, a banner of engineering that allows us to flit across oceans in two hours and see the curvature of our planet from creased leather seats. However, it does pollute. For commercial air traffic, climate impact is currently dictated by the CO2 emissions (of 2–3 % worldwide), but becomes around 4–5 % if a complete analysis (i.e. not restricted to CO2 emissions, also including non-CO2 effects such as nitrogen oxides (NOx) and contrail-induced cirrus clouds is considered. The challenge is different to land transport, in which electric fleets are now scaling – aviation must deliver the same sort of “safety case” with high energy density, demonstrate into a very harsh and demanding environment replication of that capability, and support a 20-30 year life airplane. And for the vast majority of the world fleet, that reality means the immediate shift to truly zero-emission flight — electric or hydrogen propulsion — remains a distant dream.

And this is where Sustainable Aviation Fuel (SAF) comes in. It is a family of aviation fuels that are produced within SAF, made from renewable or waste building blocks and intended to emulate Jet A-1.A-1 equivalent. It could be made from many feedstocks: waste cooking oils and animal fats, agricultural leftovers, municipal solid waste, algae, or even captured CO_2 integrated with green hydrogen. As SAF replicates the chemical behavior of fossil-based kerosene, it is possible to use oils in current original design, non-converted engines and fly the aircraft with standard pre-existing fuel tanks, varying thermal stability, prior to departure; a potentially attractive bridging technology to net-zero aviation.

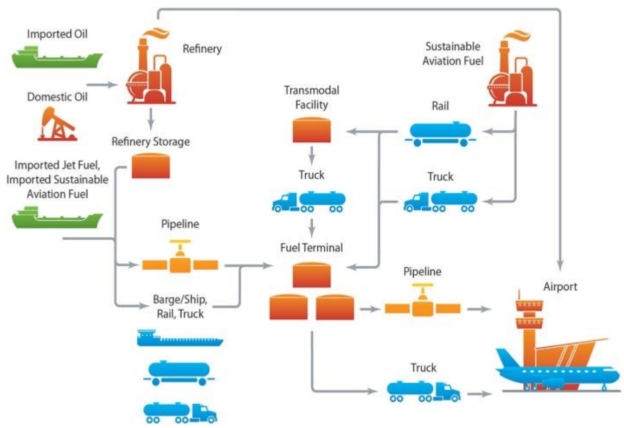
But the story of SAF is also a mixed one. While it has the potential to at least reduce life-cycle greenhouse gas emissions from use of conventional fuel by as much as 80%, its climate benefit really hinges on where and how feedstock is grown, processes used and energy sources through the supply chain. For instance, making SAF from waste oil is far better in terms of carbon profile than using purpose grown crops that potentially compete with food crops and cause indirect land use change. This, coupled with production capacity also inhibiting expansion. In fact, SAF accounts for less than 0. 1% of the global jet fuel consumption — a long step from the International Air Transport Association’s (IATA) ambitious goal of mandating a 65% SAF blend by 2050 to meet climte goals.

It is an economically based issue as well. SAF currently has a price that is two to five times higher than fossil aviation fuels because of limited feedstock availability, the capital-intensive nature of the process, and the scale of the economy. Governments and industry are searching for incentives — the tax credits in the U.S., blending mandates through the E.U. — but there has been no global synchronization of purpose. Without coordinated policy, there is a danger that international SAF uptake will lead to a small number of market regions becoming “islands of prosperity” with regions left behind.

So ascribing to zero-emission aviation is not a linear path. No, it’s not an ideal nor a permanent solution, but it’s the only scalable solution available today which could fit in your existing aircraft and infrastructure. It evaluates SAFs critically in light of science sources and pathways, environmental impacts, economic viability, legislative views, technical synergy etc., to establish whether indeed it is the fuel that will power Sustainable Aviation in near future.

III. SAF CHEMISTRY AND PRODUCTION ROUTES

While SAF is not a specific substance with a specific composition – rather, as the name suggests, it is a developing class of generic aviation fuels that can match the physical properties of conventional Jet A-1 kerosene enabling them to be used in normal aircraft engine technology without the need for any adaptation from the operators or manufacturers. What sets SAF apart from fossil-based fuel is the origin, as it is made from different shares of renewable or waste-based feedstock originating from responsibly sourced and managed to achieve lower net greenhouse gas (GHG) emissions throughout the fuel's life cycle. Feedstocks can be divided into three categories: lipid-based feeds such as waste cooking oils, animal fats and algal oils; lignocellulosic biomass including agricultural residues, forestry residues, and dedicated biomass crops; and non-biological feeds such as municipal solid waste, industrial off-gases, and captured CO_2 and green hydrogen in "power-to-liquid" processes. Each of them has sustainability trade-offs that are different: waste oils and fats has no competition with food crops; algae can be grown on non-arable land with low freshwater requirements; PtL fuels based on renewable electricity have almost no fossil carbon overhead if fully grown by primary energy, while purpose-grown bioenergy crops may lead to land use change which may even worsen the climate impact. A number of production pathways have been ASTM D7566 certified for producing jet-range hydrocarbons from those feedstocks. The most advanced alcohol-to-jet process, is hydroprocessed esters and fatty acids (HEFA) that deoxygenizes oils and fats with hydrogen to yield jet fuel-like hydrocarbons (Figure previous page). Fischer–Tropsch (FT) synthesis gasifies biomass or waste to syngas, which is subsequently catalytically converted to liquids; it is (feedstock) flexible but capital (intensive). Alcohol to Jet (ATJ) renders bio-ethanol or bio-butanol into longer hydrocarbons using dehydration and oligomerisation for aviation applications. Power-to-Liquid (PtL) fuels — sometimes referred to as "e-fuels" — fuse renewable hydrogen together with CO_2 captured from the atmosphere to produce hydrocarbons via FT-like processes, leading to - at least on paper - a carbon-neutral flight provided all of the input energy is renewable. Fuels are chemically identical to petroleum based kerosene, however the pathways have not been demonstrated at the production scale. Despite global waste lipid availability being insufficient to meet as much as a smaller fraction of aviation demand, HEFA technologies currently dominate SAF market production due to lower technology risk. In theory FT and PtL can scale to very large volumes but in either case there would be a hard cap on renewable resources and the technologies would need this sort of mass infrastructure investment, vast flows of low-cost renewables, and ongoing policy support to compete economically against the volume-priced fossil fuels. And yet the climate benefits of SAF are not all the same, something that marketing-speak usually takes no note of. Key reasons why life cycle GHG emissions vary widely are due to the original feedstock (and how it was grown or gathered), and the carbon intensity of production. HEFA SAF from waste fatty oils can reduce greenhouse gases by over 80% against Jet A-1, HEFA made from palm oil may achieve only limited benefits net of forest clearings that had to occur to free up land, whereas PtL fuels might be —individually— the most climate-friendly of all, but are also very energy intensive and have very large carbon footprints if they are fuelled by fossil-heavy grids at their base. While the chemistry is fairly simple for SAF and the production technologies are now validated at pilot and early commercial scales, scaling of this central decarbonization solution poses special challenges in that as we scale up we can't just shift environmental burdens from the atmosphere down to the land, water and energy systems that underpin its production.



IV. THE LIFE CYCLE OF A PAN, LCA

The environmental justification for SAF is namely that it can help mitigate the climate impact, in particular its life cycle GHG emissions of aviation by assuming a variety (and a certain combination) of interrelated conditions that in the present article are derived as no panacea, nor self-consistent, and dependent on a few provisos. SAF, meanwhile, can cut life cycle CO2 emissions by up to 80% (the majority of that comes from stripping the carbon atoms out of jet fuel, where they'd remained stored for millions of years underground and replacing them with newly biologically or air capture sequestered carbon) at its best. Those numbers are highly dependent upon the feedstock, what's used as an input, the production pathway, energy inputs and land-use impacts. A detailed power-intensive process known as Life Cycle Assessment (LCA) is required to account for everything involved, from tailpipe emissions and growing or harvesting feedstock to transporting, processing and turning it into fuel, as well as distributing and burning the fuel in aircraft engines. At the exhaust, burning SAF still produces CO_2, but the thinking is that this CO_2 was already in the atmosphere or siphoned out of waste streams, and if managed well it becomes a nearly balanced carbon loop. UNEP's Global Environment Report identifies various different genera of bioenergy feedstocks and some Riposte to land use, LUCS and GHG mitigiation questions: quoth; one example cited in EAR of HEFA SAF from waste cooking oil that can potentially deliver up to 80% savings of GHGs with virtually nil net land use impacts (vs for instance saf derived from palm oil and so,or purpose grown bioenergy crops) can themselves effect LUC scenarios – including deforestation or peatland drainage among others – that releases vast amounts of carbon sequestered since the stone age and that ensures no climate gains will be realised for decades just for the one good reason not to be bringing on board all fuels that can demonstrate CCW conditions. Alongside CO_2, SAF could also lower other pollutants such as sulfur oxides (SOx) due to its low sulfur content, providing the opportunity to increase local air quality at airports. On the other hand, NOx emissions are usually the same as for conventional fuel, since the combustion conditions will be more or less the same and some investigations have reported that no major decreases in NOx will be observed in any blending of SAF. Research is also underway into non-CO_2 impacts of the climate from contrail formation and the production of induced cirrus clouds, with early studies even hinting that lower aromatics in SAFs might diminish soot particle emissions (the nuclei around which ice crystals grow in contrails) and therefore their warming effects, but not yet evidenced at scale. Life cycle assessments also reveal trade-offs in other environmental categories. Water Cost in SAF In most SAF paths, especially in algae growth or some of the biomass pretreatment processes, large amount of water uses are still a concern (108). The choice of energy source also makes a difference: a PtL fuel plant drawing its fuel from coal-heavy electricity can eliminate much of its carbon benefit, while the same plant linked to an input of wind or solar energy is likely to have nearly net-zero life-cycle emissions. Its place in the circular economy is also key in terms of SAF – in particular if produced from waste streams it is a way to divert materials from land-fills and reduces methane. But waste feedstocks are only as useful a resource the following conditions are met; namely: If a) the existing use of the resource is able to accommodate increases in demand and b) the resource is not being over-harvested to meet low- tipping waste reduction. In summary, environmental analysis of SAF requires more than tailpipe emissions calculations and simplistic percentage savings—instead, a systems view of feedstock sustainability, energy source and co-product management will be necessary to include the indirect effects. Unless SAFe is introduced with stringent and transparent life cycle assessments, this may instead be turning into a SAFe brasion, rather than a genuine climate anything. When sustainably sourced and produced with low-carbon energy, SAF are also a powerful short-to-medium-term decarbonization lever for the aviation industry; environmental opportunity is tempered by unsustainable feedstock sourcing, land use change, and fossil-intensive energy inputs.

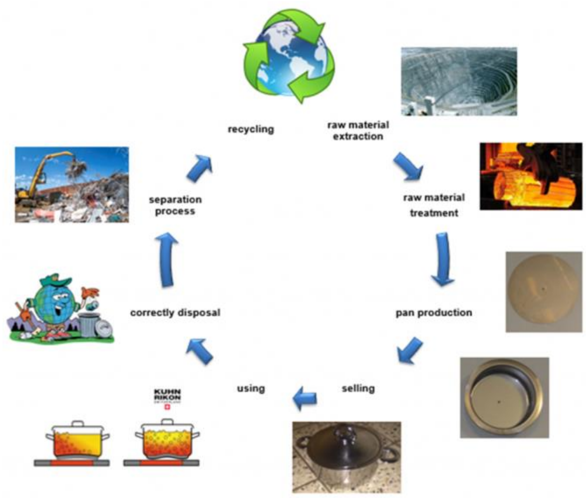


Figure 2: The Life Cycle Of A Pan, Lca

V. ECONOMIC VIABILITY AND MARKET CHALLENGES

The single biggest obstacle to widespread adoption of SAF for heavy commercial use is obviously economics, as SAF currently sells for up to two to five more times the price of regular Jet A-1 fuel — a margin that many airlines, which work on low margins as it is, simply will not swallow without government intervention or consumer acceptance and willingness to pay the so-called "green premium." There are many reasons for this cost difference, such as the constraints on the availability of feedstock to produce SAF, the scale at which SAF producing facilities can operate and the large capital costs that are incurred when producing SAF (5)(5) in addition, many facilities will require more input of energy in the form of electricity when compared to normal petroleum refining. For the oldest of the SAF pathways, fuels produced via the Hydroprocessed Esters and Fatty Acids (HEFA) process - it could run into some feedstock issues as it is based on waste oils and fats; a feedstock in global demands, likely to make competing industries such as biodiesel and oleochemicals production push the feedstock price range higher. Although more developed routes, such as Fischer–Tropsch (FT) and Power-to-Liquid (PtL), can in principle be up-scaled to meet the global demand for aviation, both require upfront investments of billions and PtL even also significant existing renewables and years until they reach commercial competitiveness. As with any industrial process, the economics of SAF are already being shaped by government incentives and other interventions: in the U.S. tax credits tied to lifecycle carbon reductions for SAF producers that section 92405 of the Infrastructure Investment and Jobs Act creates, in Europe quotas for blends mandated by ReFuelEU Aviation, in many places carbon pricing that tries to put a price on fossil fuel emissions. But they are often piecemeal and inconsistent in different regions and thus open to challenge that could create investor uncertainty and delay the development of a truly global SAF market. That's just as airlines have begun to sign long-term offtake agreements with SAF producers, to secure future deliveries, and to hedge against price risk — though these contracts generally come at a premium, and in many instances are open only to well-capitalized carriers. But it's an open question how much consumers will be willing to pay; what little survey data does exist from passengers suggests that they are on board with decarbonizing but less likely to be willing to shell out a significant premium for tickets, especially in price-sensitive markets. Additionally SAF economics are tied at the hip to oil prices–when brent prices go down, it actually makes SAF much less of a delta to overcome for jet fuel and when those prices are high: SAF moves up in value where it should be but that also is going to drive competitive pressure for feedstocks in the same enviromony. The promise is that economies of scale will kick in: as volumes increase, costs will go down through efficiency in process, learning in technology, and streamlining of logistics. But scaling requires a chicken-and-egg solution: producers won't build capacity without demand, and airlines won't commit to buying without cheap supply This is especially acute in the case of SAF – without strong policy frameworks in place, there is a risk that SAF deployment would be concentrated in wealthier markets and the decarbonization of aviation would become even more unbalanced between emerging and mature markets. At the end of the day (although if I were reading this article, I believe I would have already concluded it a few pages back) an economically profitable SAF value chain capable of sustainably growing capacity requires some sort of a synchronized combination or market act of public investment, private money, technology scale-up, and policy stability – without which SAF runs the risk of being a high priced competing fuel as opposed to having access to mainstream aviation energy on par both in price and availability with the fossil based jet fuel.

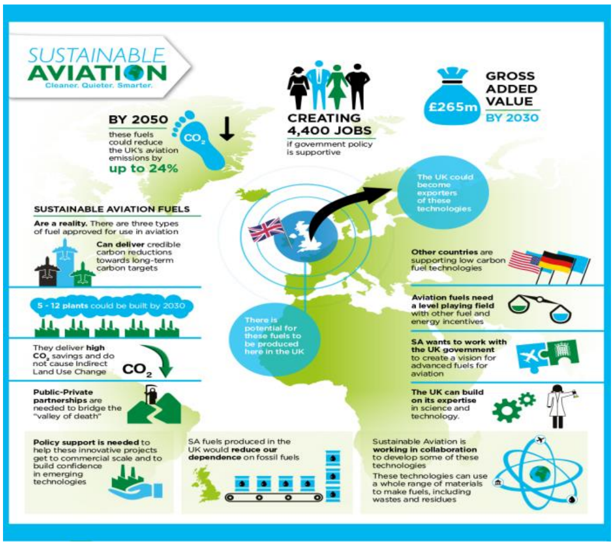


Figure 3: Economic Viability And Market Challenges

VI. HYBRIDIZATION IN CURRENT/FUTURE AIRCRAFT

The most appealing aspects of Sustainable Aviation Fuel (SAF), is that it is a "drop-in" fuel, meaning it is similar enough to the Jet A-1 that can be mixed and used in the current aircraft engines and in the fueling infrastructure with minor to no changes, a characteristic that greatly reduces the barrier of adoption as compared to disruptive solutions such as hydrogen or battery-electric propulsion. This is because SAF is chemically similar to petroleum kerosene, the cloud point range, vapor pressure, freezing point, energy density etc., compatability (also known as "compatibility") requirements laid down under ASTM International specifications are met. SAF is today certified under the ASTM D7566 standard process for blending up to 50% with conventional jet fuel, although testing is being heavily conducted to get the 100% SAF certification — a key factor if the aviation industry is to reduce its carbon footprint without demanding for a total re-engineering of aircraft. But the technology implementation does not involve only the fuel, but also the transformation of operations, maintenance and even of the fuel supply chain, regarding the similarity of SAF. On one hand, some SAFs types (50 % of global aviation fuel demand by around 2050, then SAF could help the industry achieve its net-zero emissions goals while maintaining the economic and social value of air travel. But this is only achievable if we see SAF as more than a boutique sustainability initiative and as one of the keystones of aviation scale decarbonization exercises instead. The urgency of now need not be rehashed, but the sobering lesson of 2019 is that each year of delay locks in this legacy of ever more challenging (and expensive) catch-up in the years that follow if we are to meet climate goals. This critical review ultimately underscores the fact that while SAF is not a panacea, it's a critical weapon in the war on aviation carbon emissions. And, with strong policy support as well as technological innovation and a clear long-term vision, it could help moving SAF from today's expensive experiment to the leading carbon-free fuel choice of the future for aviation. For aviation, this is where the challenge lies to demonstrate that economic ambition and environmental responsibility are not mutually exclusive, they are in fact mutually reinforcing along a pathway of clean skies linking the future.

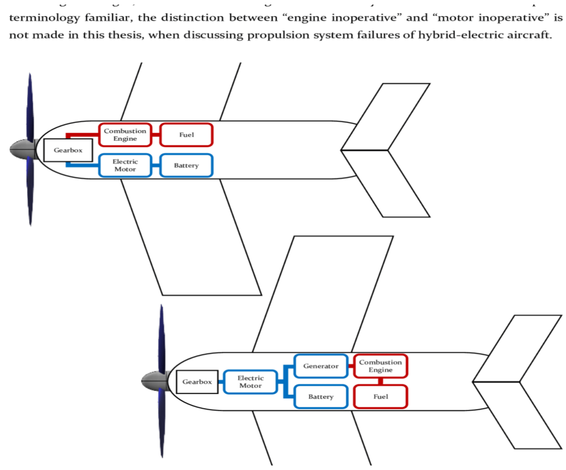


Figure 4: Hybridization In Current/Future Aircraft

VII. CONCLUSION

The path to zero-emission flying is not a straight line, it's a sophisticated and evolving delta, with sustainable aviation fuel (SAF) acting as a critical bridge. The critical discussion above shows that indeed SAF is not a silver bullet, panacea solution but it is one of the practicable and most immediate routes for mitigating GHGs for aviation. Unlike futuristic propulsion systems like hydrogen or fully electric aircraft, which require completely new infrastructure and technology overhauls, SAF provides a "drop-in" replacement that can be used in the existing engines and fueling systems. This compatibility also provides an invaluable head start, as it means that airlines and airports can begin cutting emissions now — without needing to wait years or decades for breakthrough technologies to be readied.But the potential of SAF has its obstacles. The first can be found in feedstock availability, and sustainability. Using food crops for biofuel raises moral concerns regarding food security and land use, and waste-based and advanced biofuels, while more sustainable, are not yet available on a large scale. Increasing the scale to accommodate the world's requirements, without damaging biodiversity or driving indirect land use change, is a finely weighed tightrope. And synthetic fuels produced from renewable electricity and with carbon capture, while theoretically promising, are still energy hungry and economically uneconomical—perhaps perpetually. This is illustrative of a contradiction: in theory SAF can significantly cut emissions but its practical use depends on how it is sourced, processed and blended into the wider energy system.But yet again, cost is a motif in this analysis. SAF is much more expensive than fossil-based jet fuel, making it a challenge for broad industry acceptance. In the absence of coherent policy measures, subsidies, and international cooperation, airlines might not have enough reasons to adopt SAF in a very significant proportion. And consumer pressure and the right carbon pricing mechanisms have to be connected to the fact that it's the actual business of aviation (not merely a marketing trope) that shifts to SAF. This underlines that the shift to SAF is not just one of technology - it's profoundly political and economic, and demands a concerted effort from governments, the industry and passengers.However, despite the obstacles, SAF must not be ignored. Its role is especially crucial in the vicinity for the short and medium term, where battery-electric and hydrogen-powered substitutes could remain a non-starter for decades, particularly for long-haul flights. In this way, SAF serves as a bridging technology—lowering emissions today while researchers, manufacturers, and policy makers have time to perfect next-generation propulsion systems. The movement toward SAF represents a cultural change in aviation where the industry has come to terms with its environmental responsibilities and is now mapping the way forward to sustainability.In summary, the critical SAF analysis for zero-emission aircraft presents a cups-half-full glass. SAF is not a silver bullet that will deliver complete decarbonization, but it is a major piece of the puzzle. The future of aviation likely involves a patchwork of solutions: SAF to deliver immediate reductions, hydrogen and electrification to deliver them long term, and efficiency gains up and down the spectrum of aircraft design and operations. The world should avoid the trap of treating SAF as a silver bullet, and instead acknowledge that it has the potential to make important strides in what is known as a “hard to abate” sector. The follow-up could then be to supplement promising projects with even stronger policy backing, inspire more substantial investment, and attract the necessary genuine commitment from the stakeholders so that SAF can be the aviation sector’s first big thoughts on flying without harming the world.

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