Sustainable Aviation: Driven by Policy or Technology?

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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(6420 Words)

I. Introduction

With unrivaled speed and increasing convenience through ever-expanding route networks, aviation has become a dominant form of transportation in today's world. Change in this regard appears unlikely as new transportation technologies, such as Hyperloop, with the ability to rival aviation's breadth and speed, have not come to fruition as originally intended (Smil, 2025). Furthermore, continuously growing passenger counts since 1980 have only cemented aviation's role as a key transportation method in the 21st Century (IEA, 2020). The aviation industry, however, is reliant on fossil fuels as combustion remains the principal means of propulsion for aircraft and viable alternatives do not yet exist (Nelson & Reddy, 2017).

Currently, the aviation industry emits 1.3 billion tonnes of CO_2 accounting for nearly 2.5% of global CO_2 emissions (Ritchie, 2024). As other industries decarbonize, the aviation industry's share of global CO_2 emissions is set to drastically increase and the industry will become a key driver of continued anthropogenic climate change. As has been previously mentioned, alternative propulsion methods for aircraft such as electricity or hydrogen fuel cells do not exist, presenting a key challenge to the industry (Nelson & Reddy, 2017). Having an unknown delivery timeline for these prospective technologies does not bode well for the environment and will be responsible for an increase in the share of physical global warming caused by the aviation industry.

With an ongoing global effort to combat climate change there has been an environmental lens applied to the activities of all industries. Subsequently, policy and technological changes have been pursued in hopes of reducing the environmental impact of said industry. It is evident that such changes are being sought for the aviation industry. However, this paper claims that the aviation industry presents a unique case in which simple political solutions have a limited effect on overall sustainability and that any major reduction in the impact of aviation on the environment will be driven by technological changes. However, this is not to say that policy plays no part in creating a more sustainable aviation industry, but rather that political actions will be most effective in a supporting role to technological innovation. The intention of the paper is to utilize a system analysis lens to evaluate the effectiveness of various policies and technologies towards generating a sustainable solution for the aviation industry and the reflexive impacts that these two interrelated components have on each other.

II. Problem Definition: The Growth of Air Travel and its Emissions

Since its inception, the airplane has provided a fast, reliable, and far-reaching mode of transportation. With the jet age having resulted in the significant technological advancement of aircraft propulsion and the Boeing Company's revolutionary 707 making its first transatlantic flight in 1958 from New York City to Paris in record time, the age of modern air travel had begun (Lukas, 2004). Combustion-powered jets drove the dramatic increase in passenger counts during the start of the era with an increase from 42 million to 205 million passengers over the period from 1955 - 1972. This rapid and unprecedented growth in popularity is further demonstrated by the number of total airline passengers internationally surpassing the 1 billion mark for the first time in 1985 (IEA, 2020). The number of passengers has continued to increase with an estimated 5 billion traveling the world's skies in 2024 (IATA, 2024). Such an increase in passenger counts requires that more planes are in operation. Ergo, it is no surprise that the aviation industry has been responsible for rising emissions of CO_2 and other greenhouse gasses (GHG) responsible for contributing to human-caused climate change.

Currently, almost all aircraft, with the exception of a few experimental and prototype models, rely on combustion as a main means of propulsion. This in turn means that aircraft, and consequently the aviation industry, are heavily dependent on the use of fossil fuels. As the industry has grown, so too has its environmental impact. This is evidenced by the quadrupling of yearly CO_2 emissions from 1960 to 2019 as shown below in Figure 1 (Ritchie, 2024).

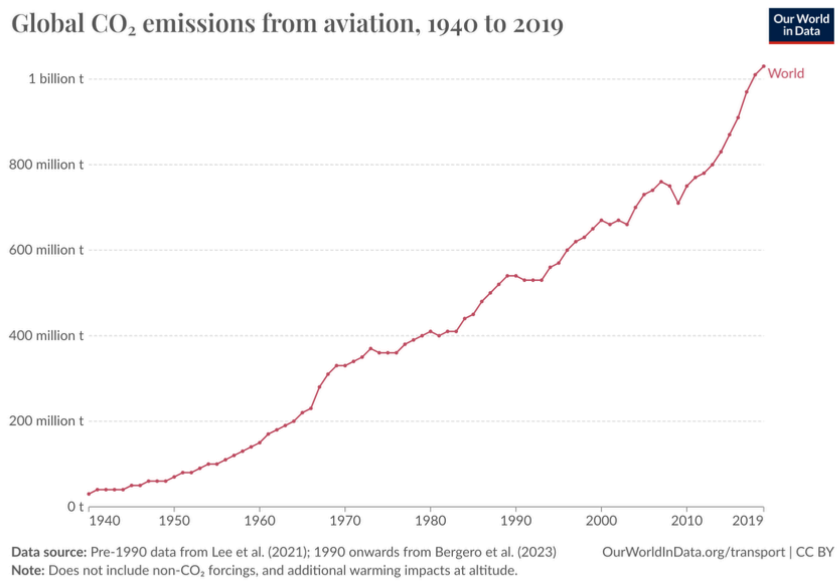

Figure 1. Global CO_2 emissions from aviation from 1940 to 2019, (Ritchie, 2024).

It is common knowledge that CO_2 is one of the greatest drivers of global warming which does not bode well for the aviation industry's sustainability. While these CO_2 emissions only constitute 2.5% of the global total and are far surpassed by the 15% of overall emissions released by cars and trucks, the contribution of the aviation industry to climate change remains outsized (Ritchie, 2020, Ritchie, 2024). Other heat-trapping gasses and substances such as soot, sulfur dioxide, and water vapor are released throughout an aircraft's flight. As a result the total percentage contribution of the aviation industry to the total warming experienced since pre-industrial times is estimated at between 3.5% and 4% (Ritchie, 2024).

While seemingly insignificant, these percentages are not representative of the industry's impact in the near future. As other industries decarbonize, the proportion of global emissions attributable to aviation is set to increase. By 2050, it is estimated that the industry will be responsible for 27% of global emissions representing a nearly fourteen-fold increase from the present day (Delbert, 2022). Clearly, without drastic decarbonization efforts, the aviation industry will become one of the foremost drivers of climate change. What is more difficult, however, is adapting an industry dependent on the combustion of fossil fuels to a more sustainable era of transportation.

Important to note is that while two-thirds of the aviation industry's radiative forcing is caused by non-CO_2 emissions, this paper intends to focus primarily on CO_2 emissions (Ritchie, 2024). This decision was made considering a variety of factors. First, CO_2 is the most notable GHG and the proportion of its emissions from aviation stands to grow significantly with respect to global CO_2 emissions (Delbert, 2022). Additionally, CO_2 emissions have the longest warming impact in the atmosphere while the effect of non-CO_2 emissions on the climate is short-lived (Air Transport Action Group Project, 2021, Federal Aviation Administration, 2021).Also necessary to point out, is that most solutions to the issue of aviation sustainability are evaluated on their ability to reduce CO_2 emissions which are proportional to fuel burnt as are a portion of the other emissions and chemical species that result from air travel (Dobruszkes, et al., 2022). Thus, while the industry's contribution to climate change is also dependent on certain GHGs that are emitted disproportionately to fuel burn, their inclusion in this analysis would drastically expand the scope of this research paper. Such a venture would detract from the true intent of this research to determine the role of technology and policy in creating a more sustainable aviation industry.

Key segments of the transportation industry look set to be on a course toward decarbonization. While road vehicles have long been the top emitters of greenhouse gas emissions accounting for nearly 75% of transportation emissions, this appears set to change

(Ritchie, 2020). As Hannah Ritchie notes in her article, “The rise of electric vehicles offers a viable option to reduce emissions from passenger vehicles” (Ritchie, 2020). In fact, such adoption of the technology is already occurring with electric cars comprising 18% of all new vehicle sales (Ritchie, 2024). Electric vehicles result in decreased CO_2 emissions, even when powered by electricity from non-renewable sources with an average 66% reduction in emissions across the United States (Kirk, 2023). Without rapid change, the aviation industry is set to take on a much more significant role as a carbon emitter within the transportation sector.

Designing less environmentally impactful aircraft would certainly have boundless benefits, and such advancements have indeed been made. Since 1970 the energy intensity of aircraft has decreased by 1% per year representing an increase in efficiency (Bergero, et al., 2023). While the quantity of CO_2 emitted per passenger has also declined, emissions from the aviation industry have still continued to increase due to growing global demand with slight aberrations due to the COVID-19 Pandemic (Ritchie, 2024). This is demonstrated below in Figure 2.

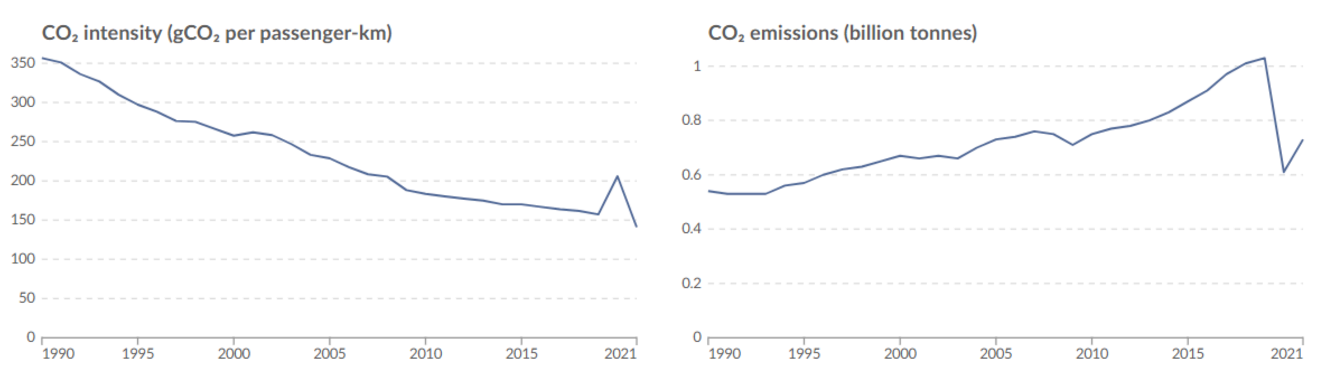

Figure 2. Carbon intensity per passenger in comparison to overall CO_2 emissions by the aviation industry, (Ritchie, 2024).

Such a trend exemplifies the concrete need for a radical redesign of aircraft in order to minimize carbon emissions. However, “when it comes to electrification of the aircraft technology, there are several challenges and technological limitations faced by the designer such as vicious weight cycle, in-sufficient energy density and power constraints in batteries" (Siddhartha, et al., 2019). Simply put, the ratio of battery weight to the amount of energy they are able to store is not comparable to conventional jet fuel. To compensate, more battery cells would be required further increasing the weight of the aircraft. As such, the development of electric aircraft has yielded no practical results, and today there does not yet exist an electric aircraft comparable to their traditional, combustion-based counterparts (Nelson & Reddy, 2017). The electric aircraft in development today target short to medium-haul flights such as *Alice* designed by the startup Eviation (Delbert, 2022). Highlighting the current impracticality of a rapid switch to electric aircraft is the ability of Eviation's electric plane to only carry nine passengers at a maximum range of just over 400 kilometers. Further at issue is the fact that such short flights are not a significant source of fuel burnt and emissions. While accounting for 27.9% of total departures from airports in 31 European countries, flights under 500 kilometers were responsible for 5.9% of fuel burnt (Dobruszkes, et al., 2022). Conversely, while only 6.2% of departures were for flights in excess of 4000 kilometers, these flights accounted for 47% of fuel burnt (Dobruszkes, et al., 2022). It is evident that while electric aircraft have the potential to operate effectively on short to medium-haul routes, the vast majority of the aviation industry's emissions stem from less common, longer-distance flights.

Hydrogen has also been touted as a replacement for traditional jet fuel; however, this alternative also suffers from a low energy density (Lecca & E&E News., 2024). With the lack of truly revolutionary technologies that eliminate the need for traditional jet fuel, other solutions have emerged in hopes of reducing the negative impact that aviation has on the environment. For this research paper these solutions will be divided into two groups, those being technological and political. As the name suggests, technological solutions attempt to minimize the effect of the aviation industry via physical technologies which include advancements such as sustainable aviation fuel (SAF), upgrades to airport infrastructures, and enhancements to aircraft to improve efficiency among others (Budd, et al., 2013, Nelson & Reddy, 2017, Deshpande, et al., 2022, United States Congress House Committee on Transportation and Infrastructure Subcommittee on Aviation, 2023).

The political solutions group includes proposed policies that ban short-haul flights when alternative transportation methods are available or carbon budgets for airlines through carbon markets to achieve net zero emissions (Budd, et al., 2013, Dobruszkes, et al., 2022) Such technologies and policies will be discussed in the succeeding section with focus on their respective abilities to contribute to a cleaner aviation industry. The individual impacts of each of these solutions, be they technological or political, are well established. Afterall, such information is required to assess these solutions effectiveness and to determine which deserve investment and implementation. However, political and technological solutions do not exist in a vacuum irrespective of one another. Interaction is all but guaranteed, and the intention of this paper is to explore said interaction in more depth. Analysis will be conducted to determine what effects both groups of solutions can exert on one another. Such analysis lends itself well to the utilization of Sociotechnical Research Rationale, alternatively STSR.

III. Research Approach: Utilizing a Systems Analysis Lens

According to Professor Kathryn Neeley, at the University of Virginia, “STSR draws on a deep understanding of the contexts in which engineering problems are defined and new technical capability is implemented” (Neeley, 2024). STSR is a form of analysis that can be applied to any situation in which technology plays a role in human activity. In the instance of this paper, interplay between technology and policy is of prominent focus with anthropogenic climate change undoubtedly classified as a human activity. The justification for employing STSR analysis is rooted in a desire to develop an awareness that the development of technologies is often dependent on contextual factors that extend far beyond the technologies themselves (Neeley, 2024). However, at its core, STSR seeks to "achieve positive change in large sociotechnical systems or to promote more constructive discourse about controversial issues" (Neeley, 2024). As such, STSR can be utilized as this paper intends to explore the possible ways in which positive change can be brought about in the large sociotechnical system of the aviation industry.

The process of conducting research using STSR can occur via a variety of modes. These three modes of analysis are historical, discourse, and systems (Neeley, 2024). A systems analysis lens will be drawn on to evaluate the effectiveness, impact of, and interplay between political and technical solutions to the issue of the aviation industry's sustainability. As described by Professor Neeley, "System Analysis focuses on relationships between interrelated components that form a whole" (Neeley, 2024). The ultimate goal of such an analysis is to "discern patterns of cause and effect that may–or may not–occur in the system that is the subject" (Neeley, 2024) and to positively change said system. The process of systems analysis consists of three essential steps. To begin, one must develop categories in order to classify the components being investigated (Neeley, 2024). Second, research and analysis must be conducted to understand the relationship between and the ways in which the components interact with one another. Finally, a model of the system including the connections between its components can be constructed. In such a way, conducting a systems analysis of a given sociotechnical system can provide beneficial insight into how to better improve the system (Neeley, 2024).

By definition, systems analysis is responsible for analyzing various constituents in a larger sociotechnical system. As such, it is justified to utilize this lens when examining the sustainability of the aviation industry. Political and technological solutions are both components that form a whole. Both are related, influence each other, and are part of the greater sociotechnical system that is the ultimate solution to the issue of sustainability in aviation. The ability to divide these solutions into two clear groups and their presence in one greater solution system makes systems analysis an optimal approach. As has been mentioned previously, policy and technology do not exist without interdependence. In some cases both can be used separately with the intent to address a problem, and in others can be dually applied. Given the intention of this research paper to determine the true role of policy and technology in solving the aviation industry's sustainability crisis, both political solutions and their technological counterparts will be analyzed individually by merit, and together to develop a greater understanding of the solutions available at present. With a focus on interconnection and relation between these components in the overall system, this STSR lens will help to bring clarity to the complex bond of policy and tech, hence why it has been selected as the main research approach.

To begin with a systems analysis approach the components of the greater sociotechnical system are divided into relevant categories. In this case, these categories are technological solutions and political solutions that further the sustainability of the aviation industry. Within these groups, the solutions are specified, and the division is shown below in Figure 3.

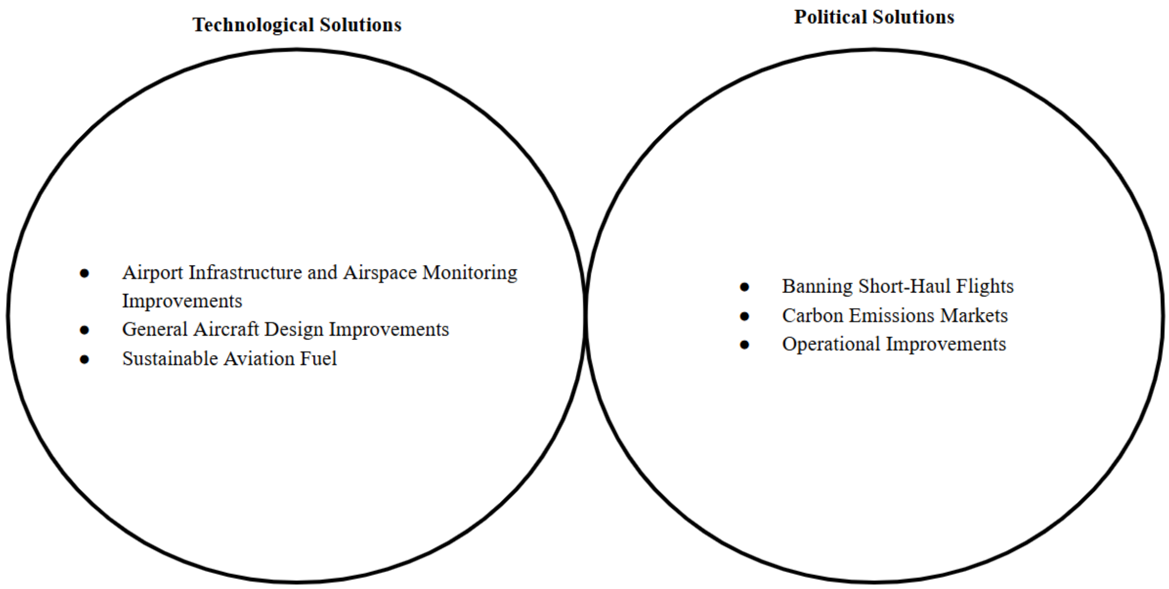

Figure 3. Division of solutions for STSR systems analysis, (Stambaugh, 2025).

This division is intentional in its clarity and divisiveness. Technological solutions only include those that are physical. Standing in contrast are the political solutions, which while intent on producing tangible results are intangible themselves. However, this simple division does not account for the interrelatedness between the two categories of solutions and a third overlapping group can be created as demonstrated in Figure 4.

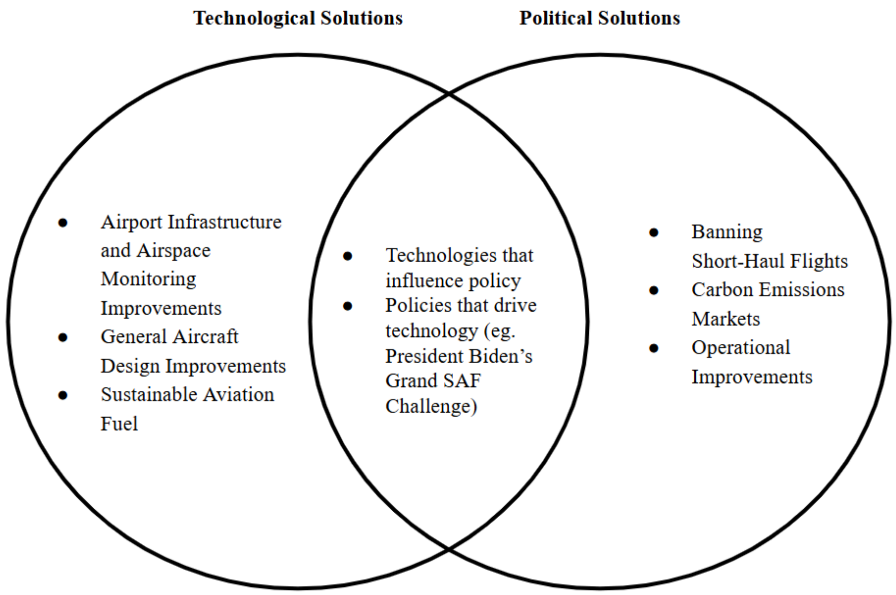

Figure 4. STSR systems analysis grouping with technical-political interplay included, (Stambaugh, 2025).

Both of the original technological and political solution categories contain the same components, however, the inherent overlap of the two categories is acknowledged. With this second grouping, the complexity of the sociotechnical system of sustainable solutions for the aviation industry is established providing the basis for further analysis of the interinfluence between the two sub-categories.

IV. Results

A. Implemented and Proposed Solution Descriptions

Before delving into an in-depth analysis of the decarbonization potential of the various aforementioned solutions, it is necessary to provide more information on their background. First amongst the technological solutions that achieve decarbonization through reducing the amount of aviation turbine fuel (ATF) burnt are *Airport Infrastructure and Airspace Monitoring*

Improvements (Deshpande, et al., 2022). In the case of the United States, such efficiency-increasing initiatives include the realization of the Next Generation Air Transportation System (NextGen) (FAA, 2021). According to the Federal Aviation Administration (FAA), "Many of NextGen's planned infrastructure improvements are complete, having deployed advanced navigation, surveillance, communication, automation, and information infrastructure across the U.S. [national air space]" (FAA, 2021). Additionally, upgrades directly to the infrastructure of existing airports can have an impact on the overall emissions from the aviation sector. Such improvements include gate electrification to reduce the use of aircraft's auxiliary power units (APUs), improved airfield design to reduce taxi times and minimize fuel consumption, and the installation of infrastructure required to implement alternative fuels such as SAF (United States Congress House Committee on Transportation and Infrastructure Subcommittee on Aviation, 2023). The group of *General Aircraft Design Improvements* consists of evolutionary changes to aircraft design, concerning both airframe and propulsion systems. Such efforts enhance the efficiency of aircraft using already existing and not far-off technologies. For example, these technologies include decreasing aircraft weight by using composite materials, geared turbofan engines, very high bypass ratio engines, and wingtip devices to name a few (Air Transport Action Group Project, 2021). The final solution within the technical solutions group is *SAF.* At a 2021 United States congressional hearing centered on addressing climate change at the nation's airports, *SAF* was described as "a type of jet fuel refined from biomass, waste streams, or gaseous carbon oxides", and "has emerged as a leading contender to reduce aviation emissions" (United States Congress House Committee on Transportation and Infrastructure Subcommittee on Aviation, 2023). *SAF*'s advantage is derived from its ability to be blended with traditional ATF and easily integrated into current aircraft engines without the need to develop revolutionary technologies. Notably, there are still challenges to widespread adoption of *SAF* such as production and acquisition costs, two factors responsible for the fuel's limited availability. While technological solutions are often the more visible and advertised, important policy objectives that have been both proposed and implemented.

The first of the political solutions, *Banning Short-Haul Flights,* has seen introduction within Europe. Both Austria and France have banned select flights for which an alternative by train only takes between 2.5 and 3 hours (Deshpande, et al., 2022). Several other countries have also considered this strategy as a method of reducing carbon emissions (Dobruszkes, et al., 2022). The term *Carbon Markets* refers to a strategy known as "cap-and-trade". For example, the European Union Emissions Trading System (EU ETS) operates to mitigate carbon emissions (Pace, 2024). In this system "[t]he [European Union] sets a cap on the total volume of greenhouse gases that can be emitted by all the [aircraft operators] covered by the EU ETS [with] [t]his cap [decreasing] each year to meet emissions reduction targets" (Pace, 2024). To compensate for their environmental impacts, airline companies are given and also must purchase allowances through an auction that permit a certain quantity of emissions. For the EU ETS, the percentage of allowances freely allocated has continually decreased, with 100% of allowances to be auctioned from 2026 onwards (European Commission, 2025). Annually, aircraft companies must surrender enough allowances to cover their total emissions for the year (Pace, 2024). These allowances can also be saved for future use or sold to other companies should the original company not emit enough GHGs to require the total surrender of their allowances. As time goes on, the percentage of allowances that are auctioned increases. The final policy solution to be discussed is *Operational Improvements*. Examples of these improvements are planning more efficient flight trajectories, safely allowing more aircraft to fly at their most fuel-efficient speeds and altitudes by reducing separation distances, and more well-organized sequencing of flights (FAA, 2021). Two further examples of operational improvements are reduced-engine taxi and last-minute fuel and water uplift (Air Transport Action Group Project, 2021). The above political solutions hold promise for reducing aircraft emissions; however, to determine whether their impact can exceed those of technological innovation, their carbon reduction potentials must be compared.

B. Effectiveness of the Solutions in Eliminating Emissions

The solutions discussed previously, both technical and political, can be evaluated on their ability to reduce carbon emissions and the contribution of the aviation sector to climate change. While any effort to minimize environmental impact is a welcome improvement, the solutions differ in their scope of effectiveness. Additionally, appearing here, in the analysis of decarbonization potential, where the first inextricable connections between technology and policy are revealed. Such relation is evident when viewing the effectiveness of *Airport Infrastructure and Airspace Monitoring Improvements* and the resulting *Operational Improvements* made possible. Deshpande, et al. estimate that, from these modifications, a decarbonization potential of 10% of tail-pipe emissions is achievable (Deshpande, et al, 2022). The result is that a modest, yet tangible reduction in carbon emissions is possible given upgrades to airport infrastructure and airspace monitoring in combination with revised operational policies. While the impact of these solutions can be significant, they “will not provide the largest contributions to long-term CO_2 reduction” according to the Air Transport Action Group (Air Transport Action Group Project, 2021). However, significant to note is that “it will be a challenge to maintain and improve upon current efficiency levels as demand for airspace increases and modernization efforts focus on safely accommodating that demand” the FAA

(FAA, 2021). As a purely technological solution, *General Aircraft Design Improvements*, has a decarbonization potential of up to 22%, a markedly higher increase over the previous solutions discussed (Deshpande, et al., 2022). Of further importance is that the three preceding solutions all are deemed as medium to high in their readiness and scale-up potential.

While not included in the technological solution group due to their low technological readiness and scale-up potential, both all-electric and hydrogen-powered aircraft have significant carbon emissions reduction potential. For all-electric aircraft this decarbonisation value stands at 100% while for hydrogen-powered aircraft it is lower, ranging from 50-90% (Deshpande, et al., 2022). Such technologies possess significant capabilities for reducing the environmental impacts of the aviation industry. However, without immediate promise, it is essential to look towards current technologies such as *SAF*. Tremendous potential exists with the further adoption of *SAF* as a sustainable solution for the aviation sector. Estimates for life-cycle emissions reductions vary, ranging from 65-80% while tail-pipe emissions could be reduced by up to 100% (Deshpande, et al., 2022, United States Congress House Committee on Transportation and Infrastructure Subcommittee on Aviation, 2023). While the global technological readiness of *SAF* is rated as low-medium, its potential scalability being rated medium-high positions the fuel as a critical tool in the aviation sector's transition towards sustainable operation.

The effectiveness of policy in combating the growing environmental impact of aviation should also be evaluated. First amongst the policy interventions is the *Banning of Short Haul Flights*. While in principle, decreasing the overall amount of fuel burnt would seemingly reduce emissions, the reality is that the flights targeted by these initiatives are not key contributors to aviation's environmental impact (Dobruszkes, et al., 2022). Given this, "banning super short-haul flights will help very little in mitigating aviation's contribution to climate change" (Dobruszkes, et al., 2022). This is evident when viewing the results of the short-haul flight ban in France. Prohibiting flights for which a train alternative of less than 2.5 hours would only cut 0.5-1.6% of total carbon emissions from the French aviation sector depending on the routes cut (Txapartegi, et al., 2024). Such modest reductions pale in comparison to those offered by even the most basic technological solutions such as *Airport Infrastructure and Airspace Monitoring Improvements.*

Carbon Emissions Markets have also been touted as an intervention capable of incentivizing aircraft companies to operate more sustainably. However, an analysis of the EU ETS with a specific focus on the aviation sector provides insight into the system's questionable effectiveness. A 2013 study evaluating the potential efficacy of such a system found that carbon emissions reductions did not exceed 7% (Anger-Kraavi & Köhler, 2013). Such findings are corroborated by a recent study that found a 5% reduction in carbon emissions as a result of aviation’s inclusion into the EU ETS (Leanain & Sahib, 2025). *Carbon Emissions Markets* would seem a more effective policy intervention, however, there has existed some criticism of the “cap-and-trade” ideology which can allow companies to manipulate the complex carbon markets established (Chan, 2010). Even so, the reductions in carbon emissions achieved via *Carbon Emissions Markets* are not on a similar level of effectiveness to the technological solutions presented earlier. The final policy-driven intervention, *Operational Improvements,* and its effectiveness was discussed previously in conjunction with *Airport Infrastructure and Airspace Monitoring Improvements*. The combination of the decarbonization potential of these two solutions in academia and this paper serves as a brief introduction to the intrinsic connection between policy and technology.

The solutions analyzed in this paper all have value in combating the aviation sector’s detrimental role in climate change. Indeed it is a valid argument, that in the absence of revolutionary technologies with the true potential to fully mitigate the aviation industry's climate impacts, any solutions with decarbonization potential should be pursued. To recap, the impact of each of these political and technological solutions concerning carbon emissions reduction is compiled below in Table 1.

Table 1. Carbon reduction potential of solutions researched compiled, *Indicates tail-pipe not overall or lifecycle emissions, Red font indicates revolutionary technologies, (Stambaugh, 2025).

Solution	Carbon Emissions Reduction (%)
Airport Infrastructure and Airspace Monitoring Improvements (In combination with *Operational Improvements)*	10%*
General Aircraft Design Improvements	22%*
SAF	65-80%, 100%*
Banning Short-Haul Flights	0.5-1.6%
Carbon Emissions Markets	5-7%
Hydrogen-Powered	**50-90%***
All-Electric Aircraft	**100%***

An important caveat is that the results compiled in the table above are based on research from various sources. As such, there are different models used, locations studied, and criteria evaluated. Also important to note, is that the interventions included do not represent all possible solutions as such an analysis would far exceed any reasonable scope. Still, a reasonable conclusion can be drawn that ultimately technology will be responsible for the complete decarbonization of the aviation industry. Furthermore, it is evident that *SAF* will play a key role in this transition as the technology for *All-Electric Aircraft* is still in its infancy, and sustainable fuels are perhaps the best solution currently available. While the key drivers of the aviation industry's reduction in carbon emissions have been identified, it is also imperative to understand how policy and technology can affect one another. In line with the findings of this paper, even more beneficial is to determine how policy can encourage and support innovative technological development which offers tremendous promise for reducing emissions.

C. The Reciprocal Effects of Technology and Policy

The idea that policy and technology can have a reciprocal influence on each other is by no means novel. As written by Merrit Smith in a submission to the MIT Press, "The belief in technology as a key governing force in society dates back at least to the early stages of the industrial revolution" (Smith, 1994). Termed "technological determinism", proponents of this belief consider that "changes in technology exert a greater influence on societies and their processes than any other factor" (Smith, 1994). While the extent of this influence is interpreted differently by individuals, what is indisputable is that technological progression can hold sway over society and by extent policy. This impact is also notable with a lens solely focused on the aviation sector. For example, the new navigational and monitoring technologies being implemented by the FAA through their NextGen initiative have allowed for policy change with respect to flight planning and air traffic control. Expanding further, fully electric aircraft or sustainable fuel could render short-haul flight bans unnecessary. Cleaner, more technologically advanced aircraft could also reduce the need for operational modifications such as reduced-engine taxi and last-minute fuel and water uptake. Said potential modifications demonstrate how, within the aerospace sector, advancements in technology can play a crucial role in determining policy.

Given that the issue of aviation's sustainability will ultimately be solved by technological interventions, it would appear prudent to focus considerably on the effect that policy can have on technology. More specifically, being that *SAF* is the most plausible technological solution in the interim, the policy objectives relating to this innovation can be examined to create a model for utilizing policy in support of technological advancement. To be analyzed are President Joe Biden's *Grand SAF Challenge* and a *Menu of Policy Options for Incentivizing SAF Production and Use* put forward by the Atlantic Council.

President Biden's *Grand SAF Challenge* exemplifies the first way in which policy can be used to shape technology. This policy objective works by clearly *Establishing Goals* against which progress can be compared. The two goals of the *Grand SAF Challenge* are to "by 2030, expand SAF production to achieve 3 billion gallons per year of domestic SAF production and [to] by 2050, meet 100 percent of projected domestic jet fuel demand—about 35 billion gallons of annual production" (United States Government Accountability Office, 2023). Instituting goals can be the initial method by which policy is used to encourage innovations such as *SAF*, but without further planning and incentives, adoption and production of technologies can lag behind desired levels.

An example of policy being utilized for *Planning* is the drafting of the *SAF Grand Challenge Roadmap*. As described by the United States Government Accountability Office (GAO), "The roadmap outlines a whole-of-government approach with coordinated policies and specific activities to support the Grand Challenge goals" (United States Government Accountability Office, 2023). Agencies such as the Departments of Energy, Transportation, and Agriculture, in conjunction with the FAA, have been responsible for the creation of the roadmap. The organizations involved influence technology, first through planning, and followed by concerted action in their areas of strength. Dividing the resources of agencies through the planning process is an essential step toward offering better support for technological innovation. Through the *SAF Grand Challenge Roadmap*, six areas requiring continued focus were identified. The action areas along with corresponding examples of policy initiatives are shown below in Figure 5.

Action area	Description	Examples of associated agency activities
Feedstock Innovation	Support and conduct feedstock R&D to reduce the cost, technology uncertainty, and risk of producing SAF; increase yield and sustainability; and optimize SAF precursors (i.e. ethanol and isobutanol)	In fiscal year 2022, the U.S. Department of Agriculture announced a $1 billion investment in Partnerships for Climate-Smart Commodities, and provided funding in 2022 to producers of agricultural and forestry products that use climate-smart practices
Conversion Technology Innovation	Support and conduct R&D on SAF through pilot scale to achieve technology improvements and carbon intensity reductions	In fiscal year 2022, the Department of Energy announced a $34.5 million funding opportunity to improve the science and infrastructure for converting waste into biofuels and help support the 2050 goal
Building Supply Chains	Support SAF production expansion both through R&D transitions from pilot to large-scale demonstration projects, and validating supply chain logistics, as well as through public-private partnerships and collaboration with regional, state, and local stakeholders	In fiscal year 2021, the Department of Energy awarded $64 million to 22 SAF and other biofuel producers, and in fiscal year 2022, announced it would award another $59 million to accelerate the production of biofuels, including SAF
Policy and Valuation Analysis	Provide data, tools, and analysis to support policy decisions and maximize social, economic, and environmental value of SAF	According to the roadmap, the Department of Energy will update their study on the availability of potential feedstocks and continue to improve environmental models and data for SAF to evaluate scenarios and provide direction for greater SAF production
Enabling End Use	Facilitate SAF end use by supporting SAF R&D that addresses barriers to greater SAF deployment, such as more efficient testing, expansion of blending limits, and integrating SAF into existing infrastructure	The Federal Aviation Administration is funding research as part of its ongoing efforts to enable neat unblended SAF and SAF blends up to 100 percent
Communicating Progress and Building Support	Monitor and measure progress against SAF goals and communicate to the public the environmental, climate, and economic benefits of SAF	According to the roadmap, agencies will create a public database to track SAF facilities, production, and use

Figure 5. Areas of focus in combination with description and example of policy initiatives aimed at supporting *SAF*, (United States Government Accountability Office, 2023).

Additional means by which policy can hold influence over technological development can be derived from Figure 5. *Governmental Financial Investments* are a key tool for furthering the advancement of *SAF* as demonstrated by its use in amplifying feedstock and conversion technology innovation while also enhancing supply chains. *Governmental Support* with policy analysis, research and development, and progress monitoring are additional methods of using policy to push technology. (United States Government Accountability Office, 2023)

Additional policy proposals in six key areas have been put forward by the Atlantic Council (Ghatala, 2020). Those key areas are listed below in Table 2. While each category includes a multitude of proposals, only one will be selected from each category to construct a model of policy's weightage.

Table 2. Key policy option categories suggested identified by the Atlantic Council, (Ghatala, 2020)

Key Policy Goal Categories
Attract capital to expand SAF supply *(Category 1)*
Assist SAF facility operation through targeted incentives and tax relief *(Category 2)*
Recognize SAF environmental benefits *(Category 3)*
Create demand by further incorporating SAF into existing Renewable Fuel Standard (RFS) policies *(Category 4)*
Create demand by further incorporating SAF into existing Low Carbon Fuel Standard-type (LCFS) regulations *(Category 5)*
Demonstrate government leadership through ongoing SAF purchase, research and demonstration activities, and a clear statement of policy direction *(Category 6)*

Beginning with *Category 1*, an Investment Tax Credit (ITC) could be established. Such a policy would allow for the "deduction of construction and/or commission[ing] costs of a qualifying asset which can reduce income tax payable" (Ghatala, 2020). With a specific focus on *SAF*, this initiative would encourage investment in new production facilities by advancing "longer-term stability and accelerated payback [for investors]" (Ghatala, 2020). Within *Category 2*, a notable proposal is the creation of a Producer's Tax Credit (PTC) which would be paid to any producer of *SAF*. Contributing to its efficacy, PTC initiatives would directly promote expanded *SAF* production through the direct financial incentive of reduced income tax burden. Designiating *SAF* as an exempt fuel within emissions markets is another proposed action. This *Category 3* policy would "[e]ncourage SAF's recognition as an exempt low carbon fuel" within carbon markets (Ghatala, 2020). Such action would increase the price competitiveness of *SAF* in comparison to traditional ATF, the emissions of which are of financial importance to companies that must comply with carbon caps (Ghatala, 2020). The aforementioned approaches represent the ways that policy can create *Financial Incentives* for technology.

In the political space, *Mandates and Obligations can* be used to increase the adoption of novel technologies. An example proposed by the Atlantic Council in *Category 4* is the inclusion of jet fuel in an RFS obligation (Ghatala, 2020). As a result, a required volume of *SAF* would be included in future fuel blends in an attempt to expand use. Continuing on, another method proposed to increase demand for *SAF* in *Category 5* is the LCFS regulations which mandate that fuel producers "gradually reduce the [carbon intensity] of fuels provided to the market" (Ghatala, 2020). Being an inherently lower carbon alternative to ATF, *SAF* is more compliant with these regulations and thus more desirable. In such a way, demand for *SAF* as a novel technology is obligated to increase, representing yet another means by which political initiatives can influence technology (Ghatala, 2020).

Finally, *Category 6* details policies that exemplify the effect of *Government Leadership*. Certain policy recommendations from this section have already been covered with the

Establishing Goals and *Government Support* classifications. However, the *Government Leadership* classification refers to a policy proposal by which the government demonstrates its vested interest in *SAF*. This is done through a commitment to procure *SAF* by federal, state, and local governments, in addition to the US military (Ghatala, 2020). Such a method enhances *SAF's* viability by offering a continuous source of demand, while also demonstrating to industry how a novel fuel source can be implemented.

The policies discussed by no means constitute an exhaustive list of all possible interventions within the political space. However, a rough model of various policy classifications and their respective effect on technology can be constructed to achieve the aim of an STSR systems analysis. The results of said research are compiled below in Table 3.

Table 3. Basic model of policy classifications and their effect on technology, (Stambaugh, 2025).

Policy Classification	**Effect on Technology**
Establishing Goals	By establishing goals (eg. sustainability goals), policy can require that technology be advanced and researched to meet said goals.
Planning	Policy can create a plan that guides technological development and identifies key areas of focus.
Governmental Financial Investment	Government grants and investment can fuel the research, development, and production of technologies.
Governmental Support	Government agencies with relevant expertise can conduct research and advise those developing and producing technology. Additionally, progress tracking by the government can ensure that technological development goals are achieved.
Financial Incentives	Tax credits can encourage investment in the development and production of new technologies. Such policies are also useful as de-risking tools so that investors and

	manufacturers feel more incentivized to pursue novel albeit high risk technologies. Additionally, certain incentives and exemptions can make new technologies more cost competitive.
Mandates and Obligations	Can require the production and/or adoption of technologies. Can enhance demand for novel technologies by creating obligations that favor newer technologies over their older counterparts.
Government Leadership	By adopting policies that require novel technology adoption, governments can demonstrate the effectiveness of said technology and a process by which to implement it.

Thus, in conclusion, within the sociotechnical system of sustainable aviation, policy and technology maintain a strong influence on one another. Furthermore, it is important to realize that technological advancement will be the ultimate solution to the sustainability challenges faced by the aviation industry. Bearing in mind that policy can have a positive effect will be essential to achieve the quickest, most successful decarbonization of the sector.

V. Conclusion

Given the aviation sector's position as a key transportation provider with ever-growing demand, the challenges this industry faces concerning sustainability are great. The share of carbon emissions attributed to the aircraft is only set to rise as other key emitters decarbonize. Further at issue is a substantial lack of revolutionary technologies that have the potential to drastically reduce GHG emissions which has led to a myriad of proposed political and technological solutions. While all of the solutions both proposed and implemented have had some measurable effect on reducing carbon emissions, the decarbonization potential of new technologies far outweighs that of any policy intervention to date. While all current solutions are valuable tools in addressing the climate impacts of aviation in the interim, ultimately policy appears to be best used in a supporting role to technological development. Therefore, it can be argued that a mixture of policies in conjunction with their supported technologies will represent the most effective manifestation of a complete solution.

The main implication of this research is the acknowledgment that emphasizing policies that spur the development and adoption of new high-promise technologies is of high value. Such findings can be incorporated practically, by holding focus on the impact of policy on technology when drafting new interventions. Still, there are limitations. Even with supportive policies and strong investment, the widespread adoption and roll-out of new revolutionary technologies is still, at the very least, many years away. As such, until the world's skies are brimming with *All-Electric Aircraft*, any and all mechanisms with the ability to limit the emissions of the aviation industry should be pursued to their fullest potential. In that way, humanity can achieve the interconnectedness of the world at no cost to its health.

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