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Advancing Alternative Fuel Aviation Technologies in California

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16. Abstract

The aviation sector in California is facing increased pressure to reduce its carbon footprint, leading to a growing interest in alternative fuel aviation (AFA) technologies such as sustainable aviation fuel (SAF), as well as electric- and hydrogen-powered aircraft. The report develops a California Aviation Energy Model (CAVEM), examining various AFA technologies and analyzing possible policy options. The analysis emphasizes the importance of SAF in the short term, with projections indicating sufficient supply for intrastate flights and capped vegetable oil-based fuel consumption. Long-term efforts are focused on electric and hydrogen-powered aircraft, which remain in the early stages of development. Electrification of intrastate flights is deemed feasible, with estimated electricity consumption amounting to a small percentage of overall electricity generation. The report highlights the necessity for additional policy incentives (such as tax exemptions) and a comprehensive policy framework to effectively promote sustainable aviation in the long run.

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The California Resilient and Innovative Mobility Initiative

The California Resilient and Innovative Mobility Initiative (RIMI) serves as a living laboratory – bringing together university experts from across the four UC ITS campuses, policymakers, public agencies, industry stakeholders, and community leaders—to inform the state transportation system's immediate COVID-19 response and recovery needs, while establishing a long-term vision and pathway for directing innovative mobility to develop sustainable and resilient transportation in California. RIMI is organized around three core research pillars: Carbon Neutral Transportation, Emerging Transportation Technology, and Public Transit and Shared Mobility. Equity and high-road jobs serve as cross-cutting themes that are integrated across the three pillars.

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List of Abbreviations

AFA	Alternative Fuel Aviation
ASPM	Aviation System Performance Metrics
ASTM	American Society for Testing and Materials
BADA	Base of Aircraft Data
CARB	California Air Resources Board
CAVEM	California Aviation Energy Model
CO_2	Carbon Dioxide
FAA	Federal Aviation Administration
GH_2	Gas Hydrogen
GI	Gravimetric Index
ICAO	International Civil Aviation Organization
ILUC	Indirect Land Use Change
LCFS	Low Carbon Fuel Standard
LH_2	Liquid Hydrogen
MF	Mass Fraction
MMT	Million Metric Ton
MTOW	Maximum Takeoff Weight
MV	Metric Value
NM	Nautical Miles
NO_x	Nitrogen Oxides
OEW	Operational Empty Weight
PF	Performance Factor
RD	Renewable Diesel

TAF	Terminal Area Forecast
TTW	Tank to Wake

Executive Summary

Executive Summary

California's ambitious goal of becoming carbon neutral by 2045 has put the aviation sector under close scrutiny. As a major contributor to greenhouse gas emissions, the challenges of this sustainable transition are daunting for the entire aviation sector. There is a growing interest in alternative fuel aviation (AFA) technologies, including sustainable aviation fuel (SAF), electric aircraft, and hydrogen-powered technologies. However, efforts to decarbonize aviation are still in their infancy and California, like most jurisdictions, currently lacks a comprehensive decarbonization plan, which could hinder long-term efforts. Attempts to implement policies to decarbonize aviation are complicated by the complex nature of the jurisdictional authority that governs the sector. International aviation is largely regulated by the International Civil Aviation Organization, and interstate aviation is governed by U.S. law. This leaves California with few tools with which to address aviation emissions that occur in-state.

The report introduces a comprehensive California Aviation Energy Model (CAVEM) for fuel projections and alternative energy estimates for 2030 and 2035. The report evaluates various AFA technologies, considering their carbon reduction potential, cost, scalability, and impact on aircraft performance. In addition, the report provides an in-depth study of existing policy frameworks around the world and conducts a policy scenario analysis to estimate the costs and effects of using exclusive SAF policies.

For the short term, SAF is the only useful tool available. The analysis shows that by 2030, the available supply for SAF is projected to meet the demand for intrastate flight, while also maintaining vegetable oil-based jet fuel consumption below 500 million gallons per year to limit potential indirect land use change (ILUC) risks in the short term.

While long-term technological solutions remain uncertain, the state has recognized the promise of zero-emission technologies, with a goal of replacing 20 percent of conventional fuels with battery- or hydrogen-powered aircraft. Both electric- and hydrogen-powered aircraft are at an early stage of development, with a technology readiness level of 3-4 out of 11 assigned by the ETP Clean Energy Technology Guide (IEA, 2022).

Electrifying intrastate flights using battery aircraft is feasible. Based on the calculations, the total electricity consumption for the scenario of achieving full replacement of all intrastate flights with all-electric aircraft is projected to be 1.2 percent and 1.0 percent of the state's electricity generation in 2030 and 2035, which is a relatively small percentage of the overall electricity generation.

However, there are two major challenges to transitioning to battery airplanes. One is the weight penalty. Based on the estimation results, on average, battery-electric aircraft would require approximately 1.8 times more weight compared to the conventional jet for the same flight. The other is the speed penalty. It is estimated that the speed of a battery aircraft is approximately 77 percent of the speed of a conventional jet. The lower speed

and longer travel time of the battery aircraft can indeed pose challenges to its commercialization and integration into the airline industry.

For Liquid Hydorgen (LH_2) powered aircraft, the increased weight in both the fuel system and the overall aircraft were detrimental. The results showed an average 21 percent increase in total fuel system and a 23 percent increase in Operational Empty Weight[1] (OEW) for LH_2-powered aircraft.

While reliance on SAF appears to be critical in the short term, the report emphasizes that additional policy incentives will be needed to promote decarbonization of the aviation industry in the long term. The report suggests exploring policies such as tax exemptions and assessing their cost-effectiveness and potential impact.

A well-defined and clear-structured decarbonization plan is necessary to effectively drive California's aviation industry toward a cleaner future. The possible policy solution includes:

- Promulgating regulations to establish a Low Carbon Fuel Standard for aviation fuels, ensuring consistency with federal laws (Elkind et al., 2022).
- Creating and approving incentives that encourage the adoption of electric aircraft and hydrogen aircraft technologies.
- Offering financial incentives, such as fee exemptions, to promote the use of electric aircraft and hydrogen aircraft.
- Expanding the scope of the Low Carbon Fuel Standard[2] (LCFS) to not only intrastate flights but total jet fuel use, reflecting a broader policy focus.

[1] The Operational Empty Wight is the sum of the aircraft's empty weight, along with the crew and their baggage.
[2] The Low Carbon Fuel Standard, established by the California Air Resources Board, is designed to decrease the carbon intensity of California’s transportation fuel pool and promote the use of low-carbon fuels.

Contents

Introduction

The State of California has established ambitious carbon neutrality goals, including full carbon neutrality by no later than 2045 (California Air Resources Board, 2023c). To meet this challenge, hard-to-decarbonize sectors, such as aviation, are receiving heightened scrutiny from state policymakers. In particular, there is growing interest in policies to encourage the use of alternative-fueled aviation (AFA), including sustainable aviation fuel (SAF, SAF has become the default term used within the aviation industry to indicate non-petroleum alternative liquid fuels. These fuels can reduce GHG emissions over the fuel's full life cycle, however not all varieties of SAF do so, and the use of some feedstocks for SAF production results in life cycle GHG impacts worse than the petroleum they seek to displace, as well as other negative environmental impacts. There are no universal standards or tests applied to alternative aviation fuels to certify their sustainability. The use of the word "sustainable" in SAF therefore represents an aspirational description; not all forms of so-called SAF are truly sustainable.), hydrogen, and electricity.

California will likely play a leading role in the area, as it accounts for 17% of the nation's jet fuel consumption, by far the largest share of any state (EIA, 2021a). The Low Carbon Fuel Standard (LCFS) provides a larger incentive for SAF use than in any other state (California Air Resources Board, 2023b), however, in most cases the total incentives for producing renewable diesel – made from the same feedstocks by a similar conversion process as SAF – are typically greater, meaning that comparatively little has actually entered the market at the time of writing. State initiatives regarding SAF can also leverage a well-established and pathbreaking environmental policy infrastructure that has heretofore been directed at surface transportation.

However, California lacks a comprehensive plan to decarbonize the aviation sector. The design of state policies that effectively promote aviation decarbonization must recognize the unique characteristics of the aviation sector when compared to other forms of transportation. These include, among other factors, the unique importance of fuel weight and volume on aircraft performance, long aircraft lifetimes, the high proportion of interstate aviation traffic, the large role of the Federal government and treaty-based international organizations in aviation policymaking, and the diversity of mechanisms through which aircraft operations affect the climate.

Recognizing these challenges, this report contributes to the decarbonization process in the aviation sector in California in five ways. First, it provides an overall model to estimate future fuel consumption using detailed flight information, which can be applied to any year beyond 2019. Second, it informs policymakers of the significance of making a comprehensive plan for reducing aviation emissions in California. Third, it identifies the potential for replacing conventional jet fuel demand with AFA technologies, emphasizing the advantages and possible challenges of those technologies. Fourth, it explores the possibilities for filling policy gaps to facilitate the transition to cleaner California aviation in the near future. Fifth, examines the barriers to implementing SAF policies and provides insights for modifying the LCFS accordingly.

The structure of the report is as follows. The first chapter presents a baseline fuel estimation model, while the second chapter introduces the California Aviation Energy Model (CAVEM) for forecasting fuel demand in 2030 and 2035. The third chapter conducts a technology assessment, evaluating the carbon reduction potential, cost, scalability, and impact on aircraft performance of various AFA technologies. The fourth chapter entails a comprehensive policy inventory. The last chapter involves a policy scenario analysis, estimates the costs and effectiveness of SAF policies, and summarizes the main conclusions.

Fuel Estimation Model

Background

The objective of examining the current jet fuel use in California is to predict future jet fuel use. The year 2019 was selected as the baseline year to exclude the impact of the COVID-19 pandemic.

With regard to scope, we examined commercial flights at the state level. Specifically, the California aviation industry was categorized into three groups, namely intrastate flights, interstate flights, and international flights (California Air Resources Board, 2016). Intrastate flights refer to flights departing and arriving in California. Interstate flights are domestic flights that depart from California but arrive in other states. International flights denote flights departing from California and arriving at international airports in other countries.

Methodology and Modeling

The fundamental modeling unit in this study is per single flight. We estimated the fuel burn of each flight based on the aircraft type, and route characteristics. The model can analyze the fuel consumption from gate-to-gate for each flight. We used Base of Aircraft Data (BADA) Family 3 to simulate airborne fuel and applied taxi fuel allowance data from BADA 4.2 to simulate taxi fuel separately.

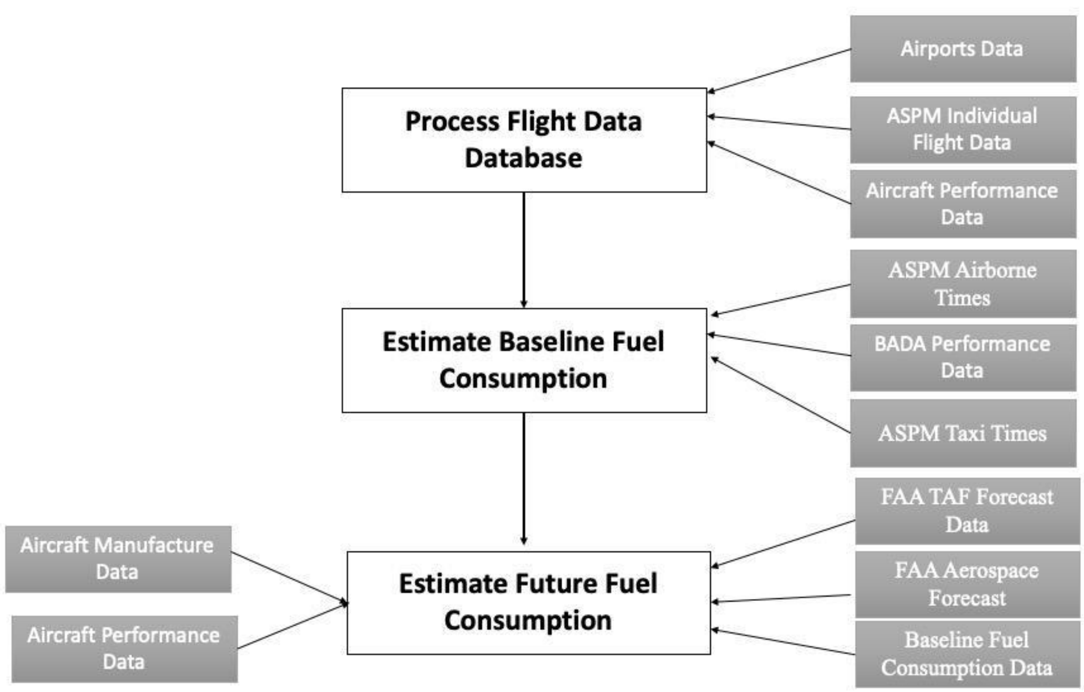

Figure 1. Methodology Overview

The fundamental modeling unit in this study is per single flight. We estimated the fuel burn of each flight based on the aircraft type, and route characteristics. The model is capable of analyzing the fuel consumption from gate-to-gate for each flight. We used Base of Aircraft Data (BADA) Family 3 to simulate airborne fuel and applied taxi fuel allowance data from BADA 4.2 to simulate taxi fuel separately.

Data were collected from two main sources: the fuel flow data from the BADA 3 and individual flight performance data from the Aviation System Performance Metrics (ASPM) database.

BADA provides fuel flow parameters for enroute phase (climb, cruise, and descent) of each flight. In version 3.16 (Moulinet, 2022), BADA covers 264 aircraft types. Given the synonym aircraft table, a total of 1822 different aircraft types can be modeled.

ASPM provides detailed time information for each commercial flight. We considered only the airborne time for the enroute phase. For the ground movement phase, we used both nominal taxi time and taxi delay to simulate fuel emissions.

In 2019, the Federal Aviation Administration (FAA) ASPM database includes 11 million records of individual flight data and accounted for over 451 types of aircraft. Referring to the synonym table of BADA 3, out of a total of 451 aircraft types, only a subset has specific performance data. The synonym table is used to convert the rest, resulting in a total of 214 types with available performance data. 11% of domestic flights in 2019 are California flights, covering 101 airports in California.

Airborne Fuel Consumption

Fuel Flow Algorithm

We can access fuel consumption parameters at different flight levels for specific aircraft type using the BADA thrust specific fuel consumption equations:

$$\text{Climb: } f_{jet} = C_{f1} \times \left(1 + \frac{V_{TAS}}{C_{f2}}\right) \times Thr$$

$$f_{turboprop} = C_{f1} \times \left(1 - \frac{V_{TAS}}{C_{f2}}\right) \times \left(\frac{V_{TAS}}{1000}\right) \times Thr$$

$$\text{Descent: } f = C_{f3} \times \left(1 - \frac{H_p}{C_{f4}}\right) \times Thr$$

$$\text{Cruise: } f = C_{f1} \times \left(1 + \frac{V_{TAS}}{C_{f2}}\right) \times Thr \times C_{fcr}$$

Where f is fuel flow (kg/min),

C_{f1} is the 1st thrust specific fuel consumption coefficient (kg/(min×kN),

C_{f2} is the 2nd thrust specific fuel consumption coefficient (knots),

C_{f3} is 1st descent fuel flow coefficient (kg/min),

C_{f4} is 2nd descent fuel flow coefficient (ft),

C_{fcr} is the cruise fuel flow correction coefficient.

Business Route Case Scenario Assumption

The FAA developed a set of cruise altitude bands based on distance and engine type references by analyzing large amounts of radar data (Kim et al., 2005). However, airborne time can vary significantly within similar distance ranges due to weather or air traffic control reasons. For example, the actual maximum airborne time of the ASPM can reach up to 900 minutes in the range of 500-550 km, while the minimum flight time is less than 5 minutes. Thus, in order to capture every flight in the ASPM dataset, airborne time was considered as one of the main elements rather than the distance. Airborne time and aircraft type combinations of cruise altitude groups were used to establish the assumptions of the business routes.

The maximum cruise altitude was aircraft-specific. Depending on the length of airborne time for a given flight and the maximum operating altitude for a given aircraft, the cruise altitudes were restricted as shown in Table 1. The maximum typical commercial flight altitude is usually set up between FL 290 to FL 410. The minimum cruise altitude prescribed by the FAA is between FL10 and FL20. For shorter hauls (e.g., airborne time less than 5 min), it is assumed that only the climb and descent phases are included, excluding cruise. Tests were conducted at airborne times of 7, 11, 30, and 60 minutes to obtain the maximum cruise altitude within the time range. 6 business route case scenarios were assumed. By sensitivity analysis, the total airborne fuel simulation variance obtained by changing the maximum cruise altitude is less than 5%.

Table 1. Business Route Case Scenario

Maximum Operating Altitude	Airborne time (min)	Cruise Altitude(feet)
> FL 400	0<Time<=7	1,000
	7<Time<=11	4,000
	11< Time <= 30	8,000
	30< Time <=60	24,000
	Time > 60	37,000
FL 350 – FL 400	0<Time<=7	1,000
	7<Time<=11	4,000
	11< Time <= 30	8,000
	30< Time <=60	24,000
	Time > 60	37,000
FL 300 – FL 350	0<Time<=7	1,000
	7<Time<=11	2,000
	11< Time <= 30	4,000
	30< Time <=60	8,000
	Time > 60	29,000
FL 250 – FL 300	0<Time<=7	1,000
	7<Time<=11	2,000
	11< Time <= 30	4,000
	30< Time <=60	8,000
	Time > 60	22,000
FL 180 – FL 220	0<Time<=8	1,000
	8<Time<=15	2,000
	15< Time <= 30	3,000
	30< Time <=60	8,000

Maximum Operating Altitude	Airborne time (min)	Cruise Altitude(feet)
	Time > 60	14,000
< FL 180	0<Time<=8	1,000
	8<Time<=12	2,000
	12< Time <= 30	3,000
	30< Time <=60	6,000
	Time > 60	12,000

Source: Author's Model

Fuel Burn Algorithm

The BADA performance table contains the rate of climb, rate of descent and fuel flow rate for specific aircraft at various flight levels. ASPM provides airborne time and specific aircraft used for each flight. Since the fuel flow were already calculated and the maximum altitude scenarios were set up, fuel burn can be calculated by using the following equations:

$$T_{Climb} = \frac{FL}{ROC}$$

$$T_{Descent} = \frac{FL}{ROD}$$

$$T_{Cruise} = T_{Airborne} - T_{Climb} - T_{Descent}$$

$$Fuel_{Airborne} = f_{Climb} \times T_{Climb} + f_{Cruise} \times T_{Cruise} + f_{Descent} \times T_{Descent}$$

Where FL is the given flight level, ROC/ROD is the rate of climb/descent, f is the fuel flow rate and T is the time.

Taxi Fuel Consumption

BADA Family 4.2 provides taxi fuel allowance data for 58 types of aircraft which covers 70% of the data. Based on the maximum takeoff weight (MTOW), the remaining data in the dataset can be divided into eleven groups (Table 2) with taxi fuel allowances set according to the weight of the given aircrafts in BADA 4.2.

Table 2. Taxi Fuel Allowance

MTOW (tones)	Taxi fuel allowance (kg/min)
MTOW<=24.10	7.0
24.10< MTOW <38.60	7.3
38.60< MTOW <=51.80	8.0
51.80< MTOW <=52.60	9.0
52.60< MTOW <=65.00	11.3
65.00< MTOW <=115.90	12.0
115.90< MTOW <=204.10	20.0
204.10<MTOW<=247.21	22.0
247.21<MTOW<=287.00	25.0
287.00<MTOW<=377.80	33.0
377.80<MTOW	45.0

Source: BADA 4.2 and Author's Model

Taxi fuel consumption can be calculated by the following equations (Csanda, 2018),

$$Fuel_{Taxi} = TFA \times (T_{Taxi\_in} + T_{Taxi\_out})$$

Where TFA is the taxi fuel allowance (kg/min), $T_{Taxi_in}$and T_{Taxi_out} is the time of taxi in/out (min).

Results

Jet fuel usage was categorized into three sectors: general aviation, military activities, and scheduled commercial flights. The results from our model showed that the fuel consumption of interstate commercial flights in 2019 was 0.239 billion. Since all general aviation jet fuel was consumed within the state (California Air Resources Board, 2016), in other words by intrastate flights, the fuel consumption for general aviation was 0.164 billion gallons in 2019 (California State Board of Equalization, 2022). Based on this information, the ultimate estimated fuel consumption for intrastate flights was 0.403 billion gallons. The fuel consumption for interstate flights was estimated to be 1.858 billion gallons, and for international flights, it was estimated to be 1.919 billion gallons, as shown in Table 3. The results from our model showed a 4.8% difference compared to the estimates provided by CARB. The discrepancy was due to the lack of military flight information and the possibility of lost flight information in the ASPM dataset.

Table 3. California Fuel Consumption in 2019

Category	Model Results (Billion gallons)				CARB Model Results1 (Billion gallons)
	Commercial3	General Aviation2	Military	Total3	
Intrastate	0.239	0.164	-	0.403	0.428
Interstate	1.858	-	-	1.858	1.873
International	1.919	-	-	1.919	1.939

Source: California Air Resources Board (2022a)[1], California State Board of Equalization (2022)[2], Author's Calculation[3]

The distribution of fuel consumption from commercial flights across the three categories in our model aligned with the percentages provided by CARB's greenhouse gas emissions inventory (California Air Resources Board, 2022a). In 2019, intrastate flights accounted for 5.94% of fuel consumption. However, despite their relatively lower fuel consumption, intrastate flights accounted for a significant portion of the overall flight numbers, representing 30.93% of all flights (Table 4). On the other hand, international flights accounted for 9.68% of the total flights, but their fuel consumption was much higher, representing 47.78% of the total fuel usage. Interstate flights accounted for a larger share of both fuel consumption and flight numbers. They represented 46.28% of the total fuel usage and 59.39% of the total flights.

Table 4. Share of Commercial Jet Fuel Consumption in 2019

Commercial Flight	Fuel Consumption (Billion gallons)	Share of Fuel Use	Share of Flight Number
Intrastate	0.239	5.94%	30.93%
Interstate	1.858	46.28%	59.39%
International	1.919	47.78%	9.68%
Total	4.016	100%	100%

Source: Author's Calculation

Compared to CARB's method, we considered the complete standard flying cycle as well as incorporated time as a key factor. This approach allowed us to capture the fuel usage for each stage during the flight and provided a more detailed analysis by calculating fuel usage on a flight-by-flight basis. CARB's method, on the other hand, relied solely on aircraft type and flight distance to estimate consumption. To allocate the commercial fuel consumption for each category, CARB first estimated the total commercial jet fuel sales by subtracting the fuel used in the military and general aviation sectors from the overall jet fuel sales. Then, CARB applied the share of the total jet fuel consumption of each category to the estimated commercial jet fuel sales to determine the fuel consumption for each category.

While CARB's approach provided a general estimation of fuel consumption, it may not capture detailed information such as fuel usage for each airline, fuel usage from departing airports, or other specific factors relating to fuel consumption. Our model, on the other hand, was allowed to analyze fuel consumption patterns at a more granular level, providing insights into the fuel usage of individual flights, airlines, airports, etc. This level of detail can be valuable for identifying areas of improvement and implementing targeted strategies to reduce fuel consumption and associated emissions.

The results from our model revealed that 91.20% of the fuel consumption was attributed to six major airports (Table 5). These airports include Los Angeles International Airport (LAX), San Francisco International Airport (SFO), San Diego International Airport (SAN), Oakland International Airport (OAK), San Jose Mineta International Airport (SJC), and Ontario International Airport (ONT). LAX was the pillar airport in 2019, which consumed almost half (46.35%) of the total fuel used in California. It also accounted for a significant portion of the flight volume, with a share of 28.54%. SFO, the second busiest airport, had a fuel usage share of 28.42% and a flight number share of 18.86%.

Table 5. California Jet Fuel Consumption from Departing Airports in 2019

Airport	Fuel Consumption (Million gallons)	Share of Fuel Use	Share of Flight Number
LAX	1861.48	46.35%	28.54%
SFO	1141.44	28.42%	18.86%
SAN	229.73	5.72%	9.45%
OAK	161.83	4.03%	6.92%
SJC	137.68	3.43%	7.30%
ONT	129.97	3.24%	3.68%
Other Airports	353.57	8.80%	25.25%
Total	4015.71	100%	100%

Source: Author's Calculation

The distribution of commercial fuel consumption by flight distance in California was shown in Table 6. Flights in the range of 250-500 nautical miles (nm) accounted for 31.45% of the total flight number but contributed to only 7.87% of the overall fuel usage, with 70.92% of these flights being intrastate. On the other hand, long-haul flights with distances longer than 2500 nm represented only 5.59% of the total flight number, but they accounted for a significant share of 43.94% in fuel consumption. This is mainly because 91.04% of flights with distances longer than 2500 nm were international flights.

Table 6. Commercial Jet Fuel Consumption by Distance Range in 2019

Flight Distance (nm)	Fuel Consumption (Million gallons)	Share of Fuel Use	Share of Flight Number
<125	9.71	0.24%	4.67%
125-250	40.51	1.01%	7.72%
250-500	315.89	7.87%	31.45%
500-750	185.45	4.62%	12.21%
750-1000	124.42	3.10%	5.74%
1000-1500	384.41	9.57%	12.18%
1500-2000	473.68	11.80%	9.38%
2000-2500	717.41	17.86%	11.06%
>2500	1764.23	43.93%	5.59%
Total	4015.71	100%	100%

Source: Author's Calculation

Table 7 presented the fuel consumption for the top 10 aircraft types in California in 2019. The B777-300ER aircraft type consumed the most fuel, totaling 692.55 million gallons, representing 17.25% of the total fuel usage with a relatively low share of flight numbers at 1.75%. This aircraft was predominantly used for long-haul international flights, with an overwhelming 97.57% of B777-300ER flights falling into this category, leading to higher fuel consumption.

Among the aircraft types used for interstate flights, the top three were B737-800, B737-700, and A-321. B737-800 accounted for 8.48% of the total fuel share and 12.23% of the total flight count share, with 75.47% of its flights being interstate flights and 16.62% being intrastate flights. While it had a much higher flight number share (6.97 times more flights) than B777-300ER, B737-800 consumed only 49.18% of the fuel used by B777-300ER flights.

B737-700 was not only one of the most commonly used aircraft types for interstate flights, but it was also the most frequently used for intrastate flights, with 29.85% of intrastate flights served by this aircraft type. Consequently, it had a higher share of flight counts at 18.20%, while its share of fuel usage was lower at 6.25%. Other aircraft types not specifically mentioned in the table collectively accounted for 30.50% of the total fuel usage but had a higher share of flight operations at 42.35%.

Table 7. California Jet Fuel Consumption by Top 10 Aircraft Types in 2019

Aircraft Type	Fuel Consumption (Million gallons)	Share of Fuel Use	Share of Flight Number
B777-300ER	692.55	17.25%	1.75%
B737-800	340.63	8.48%	12.23%
B787-9	317.55	7.91%	1.37%
A-321	276.29	6.88%	6.12%
B737-700	250.81	6.25%	18.20%
A380-800	229.83	5.72%	0.35%
B737-900	195.58	4.87%	6.08%
A-320	187.73	4.67%	7.96%
B757-200	164.72	4.10%	2.80%
B777-200ER	135.33	3.37%	0.79%
Other Aircraft Types	1224.69	30.50%	42.35%
Total	4015.71	100%	100%

Source: Author’s Calculation

The fuel consumption and flight count share for top airlines for both passenger and cargo in California in 2019 were presented in Table 8 and Table 9.

Among the passenger airlines, Southwest Airlines (SWA) emerged as the state’s busiest airline, commanding a significant share of 24.03% of the total flight count. Despite its high flight count, SWA consumed only 8.9% of the total fuel usage. SWA's dominance extended to both intrastate and interstate flights. For intrastate flights, SWA accounted for 33.75% of all flights, making it the busiest airline in the category. SWA showcased its prominence for interstate flights as well, capturing 19.02% of the total flight number. Major hubs for SWA's operations within California were OAK, LAX, SAN, SJC, and Sacramento International Airport (SMF) in 2019.

SkyWest Airlines (SKW) ranked second in terms of flight count share at 13.44%. The most popular flight type served by SKW was flights within California. Among SKW flights, over half of them (51.51%) were intrastate flights and nearly half (47.70%) were interstate flights, resulting in a lower fuel usage percentage (2.63%) among all airlines. The most popular departing airports for SKW were SFO, LAX, Fresno Yosemite International Airport (FAT), SAN, and SJC.

While SWA and SKW took the lead in flight count, United Airlines (UAL) emerged as the airline with the highest fuel consumption, accounting for 16.70% of the total fuel usage in California in 2019. In terms of international flights departing from California, UAL ranked first, representing 13.19% of the total flights. Moreover, UAL also held a significant share in terms of interstate flights, accounting for 13.31% of total flights and a notably 72.57% of UAL's own flights.

Korean Airlines (KAL), Qantas Airlines (QFA), and Copa Airlines (CPA) stood out with a larger share of jet fuel usage, each accounting for more than 2% of the total jet fuel share, despite their relatively lower flight counts share at around 0.2%. The reason was that most of their flights were international, with KAL and QFA having 79.6% of flights and CPA having 84.4% as international flights. For KAL, typical flight routes included LAX to Brisbane Airport (YBBN), LAX to Melbourne Airport (YMML), LAX to Sydney Airport (YSSY), SFO to YMML, and SFO to YSSY. Meanwhile, for both QFA and CPA, typical flight routes consisted of LAX to Narita International Airport (RJAA), LAX to Incheon International Airport (RKSI), and SFO to RKSI. These international flight routes contributed significantly to their higher fuel consumption.

As for the cargo airlines, FedEx Express (FDX) was the busiest, accounting for 49.13% of total fuel usage and 40.60% of flight counts. UPS Airlines (UPS) ranked second with a 9.73% share of total fuel consumption and 34.24% of flight counts. Ameriflight (AMF) had a larger flight count share at 15.61% because it only served intercity cargo flights domestically. 95.89% of AMF's flights were intrastate, 4.11% were interstate, and there were no international flights served by AMF departing from California.

Table 8. California Jet Fuel Consumption by Top 10 Passenger Airlines in 2019

Passenger Airlines	Fuel Consumption (Million gallons)	Share of Fuel Use	Share of Flight Number
United Airlines (UAL)	623.88	16.70%	11.95%
American Airlines (AAL)	363.33	9.73%	8.46%
Southwest Airlines (SWA)	332.43	8.90%	24.03%
Delta Airlines (DAL)	299.04	8.00%	7.58%
Atlantic Southeast (ASA)	187.28	5.01%	7.58%
SkyWest Airlines (SKW)	98.08	2.63%	13.44%
JetBlue Airlines (JBU)	94.03	2.52%	2.60%
Korean Airlines (KAL)	89.07	2.38%	0.22%
Qantas Airlines (QFA)	87.67	2.35%	0.22%
Copa Airlines (CPA)	83.92	2.25%	0.23%
Other Airlines	1476.83	39.53%	23.70%
Total	3735.56	100%	100%

Source: Author's Calculation

Table 9. California Jet Fuel Consumption by Top 6 Cargo Airlines in 2019

Cargo Airlines	Fuel Consumption (Million gallons)	Share of Fuel Use	Share of Flight Number
FedEx Express (FDX)	119.14	49.13%	40.60%
UPS Airlines (UPS)	90.38	37.27%	34.24%
Kalitta Air (CKS)	19.47	8.03%	4.21%
ABX Air (ABX)	9.67	3.99%	3.33%
AirBridgeCargo Airlines (ABW)	2.99	1.23%	0.51%
Ameriflight (AMF)	0.63	0.26%	15.61%
Other Airlines	0.22	0.09%	1.40%
Total	242.50	100%	100%

Source: Author's Calculation

California Aviation Energy Model (CAVEM)

Background

Based on the baseline results, we can predict future fuel requirements for California commercial flights in both 2030 and 2035. The findings from the inventory of future jet fuel demand can provide crucial insights to policymakers at the state level on how to promote the adoption of sustainable aviation fuels in both 2030 and 2035.

Methodology and Modeling

The forecasting module utilized dynamic scenarios to account for the impact of fleet performance uncertainty on future fuel burn. The forecasting module involved three components:

1. Future flight distribution generation,
2. Future fleet mix generation, and
3. Fuel consumption scenario assumption.

To project the future schedule, we employed the frater algorithm to project the future schedule and leveraged the fleet evolution models (EPA, 2020) to modulate fleet retirement and replacement. Furthermore, our analysis took into account other uncertainties related to aircraft performance and manufacturing changes such as engine and airframe deterioration, technology upgrades, etc. These factors contribute to a comprehensive and robust forecasting approach for estimating future fuel consumption.

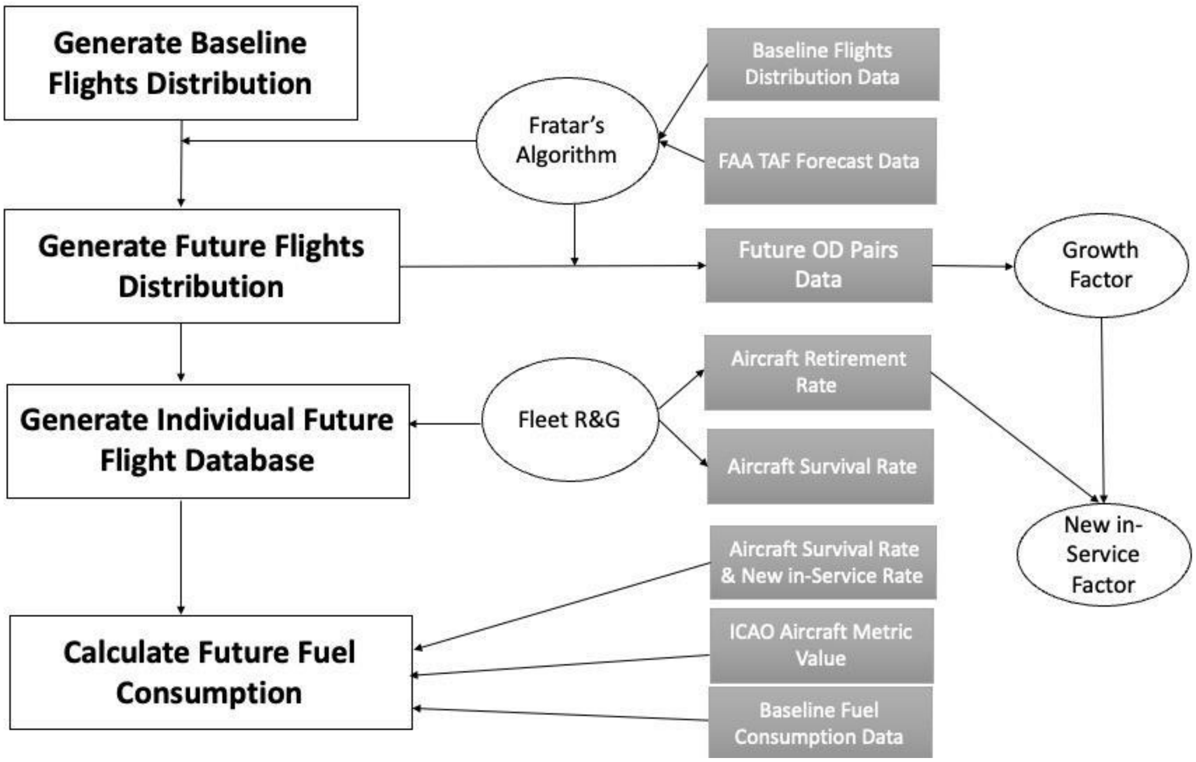

Figure 2. Methodology Overview

Future Flight Distribution Generation

Growth of Flights

To predict the growth of flights, the first step involved utilizing the prediction growth results from FAA's Terminal Area Forecast (TAF) (FAA, 2022). The TAF provided future demand forecasts for enplanements (passenger numbers) and operations for each U.S. airport, specifically for national flights. The current version of TAF uses 2021 as the baseline year. However, since TAF only covers domestic airports, growth data for international airports are sourced from alternative sources.

To gather these data, we categorized arrival international airports by nationality and used this as an index to search for the respective airport's growth forecast. If any information is missing, we use the reference data of growth rates from International Civil Aviation Organization's (ICAO) long-term traffic forecast for passengers and freighters (ICAO, 2016).

Fratar's Algorithm

Fratar's Algorithm is the most widely used method to generate growth factors for flight schedules based on TAF forecast (Kim et al., 2005). TAF provided annual flight operations projections starting in 2021, and the projections were used to determine the growth factor. In our baseline dataset, each origin-destination (OD) pair served as an entity. Flights with the same OD pairs were grouped together to count the total number of flight frequencies from that entity in the base year.

The iterative Fratar's algorithm comprised five steps:

1. Compute annual flight frequency t_{ij} for each OD pair, total annual departures d_i, and total annual arrivals a_j in the baseline year based on the data in the ASPM dataset.

$$d_i = \sum_j t_{ij}$$

$$a_j = \sum_i t_{ij}$$

   Where t_{ij} is the flight frequency from airport i to airport j in 2019, i is for an airport in California (departure airport), J is for a domestic and international airport (arrival airport); d_i is the total annual departure from airport i in 2019, a_j is the total annual arrival from airport j in 2019.

2. Determine the growth factor g_i and g_j at airport i and airport j for the projection year using operation projection data from TAF.

$$g_i = \frac{D_i}{dd_i}$$

$$g_j = \frac{A_j}{aa_j}$$

   Where D_i represents the total number of operations estimation from airport i in the forecast year from TAF, and dd_i denotes the total number of operations from airport i in the 2019; A_j is the total number of operations estimation from airport i in the forecast year from TAF, aa_j is the total number of operations from airport i in the 2019; If the data is missing from TAF, then growth factor is set to be 1.

3. Determine future flight frequency T_{ij} between airport i and airport j.

$$T_{ij} = t_{ij} \times g_i \times g_j \times \frac{1}{2} \times \left(\frac{d_i}{\sum_k t_{ik} g_k} + \frac{a_j}{\sum_k t_{kj} g_k} \right)$$

Where T_{ij} is the future flight frequency from airport i to airport j, $\sum_k \quad t_{ik} g_k$ is the future flight frequency departing from airport i to airport k, $\sum_k \quad t_{kj} g_k$ is the future arriving at airport j from airport k.

4. The iterative process converges when the sum of projected annual departure flights $\sum_k \quad T_{ik}$ equals the reference number of departures DD_i in the target year. To avoid possible infinite looping, we accept a 1% tolerance gap. If the condition is not met, we substitute the annual flight frequency t_{ij} with T_{ij}, and update d_i and a_j accordingly. The first three steps are repeated until convergence is achieved.

   TAF projection numbers cannot be directly used as an estimate of DD_i because TFA data accounts for itineraries that are not reflected in the ASPM dataset. In contrast, ASPM data only considers OAG scheduled operations and excludes general aviation and military flights, resulting in a smaller dataset. As a result, we used growth rates generated from TAF to estimate future flights based on the ASPM data. There are two distinct annual growth rates in TAF, one from 2019 to 2021 and the other from 2021 to 2035. Thus, DD_i is calculated using the compound annual growth rates from the formulas below:

$$G_1 = \left(\frac{D_{i,2021}}{D_{i,2019}}\right)^{\frac{1}{2}} - 1$$

$$G_2 = \left(\frac{D_{i,t}}{D_{i,2021}}\right)^{\frac{1}{t-2021}} - 1$$

$$DD_i = \left(t_{ij} \times (1 + G_1)^2\right) \times (1 + G_2)^{t-2021}$$

   Where G_1 is the compound annual growth rate from 2019 to 2021, G_2 is the compound annual growth rate from 2021 to the target year.

5. Compute the growth factor r_{ij} for the target year.

$$r_{ij} = \frac{T_{ij}}{t_{ij}} - 1$$

Future Fleet Mix Generation

Fleet Evolution Model

In addition to mapping growth rates to flight schedules, fleet retirement rates and replacement parameters were also imperative to model flight activity. There were 30732 route-aircraft type combos in total.

Retirement curves were estimated based on different aircraft groups and ages. According to ICCT and EPA, there were six distinct aircraft groups categorized by their engine type and maximum takeoff weight (MTOW) as shown in Table 10 (Rutherford & Kharina, 2016; EPA, 2020). Each of these aircraft groups had two specific retirement curve coefficients, denoted as coefficient a and coefficient b. ASPM contained aircraft tail number details for every flight, facilitating the integration of aircraft manufacturing data that specifies the year of manufacture for each plane with ASPM. This integration enabled us to obtain the age of the aircraft listed in the schedule for the target year. A copy of the baseline fleet was created, and each aircraft was aged to the target year.

Table 10. Retirement Curve Coefficients by Aircraft Category

Aircraft Category		MTOW (Tonnes)	a	b
Jet	Large quad freighters	>372	6.905901	0.205267
	Twin aisle	120-372	5.611526	0.223511
	Single aisle	60-120	5.393337	0.222211
	Regional jets	22-60	4.752779	0.178659
	Business jets	<22	6.265852	0.150800
Turboprop		N/A	3.477281	0.103332

Source: Rutherford & Kharina (2016); EPA (2020)

Retirement rates for different aircraft groups were estimated by a logistic regression model (EPA, 2020) while survival rates were calculated as one minus retirement rates.

$$R = \frac{1}{1 + e^{a-b\times age}}$$

$$S = \frac{e^{a-b\times age}}{1 + e^{a-b\times age}}$$

Where a and b are coefficients based on the aircraft categories shown in the above table.

The new in service rate (NIS) is a metric used to measure the number of new aircraft that enter into service in the target year. Combining the growth rate of flights and the retirement rate of the fleet together, we determined the number of new aircraft that needed to be added to the fleet for the target year from the baseline year.

$$NIS = R + r$$

Where R is the retirement rate for the fleet and r is the growth factor for the flight schedule.

Aircraft Metric Values Improvement

To capture and assess the dynamic impact of aircraft technology improvements contributing to fuel consumption reduction, we introduced the ICF's annual metric value (MV) adjustment factor with the fleet evolution. The adjustment factor η represented the fuel reduction changes in the baseline fleet over time, including the gradual annual improvement of current in-production aircraft and the introduction of additional new and more fuel-efficient aircraft. 1% of MV reduction represents 1% fuel consumption reduction (ICF, 2018). The adjustment factor can be calculated as the following formula:

$$\eta_t = \frac{MV_t}{MV_{2019}}$$

Where MV_t is the metric value for the target year and MV_{2019} is the metric value in the base year.

According to ICF, two-thirds of fuel efficiency improvement (1.5% annually) is attributed to major redesign activities, such as re-engine, re-wing, or clean sheet development. However, these activities are not expected to occur frequently and may take 10-15 years from 2018 to materialize. ICF further projected that cleaner aircraft replacements are expected to be delivered starting in 2030, and this is projected to result in significant improvements in fuel efficiency (Table 11).

Table 11. Long-term Improvement and Fuel Reduction Rate

Aircraft Category		Rate Reduction Estimate after 2030 (D)
Jet	Large quad freighters	10%
	Twin aisle	15%
	Single aisle	20%
	Regional jets	10%
	Business jets	10%
Turboprop		10%

Source: ICF (2018)

If long-term replacement is considered in the improvement forecast, then the adjustment factor is calculated as follows:

$$\eta_t = \frac{MV_t}{MV_{2019}} \times (1 - D)$$

where D is the long-term percent improvement provided by ICF as table above.

Effects of Engine Aging

Engine wear and airframe imperfections can contribute to an increase in fuel consumption over time (ICAO, 2014). According to Airbus, after a period of 5 years, engine and airframe deterioration may increase the drag of the aircraft by up to 2% (Airbus, 2002). Furthermore, engine performance degradation can cause 2-6% more fuel consumption (Boeing, 2004). Within the first 4 years of operation, commercial aircraft typically exhibit fuel burn that is 2-4% above the book value. However, comprehensive maintenance and operational procedures can offset the impact of aged engines by 1-3% (Board, 2007).

To measure the impact of engine aging on fuel consumption, we introduced the performance factor (PF). This metric represents the efficiency loss in the flight management system (FMS) due to the deterioration of aircraft engines. The PF is initially set to 1.0 and increases as the engine deteriorates. It comprises two components: 20% of the PF represents the impact of aerodynamic effects on engine performance, while the remaining 80% represents the losses in engine efficiency due to wear and aging (Lindner et al., 2019).

The calculation of the logarithmic engine degradation δ is different for domestic flights and international flights (Seymour et al., 2020).

$$For\ domestic\ flight, \qquad \delta = \frac{-1.28 \times log\ (t+1)}{100}$$

$$For\ international\ flight, \qquad \delta = \frac{-1.34 \times log\ (t+1)}{100}$$

Where t is the age of the aircraft at the target year.

After estimating the percentage of engine degradation, we mapped the engine degradation effect to the PF value and adjusted the future fuel consumption projections for the new in service aircraft.

$$PF = 1 - 0.8 * \delta(t)$$

Future Fuel Consumption Scenario Assumption

The estimates are subject to various assumptions and simplifications, including:

1. All fleet growth will be served by new aircraft of the same model as those in the baseline fleet.
2. New aircraft will be delivered on average over 16 years from 2021-2035.
3. A significant improvement in fuel efficiency is expected in 2030 and thus adjustment factor aligned with tech response is taken into account.
4. The fuel reduction rate for general aviation is assumed to be equivalent to that for small business jets.
5. Metric values will decrease at a constant rate over time.

6. If a specific value is missing, the average adjustment factor for the corresponding aircraft category is used.
7. The engine degradation factor for general aviation is based on an average age of 30.

Results

According to our estimates, flights witnessed an increase of 22.47% in 2030 and 33.58% in 2035, resulting in total fuel consumption of 5.198 billion gallons and 5.489 billion gallons respectively in those years (Table 12).

Table 12. Estimated Fuel Consumption in 2030 and 2035

Year	Total Fuel Consumption (Billion Gallons)	Flight Number	Flight Number Increase (%)
Baseline (2019)	4.180	1,157,775	-
2030	5.198	1,417,875	22.47
2035	5.489	1,546,499	33.58

Source: Author's Calculation

As shown in Table 13, the growth rate of domestic flights is smaller compared to international ones based on the baseline. In 2030, international flights, comprising only 10.04% of the total flight numbers, substantially contribute to 49.23% of the total jet fuel consumption, accounting for 2.472 billion gallons. Similarly, the trend persists in 2035, where international flights, with a flight number share of 10.25%, dominate fuel usage with a 49.92% share, equivalent to 2.653 billion gallons of fuel consumed.

In contrast, intrastate flights exhibit a different pattern. In 2030, they represent 30.76% of total flight numbers, but their fuel consumption share remains relatively lower at 5.95%, corresponding to 0.299 billion gallons of fuel. This trend continues into 2035, where intrastate flights constitute 30.69% of the flight numbers but contribute only 5.90% to fuel usage, resulting in the consumption of 0.314 billion gallons of fuel.

The category of interstate flights emerges as the largest share of flight numbers, constituting 59.20% of all flights in 2030 and 59.06% in 2035. Consequently, these flights account for a significant portion of fuel use, representing 44.82% and 44.18% in 2030 and 2035, respectively.

Table 13. Share of Commercial Jet Fuel Consumption Projection

Year	Fuel Consumption (Billion Gallons)		Share of Fuel Use (%)		Share of Flight Number (%)	
	2030	2035	2030	2035	2030	2035
Intrastate	0.299	0.314	6.0	5.9	30.8	30.7
Interstate	2.251	2.348	44.8	44.2	59.2	59.1
International	2.472	2.653	49.2	49.9	10.0	10.2
Total	5.022	5.315	100	100	100	100

Source: Author's Calculation

The commercial future fleet will be compromised with new aircraft and aging aircraft survived (Table 14). Based on this composition, in 2035, a smaller portion of flights, specifically 35.90%, will be operated by surviving aircraft. This will result in a fuel consumption of 2.208 billion gallons, representing 41.54% of the total fuel usage. The majority of flights, comprising 64.10%, will be serviced by new aircraft, contributing significantly to the consumption of 3.107 billion gallons of fuel. Conversely, in 2030, over half of the flights (52.69%) will be operated by surviving aircraft, contributing to a fuel consumption of 2.889 billion gallons, which corresponds to 57.53% of the total fuel use. The remaining flights, comprising 47.31% of the total, will be catered to by new aircraft, leading to a fuel consumption of 2.133 billion gallons, representing 42.47% of the total fuel use.

Table 14. Fuel Use Information by Fleet Composition (General Aviation not included)

Fleet Composition for Commercial Flight	New Aircraft		Surviving Aircraft		Total	
	2030	2035	2030	2035	2030	2035
Fuel Consumption (Billion Gallons)	2.133	3.107	2.889	2.208	5.022	5.315
Share of Fuel Use (%)	42.5	58.5	57.5	41.5	100	100
Share of Flight Number (%)	47.3	64.1	52.7	35.9	100	100

Source: Author's Calculation

In comparison to the baseline findings, the fuel share for commercial flights at LAX and SFO is projected to expand, largely attributed to the anticipated rise in flight frequency (

Table 15). LAX is projected to account for 46.60% of fuel consumption in 2030 and even more at 47.18% in 2035, solidifying its position as California's top fuel-consuming airport. The substantial portion of new aircraft serving ONT (82.73% in 2035) contributes to an improved fuel efficiency within the fleet, resulting in a relatively minor uptick in fuel consumption, rising from 175.29 million gallons in 2030 to 177.92 million gallons in 2035. Across all six airports, interstate flights remained the prevailing dominant.

Table 15. Estimated Fuel Consumption from Departing Airports in 2030 and 2035

Airport	Fuel Consumption (Million gallons)		*Share of Total Fuel Use (%)		**Share of Total Flight Number (%)		***Share of Fuel Use Served by New Aircraft (%)	
	2030	2035	2030	2035	2030	2035	2030	2035
LAX	2340	2507	46.6	47.2	28.8	29.4	46.2	62.6
SFO	1452	1541	28.9	29.0	19.6	19.7	53.0	67.3
SAN	280	301	5.6	5.6	9.5	9.8	44.4	62.0
OAK	184	189	3.7	3.6	6.3	6.3	48.9	67.6
SJC	182	189	3.6	3.6	7.8	7.8	49.6	64.6
ONT	175	178	3.5	3.3	4.1	4.1	69.2	82.7
Other Airports	408	409	8.1	7.7	23.9	22.9	50.2	65.5
Total	5021	5314	100	100	100	100	42.5	58.5

$$* \, Share\ of\ Total\ Fuel\ Use = \frac{Fuel\ Consumpion\ in\ Each\ Airport}{Total\ Fuel\ Consumpiton\ for\ all\ Airports}$$

$$** \, Share\ of\ Total\ Flight\ Number = \frac{Flight\ Number\ in\ Each\ Airport}{Total\ Flight\ Number\ for\ all\ Airports}$$

$$*** \, Share\ of\ Fuel\ Use\ Served\ by\ New\ Aircraft = \frac{Fuel\ Consumpion\ served\ by\ new\ aircraft\ in\ Each\ Airport}{Fuel\ Consumpiton\ for\ that\ Airport}$$

Source: Author’s Calculation

The projected jet fuel consumption by distance range for commercial flights in both 2030 and 2035 was shown in Table 16. The range of 1500-2000 km emerges with the highest share of flights served by new aircraft. In 2035, flights operating within this distance range experience a slight reduction in their fuel consumption share, declining from 11.80% in 2019 to 11.47%. However, despite this decrease in fuel consumption share, the portion of flights within the same range has actually risen from 9.38% in 2019 to 9.45% in 2035. This intriguing trend can be attributed to the substantial proportion (68.78%) of new aircraft in the fleet composition for 2035 and the potential enhancement in the fuel efficiency of these flights.

Table 16. Estimated Commercial Jet Fuel Consumption by Distance Range in 2030 and 2035

Flight Distance (nm)	Fuel Consumption (Million gallons)		*Share of Total Fuel Use (%)		**Share of Flight Number (%)		***Share of Fuel Use Served by New Aircraft (%)	
	2030	2035	2030	2035	2030	2035	2030	2035
<125	12	13	0.2	0.2	4.5	4.4	39.3	54.4
125-250	47	49	0.9	0.9	7.2	6.9	44.8	61.3
250-500	401	419	8.0	7.9	32.2	32.4	52.4	68.8
500-750	236	245	4.7	4.6	12.6	12.5	50.5	65.7
750-1000	156	162	3.1	3.1	5.8	5.8	48.1	64.9
1000-1500	471	491	9.4	9.2	12.1	12.1	47.9	63.8
1500-2000	583	610	11.6	11.5	9.3	9.4	52.9	68.8
2000-2500	842	883	16.8	16.6	10.6	10.7	48.5	44.1
>2500	2273	2442	45.3	46.0	5.7	5.8	33.5	49.9
Total	5021	5314	100	100	100	100	42.5	58.5

$$* \, Share \ of \ Total \ Fuel \ Use = \frac{Fuel \ Consumpion \ in \ Each \ Flight \ Distance \ Range}{Total \ Fuel \ Consumpiton}$$

$$** \ Share \ of \ Total \ Flight \ Number = \frac{Flight \ Number \ in \ Each \ Flight \ Distance \ Range}{Total \ Flight \ Number}$$

$$*** \ Share \ of \ Fuel \ Use \ Served \ by \ New \ Aircraft \ = \frac{Fuel \ Consumpion \ served \ by \ new \ aircraft \ in \ Each \ Flight \ Distance \ Range}{Fuel \ Consumpiton \ for \ that \ Distance \ Range}$$

Source: Author's Calculation

Table 17 presents a trend that when the share of fuel used by new aircraft surpasses 60%, there is a concurrent decrease in the overall fuel use share from 2030 to 2035. The shift can be attributed to higher fuel efficiency of these new aircraft types. This balance between increased flight frequency and enhanced efficiency underscores the positive impact of advanced aviation technology that we anticipate. Among the most fuel-consuming types, B737-700, B757-200, and B777-200ER emerge as the top three aircraft types with the highest replacement rate.

Table 17. Estimated Fuel Consumption by Top 10 Aircraft Types in 2030 and 2035

Aircraft Type	Fuel Consumption (Million gallons)		*Share of Total Fuel Use (%)		**Share of Flight Number (%)		***Share of Fuel Use by New aircraft (%)	
	2030	2035	2030	2035	2030	2035	2030	2035
B777-300ER	893	954	17.8	18.0	1.7	1.8	22.2	39.5
B737-800	419	437	8.3	8.2	11.3	12.4	43.9	61.5
B787-9	409	441	8.1	8.3	1.3	1.4	31.0	50.3
A-321	342	367	6.8	6.9	5.7	6.3	29.6	47.4
B737-700	309	317	6.2	6.0	16.8	18.4	63.7	81.4
A380-800	297	325	5.9	6.1	0.3	0.4	25.3	39.2
B737-900	241	256	4.8	4.8	5.6	6.3	30.6	48.4
A-320	234	244	4.7	4.6	7.4	8.2	51.6	67.1
B757-200	191	199	3.8	3.7	2.5	2.8	85.2	94.1
B777-200ER	166	174	3.3	3.3	0.7	0.8	80.7	92.0
Other Aircraft Types	1520	1600	30.3	30.1	46.7	41.2	44.3	59.8
Total	5021	5314	100	100	100	100	42.5	58.5

$$* \, Share\ of\ Total\ Fuel\ Use = \frac{Fuel\ Consumpion\ in\ Each\ Aircraft\ Type}{Total\ Fuel\ Consumpiton}$$

$$** \, Share\ of\ Total\ Flight\ Number = \frac{Flight\ Number\ in\ Each\ Aircraft\ Type}{Total\ Flight\ Number}$$

$$*** \, Share\ of\ Fuel\ Use\ Served\ by\ New\ Aircraft = \frac{Fuel\ Consumpion\ served\ by\ new\ aircraft\ in\ Aircraft\ Type}{Fuel\ Consumpiton\ for\ that\ Aircraft\ Type}$$

Source: Author's Calculation

Table 18 presents the estimated changes in fuel consumption among major passenger airlines between 2030 and 2035. United Airlines (UAL) saw a notable increase in fuel consumption, rising from 623.88 million gallons in 2019 to 803.16 million gallons in 2035, signifying a substantial growth of 29%. Despite varying rates of fuel consumption growth, the market shares among the leading airlines have remained relatively stable. For instance, AAL's share of flight numbers exhibited a slight increase from 8.62% to 8.69% between 2030 and 2035. However, both the share of total fuel use and the share of total flight numbers from SkyWest Airlines (SKW) declined. This shift can be attributed to SKW's strategic focus on intrastate and interstate flights, indicative of a preference for regional and shorter routes. The specific operational emphasis on these routes likely contributes to the observed changes in both fuel consumption and flight number shares for SKW.

Table 18.Estimated Fuel Consumption by Top 10 Passenger Airlines in 2030 and 2035

Passenger Airlines	Fuel Consumption (Million gallons)		*Share of Total Fuel Use (%)		**Share of Total Flight Number (%)		***Share of Fuel Use by New aircraft (%)	
	2030	2035	2030	2035	2030	2035	2030	2035
United Airlines (UAL)	761	803	16.3	16.2	11.9	12.1	63.9	77.9
American Airlines (AAL)	453	480	9.7	9.7	8.6	8.7	36.9	54.4
Southwest Airlines (SWA)	410	425	8.8	8.6	24.2	24.2	49.2	66.5
Delta Airlines (DAL)	368	390	7.9	7.9	7.7	7.8	61.4	74.2
Atlantic Southeast (ASA)	232	245	4.9	4.9	7.7	7.9	35.9	54.6
SkyWest Airlines (SKW)	121	126	2.6	2.5	13.4	13.1	35.0	48.3
JetBlue Airlines (JBU)	118	125	2.5	2.5	2.6	2.6	35.8	53.5
Korean Airlines (KAL)	115	125	2.4	2.5	0.2	0.2	28.6	48.1
Qantas Airlines (QFA)	113	122	2.4	2.5	0.2	0.2	32.2	53.3
Copa Airlines (CPA)	108	116	2.3	2.3	0.2	0.2	26.2	36.0
Other Airlines	1879	2006	40.2	40.4	23.3	23.0	37.9	53.8

Passenger Airlines	Fuel Consumption (Million gallons)		*Share of Total Fuel Use (%)		**Share of Total Flight Number (%)		***Share of Fuel Use by New aircraft (%)	
	2030	2035	2030	2035	2030	2035	2030	2035
Total	4678	4963	100	100	100	100	41.2	57.2

$$* \, Share\ of\ Total\ Fuel\ Use = \frac{Fuel\ Consumpion\ in\ Each\ Airline}{Total\ Fuel\ Consumpiton}$$

$$** \, Share\ of\ Total\ Flight\ Number = \frac{Flight\ Number\ in\ Each\ Airline}{Total\ Flight\ Number}$$

$$*** \, Share\ of\ Fuel\ Use\ Served\ by\ New\ Aircraft\ = \frac{Fuel\ Consumpion\ served\ by\ new\ aircraft\ in\ Airline}{Fuel\ Consumpiton\ for\ that\ Airline}$$

Source: Author's Calculation

For all major cargo airlines, there has been an increase in fuel consumption from 2019 to 2035 (Table 19). While the total fuel consumption has increased, the share of fuel consumption for each cargo airline has remained relatively stable or slightly decreased, suggesting that while fuel consumption has increased for these airlines, the growth rate of their fuel consumption is likely to be relatively lower than the overall growth rate of the cargo airline industry. The difference in fuel consumption and flight number shares for Ameriflight (AMF) reflects its specialized operational approach, focusing exclusively on intercity cargo flights within California.

Table 19. Estimated Fuel Consumption by Top 6 Cargo Airlines in 2030 and 2035

Cargo Airlines	Fuel Consumption (Million gallons)		*Share of Total Fuel Use (%)		**Share of Total Flight Number (%)		***Share of Fuel Use by New aircraft (%)	
	2030	2035	2030	2035	2030	2035	2030	2035
FedEx Express (FDX)	143	147	48.3	48.9	40.6	41.4	65.0	84.5
UPS Airlines (UPS)	113	113	38.2	37.6	35.5	35.2	69.4	85.4
Kalitta Air (CKS)	23	24	7.8	8.0	4.3	4.5	38.0	59.5
ABX Air (ABX)	12	12	4.1	4.0	3.6	3.7	98.1	99.4
AirBridgeCargo Airlines (ABW)	4	4	1.4	1.3	0.5	0.5	19.0	30.9
Ameriflight (AMF)	0.7	0.7	0.2	0.2	14.0	13.3	39.6	54.5
Other Airlines	0.2	0.2	0.0	0.0	1.5	1.4	41.0	57.0
Total	295.9	300.9	100	100	100	100	65.6	82.9

$$* \ Share\ of\ Total\ Fuel\ Use = \frac{Fuel\ Consumpion\ in\ Each\ Airline}{Total\ Fuel\ Consumpiton}$$

$$** \ Share\ of\ Total\ Flight\ Number = \frac{Flight\ Number\ in\ Each\ Airline}{Total\ Flight\ Number}$$

$$*** \ Share\ of\ Fuel\ Use\ Served\ by\ New\ Aircraft = \frac{Fuel\ Consumpion\ served\ by\ new\ aircraft\ in\ Airline}{Fuel\ Consumpiton\ for\ that\ Airline}$$

Source: Author's Calculation

Technical Assessment

Background

In this section, we undertook a comprehensive evaluation of sustainable alternative aviation fuels, namely drop-in sustainable aviation fuels (SAF, including biofuels and e-fuel), batteries, and liquid hydrogen. The objective of the assessment was to address the demand for conventional jet fuels and facilitate their substitution with sustainable options. To achieve this, we thoroughly examined key factors including energy use, carbon reduction potentiality, cost implications, scalability, aircraft performance impact, and technological readiness. Moreover, this assessment specifically focused on the intrastate market, acknowledging the significance of sustainable intercity air travel within regional contexts as a crucial contributor to fostering an environmentally conscious aviation sector.

Definition of Sustainable Aviation Alternative

Three types of sustainable aviation alternatives are examined:

1. Drop-in Sustainable Aviation Fuel (SAF): SAF is a lower carbon substitute for fossil jet fuels that meets the American Society for Testing and Materials (ASTM) jet fuel standards (Bardell et al., 2018). It is produced from sustainable resources such as organic wastes, agricultural residues, or non-fossil derived carbon dioxide (CO_2) (Eswaran et al., 2021). SAF is a drop-in fuel, meaning it can be used in current aviation systems without requiring modifications, though some forms of SAF are only certified for use when blended with conventional jet fuel. It closely resembles conventional jet fuels in terms of physical and chemical characteristics but offers the potential for lower carbon intensity than conventional fuels. The life cycle emissions of SAF largely depend on the feedstocks and energy sources used for production; at present most SAF on the market is made by hydrotreatment of lipids such as used cooking oil, rendered tallow, or vegetable oil.
2. All-electric (Battery): All-electric aircraft rely solely on stored electrical energy from batteries as their power source (Gnadt et al., 2019). They distribute electric power throughout the entire airframe, replacing the secondary power distribution systems in conventional aircraft (Avery et al., 2007). The carbon intensity of electricity depends on the type of generation.
3. Liquid Hydrogen (LH_2): LH_2 can be utilized as the fuel for aircraft, replacing conventional jet fuel, with the goal of reducing fuel consumption and greenhouse gas emissions (Baharozu et al., 2017). The carbon intensity of hydrogen depends on how its made, at present most hydrogen is made through steam methane reformation of natural gas, which yields hydrogen with a higher carbon intensity than petroleum jet fuel. Electrolysis of water using low-carbon electricity can deliver significantly lower carbon intensity hydrogen, though liquefaction of hydrogen is extremely energy intensive, requiring about 1/3 as much energy as is contained in the hydrogen being liquefied.

Drop-in SAF

Drop-in SAFs have the advantage of seamless integration into existing fuel systems and airframes. Apart from small changes in engine performance due to minor differences in fuel composition compared to conventional jet fuel, the weight and performance of SAF is essentially identical to that of conventional jet fuel. This allows existing airframes to be operated and gain potential GHG benefits when using SAF instead of conventional jet fuel. The GHG impact of SAF is almost entirely determined by factors earlier in its life cycle, as it is produced.

Energy Use

There are four types of hydrocarbon that are acceptable as alternatives to conventional jet fuel: aromatics, cycloalkanes, iso-alkanes, and n-alkanes. While the specific energy of conventional jet fuel is around 43 MJ/kg, the specific energy values of these hydrocarbons vary between 40 and 45 MJ/kg (Holladay et al., 2020). Currently, nine SAF production processes have been certified under the ASTM standards, and the ASTM certified drop-in SAFs are mixture of these hydrocarbon molecules. (Table 20) In addition, the drop-in SAFs should be blended with the conventional jet fuel at a certain level. Thus, the composition of each drop-in SAF may vary depending on the production pathway, but the specific energy of drop-in SAF is similar to the conventional jet fuel.

Table 20. Production Pathways for Drop-in Sustainable Aviation Fuel (SAF)

Pathway	Blending limitation	Feedstocks
Fischer-Tropsch (FT) Synthetic Paraffinic Kerosene (SPK)	50%	Municipal solid waste, agricultural and forest wastes, energy crops
Hydroprocessed Esters and Fatty Acids (HEFA) SPK	50%	Oil-based feedstocks
Hydroprocessed Fermented Sugars to Synthetic Isoparaffins (HFS-SIP)	10%	Sugar
FT-SPK with aromatics	50%	Municipal solid waste, agricultural and forest wastes, energy crops
Alcohol-to-Jet (AtJ) SPK	30%	Cellulosic biomass
Catalytic Hydrothermolysis Synthesized Kerosene	50%	Fatty acids or fatty acid esters or lipids from fat, oil, and greases
Hydrocarbon-HEFA	10%	Algal oil
Fats, Oils, and Greases (FOG) Co-processing	5%	Fats, oils, and greases
FT Co-processing	5%	FT biocrude

The carbon intensity from SAF available in California's market today (almost entirely HEFA) ranges from around 20 g CO_2e/MJ for waste-based fuels to around 50 g CO_2e/MJ for soybean oil fuels (CARB, 2023d). The difference between the two is in part, due to the fertilizer and energy used during the production of soybeans, or other vegetable oils, and in part due to the adjustment added to reflect the estimated ILUC impact of crop based feedstocks. Life cycle energy flows through both systems show a net positive energy ratio, indicating that both yield more fuel energy than it takes to produce them, however life cycle energy ratios are highly sensitive to assumptions around system boundary and allocation methods.

Emission Trade-offs

Jet fuel is a mixture of hydrocarbons, primarily alkanes and aromatics. Despite a chemical composition largely similar to conventional jet fuel, SAF achieves GHG benefits by obtaining its embodied carbon from non-fossil sources. Since this carbon was removed from the atmosphere during production, by photosynthetic uptake in plants or technological carbon capture approaches, when it is converted back into CO_2 and released by combustion, it results in no net change in atmospheric GHG concentrations. Thus, life cycle GHG emissions can be significantly lower for SAF than for petroleum fuels, provided a low-carbon feedstock is used for fuel production. Despite this, almost all forms of SAF have a non-zero life cycle GHG input due to energy and materials consumed during its production. Like most biofuels, the life cycle GHG intensity of the fuel is predominantly determined by the feedstock, rather than the process used to produce it. Waste-based feedstocks almost always have a lower GHG intensity than those made from crops or other valuable products. Biofuels that account for ILUC impacts via GHG adjustment factors (e.g. the LCFS) will typically assign them higher carbon intensity scores as a result.

In addition to lower GHG emissions, SAF may also reduce the warming effects of high-altitude contrail formation, by reduced emissions of sulfate and soot, which serve as nucleation sites for cloud formation. These non-GHG climate effects are uncertain and highly dependent on local atmospheric conditions.

SAF also consistently yields lower air pollutant emissions than conventional fuel, especially for particulate matter due to its lower sulfur and aromatic concentrations. At higher blending rates, these can yield significant health impacts (Arter et al., 2022), especially for communities nearby or downwind from airports. SAF benefits from pollutants other than particulate matter are more challenging to assess, and often depend in part on the characteristics of the engine as much or more than the fuel. In almost all cases, SAF has a neutral or positive impact on emissions from aviation when it is used in place of petroleum fuels (National Academies of Sciences, Engineering, and Medicine, 2019). Because HEFA SAF is made from the same feedstocks and often in the same facilities as hydrotreated renewable diesel, near-term expansion of SAF supply may come at the expense of reduced renewable diesel supply. While this is unlikely to have a significant negative net impact on air quality, the possibility should be considered while developing SAF policy (Li et al., in press). Additionally, the air quality impacts of SAF production should be considered when evaluating the net air quality impacts of SAF. While in-use combustion emissions typically dominate the air quality impact profile of most transportation fuels, production activities can create significant local impacts in some cases, such as fertilizer or pesticides applied to the fields where feedstock is grown.

Cost and Scalability

One of the advantages of using drop-in SAF is an energy density and material properties that largely mirror those of conventional jet fuel, allowing it to be burned in existing jet engines without modification. While most forms of SAF are only ASTM certified in blends up to 50%, several aircraft makers, engine makers, and airlines have demonstrated their use in modern engines as unblended neat fuels, suggesting that operating aircraft on 100% SAF in the future is feasible. Due to its compatibility with the existing infrastructure for conventional jet fuels, cost and scalability issues only need to be addressed for drop-in SAF production, not for additional infrastructure needs like charging station or storage.

According to the techno-economic analysis results for diverse production pathways, the feedstock cost and capital cost are the major contributors to the production cost of drop-in SAF (Holladay et al., 2020), and the cost of drop-in SAF is highly sensitive to hydrocarbon yield and feedstock cost (Eswaran et al., 2021) For example, FT-SPK from agricultural residuals costs double of FT-SPK from municipal solid waste (MSW), and ATJ-SPK from cellulosic ethanol costs three times of ATJ-SPK from corn ethanol (Brandt et al., 2022). Thus, the production cost of drop-in SAF may be reduced to the competitive level with improvement of conversion technology and increase in use of waste feedstock at lower cost.

Similar to FT-SPK and ATJ-SPK, production cost of HEFA-SPK also varies depending on the feedstock, at most about 5 times (Ng et al., 2021), and the cost reduction may be addressed in a similar way with other pathways. However, for the scalability, HEFA drop-in SAFs, which are from lipid-based feedstocks, have a significant risk. They present a significant risk of indirect GHG impacts via consumption of agricultural commodities and/or competition for scarce arable land. This indirect land use change (ILUC) is a significant, though highly uncertain and variable risk associated with almost all biofuels. ILUC cannot be directly measured, and must be assessed by modeling, which means that model assumptions lead to substantial variability across estimates. The range of uncertainty on estimates of GHG impact due to ILUC for vegetable oil based fuels can sometimes be several times greater than the GHG footprint of a conventional jet fuel (Woltjer et al., 2017). Some sources of feedstock for biofuels pose greater ILUC risk than others, vegetable oils, such as those commonly used in the HEFA fuel production process typically have a greater, and more uncertain land use change impact than grain or cellulosic biomass crops. Wastes and residues, such as used cooking oil, tallow from meat processing, and technical (inedible) corn oil byproduct from ethanol production have much lower ILUC impacts than virgin vegetable oils, in which the emissions from fertilizer and farm energy use impact the fuel's life cycle emissions.

The potential supply of HEFA SAF ultimately depends on the availability of suitable lipid feedstock. While wastes and residues offer the opportunity for production of very low-carbon fuels, most readily available sources of waste lipids have already been utilized for fuel production.

Aircraft Performance Impact

Other than the blending limitation, drop-in SAF may not impose any impact on aircraft performance. Drop-in SAF may have different composition of molecular families such as n-alkanes, aromatics, and cycloalkanes compared to conventional jet fuel, and different molecular structures affect physical and chemical properties of fuels. However, a blending limitation for each type of fuel has been determined and certified considering the composition and chemical properties, and thus, with the ASTM approval, the impact of drop-in SAF on aircraft performance can be considered as negligible.

Technological Readiness

Of the nine SAF production processes certified under the ASTM standards, only HEFA fuels, made from lipids like fats, oils, and greases, have been produced at commercial scale to date. In California, the drop-in SAF can generate credits under the LCFS, and the fuel pathways currently approved under the LCFS are HEFA pathways using lipid-based feedstocks such as tallow, used cooking oil, distillers' corn oil, etc. One reason that HEFA drop-in SAFs are already at the commercial scale is its similarity to HEFA renewable diesel (RD) production process. HEFA Drop-in SAF and HEFA RD are produced from the same feedstock using almost identical processes. The operating conditions for SAF and RD can be easily modified to either SAF-optimized or RD-optimized processes, and one can be produced more at the expense of the other. Since the market and production of HEFA RD have already been at the commercially feasible scale, the HEFA SAF has been able to reach at the level faster compared to other drop-in SAF pathways.

Several producers are developing SAF production systems that use technologies other than HEFA to make SAF. Alcohol-to-jet synthesis, gasification of cellulosic biomass coupled with Fischer-Tropsch synthesis, direct-air-capture CO_2 e-fuel synthesis, and pyrolysis of waste wood followed by upgrading to SAF have prototype or pilot facilities either operational or announced. As with previous attempts to deploy advanced fuel production capacity, however, several have experienced setbacks along their path to full operational status and one project was abandoned partway through construction.

Battery-Electric

Energy Use

For each flight within the ASPM dataset, we considered the scenario where all intrastate flights are replaced by all-electric aircraft. We assumed no specific details regarding the all-electric aircraft itself, and the estimation of energy requirements aligned with the results from our California Aviation Energy Model (CAVEM). By applying the Breguet range equation (Schäfer et al., 2019), we calculated the estimated volume of energy required for each flight. Additionally, we determined the weight of the all-electric aircraft and battery necessary to meet the energy requirements.

$$For\ Conventional\ Jet\ (JEA),\qquad \frac{E}{RPK_{JEA}} = \frac{1}{(\eta_{total,JEA} \cdot PAX \cdot \left(\frac{L}{D}\right))} \cdot \frac{W_{fuel}}{In(\frac{W_i}{W_f})}$$

$$For\ All-electric\ Jet\ (AEA),\qquad \frac{E}{RPK_{AEA}} = \frac{1}{(\eta_{total,AEA} \cdot PAX \cdot \left(\frac{L}{D}\right))} \cdot W_{AEA}$$

Where E is aircraft energy use, RPK is revenue passenger kilometers, PAX is the number of passengers, L/D is the lift-to-drag (L/D) ratio, $\eta_{total,JEA/AEA}$ is the total tank-to-wake efficiency of the jet engine or electric propulsion system, W_{fuel} is the weight of fuel, $W_{i/f}$ is the weight of conventional jet aircraft at the beginning (i) or the end (f) of the flight, W_{AEA} is the weight of all-electric aircraft at any point during the flight.

To estimate the volume of energy required, we made several assumptions. We assumed equal passenger count, RPK, and L/D ratio for both conventional jet and all-electric aircraft. We considered that the high-efficiency electric motor, along with inverters and propfan, could achieve a 77% Tank to Wake (TTW) efficiency, while current turbofan engines can achieve 37% TTW efficiency. In terms of energy density, the current best available Li-ion battery cells have a specific energy of around 250 Wh/kg, whereas jet fuel has an energy density of approximately 11,950 Wh/kg (Staack et al., 2021).

Taking all these assumptions into account, the weight of the all-electric aircraft (W_{AEA}) can be estimated using the following formula:

$$W_{AEA} = \frac{\eta_{total,AEA} \cdot W_{fuel}}{\eta_{total,JEA} \cdot In\left(\frac{W_i}{W_f}\right)}$$

Furthermore, we made the assumption that the payload weight of all electric aircraft is equal to the payload weight of the conventional jet:

$$W_{Payload} = W_{JEA} - W_{OEW,JEA} - W_{fuel} = W_{AEA} - W_{OEW,AEA} - W_b$$

Additionally, we assumed that the ratio of operational empty weight (OEW) to the initial aircraft weight is equal for both the conventional and all-electric aircraft, where OEW does not include the weights of the electric drive and batteries or fuel tank:

$$\frac{W_{OEW,JEA}}{W_{JEA,i}} = \frac{W_{OEW,AEA}}{W_{AEA}}$$

Thus, we can rearrange the equations for the weight ratio of fuel to the weight of the jet aircraft ($\frac{W_{fuel}}{W_{JEA,i}}$) and the weight ratio of the battery to the weight of electric aircraft ($\frac{W_b}{W_{AEA}}$) as follows:

$$\frac{W_{fuel}}{W_{JEA,i}} = 1 - \frac{W_{OEW,JEA}}{W_{JEA,i}} - \frac{W_{Payload}}{W_{JEA,i}}$$

$$\frac{W_b}{W_{AEA}} = 1 - \frac{W_{OEW,AEA}}{W_{AEA}} - \frac{W_{Payload}}{W_{AEA}} = 1 - \frac{W_{OEW,JEA}}{W_{JEA}} - \frac{W_{Payload}}{W_{AEA}}$$

Given the W_{AEA} estimated using the previous equation and the known values of $\frac{W_{OEW,AEA}}{W_{AEA}}$ and $W_{Payload}$, we can estimate the weight of the battery (W_b) using the following equation:

$$W_b = (1 - \frac{W_{OEW,JEA}}{W_{JEA}} - \frac{W_{payload}}{W_{AEA}}) \cdot W_{AEA}$$

Based on the calculations, achieving the scenario where all intrastate flights are replaced by all-electric aircraft would result in an estimated total electricity consumption of 2262 GWh in 2030 and 2025 GWh in 2035. These values represented approximately 1.2% and 1.0% of the in-state electricity generation in 2021, which was measured at 193,569 GWh. However, it is important to note that these values could be lower if the higher energy density of batteries is considered, as advancements in battery technology could significantly impact the energy requirements of all-electric aircraft. The results highlighted the advantages and potential of using all-electric aircraft, as they demonstrate the feasibility of electrifying intrastate flights while accounting for a relatively small percentage of the overall electricity generation.

Emission Trade-offs

Based on the emission indices information provided in Table 21, burning 1 kg of jet fuel produces 3.16 kg of carbon dioxide (CO_2), 1.24 kg of water vapor (H_2O), 1 gram of nitrogen oxides (NO_x), and 1 to 2.5 grams of carbon dioxide (CO) (Nojoumi et al., 2009). Considering that all-electric aircraft produce zero carbon emissions and contrails, replacing all intrastate flights with all-electric aircraft would lead to significant reductions in carbon dioxide (CO_2) emissions. It is estimated that we can reduce 2.833 million metric tons (MMT) CO_2 in 2030 and 2.972 MMT CO_2 in 2035. This reduction in emissions highlights the potential environmental benefits of transitioning to all-electric aircraft for intrastate flights.

Table 21. Emission Indices Per kg Jet Fuel Combustion

Emission	CO_2	H_2O	NO_x	CO
Per kg Jet fuel	3.16 kg	1.24 kg	1 g	1-2.5 g

Source: Author's Calculation

Cost and Scalability

Compared to conventional jet aircraft, all-electric aircraft will have varying operational costs across. There are several factors that contribute to this cost difference (Schäfer et al., 2019). On one hand, the high energy density of batteries used in all-electric aircraft can be expensive, leading to increased capital costs. The initial investment required for the batteries can be significant. Additionally, the weight penalty associated with accommodating the battery system may increase maintenance requirements, which can also contribute to higher costs. On the other hand, all-electric aircraft benefit from the simplified mechanics of electric motors, which can potentially lower maintenance costs (Wheeler 2016). The absence of a fuel system and the elimination of an auxiliary power unit for generating electricity and engine starting can result in cost savings. These factors contribute to reduced operational expenses for all-electric aircraft.

With the current limitations in battery energy density, the operational range of all-electric aircraft is generally more suitable for short-haul flights. Recharging will be another big challenge. However, despite this limitation, focusing on the short-range market for all-electric aircraft can still have significant and ripple impacts. It can serve as an important step towards achieving sustainable air travel and can lay the foundation for future advancements in electric aviation technology.

Aircraft Performance Impact

One challenge that all-electric aircraft face is the weight penalty. Based on the estimation results obtained from the Breguet range equation, it is projected that the battery-electric aircraft would require approximately 1.8 times more weight compared to the conventional jet for the same flight on average. This increase in weight is primarily due to the need to accommodate the volume and weight of the battery, assuming that the weight of the battery remains unchanged during the mission. The increased weight of the all-electric aircraft can have implications for its range fungibility. The additional weight from the battery would reduce the capacity of the payload and may limit the range of the mission which hinders the commercial viability of all-electric aircraft.

The other challenge posed by all-electric aircraft is the speed penalty. Due to their lower power requirements compared to conventional jets (Moore, 2012), all-electric aircraft generally operate at lower speeds. The propulsive efficiency of a conventional jet can be defined as the ratio of propulsive power to fuel power (Lewis III, 1976).

$$\eta_{propulsive,JEA} = \frac{Propulsive\ Power}{Fuel\ Power} = \frac{T \cdot V}{\rho \cdot ff}$$

Where T represents thrust, V is velocity, ρ is energy density and ff is fuel flow rate. With knowledge of the propulsive power percentage (37%) and data on fuel power and velocity from the CAVEM model, we can calculate the thrust of the conventional jet using this equation.

Assuming a constant cruise speed for all-electric aircraft, the power required to overcome drag at a specific speed, where drag (D) is equal to thrust (T) during the cruise, can be expressed as the product of thrust and aircraft cruising velocity divided by the propulsive efficiency.

$$P_{AEA} = \frac{D \cdot V}{\eta_{propulsive,AEA}} = \frac{T \cdot V_{AEA}}{\eta_{propulsive,AEA}}$$

During level flight, the lift force is equal to the weight of the aircraft. Hence, the weight of the all-electric aircraft and the power required can be expressed accordingly:

$$W_{AEA} = L = T \cdot (\frac{L}{D})$$

$$P_{AEA} = \frac{T \cdot V}{\eta_{propulsive,AEA}} = \frac{W_{AEA}}{(\frac{L}{D})} \cdot V_{AEA}$$

By comparing two formats of the power required for conventional jets, we can derive the equation for the L/D ratio.

$$P_{JEA} = \eta_{propulsive,JEA} \cdot \rho \cdot ff = \frac{W_{JEA,i}}{(\frac{L}{D})} \cdot V_{JEA}$$

$$\frac{L}{D} = \frac{\eta_{propulsive,JEA} \cdot ff \cdot \rho}{W_{JEA,i} \cdot V_{JEA} \cdot g}$$

Assuming the same lift-to-drag ratio (L/D) as the conventional jet, we can calculate the cruising velocity of the all-electric aircraft (V_{AEA}) using the propulsive efficiency, energy ($E_{Battery}$), lift-to-drag ratio (L/D), gravitational acceleration (g), weight of the all-electric aircraft (W_{AEA}), and the cruising time assumption (t_{AEA}) based on the battery configuration (e.g., 4C discharging rate with 20 batteries of 24 volts each). The cruising time of all electric aircraft (t_{AEA}) is calculated as the battery energy divided by the product of batteries voltage and discharging rate (Cr).

$$t_{AEA} = \frac{I}{Cr} = \frac{E_{Battery}}{V * Cr}$$

$$V_{AEA} = \frac{\eta_{propulsive} \cdot E_{Battery} \cdot (\frac{L}{D})}{g \cdot W_{AEA} \cdot t_{AEA}}$$

Based on the calculations and assumptions made, it is estimated that the speed of an all-electric aircraft is approximately 77% of the speed of a conventional jet. This suggests that the speed of the all-electric aircraft is approximately 23% lower than that of the conventional jet aircraft. The lower speed and longer travel time of the all-electric aircraft can indeed pose challenges to its commercialization and integration into the airline industry.

Technological Readiness

The introduction of all-electric aircraft into commercial aviation would have significant impacts on aircraft manufacturers, airlines, airports, and the transportation system as a whole. While current battery technology limits the feasibility of all-electric aircraft with 180 passengers, a four-fold increase in battery pack specific energy could enable flights of up to 500 nm (Gnadt et al., 2019).

The development of small-scale electric aircraft is underway, with some already certified to fly and test flights being conducted for retrofits of existing aircraft. As of February 2020, there were approximately 170 electric aircraft projects ongoing internationally (Schwab et al., 2021).

For battery-electric aircraft to become commercially viable, the development of electric charging infrastructure is crucial, alongside addressing the challenges of integrating charging systems into existing airports. Pipistrel, an aircraft manufacturer, has introduced the SkyCharge system, which can charge two aircraft at 20 kW or one at 40 kW. While this charging rate is suitable for small-scale personal-use planes, it is too slow to meet the schedules of commercial flights. However, companies like Clay Lacy Aviation are working on charging systems that can charge larger electric aircraft, such as the nine-passenger Eviation Alice, in 30 minutes or less per flight hour. The deployment of Alice eCargo planes is set to begin in 2024, marking the commercialization of electric aircraft in the short-haul aviation sector (Cox et al., 2023).

Despite progress in areas like battery technology and lightweight materials, challenges remain in the development of all-electric aircraft. These challenges include energy storage, weight, safety, infrastructure, and cost. The technology readiness level for all-electric aircraft propulsion is currently low. Achieving large commercial AEA capable of operating over long-haul missions will likely require advances in electric propulsion system components, as generating and distributing tens of megawatts of electric power for thrust is a significant challenge. It is unlikely that a large commercial aircraft will be possible within the next 20-30 years (Barzkar et al., 2022).

Overall, the technology is still at an early stage of development, with a technology readiness level (TRL) of 3-4 assigned by the ETP Clean Energy Technology Guide (IEA, 2022).

Liquid Hydrogen

Energy Use

Compared to the conventional jet, a lighter fuel load is required for LH_2-powered aircraft due to the higher energy density of LH_2. We considered the conversion of all intrastate flights to Liquid Hydrogen (LH_2)-powered aircraft, similar to the approach taken for all-electric aircraft. To determine the equivalent amount of LH_2 required to meet the jet fuel demand modeled in the CAVEM, we utilized the following formula (Choi and Jinkwang, 2022):

$$W_{LH_2} = W_{fuel} \cdot \frac{\rho_{fuel}}{\rho_{LH_2}} \cdot \frac{\eta_{JEA}}{\eta_{LH_2,jet}}$$

Where $W_{LH_{2/fuel}}$ is the weight of LH_2 or jet fuel, ρ_{fuel/LH_2} is the energy density of jet fuel or LH_2, and $\eta_{JEA/LH_2,jet}$ is the total tank-to-wake efficiency of the jet engine or LH_2-powered aircraft.

If neglecting the efficiency difference between the two aircraft types, the results would depend solely on the difference between the two fuels. Considering the significantly higher energy density of LH_2, which is approximately 2.8 times that of jet fuel, the calculated results were presented in Table 22 below:

Table 22. LH2 for Intrastate Commercial Flight

Intrastate Commercial Flight	2030 (Billion gallon)	2035 (Billion gallon)
Jet Fuel	0.299	0.314
Liquid Hydrogen	0.107	0.112

Source: Author's Calculation

The results showcased the advantage of LH_2 as a fuel for aviation and emphasized its potential for reducing fuel weight. It is worth noting that the calculated values provided in the analysis did not account for the potential impact of engine efficiency. The fuel energy content of LH_2 may also change as a function of time due to advancements in engine development (Choi and Jinkwang, 2022). If the engine efficiency of LH_2-powered aircraft is taken into consideration, the required LH_2 fuel load may be lower than the values presented.

Emission Trade-offs

The utilization of LH_2 as a fuel in aircraft engines offers notable environmental advantages due to its combustion characteristics. When 1 kg of LH_2 is combusted, it produces approximately 9 kg of water vapor as the primary byproduct (Seeckt et al., 2009), along with a minor quantity of nitrogen oxides (NO_x), with the amount being dependent on the design of the combustor (Khandelwal et al., 2013). The combustion of hydrocarbon-based fuels results in the emission of carbon dioxide (CO_2) which can remain in the upper atmosphere for approximately 100 years. In comparison, water vapor has a much shorter residence time, typically lasting up to a year in the atmosphere (Wentz et al., 2005). This difference in residence time, as well as natural limits on the concentration of water vapor in the atmosphere contributes to the lesser unfavorable impact of water vapor compared to CO_2 emissions.

In the scenario of converting intrastate flights to LH_2-powered aircraft, the reduction in CO_2 emissions can be estimated. Considering the fuel demand values mentioned earlier for 2030 and 2035, the use of LH_2 instead of jet fuel would result in a reduction of approximately 2.833 billion kg of CO_2 in 2030 and 2.972 billion kg of CO_2 in 2035. But the increase in water vapor due to LH_2 combustion is estimated to be 1.59 times higher for both 2030 and 2035.

Cost and Scalability

The cost difference between jet fuel and LH_2 is significant, with LH_2 generally being three times more expensive than jet fuel (Baharozu et al., 2017). This cost disparity is an important factor to consider when assessing the feasibility of LH_2 as an aviation fuel. However, an increase of approximately 0.5 dollars per gallon of jet fuel energy can be tolerated to maintain similar direct operating costs which represent 10-20% of the baseline fuel price (Verstraete, 2013). The initial and operational costs of hydrogen production technologies are also relatively high compared to other fuel types (Baroutaji et al., 2019). The main costs in supplying LH_2 come from producing gas hydrogen offsite and the consequent liquefication at the airport (Hoelzen et al., 2022). Overall, the infrastructure required for hydrogen aircraft resulted in approximately double the fuel cost compared to jet fuel, but predictions suggested a potential 25% decrease in fuel costs by 2030 if the switch is made from jet fuel to hydrogen. (Amy et al., 2019). Thus, from a cost perspective, LH_2 demonstrated more advantages over jet fuel for long-haul flights rather than short and medium -haul flights (Baharozu et al., 2017).

Aircraft Performance Impact

As shown in Table 23, liquid hydrogen (LH_2) contains 2.8 times more energy than jet fuel gravimetrically, but the volume required to carry the same energy is four times larger, inducing adjustments and redesign of the size and positioning of the fuselage (Klug and Reinhard, 2001).

Table 23. Comparison of Liquid Hydrogen and Jet Fuel

Category	Jet Fuel[1]	Liquid Hydrogen[2]
Gravimetric Energy Density	43 MJ/kg	120 MJ/kg
Volumetric Energy Density	34.5 MJ/L	8.5 MJ/L

Source: [1]Holladay et al. (2020); [2]Fichtner & Farikha (2009)

LH_2-powered aircraft generally have lower storage efficiency compared to conventional jet aircraft. The storage efficiency is commonly quantified using the Mass Fraction (MF), which represents the fuel weight divided by the total tank system weight including fuel. The weight fraction (tank weight to fuel weight ratio) of LH_2 aircraft ranges from 0.21 to 0.35 (Gomez and Howard, 2019), resulting in an MF ranging from 0.74 to 0.8. In contrast, conventional jet aircraft with integral fuel tanks can achieve an MF close to 1.

The lower storage efficiency of LH_2-powered aircraft can be attributed to the extensive volume required for larger LH_2 tanks. Due to this requirement, LH_2 tanks need to be distributed alongside the longitudinal axis of the aircraft, which may even affect the longitudinal stability of the aircraft (Gomez and Howard, 2019). Additionally, the weight of the LH_2-powered aircraft increases due to modifications in the fuel delivery system, including the incorporation of a heat exchanger to convert LH_2 to gas hydrogen (GH_2) before combustion, as well as redesigned fuel pipes, pumps, seals, and valves to handle the increased volumetric flow and cryogenic temperatures.

To evaluate the weight penalty of LH2-powered aircraft, the Gravimetric Index (GI) of the fuel system is introduced (Mukhopadhaya and Dan, 2022). The GI is expressed as the ratio of the weight of LH_2 to the sum of the LH_2 weight and the weight of the entire LH_2 fuel system.

$$GI_{LH_2} = \frac{W_{LH_2}}{W_{LH_2} + W_{Entire\ fuel\ system,LH_2}}$$

$$GI_{JEA} = \frac{W_{Fuel}}{W_{Fuel} + W_{Entire\ fuel\ system,JEA}}$$

The GI of the LH_2 fuel system needs to be lower than 0.34 to not mitigate the approximate three-fold energy density benefit (Mukhopadhaya and Dan, 2022). Assuming a GI of 0.28 for the LH_2-powered aircraft and a GI of 0.95 for the conventional jet, results indicated that the total fuel system of the LH_2-powered aircraft increases by an average of 21%. The increased weight of the LH_2-powered aircraft is also influenced by the need for structural reinforcement, insulation, and maintenance facilities required for LH_2 fuel tanks. These factors contribute to an increase in OEW of the aircraft by 23% in general (Westenberger, 2003).

In conclusion, the lower storage efficiency of LH_2-powered aircraft, evident from the lower MF and GI values, results in an increased weight of the fuel system and the overall aircraft, requiring structural modifications and may impact its operational performance.

Technological Readiness

Hydrogen propulsion as an alternative to traditional jet fuel in the aviation industry faces technical challenges, especially in terms of fuel storage. Unlike conventional aircraft that store fuel in the wings, accommodating larger liquid hydrogen tanks requires placing them in the aircraft's main body or fuselage. Integrating hydrogen tanks into existing aircraft designs may be challenging, but future aircraft will be designed to accommodate these new storage technologies (Winnefeld et al., 2018).

LH_2 refueling for aircraft has been deemed feasible and meets explosion protection standards without affecting the turnaround process. Comparisons showed that refueling with LH_2 is generally faster than using Jet A fuel. Refueling can be done with fuel trucks or pipeline systems at airports, avoiding direct losses like venting to the atmosphere which may involve safety concerns (Mangold et al., 2022). For airports with less than 125 kt_{LH2} annual demand, a refueling truck setup is more cost-effective. However, airports with higher LH_2 demands may benefit from implementing a pipeline and hydrant system, leading to slight cost reductions and improved safety. Refueling system costs represent only 3 to 4% of total LH_2 supply costs (Hoelzen et al., 2022).

Airbus, along with Boeing is actively involved in developing hybrid hydrogen-powered aircraft as part of its ZEROe program. These aircraft concepts, including a narrow-bodied turbofan design, are expected to be available by 2035 and have the potential to carry 165 passengers over long-haul flights (up to 3400 km). One of the latest designs of LH_2-powered aircraft is the SkyWhale; an 88-passenger jet with a high wing, two underwing engines, T-tail configuration and LH2 tanks mounted above the interior regional jet (Stauffer et al., 2023). SkyWhale has an MTOW of 93,663-lbm with a maximum payload of 22,000-lbm, a maximum flight range of 2,100-nM, and a cruise Mach number of 0.76.

However, the technology as a whole is still in its early stages, with a TRL of 3-4 according to the ETP Clean Energy Technology Guide (IEA, 2022).

Policy Inventory

Background

The policy inventory aimed to gain greater clarity on the progress and efforts in promoting alternative-fueled aviation (AFA), focusing on sustainable aviation fuels (SAF), electric aircraft, and hydrogen-powered aircraft. Given the global aviation sector's commitment to achieving climate neutrality by 2050, SAF has emerged as the key technology in the short term. Several governments have implemented policies to facilitate the adoption of SAF, as well as to promote the long-term development of electric and hydrogen-powered aircraft. This report offers a detailed policy inventory focusing on AFA, encompassing aviation decarbonization targets, SAF, electric aircraft, and hydrogen-powered aircraft.

Methodology

The methodology involved an extensive search across more than 100 countries to identify and analyze AFA policies. The analysis covered ongoing and planned policies in more than 30 countries and examined the types of examining the types of AFA policies implemented and planned for future implementation. A comprehensive inventory of policy instruments with potential for promoting AFA use was developed. Policies regarding net-zero emission targets for aviation at the state, U.S. and international scope were examined, as well as the status of their implementation and any updated policy support.

Policy Instruments

Aviation Decarbonization Vision

The goal of achieving net-zero emissions in aviation by 2050 is a commonly shared objective among many countries. The ICAO assembly, consisting of 193 countries, agreed to a long-term aspirational goal (LTAG) of achieving net-zero emissions from aviation by 2050.

While most countries are working towards the 2050 target for net-zero emissions, several nations, notably those in the Nordic region, have set even more ambitious goals (Table 24). Finland aims to achieve net zero emissions from domestic flights by 2045 and overall net zero by 2050, which includes international flights (Valtioneuvosto ja ministeriöt, 2021). Denmark and Sweden have set a domestic target of 2030, with Sweden aiming for an overall net-zero target by 2045 (Transport- og Boligministeriet, 2022; Fossilfritt Sverige, 2019).

Table 24. Decarbonization Vision in Nordic Countries

Country	Domestic Target Year	Overall Target	Policy
Finland	2045	2050	Valtioneuvoston periaatepäätös LVM/2021/64
Denmark	2030	2050	Government plan
Sweden	2030	2045	Fossil Free Sweden

Source: (Valtioneuvosto ja ministeriöt, 2021); (Transport- og Boligministeriet, 2022); (Fossilfritt Sverige, 2019)

Instead, some Asian countries have outlined their progressive decarbonization plans instead of precise net-zero targets. India is aiming for net neutrality by 2070, while China has set a goal for carbon-neutral growth target by 2035.

Policy Focus on SAF

Policies to support SAF can be categorized into four main groups (Figure 3), which include setting numerical targets, providing economic incentives, focusing on research and development (R&D), and establishing certifications and standards.

Numeric targets can be established both on the production side and the consumption side. Production targets can involve specific mandate goals or annual production capacities for suppliers. For example, France has set mandates on both sides (Ministères Écologie Énergie Territoires, 2023; French Government 2019). Suppliers are required to blend SAF into the total supply at a rate of 1% since 2022, while SAF consumption objectives aim for 2% by 2025 to 50% by 2050. While these targets are designed to build market capacity and guide investment in research and development, the implementation of mandates can carry risks, such as being overlooked or set too high.

Performance standards occupy a middle ground between several types of policies. They set quantitative targets for key parameters, such as the carbon intensity of fuel (e.g. Low Carbon Fuel Standards, a.k.a. Clean Fuel Standards) or the emissions from vehicles (e.g. fuel quality standards). They require improvement on that particular metric, but grant producers and consumers a wide range of flexibility about how to do so. In many cases, performance standards use market-based mechanisms, such as credit trading (as in the case of the Low Carbon Fuel Standard) to facilitate compliance at the lowest possible cost. Carbon pricing, via carbon taxes or carbon allowance markets (e.g. the EU Emission Trading System), are another form of policy instrument that can impact aviation, but increasing the cost of GHG emissions.

Economic incentives include not only direct investment and grants but also tax credits and subsidies. Given the high initial capital costs, direct investment and grants can help mitigate the first-mover risks and assist in scaling up new technologies. Tax incentives may include a Danish tax on passenger fees (Transport and Housing Ministry, 2022) and a carbon tax on conventional jet fuel with additional credits for SAF to encourage its ramp-up. Subsidies are also commonly used to stimulate the industry.

Certifications and standards serve to unblock institutional barriers, while research and development policies aim to lower costs and remove technology barriers.

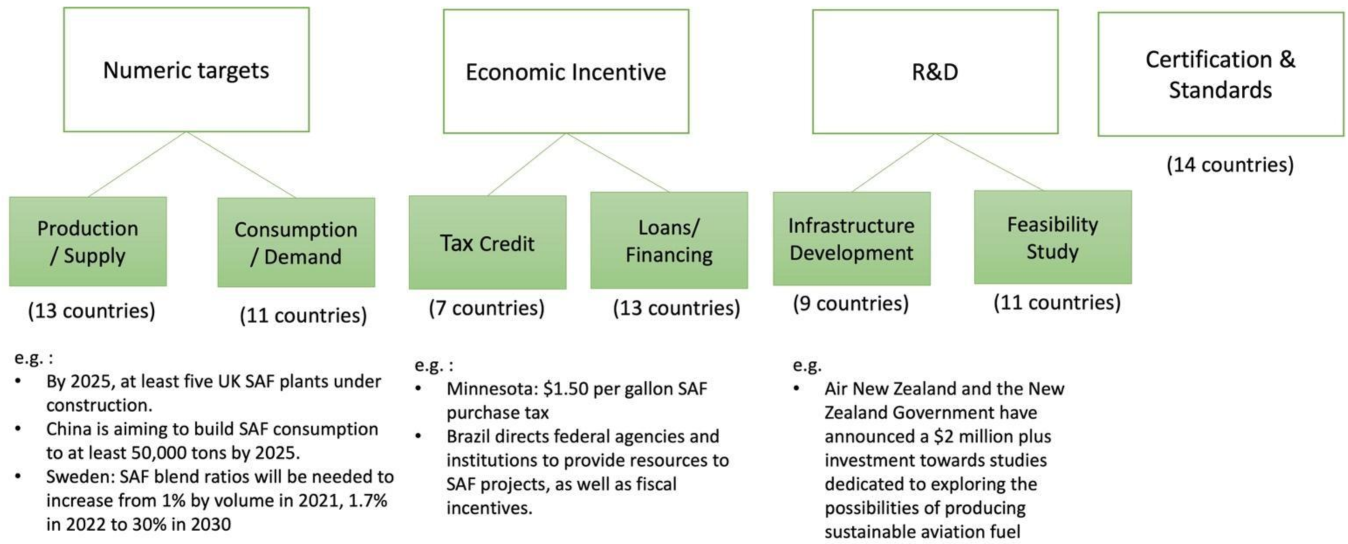

Figure 3. SAF Policies Taxonomy

Policy Focus on Electric Aircraft

The policies to accelerate the adoption of electric aircraft demonstrate a strong commitment to technological advancement and innovation as depicted in Figure 4. Most policies have a particular emphasis on horizontal vision. Norway has emerged as a key proponent, showcasing its comprehensive plans and strategies to transition to electrified aviation by 2040 (Norwegian Ministry of Climate and Environment, 2020).

The provision of grants for infrastructure development and technology testing is the popular policy approach. Economic incentives, particularly in the form of tax exemptions, have gained traction, as seen in the Norwegian tax exemption on passenger fees (Norwegian Ministry of Climate and Environment, 2020) and the Dutch tax exemption on landing fees for electric aircraft (Rijksoverheid, 2020).

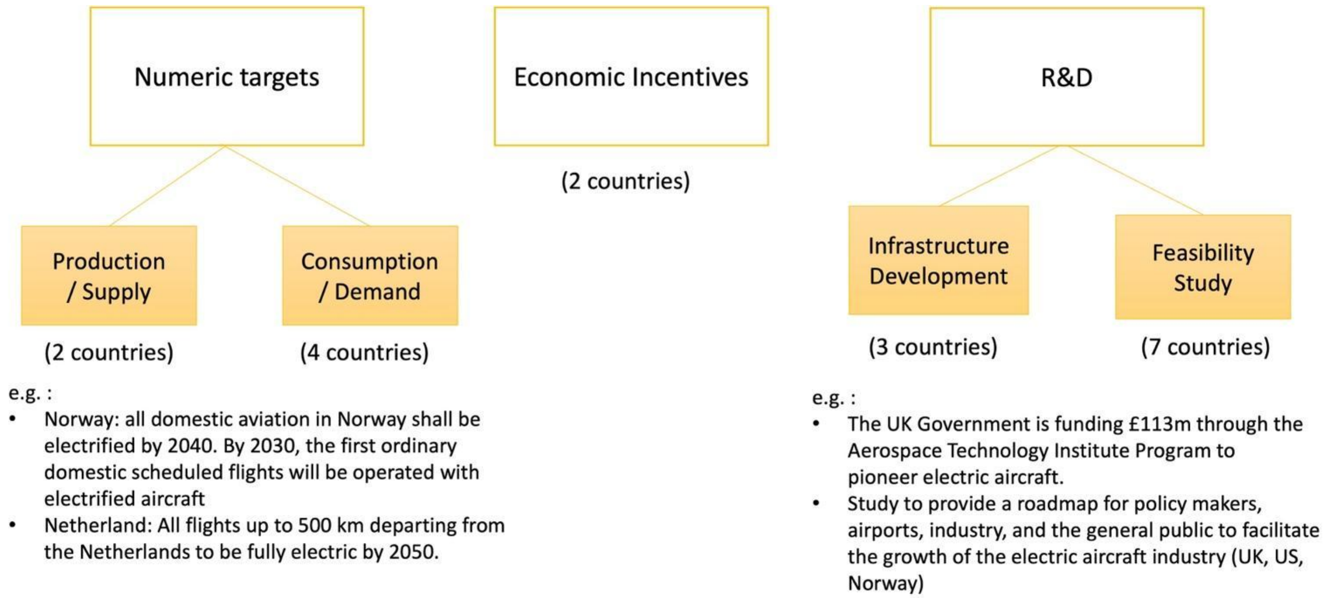

Figure 4. Battery-Electric Aircraft Policies Taxonomy

Policy Focus on Hydrogen Aircraft

More than 50 countries have announced national hydrogen strategies but only a small fraction of them have implemented policies specifically targeting the aviation sector or incorporating hydrogen-based initiatives for aviation. The policies for hydrogen aircraft are currently most focused on infrastructure development and feasibility study as shown in Figure 5.

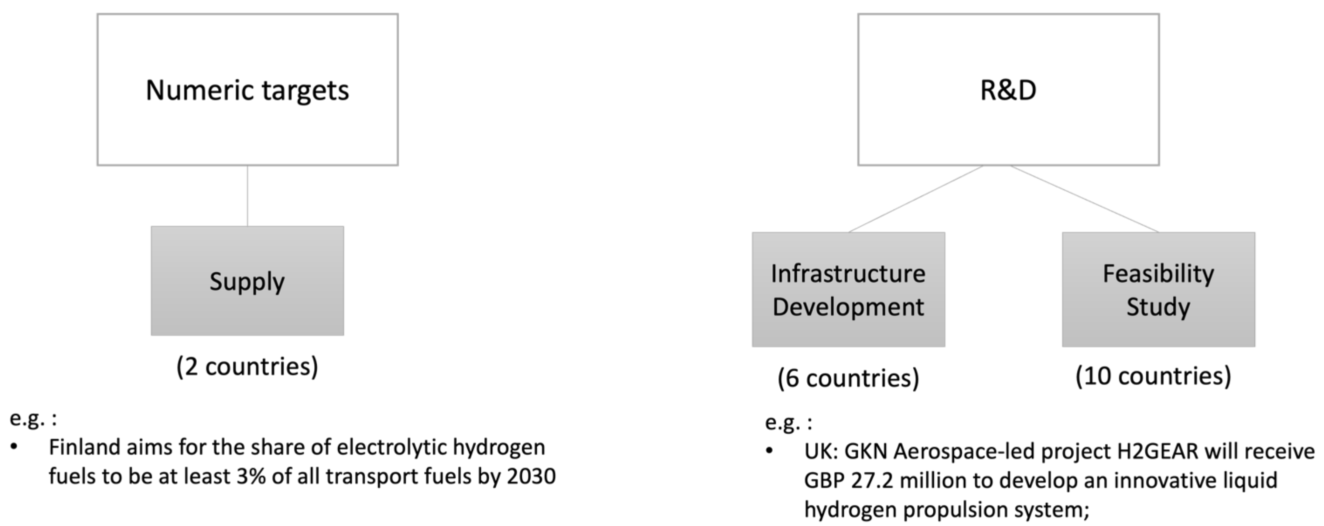

Figure 5. Hydrogen-powered Aircraft Policies Taxonomy

National Roadmaps

United States

To reach the goal of net zero in aviation by 2050 (U.S. Department of Energy, 2023), the US government undertook several policies to promote the development and deployment of AFA approaches.

To accelerate the production side of SAF, the FAA initiatives a Sustainable Aviation Fuel Grand Challenge in 2021, aiming to reach at least 3 billion gallons per year by 2030 and 35 billion gallons per year by 2050 (White House, 2021). At the same time, both tax incentives and financing programs were used. Funding opportunities to support sustainable aviation fuel projects and fuel producers totaling up to $4.3 billion. Producers of SAF are eligible for a tax credit of $1.25 per gallon (U.S. Department of Energy, 2023). Qualifying SAF must reduce greenhouse gas (GHG) emissions by 50%. SAF that decreases GHG emissions by more than 50% is eligible for an additional $0.01 per gallon for each percent the reduction exceeds 50%, up to $0.50 per gallon. At the time of writing, final determination had not been made regarding the GHG quantification methodology that will be used to determine the eligibility, and amount of credits a producer would receive. This has become a highly controversial issue, with biofuel producers advocating for a methodology that would make SAF made from corn ethanol via alcohol-to-jet synthesis, or soybean oil HEFA SAF eligible for the tax credit. Environmental groups argue that this would direct significant subsidies to fuels that have already reached commercial maturity, and offer only modest GHG benefits. The decision on this issue will play a large role in determining whether US SAF policy through 2030 will focus on expanding the use of existing biofuel technologies, or support a smaller deployment of more advanced, lower-carbon fuels.

To qualify, SAF producers must be registered with the Internal Revenue Service (IRS). R&D activities were also promoted. This credit will help cut costs and rapidly scale domestic production of sustainable fuels for aviation (Internal Revenue Service, 2022). Five States including California (California Air Resources Board, 2020), Oregon (Oregon Secretary of State, 2022), Minnesota (Minnesota State Senate, 2023), Washington[3], and Illinois[4] have independently introduced incentives to cut costs of SAF use and accelerate the scaleup of SAF. California also has an aspirational target for SAF to provide up to 80% of aviation fuel demand by 2045 (California Air Resources Board, 2023c) while the Minnesota government provided millions of dollars annually to support SAF production (Minnesota Management and Budget, 2023).

Electrification and hydrogen technologies have been recognized as solutions for short-haul aviation (FAA, 2021). In line with this, the Hydrogen Aviation Development Act was introduced to encourage the use of hydrogen in the aviation sector (Senator Jon Ossoff, 2023). In Washington State, a feasibility study on electric aircraft has been conducted to provide a roadmap for stakeholders, facilitating the growth of the electric aircraft industry (Washington State Department of Transportation, 2020). Furthermore, California aims for

[3] https://app.leg.wa.gov/billsummary?BillNumber=5447&Initiative=false&Year=2023.
[4] https://www.ilga.gov/legislation/BillStatus.asp?DocTypeID=SB&DocNum=2951&GAID=16&SessionID=110&LegID=137129.

20% of aviation fuel demand to be met by electricity (batteries) or hydrogen (fuel cells) in 2045 (California Air Resources Board, 2023c).

Canada

Canada aims to achieve net-zero emissions including the aviation sector by 2050 as outlined in the Canadian Net-Zero Emissions Accountability Act. Canada has recognized SAF as a key measure to reduce GHG emissions from the aviation sector in its 2022 Climate Action Plan (Government of Canada, 2022a). The plan set an aspirational goal of 10 percent SAF use by the year 2030. To facilitate this goal, all stakeholders involved in the Action Plan have pledged to develop a roadmap for SAF adoption. Recent amendments to the Clean Fuel Regulations (Government of Canada, 2022c) have made SAF eligible for generating compliance credits, providing further support for its use. The government would also pursue other options to support SAF deployment, such as creating a supportive policy framework through federal measures, signaling demand by purchasing SAF for its federal fleet, and considering SAF in the context of Natural Resources Canada's BioEnergy Strategy.

The plan also recognized the potential of zero-emission technologies such as electric and hydrogen-powered aircraft and committed to supporting research and development in these areas (Government of Canada, 2022a). However, the plan does not include specific policies related to these technologies.

United Kingdom

The United Kingdom has set ambitious climate goals to reach net-zero emissions in the aviation sector by 2050, aligning with making all domestic flights by 2040 (United Kingdom Government, 2021a). Furthermore, the UK is also striving for zero-emission airport operations in England by 2040.

To realize these targets, the promotion of SAF has been identified as one of the central pillars of the Jet Zero strategy. The UK plans to have at least five SAF plants under construction by 2025 and mandates a 10% SAF blend for fuel suppliers by 2030. Eligible SAF must meet both the Ministry of Defense (MOD) Defense Standard (DEF STAN) 91-091 and the American Society for Testing and Materials (ASTM) D7566 specification (UK Department for Transport, 2023). The UK has also supported SAF development and commercialization through various competitions and funds since 2014.

Acknowledging the significance and potentiality of Zero Emission Flights (ZEV), the UK has already deployed small battery electric aircraft in its General Aviation sector (United Kingdom Government, 2021b). By 2030, their vision is to establish zero-emission flight routes connecting different regions. To reach the goal, a significant investment of £113 million has been allocated to hydrogen and all-electric aircraft and related technologies (United Kingdom Government, 2023). Additionally, the UK has an ambitious plan to double hydrogen production to 10GW by 2030, with a focus on electrolytic hydrogen production. These endeavors will make an important contribution to aviation decarbonization.

France

France has set an ambitious target for achieving sustainable aviation by 2050 in 2017 (French Civil Aviation Authority, 2023; ICAO, 2023). This ambitious target encompasses a wide range of strategies, including specific SAF adoption targets, tax incentives, and substantial investments in low-carbon aircraft technology.

In the short and medium term, SAF is seen as a key solution, with consumption targets of 2% in 2025 and 5% in 2030. In the long term, the goal is to replace 50% of conventional jet fuels with SAF by 2050 (French Government, 2019). To further encourage the uptake of SAF in the short term, it has been incorporated into the scope of the Taxe Incitative Relative à l'Incorporation de Biocarburant (TIRIB) as of January 1, 2022. TIRIB is a tax policy designed to promote the adoption of sustainable fuels in the transportation sector, mandating a minimum SAF incorporation of 1% in the jet fuel sold in 2022 and 1.5% in 2024 (Ministères Écologie Énergie Territoires, 2023). In order to scale up SAF production, the French public authorities are actively contributing €1 billion ($1.1 billion) to build a plant dedicated to SAF production (Bloomberg News, 2023).

Additionally, France is investing in research, development, and industrialization of low-carbon aircraft and aims to produce the first low-carbon aircraft by 2030 (Élysée - Présidence de la République française, 2021; French Government, 2030).

Germany

Germany is committed to significantly reducing carbon emissions across its transportation sector and has set a far-reaching goal of achieving carbon neutrality by 2050 (BMVI, 2021). The aviation sector is included in this big ambition.

To realize this vision, Germany promotes the extensive use of hydrogen in aviation, both in fuel and aircraft propulsion systems. A national policy framework was promoted to increase the adoption of power-to-liquid (PtL). To goal is to use at least 200,000 tonnes of PtL kerosene in aviation by 2030 (BMVU, 2021). The National Hydrogen Strategy also mandates a 2% quota for PtL kerosene by 2030 (Germany Federal Ministry of Economic Affairs and Energy, 2020). To achieve this, Germany is actively advancing PtL production technologies to an industrial scale. Standards are expected to be established both at the European and international levels (BMVU, 2021).

In addition, Germany is planning to establish a Hydrogen Aviation Center in 2024, funded in part by the state of Baden-Württemberg's Ministry of Transport. This center will focus on the development of hydrogen-fueled passenger aircraft (Mugglehead, 2023). Germany's Aviation Research Program is also contributing to hydrogen aviation technologies, allocating €25 million for hydrogen technologies. For the period between 2020 and 2024, funding supports research into disruptive engine technologies such as fuel cells and hydrogen-powered generators, as well as flight tests with hydrogen-powered and hybrid electric technologies (Federal Ministry of Economic Affairs and Energy, Germany, 2020).

Netherlands

The Netherlands aims to achieve net zero aviation by 2050. SAF is of major importance in reaching this long-term goal. The country has established a SAF consumption target of having SAF make up 14% of aviation fuel by 2030. The ultimate goal is to entirely replace traditional fossil-based jet fuel with sustainable alternatives by 2050 (Ministerie van Infrastructuur en Waterstaat, 2019a; Ministerie van Infrastructuur en Waterstaat, 2020).

Moreover, the Netherlands is actively promoting the adoption of electric aircraft for short-haul flights through its National Action Program for Hybrid Electric Flying (AHEV) (Ministerie van Infrastructuur en Waterstaat (2019b). The ambitious goal is to have all flights departing from the Netherlands to destinations within 500 km fully electric by 2050. One million euros have been allocated to incentivize this shift. Electric aircraft operating on these routes will enjoy exemption from landing fees until 2040 (Rijksoverheid, 2020). Additionally, the Netherlands is actively exploring the feasibility of hydrogen-powered aircraft and evaluating their potential inclusion in hydrogen demand projections (Rijksoverheid, 2023).

Switzerland

In Switzerland's long-term climate strategy, synthetic SAF has been identified as the most promising measure to reduce aviation emissions. The production of synthetic SAF includes two pathways: using electricity (Power-to-Liquid, PtL) or directly from solar energy (Sun-to-Liquid, StL). The ultimate goal set by the Swiss Federal Council is to replace all conventional jet fuel demand with SAF by 2050 (Federal Office of Civil Aviation, 2022).

Italy

Italy is committed to fostering the development of a competitive market for SAF not only within the European Union (EU) but also on the global stage (Italian Civil Aviation Authority, 2021). While specific numeric targets are not mentioned, the focus of these efforts primarily revolves around infrastructure construction and the development of the SAF industry. Additionally, Fiumicino and Ciampino Airports plan to provide full availability of SAF for aircraft by 2024.

Demark

The Danish government aims to have green domestic flights available by 2025, with the ultimate goal of completely green (fossil-fuel-free) domestic aviation by 2030 (Transport- og Boligministeriet, 2022). To support these objectives, Denmark plans to allocate nearly DKK 1.9 billion in subsidies. Of this funding, DKK 0.8 billion will be designated for a green domestic route from 2025 to 2029, and DKK 1.1 billion for achieving completely green domestic air travel from 2027 to 2033. This transition will include a gradual phase-in from 2027 to 2030, ultimately leading to 100% green domestic aviation by 2030. The plan allows for the use of various green technologies, including electricity, hydrogen, Power-to-X (PtX), and biofuels, with the exclusion of first-generation biofuels due to sustainability concerns.

To finance these initiatives, the government will introduce an additional passenger tax of DKK 13 per departing passenger (excluding transfer and transit passengers) from Danish airports. This tax is designed to provide the necessary funding for the transition to green domestic aviation (Transport and Housing Ministry, 2022).

In the meantime, the Danish government and the Danish Parliament are exploring other measures (Transport and Housing Ministry, 2022). A new and ambitious CO_2 tax on domestic aviation will be introduced, aiming to make the aviation sector contribute to its emissions on an equal footing with other modes of transportation. Furthermore, over 3 billion DKK have been allocated to support Power-to-X (PtX) technology development.

Norway

Norway has set ambitious goals to achieve net-zero emissions in aviation, with a focus on transitioning to fully electric aircraft by 2040 (Norwegian Ministry of Climate and Environment, 2020).

In the short term, advanced biofuels are promoted, with a 0.5% blending requirement starting in 2020. Norway is the first country in the world with a blending mandate for advanced biofuels for aviation. This mandate is part of efforts to reduce the carbon footprint of aviation and to avoid the use of biofuels sourced from materials with sustainability concerns, such as palm oil. The eligible feedstock for these biofuels is waste and residues. Furthermore, Norway has set a target of having 30% of aviation fuels come from advanced biofuels by 2030 (Norwegian Ministry of Climate and Environment, 2020).

By 2030, the first electric domestic flights will launch, aiming to electrify all of Norway's domestic aviation by 2040. To support this transition, various fiscal incentives are proposed until 2040 (with a possible reassessment in 2035):

1. Exempting tickets for electrified aircraft from fiscal taxes.
2. Implementing an exemption from or reduced Value-Added Tax on tickets for zero- or low-emission aircraft.
3. Offering an exemption from or reduced air passenger tax for electric aircraft
4. Start-up fees to Avinor (Norway's state-owned company responsible for airports) are designed to incentivize the use of electrified aircraft, in accordance with EU regulations.

Finland

Finland is actively focusing on developing a partially hydrogen-based energy system in the aviation sector, encompassing the development of hydrogen-powered aircraft and the production of synthetic fuels derived from hydrogen (Traficom, 2023). The country has established both a production mandate and consumption target of SAF. In accordance with the Renewable Energy Directive, electric fuels (e-fuels) must constitute a minimum of 3% of all transport fuels by 2030 (Finnish Government, 2023). In addition, fuel suppliers in the air transportation sector are required to meet a 30% blending obligation by 2030 (Finnish Government, 2019).

Poland

In 2019, the Polish government introduced the National Energy and Climate Plan, aiming to reach a goal of 14% renewable energy sources in the transport sector by 2030 (Ministerstwo Infrastruktury, 2019). Poland also has plans to increase the utilization of hydrogen in aviation by 2030 from the Polish Hydrogen Strategy (Ministerstwo Infrastruktury, 2021). However, it's important to note that Poland has not yet implemented a mandate for SAF.

Poland is taking steps to create conditions for the efficient use of SAF at its airports, which includes the development of appropriate infrastructure to support the use of SAF (Ministerstwo Infrastruktury, 2023).

Sweden

Sweden aims to achieve fossil fuel-free domestic flights by 2030 and green international flights by 2045 (UNFCCC, 2019). This transition encompasses the utilization of SAF and electrified aviation from the Fossil Free Sweden roadmap (Fossilfritt Sverige, 2019). To achieve these goals, aviation fuel suppliers will need to increase SAF blend ratios from 1% in 2021 to 30% in 2030.

On the other hand, Sweden is committed to supporting electric aviation with an annual investment of at least SEK15 million ($1.4 million) to advance technology and explore the feasibility of government-supported domestic flights (Aviation Week, 2023). The government is also considering additional financial incentives including subsidies. The Swedish Transport Administration is tasked with evaluating existing regulations related to electric aircraft for public service obligation flights, with potential proposals for regulatory improvements by 2024 to expedite the adoption of electric aircraft.

Hungary

The Hungarian government is providing support for the development of electric flights (Rolls-Royce, 2023). Rolls-Royce got 4.6 million EUR funding from the Hungarian Investment Promotion Agency and the Ministry of Foreign Affairs and Trade. This funding will be used to advance research and development efforts in the field of all-electric and hybrid-electric aviation.

Spain

In 2019, the Spanish Government introduced two legislative frameworks mandating SAF obligations for fuel suppliers (Ministerio para la Transición Ecológica y el Reto Demográfico, 2020). One was the Spanish 2021-2030 Integrated Plan for Energy and Climate, emphasizing the importance of SAF, especially advanced biofuels. The second was the Climate Change Law, aiming for a 2% SAF supply mandate in 2025.

Spain also took action to promote hydrogen-powered aviation. In 2023, the Spanish transport sector forged a protocol with the aviation and energy sectors, aiming to boost the use of green hydrogen in aviation (La Moncloa - Gobierno de España, 2023). The agreement outlined the terms for collaboration in identifying the requirements for developing, producing, storing, and distributing green hydrogen for aviation in Spain.

Additionally, the Spanish government provided grants to support the development of hydrogen-powered aircraft and related airport infrastructure (FutureFlight, 2023).

Brazil

Brazil aims to implement the use of SAF from 2027 onward, initiating an emission reduction target set at 1% (Brazil Ministry of Infrastructure, 2022).

Law No. 14.248 was introduced in Brazil to initiate the National Biofuel Program, specifically promoting the adoption of SAF (Brazilian Chamber of Deputies, 2021). The law stipulated that the eligible SAF must be sourced from feedstocks that do not compete with food production. Additionally, the law mandates federal agencies and institutions to allocate resources to support SAF projects and provide fiscal incentives to encourage SAF adoption.

Argentina

Argentina has introduced a SAF mandate within its biofuel regulatory framework to boost the adoption of biofuels as part of the country's energy transition (Government of the Argentine Republic, 2022). This new regulation involves raising the mandatory biofuel blend to 15% + 1% SAF.

Chile

Chile has committed to harnessing the potential of SAF and green hydrogen, recognizing their role in reducing carbon emissions in aviation (Civil Aviation Authority of Chile, 2023; Ministerio de Energía, 2021). The Chilean government has prompt initiatives such as the Clean Flight program and ongoing SAF working groups involving both public and private stakeholders to make SAF a reality. In addition, Chile aims to make Santiago Airport the first in Latin America to accommodate and fuel aircraft powered by green hydrogen no later than 2030.

Mexico

Mexico has set targets to substitute at least 1% (approximately 40 million liters) of the country's total jet fuel demand with biofuels by 2015 and 15% (around 700 million liters) by 2020 (Gobierno de México, 2010).

To achieve this, a collaborative program involving Aeropuertos y Servicios Auxiliares (ASA), Aeromexico, and Boeing, with support from the Ministry of Energy (SENER) and the National Council of Science and Technology (CONACYT), is focusing on sustainable biofuel research and development (Gobierno de México, 2016). The research covers various aspects, including biomass sources, fuel production, sustainability, life cycle analysis, and the development of the biofuel market for aviation. With financial backing from the Mexican government and participating institutions, this four-year initiative aims to establish a self-sustaining business model.

However, the deployment of SAF in Mexico remains at a nascent stage and has not met the set targets.

Australia

The Australian government has identified aviation as a challenging industry to decarbonize, prompting a $30 million investment by the Australian Renewable Energy Agency (ARENA) in the development of SAF derived from renewable feedstocks (Australian Department of Climate Change and Energy, 2023). This initiative aims to unlock market opportunities within Australia's bioenergy sector and promote the advancement of an advanced biofuels industry (Australian Government, 2023).

New Zealand

New Zealand has implemented several policies to achieve its net zero emission target by 2050. The country introduced a Sustainable Biofuels Mandate to reduce greenhouse gas emissions from transport fuels annually, which includes specific sustainability criteria for biofuels (New Zealand Ministry of Transport, 2021). The policy covers all transport fuels, including domestic aviation fuel, and entails annual compliance reports from fuel suppliers, with penalties for non-compliance and provisions for emissions trading and deferral.

New Zealand government has also initiated feasibility studies focusing on both SAF production and the development of a green hydrogen hub (New Zealand Government, 2023; New Zealand Ministry of Business, Innovation and Employment, 2023; New Zealand Ministry of Business, Innovation and Employment, 2022). These studies aim to accelerate New Zealand's energy transition. The New Zealand government, in collaboration with Air New Zealand, is investing $765,000 in two feasibility studies to assess the viability of establishing a SAF production facility within the country. In addition, New Zealand plans to establish a pilot green hydrogen hub at a local airport. This hub will function as a centralized green hydrogen production facility primarily for airport use, with the potential to integrate various hydrogen-based services and connect with the local community. The primary uses of the pilot hub may include supplying green hydrogen to airport vehicles and fulfilling the airport's energy demand, with provisions for potential future aircraft use. The pilot green hydrogen hub is expected to have access to 100% renewable electricity by 2030.

The United Arab Emirates

The United Arab Emirates (UAE) supports the development of SAF. The UAE has established a national SAF roadmap, emphasizing a domestic SAF production target of 700 million liters annually (UAE Ministry of Energy and Infrastructure, 2022). It is also focused on enhancing the governance structure for the national SAF program to create In-Country Value (ICV). Moreover, the UAE is exploring policies for the economic sustainability of SAF facilities and supporting research and development efforts for SAF technologies. UAE aims to produce SAF at a commercial scale by 2025.

Indian

India is targeting Net Zero emissions by 2070 and aims to achieve energy self-reliance by 2047. The country recognizes the significance of SAF, considering it a crucial step towards reducing carbon emissions in the aviation sector. The government is exploring a possible 1% or 5% SAF blending mandate for domestic flights by 2025 (Indian Ministry of Petroleum & Natural Gas, 2023).

Thailand

Thailand has set a target blending rate of 1% for SAF by 2025, aiming to reach 5% by 2034 (Oils & Fats International, 2023). Additionally, the country has conducted a feasibility study on promoting SAF through various policies, including fiscal incentives and certificate standards (Thailand Department of Alternative Energy Development and Efficiency, 2022).

Indonesia

Indonesia became the first country in Asia to implement a blending mandate for SAF early in 2013. Mandated by the Ministry of Energy and Mineral Resources Decree No. 25 Year 2013 (Directorate General of Civil Aviation of Indonesia, 2021), the regulation requires 2% SAF blending in 2016, 3% by 2020, and 5% by 2025. Although challenges hindered the achievement of the 2016 goal, the 2025 target remains in place. SAF projects in Indonesia are currently concentrated on the development and testing of SAF primarily sourced from food-based feedstock.

Japan

Japan is committed to achieving carbon neutrality by 2050 (Ministry of Economy, Trade and Industry, 2020), with two key initiatives in aviation sector. The first involves a SAF roadmap, aiming to replace 10% of fuel consumption by Japanese airlines with SAF in 2030 (Ministry of Land, Infrastructure, Transport and Tourism, 2023). The second is Amendment of the Civil Aeronautics Act focusing on operational improvements to reduce CO_2 emissions through enhanced flight operations. Additionally, Japan is actively promoting research and development for the realization of hydrogen-powered aircraft (Japan Ministry of Foreign Affairs, 2021).

Singapore

Singapore is actively pursuing a Sustainable Air Hub Blueprint in collaboration with industry partners, focusing on 15 key initiatives across airport, airline, and air traffic management domains (Ministry of Trade and Industry Singapore, 2022). The initiatives include transitioning to renewable energy at Changi Airport, investing in SAF, and optimization of air traffic management procedures.

In addition, Singapore has established a national hydrogen strategy that encompasses the aviation sector (Ministry of Trade and Industry Singapore, 2022). The strategy involves studying the development of hydrogen supply and infrastructure for aviation, along with plans to evaluate the infrastructure requirements for a hydrogen airport hub and the electrification of airport operations using hydrogen fuel cells.

South Korea

The Ministry of Trade, Industry, and Energy in South Korea has announced a comprehensive plan for the development and expansion of eco-friendly biofuel (South Korean Ministry of Trade, Industry and Energy, 2022). The measures include prompt domestic introduction for SAF in aircraft by 2026. To lay the legal foundation for SAF, the government urged that research services should be concluded by 2022 and that the relevant laws be amended from 2023 onward.

China

China has yet to set a specific target year for achieving net-zero emissions in aviation. Instead, the country aims for the gradual development of a green and low-carbon aviation system, with the goal of achieving carbon-neutral growth in air transportation by 2035 (Government of the People's Republic of China, 2021). Furthermore, China is aiming to build SAF consumption to at least 50,000 tons by 2025.

The AFA policies of different countries are shown briefly in Table 25, Table 26, and Table 27.

Table 25. Summary of SAF Policies

Country		Numeric Targets		Economic Incentive		R & D support		Certification & Standards
		Production Target	Consumption Target	Tax Incentives	Loans/ Financing	Infrastructure Development	Feasibility Study	
US	National	Yes[1,2]	-	Yes[5]	Yes[1,3]	Yes[1,4]	Yes[1]	Yes[2]
US	California	Yes[6]	-	Yes[7]	-	-	-	-
US	Oregon	-	-	Yes[8]	-	-	-	-
US	Minnesota	-	-	Yes[9]	Yes[10]	-	-	-
US	Washington	-	-	Yes[11]	-	-	-	-
US	Illinois	-	-	Yes[12]	-	-	-	-
Canada		-	Yes[13]	Yes[15]	Yes[14]	Yes[14]	-	Yes[13]
UK		Yes[16]	Yes[16]	-	Yes[16]	-	Yes[16]	Yes[17]
France		-	Yes[18,21, 22]	Yes[19, 21, 22]	Yes[20]	Yes[20]	Yes[21, 22]	Yes[18]
Germany		Yes[23]	-	-	Yes[23]	Yes[23]	-	Yes[23]
Netherlands		-	Yes[24]	-	-	-	Yes[25]	Yes[25]
Switzerland		-	Yes[26]	-	Yes[26]	Yes[26]	-	-
Spain		Yes[27]	-	-	-	-	-	-
Italy		-	-	-	-	Yes[28]	-	-
Sweden		Yes[29]	-	-	-	-	-	-

Norway	Yes[30]	-	-	-	-	-	-
Finland	Yes[31]	Yes[32]	-	-	-	-	-
Denmark	-	Yes[33]	Yes[34]	Yes[29]	-	-	-
Turkey	-	-	-	-	-	Yes[29]	-
Poland	-	-	-	-	Yes[35]	-	-
Brazil	-	-	Yes[36]	Yes[36, 37]	-	-	Yes[36]
Argentina	Yes[38]	-	-	-	-	-	-
Chile	-	-	-	-	-	Yes[39]	-
Mexico	Yes[40] (Failed)	-	-	-	-	Yes[41]	Yes[40]
Australia	-	-	-	Yes[42]	-	Yes[43]	-
New Zealand	Yes[44]	-	Yes[44]	-	-	Yes[45, 46]	Yes[44]
United Arab Emirates	Yes[47]	-	-	Yes[47]	Yes[47]	Yes[47]	Yes[47]
India	Yes[48] (Plan by 2025)	-	-	-	-	-	-
Thailand	Yes[49, 50]	-	Yes[51]	Yes[51]	Yes[51]	Yes[51]	Yes[51]
Indonesia	-	Yes[52]	-	-	-	-	-
Japan	-	Yes[53]	-	Yes[54]	-	-	Yes[54]
Singapore	-	-	-	Yes[55]	-	-	-
South Korean	-	Yes[56]	-	-	-	-	Yes[56]
China	-	Yes[57]	-	-	-	-	Yes[57]

SOURCE: 1WHITE HOUSE (2021); 2U.S. DEPARTMENT OF ENERGY (2022); 3U.S. DEPARTMENT OF ENERGY (2023); 4U.S. DEPARTMENT OF TRANSPORTATION (2022); 5INTERNAL REVENUE SERVICE (2022); 6CALIFORNIA AIR RESOURCES BOARD (2023); 7CALIFORNIA AIR RESOURCES BOARD (2020); 8OREGON SECRETARY OF STATE (2022); 9MINNESOTA STATE SENATE (2023); 10MINNESOTA MANAGEMENT AND BUDGET (2023); 11WASHINGTON STATE LEGISLATURE (2023). 12ILLINOIS GENERAL ASSEMBLY (2022); 13GOVERNMENT OF CANADA (2022A); 14GOVERNMENT OF CANADA (2022B); 15GOVERNMENT OF CANADA (2022C); 16UNITED KINGDOM GOVERNMENT (2021); 17UK DEPARTMENT FOR TRANSPORT (2023); 18FRENCH GOVERNMENT (2019); 19MINISTÈRES ÉCOLOGIE ÉNERGIE TERRITOIRES. (2023). 20BLOOMBERG NEWS (2023); 21INTERNATIONAL CIVIL AVIATION ORGANIZATION (2023); 22FRENCH CIVIL AVIATION AUTHORITY (2023); 23GERMAN FEDERAL MINISTRY OF TRANSPORT AND DIGITAL INFRASTRUCTURE (2021); 24MINISTERIE VAN INFRASTRUCTUUR EN WATERSTAAT (2020); 25MINISTERIE VAN INFRASTRUCTUUR EN WATERSTAAT (2019); 26FEDERAL OFFICE OF CIVIL AVIATION (FOCA) (2022);

27MINISTERIO PARA LA TRANSICIÓN ECOLÓGICA Y EL RETO DEMOGRÁFICO (2020). 28ITALIAN CIVIL AVIATION AUTHORITY (2021); 29INTERNATIONAL CIVIL AVIATION ORGANIZATION (2022); 30NORWEGIAN GOVERNMENT (2018); 31FINNISH GOVERNMENT (2019); 32FINNISH GOVERNMENT (2023); 33TRANSPORT- OG BOLIGMINISTERIET (2022); 34KLIMA-, ENERGI- OG FORSYNINGSMINISTERIET, DENMARK (2022); 35MINISTERSTWO INFRASTRUKTURY (2023); 36BRAZIL MINISTRY OF INFRASTRUCTURE (2022); 37BRAZILIAN CHAMBER OF DEPUTIES (2021); 38GOVERNMENT OF THE ARGENTINE REPUBLIC (2022); 39CIVIL AVIATION AUTHORITY OF CHILE (2023); 40GOBIERNO DE MÉXICO (2010); 41GOBIERNO DE MÉXICO (2016); 42AUSTRALIAN DEPARTMENT OF CLIMATE CHANGE AND ENERGY (2023); 43AUSTRALIAN GOVERNMENT (2023); 44NEW ZEALAND MINISTRY OF TRANSPORT (2021); 45NEW ZEALAND GOVERNMENT (2023); 46NEW ZEALAND MINISTRY OF BUSINESS, INNOVATION AND EMPLOYMENT (2023); 47UAE MINISTRY OF ENERGY AND INFRASTRUCTURE (2022); 48INDIA MINISTRY OF PETROLEUM & NATURAL GAS (2023); 49OILS & FATS INTERNATIONAL (2023); 50ILLUMINE M (2023); 51THAILAND DEPARTMENT OF ALTERNATIVE ENERGY DEVELOPMENT AND EFFICIENCY (2022); 52DIRECTORATE GENERAL OF CIVIL AVIATION OF INDONESIA (2021); 53JAPAN MINISTRY OF LAND, INFRASTRUCTURE, TRANSPORT AND TOURISM (2023); 54JAPAN MINISTRY OF FOREIGN AFFAIRS (2021); 55CIVIL AVIATION AUTHORITY OF SINGAPORE (2022); 56SOUTH KOREAN MINISTRY OF TRADE, INDUSTRY AND ENERGY (2022); 57GOVERNMENT OF THE PEOPLE'S REPUBLIC OF CHINA (2021).

Table 26. Summary of Electric Aircraft Policies

Country		Numeric Targets		Economic Incentives	R & D support	
		Supply Target	Demand Target		Infrastructure Development	Feasibility Study
US	National	Yes[1]	-	-	-	Yes[1]
	Washington	-	-	-	-	Yes[2]
	California	Yes[3]	-	-	-	-
Canada		-	-	-	Yes[4]	Yes[4]
UK		-	-	-	Yes[6]	Yes[5]
France		Yes[7]	-	-	-	Yes[7, 8]
Netherlands		-	Yes[15]	Yes[9]	-	-
Portugal		-	Yes[10]	-	-	-
Sweden		-	Yes[11]	-	-	Yes[12]
Norway		-	Yes[13]	Yes[13]	Yes[13]	Yes[13]
Hungary		-	-	-	-	Yes[14]

Source:1FAA (2021); 2Washington State Department of Transportation (2020); 3California Air Resources Board (2023c); 4Government of Canada (2022a); 5United Kingdom Government (2023); 6United Nations Framework Convention on Climate Change (2022); 7French Government (2023); 8Élysée - Présidence de la République française (2021); 9Rijksoverheid (Government of the Netherlands) (2020); 10United Nations Framework Convention on Climate Change (2019); 11Fossilfritt Sverige (Fossil-Free Sweden) (2019); 12Aviation Week (2023); 13Norwegian Ministry of Climate and Environment (2020); 14Rolls-Royce (2023); 15Ministerie van Infrastructuur en Waterstaat (2019b);

Table 27. Summary of Hydrogen Aircraft Policies

Country		Supply Targets	R & D support	
			Infrastructure Development	Feasibility Study
US	National	Yes[1]	Yes[2]	Yes[2]
	California	Yes[3]	-	-
Germany		-	Yes[4, 5]	Yes[4, 5]
UK		-	-	Yes[6]
France		Yes[7]	-	Yes[7]
Netherland		-	-	Yes[8]
Finland		-	-	Yes[9]
Spain		-	Yes[10]	Yes[11]
New Zealand		-	Yes[12]	Yes[12]
Chile		-	Yes[13]	-
Singapore		-	Yes[14]	Yes[14]
Japan		-	-	Yes[15]

Source: 1FAA (2021); 2Senator Jon Ossoff (2023); 3California Air Resources Board (2023c); 4Mugglehead (2023); 5Federal Ministry of Economic Affairs and Energy, Germany (2020); 6UK Government (2021); 7Élysée - Présidence de la République française (2021); 8Rijksoverheid (Government of the Netherlands) (2023); 9Traficom (Finnish Transport and Communications Agency) (2023); 10La Moncloa - Gobierno de España (The Moncloa - Government of Spain) (2023); 11FutureFlight (2023); 12New Zealand Ministry of Business, Innovation and Employment (2022) 13Ministerio de Energía, Chile (2021); 14Ministry of Trade and Industry Singapore (2022); 15Ministry of Economy, Trade and Industry (METI), Japan (2020)

Policy Scenarios

Background

California has embarked on an ambitious endeavor aimed at achieving carbon neutrality by 2045, aligning closely with its climate policy framework. The California climate policy framework (Figure 6) encompasses four components: the establishment of greenhouse gas (GHG) targets and objectives, the implementation of scoping plans, the execution of various actions or programs, and the initiation of different projects.

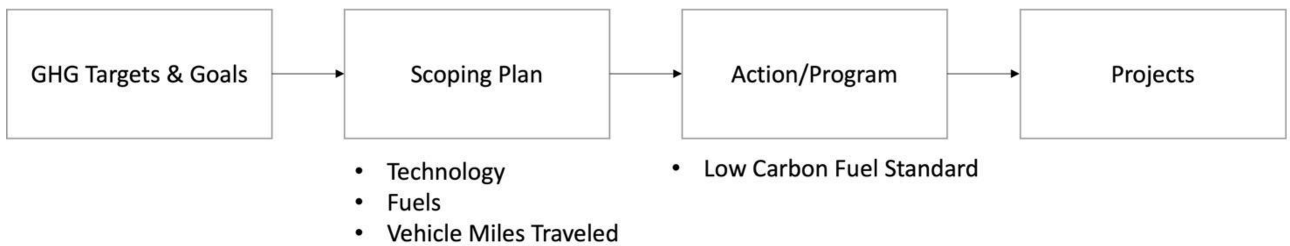

Figure 6. Current California Climate Policy Framework

In pursuit of this ambition, the Scoping Plan incorporates a transition strategy aimed at satisfying 20% of the aviation fuel demand using zero-emission technologies like electric aircraft and hydrogen-powered aircraft by 2045 (CARB, 2022b). The transition strategy is further supported by the adoption of sustainable aviation fuels (SAF) to address the remaining fuel demand. Assembly Bill (AB) 1322[5] would have further reinforced this goal, setting a near-term target of 20 percent SAF utilization by 2030, however it was vetoed by the Governor.

To facilitate the scale-up of SAF, the plan leverages the Low Carbon Fuel Standard (LCFS) as the primary available policy tool. However, the current design of LCFS is insufficient to support the transition of SAF for intrastate flights. At present, aviation fuels are part of the LCFS on an opt-in basis, meaning that unlike petroleum-based on-road fuels, petroleum-based jet fuel does not generate LCFS deficits, which increase the demand for credits. Alternative jet fuel producers can elect to enter the LCFS program and receive credits, but without the corresponding deficit obligation for conventional fuels, the price signal this sends is significantly smaller, and SAF producers must compete against more firmly established on-road fuels to sell their credits. Additionally, the current LCFS 2030 carbon intensity reduction target, 20% compared to the 2010 baseline, has been not created enough demand for credits, resulting in persistent low LCFS credit prices; at the time of writing a rulemaking to adjust the 2030 targets upward to support a more robust demand for credits is expected to begin shortly. The combination of omitted aviation fuels, low credit prices, and technological immaturity has led to only small volumes of SAF entering California's market. In 2022, SAF accounted for 11.6 million gallons, representing a mere 0.26% of LCFS credits sold (CARB, 2023a). This limited uptake can be attributed to the fact that existing renewable diesel production is more commercially viable (ICCT, 2023). As

[5] https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=202120220AB1322

renewable diesel and SAF are co-products derived from the same biomass feedstock, increasing SAF production could potentially reduce the production of renewable diesel.

To achieve long-term reduction and transition goals, there are insufficient policies in place to effectively implement and support the adoption of zero-emission technologies and the increased use of SAF in the aviation sector. Compared to the status quo, several policy changes should be considered to address the challenges in the aviation sector. These policy changes, which align with the third step of the California Policy Framework known as Action or Program, include:

- Implementing carbon pricing on conventional aviation fuels (Elkind et al., 2022), although this may not be necessary due to the presence of LCFS and will face political resistance.
- Promulgating regulations to regulate conventional aviation fuels under the LCFS, which would mean that they would generate deficits, in a fashion consistent with federal laws (Elkind et al., 2022).
- Creating and approving pathways for incentives that encourage the adoption of electric aircraft and hydrogen aircraft technologies through LCFS.
- Offering financial incentives, such as fee exemptions, to promote the use of electric aircraft and hydrogen aircraft.

To evaluate the potential impact of these policies, an economic model was employed. The evaluation considered the adaptability of the existing LCFS and how it can be extended and tailored to better support SAF adoption. Furthermore, the assessment included an analysis of the environmental implications, cost-effectiveness, and feasibility of implementing various policy options. The analysis informs policy makers about the efficiency and effectiveness of several alternative for increasing SAF use and reducing climate impact from California aviation. In this respect, our focus is more narrow than other work which considers the impacts of LCFS on overall supply and demand for low carbon fuel and the resulting greenhouse gas emissions impacts of fuel use across all sectors.

Methodology

Policy Options

The evaluation concentrated on the increase in SAF uptake and did not consider the potential policies related to zero-emission technologies. It’s essential to recognize that policies affecting zero-emission technologies can have a cascading effect on SAF adoption and the overall demand for jet fuel. However, zero-emission technologies are likely at least a decade away from broad-scale commercial deployment in California, and the range of uncertainty around their cost, performance, and capabilities is extremely high. As such, quantitative evaluation of them is left for future work. The assessment considered the entire landscape of jet fuel use in California, extending beyond the existing LCFS design, which presently covers intrastate flights only. The policy options under examination included:

1. Implementing a Carbon Tax on conventional jet fuel to incentivize the increased use of SAF;
2. Providing a subsidy for SAF in order to mitigate the higher production cost of SAF and achieve the target share of SAF;
3. Exploring a blending method that combines both a carbon tax and subsidy to attain the desired target share of SAF.

Policy Model

Figure 7 illustrates an economic model of supply and demand for SAF fuels and conventional jet fuel in the presence of various policy options within a competitive market (Mayeres et al., 2023). The figure does not incorporate the externalities associated with both SAF and conventional jet fuel. It is assumed that the demand function for aviation fuel exhibits a constant negative price elasticity, resulting in a concave curve on the graph. The price elasticity reflects changes in fuel use resulting from changes in air travel demand, the use of more fuel-efficient aircraft, and operational strategies to conserve fuel use. The supply of conventional jet fuel is presumed to be characterized by constant marginal costs, reflecting that California demand accounts for a small fraction of the total demand in the global market for conventional jet fuel. In contrast, the supply of SAF is represented as an increasing marginal cost function, primarily because of the limited feedstock supply. In the absence of government intervention, the quantity of SAF used in the market depends on the intersection of the two supply curves, which is denoted as $Q_{0,S}$ in the figure. (Note that, depending on supply parameters, the intersection may not exist, in which case $Q_{0,S}$=0.)

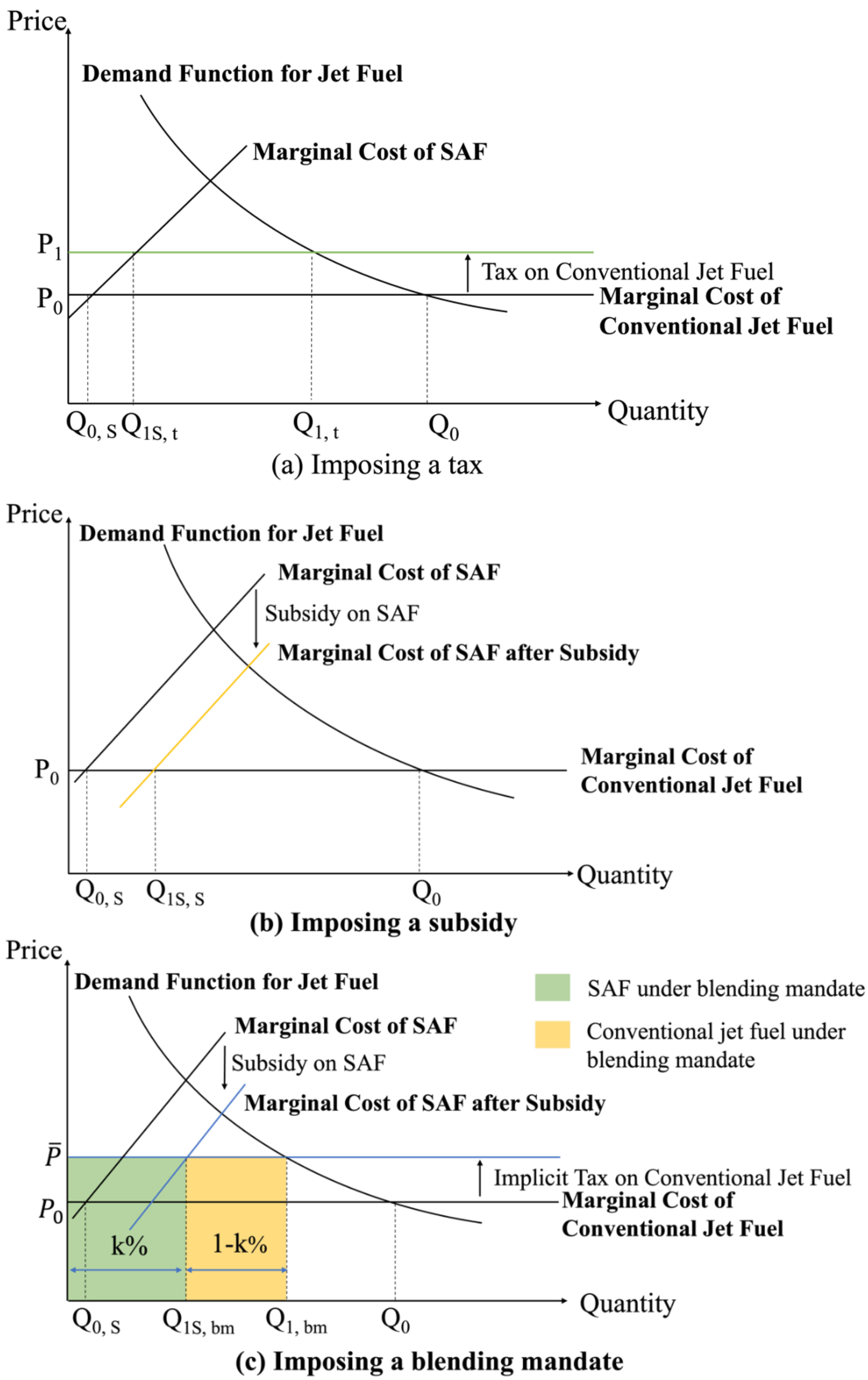

Figure 7. Economic Mechanism in the Aviation Market

In the scenario where the government imposes a carbon tax on conventional jet fuels, it results in an increase in the marginal cost of conventional jet fuel. As a consequence, this leads to a decrease in the total fuel demand and an increase in the utilization of SAF. On the graph, this policy change is illustrated by the shift from an initial price of conventional jet fuel, denoted as P_0, to a new price level, P_1. Concurrently, the total fuel demand decreases from Q_0 to Q_1 ($Q_{1,bm}$). Furthermore, the policy results in an increased uptake of SAF, transitioning from the initial quantity $Q_{0,S}$ to a new level, $Q_{1S,t}$.

The second policy option is the implementation of a subsidy for SAF. This policy option causes a shift in the supply function for SAF to the right, effectively increasing their uptake from the initial quantity $Q_{0,S}$ to a new level, $Q_{1S,s}$. However, it's important to note that despite the increase in SAF utilization, the total quantity of fuel remains unchanged at Q_0.

The final option is to utilize a blending mandate in combination with a SAF fuel subsidy. The average fuel price can be expressed by the following equation,

$$\underline{P} = (1 - k) \cdot MC_{CJF} + k \cdot MC_{SAF}$$

Where k is the mandated share of SAF, MC is the marginal cost of conventional jet fuel production or SAF production. Under the mandate, if it is binding, aviation fuel suppliers have to bear a higher effective cost of conventional jet fuel, since it must be used in combination with more expensive SAF. This price increase can be seen as an implicit tax. However, suppliers are encouraged to produce more SAF, supported by subsidies to offset the higher production cost. Under this scenario, the total demand is reduced from Q_0 to $Q_{1,bm}$ while the overall usage of SAF increases from $Q_{0,S}$ to $Q_{1S,bm}$.

Supply Curve

The policy analysis is for the year 2030. For conventional jet fuel, the supply is assumed to be perfectly elastic. The forecast marginal cost of conventional jet fuel is $16.44 per million Btu (EIA, 2021b) which is equivalent to $723.5/ton.

For SAF, the supply model was built based on the data from the California Transportation Supply Model (CATS) provided by the California Air Resources Board (CARB, 2023b). Due to limited available data and SAF being a co-product of renewable diesel production, the supply model for SAF indirectly depends on the price of renewable diesel. The supply curve for renewable diesel is expressed as a linear regression model in dollars per ton, with feedstock prices as the determining factor.

The CATS model considered two types of feedstocks. One is virgin oil such as soybean oil, corn oil, and canola oil, with soybean oil serving as the representative for regression analysis. The other is waste oil comprising tallow, white grease, and yellow grease, with used cooking oil (UCO) representing waste oil production pathways. The relationship between feedstock price and quantity is characterized by a linear pattern shown in Table 28.

Table 28. Estimated Quantity in Feedstock Based on Changes in Feedstock Price

Feedstock Price ($/ton)	Quantity of Waste Oil (tons)	Quantity of Virgin Oil (tons)
600	1688294	4431287
800	2033876	4762989
1000	2379458	5094691
1200	2725040	5426393
1400	3070622	5758095
1600	3416204	6089797
1800	3761786	6421499
2000	4107368	6753201

Source: CARB (2023b)

Based on the Table 23, the supply curves for the two feedstock oils were expressed as follows:

$$P_{fs\_WO} = -377 + \frac{Q_{fs\_WO}}{1728}$$

$$P_{fs\_VO} = -2071 + \frac{Q_{fs\_VO}}{1659}$$

Where P_{fs_WO/fs_VO} is the price of waste oil feedstock or virgin oil feedstock, and Q_{fs_WO/fs_VO} is the quantity of waste oil feedstock or virgin oil feedstock.

According to the CATS model, the forecast of SAF production costs was divided into two steps (CARB, 2023b). First, the costs of SAF were predicted from the renewable diesel supply curves to reflect how SAF costs vary with the costs of renewable diesel. Then, a regression analysis was conducted to obtain the SAF supply curve in response to changes in the feedstock price. Table 29 shows the estimated fixed costs and estimated yield for the biomass-based SAF.

Table 29. Estimating Fixed Costs and Yields for SAF

Category	[1]Estimated Fixed Costs ($/ton)	[1]Estimated Yield (MJ/ton)	[2]Energy Density (MJ/kg)
SAF Waste Oil	1155	36259	44
SAF Virgin Oil	961	37437	44

Source: [1]CARB (2023b); [2]Bezergianni & Dimitriadis (2013)

Based on Table 29, the supply of SAF can be expressed as follows:

$$P_{SAF\_WO} = 1155 + 1.21 \times P_{feedstock\_WO}$$

$$P_{SAF\_VO} = 961 + 1.18 \times P_{feedstock\_VO}$$

Where $P_{feedstock\_WO/feedstock\_VO}$ is the price of waste oil feedstock or virgin oil feedstock in dollars per ton, and P_{SAF_WO/SAF_VO} is the price of SAF made of waste oil or virgin oil in dollars per ton.

As the estimated yield provided the ratio between the quantity of a given feedstock and the quantity of SAF produced, the supply curve for SAF can be rearranged as a linear function with the quantity of SAF. The supply curves of SAF were as follows:

$$P_{SAF\_WO} = 699 + 0.00084 \cdot Q_{SAF\_WO}$$

$$P_{SAF_{VO}} = -1483 + 0.00084 \cdot Q_{SAF\_VO}$$

Where P_{SAF_WO/SAF_VO} is the price of SAF produced by waste oil feedstock or virgin oil feedstock, and Q_{SAF_WO/SAF_VO} is the price of waste oil feedstock or virgin oil feedstock.

Since there are two distinct SAF supply curves, there will be two points where the supply of SAFs intersects with that of conventional jet fuel. Due to the higher production cost of waste oil SAF compared to that of virgin oil SAF, the total quantity of waste oil SAF is less than the total quantity of virgin oil SAF. Then, the total amount of waste oil SAF is determined by the intersection of the waste oil SAF supply curve and the conventional jet fuel supply curve. Meanwhile, the quantity of virgin oil SAF is calculated by subtracting the total quantity of waste oil SAF from the intersection of the virgin oil SAF supply curve and the conventional jet fuel supply.

Demand Curve

The demand curve is established through a log-log model based on data for fuel demand and fuel prices estimated for the year 2030, as well as fuel demand elasticities. The model takes into account the total consumption of jet fuel in California rather than intrastate demand only, as outlined in Table 30.

Table 30. Estimated Demand for Years 2030 and 2035

Year	Intrastate Demand (Billion Gallon)	Total Demand (Billion Gallon)	Total Demand (Ton)
2030	0.475	5.198	15,799,392
2035	0.488	5.489	16,683,890

Source: Author's calculation (see Chapter 3 California Aviation Energy Model (CAVEM))

Two scenarios for fuel price elasticity of jet fuel demand are considered. One is -0.03 (Mazraati, 2010), and the other is -0.35 (Fukui & Miyoshi, 2017). These widely different elasticities correspond respectively to short-term price responses assuming a fixed aircraft fleet and inelastic travel demand and long-term responses that incorporate fleet adjustments and reductions in air travel demand resulting from higher airfares.

Given the estimation of fuel price, total jet fuel demand for 2030, and the elasticity assumption, the demand curve equation is expressed as follows:

$$when\ elasticity\ is - 0.03, \qquad P = e^{(\frac{16.773 - log\ (Q)}{0.03})}$$

$$when\ ealsticity\ is - 0.35, \qquad P = e^{(\frac{18.880 - log\ (Q)}{0.35})}$$

Where P is the price of jet fuel, Q is the quantity of jet fuel.

Model Assumptions

The model was built based on the assumptions below.

- The aviation fuel market is perfectly competitive.
- The total supply of conventional jet fuel should be at least as large as the total demand for that year.
- Supply should equal demand and can be met by either conventional jet fuel or SAF.
- For scenarios with blending mandates, the SAF share should be at least as large as the mandated share.

Environmental Impact

The main advantage of transitioning from conventional jet fuel to SAF is the smaller carbon intensities. To measure the net CO_2 emission reduction and the social abatement cost of using SAF, carbon intensity was applied. This report follows the practice of the LCFS and focuses on life cycle emissions in grams of carbon dioxide equivalent per megajoule (g CO_{2e}/MJ, using 100 year Global Warming Potentials for CO_2 equivalency). Thus, CI needs to be adjusted to include all stages of fuel and feedstock production and distribution such as significant indirect emissions from land use change values. The LCFS adjusts the CI scores of fuels made from crop-based feedstocks to account for indirect land use change caused by the consumption of edible feedstocks, though this adjustment factor is out of date and likely underestimates actual emissions (Malins, Plevin, & Edwards 2020). Virgin vegetable oils are generally assumed to be made from soybean oil. Based on the yield and adjusted CI for each fuel, the estimated emissions were calculated as the following equation:

$$Estimated\ Emissions = yield\ \left(\frac{MJ}{ton}\right) \cdot CI\ \left(\frac{g\ CO_{2e}}{MJ}\right) \cdot \frac{1}{1000000}\left(\frac{ton}{g}\right)$$

Table 31 provides the overview of estimated emissions for conventional jet fuel and different types of SAF, where virgin oil-based SAF reduces CO_{2e} per ton of fuel used by up to 40% and waste oil-based SAF decreases by about 89% CO_{2e} per ton of fuel used.

Table 31. Estimated Emission for Conventional Jet Fuel and SAF

Fuel Type	Adjusted CI (g CO_2e/MJ)	Estimated Emissions (ton CO_2e/ton)
Conventional Jet Fuel	89.37[3]	3.82[2]
SAF Virgin Oil	62.09[1, 3]	2.32[2]
SAF Waste Oil	11.4[1, 3]	0.41[2]

Note: CI scores Include LCFS Land Use Change adjustment factors.

Source: [1]CARB (2023b); [2]Author's Calculation; [3]CARB (2020);

Social Abatement Cost

Apart from considering net CO_2 emissions, another crucial evaluation metric for assessing policy impacts is the social abatement cost. The social abatement cost is defined as the total welfare loss incurred per unit of CO_2 emissions avoided. Social abatement costs offer a more equitable lens for assessing costs and benefits, especially when comparing the impacts of different policies. The total demand for jet fuel can vary significantly under various policy scenarios. Comparing the net CO_2 emissions alone might be unfair, especially when certain policy scenarios achieve greater emission reductions at a lower cost per unit. The social abatement cost equation is as follows, with the unit in dollars per ton of carbon dioxide equivalent (\$ / ton CO_{2e}):

$$Social\ Abatement\ Cost = \frac{Welfare\ loss}{CO_2\ Reduction}$$

In the scenario where a tax is implemented, the overall social benefit decreases theoretically. The welfare loss is indicated in the shaded grey area in Figure 5. The tax generates revenue for the government, denoted as the green area, while the consumer surplus diminishes. On the other hand, the surplus for SAF producers increases as a result of the increased adoption of SAF, and the magnitude of this change depends on the marginal cost of producing SAF.

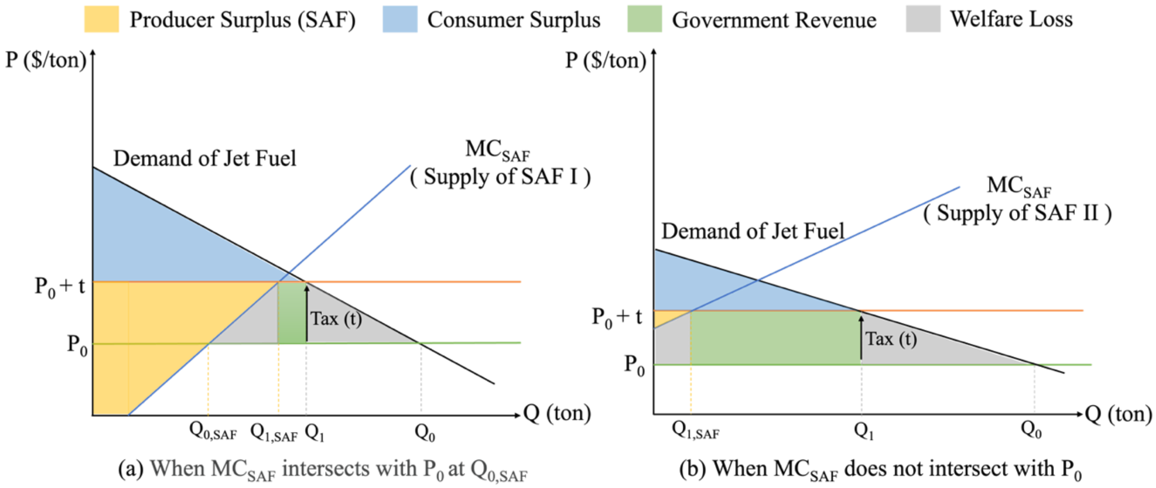

Figure 8. Simplified Representation of Welfare Loss When Imposing a Tax

In the scenario where a SAF subsidy is implemented, the subsidy incurs a cost to the government, as it is responsible for funding the subsidy program (Figure 6). A portion of the subsidy can be considered a benefit to the SAF producer, and this cost can be offset against it. However, the remainder of the subsidy is considered a welfare loss, which is indicated by the shaded grey area. This welfare loss represents the trade-off and costs associated with the subsidy program.

Figure 7 represents the overall effect of a blending mandate in combination with a subsidy, showcasing how it affects the consumer surplus, producer surplus, and net government revenue. The policy leads to an increase in SAF producer surplus driven by the subsidy incentive, while the consumer surplus decreases due to reduced total demand. Consequently, the net government revenue turns negative as a result of the subsidy cost. Although some of the subsidy cost can be offset by the increased producer surplus, the remaining portion, along with the reduction in consumer surplus, contributes to welfare loss.

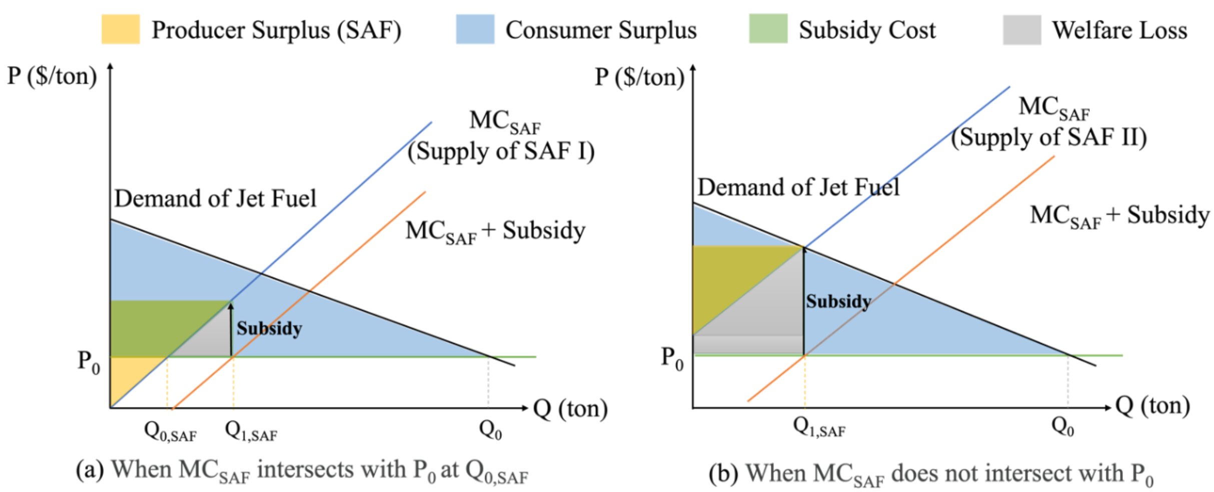

Figure 9. Simplified Representation of Welfare Loss When Imposing a Subsidy

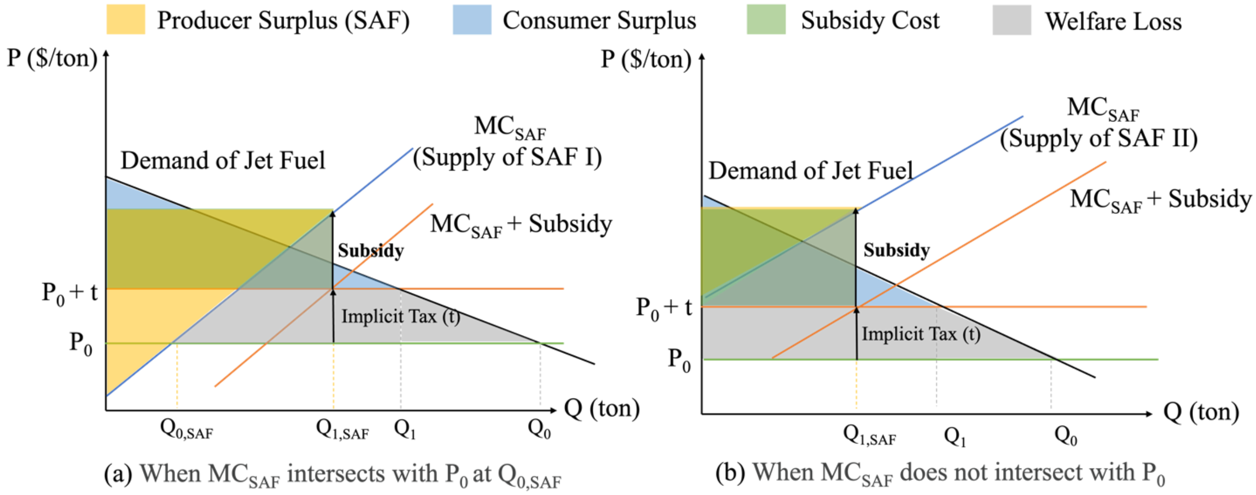

Figure 10. Simplified Representation of Welfare Loss When Imposing a Blending Mandate

Scenario Assumption

Table 28 summarizes five policy scenarios aimed at promoting SAF usage by 2030 in California. All five scenarios encompassed the total jet fuel demand in California, taking into account all flights departing from the state.

- Baseline Scenario: This scenario aligns with the existing design of the LCFS and does not involve a specific target share for SAF.
- Scenarios A, B, and C: In these scenarios, the target share for SAF usage was set at 20 percent, drawing reference from AB 1322.
- Scenario D: In this scenario, a more ambitious target share of 35% was considered to further facilitate the transition from conventional jet fuel to SAF.

Under scenarios A, B, C, and D, two different constraints were applied to eligible SAF types:

1. All types of SAF are available and permitted to be used in the aviation sector.
2. Virgin oil based SAF will be phased out by 2030. The goal is to avoid the potential competition between food and fuel resources and to address the higher carbon intensity of virgin oil-based SAF compared to waste oil-based SAF.

Table 32. Policy Scenarios Assumption for Promoting SAF

Scenario	Policy instrument	Target share
Baseline	Low Carbon Fuel Standard	-
Scenario A	Carbon Tax	20%[1]
Scenario B	SAF Subsidy	
Scenario C	Blending Mandate	
Scenario D	Blending Mandate	35%

Source: AB 1322.

Baseline Scenario

The baseline scenario integrated the design of LCFS credits. The incentive for SAF in 2030 is determined by the following equation (CARB, 2020):

$$Incentive\left(\frac{\$}{gallon}\right) = Credits\ price\left(\frac{\$}{MT\ CO_2e}\right) \times \left(CI_{standard} - \frac{CI_{reported}}{EER}\right)\left(\frac{g\ CO_2e}{MJ}\right) \times E\left(\frac{MJ}{gallon}\right) \times EER \times 10^{-6}\frac{MT\ CO_2e}{g\ CO_2e}$$

Where $CI_{standard}$ is the CI benchmark (average carbon intensity requirement) for SAF, $CI_{reported}$ is the adjusted carbon intensity value of SAF, E is energy density of SAF, EER is dimensionless Energy Economy Ratio (EER) relative to SAF given by LCFS.

For 2030, $CI_{standard}$ is 80.36 g CO_2e/MJ while the specific $CI_{reported}$ for SAFs are shown in Table 31. E is 126.37 MJ/gallon and the EER is 1. The credit price is set at $196/credit (MT CO_2e/gallon).

The estimated incentive per gallon is $0.44 for virgin oil-based SAF, equivalent to $143/ton, and $1.70 for waste oil-based SAF, equivalent to $554/ton. This adaptation results in the production of 2.1 million tons of virgin oil SAF and 0.7 million tons of waste oil SAF, accounting for 18% of the total demand in 2030.

Results

The results were summarized in Table 33 and Table 34, where the impacts and costs of the scenarios were presented in comparison to the baseline scenario. In scenarios A, B, C, and D, two distinct situations were considered. The first situation (I) had no constraints on the types of SAF that could be used. In the second situation (II), only waste oil-based SAF was able to be utilized which is denoted as II-WO. Table 33 presents the results with a jet fuel price elasticity of -0.03, whereas Table 34 shows the results with a jet fuel price elasticity of -0.35. Average emissions intensity is determined by dividing total CO_2e emissions by the total demand of jet fuel.

Table 33. Estimated Results When Jet Fuel Price Elasticity is -0.03

Policy Scenario		Baseline	Scenario A Tax		Scenario B Subsidy		Scenario C Blending Mandate		Scenario D Blending Mandate	
			I	II	I	II	I	II	I	II
Total Demand (Million Ton)		15.8	15.6	15.2	15.8	15.8	15.8	15.3	15.5	15.1
Total Demand Reduction (%)		-	-1%	-4%	0%	0%	0%	-3%	-2%	-4%
SAF (Million Ton)	Waste Oil SAF	0.7	1.0	3.0	0.7	3.2	0.8	3.1	1.5	5.3
	Virgin Oil SAF	2.1	2.1	-	2.5	-	2.4	-	3.9	-
SAF Demand Percentage (%)		18%	20%						35%	
Jet Fuel Price ($/ton)		723.5	1002	2696.5	723.5	723.5	775	1926.5	1442	3161
Jet Fuel Price Increase (%)		-	38%	273%	0%	0%	7%	166%	99%	337%
Policy Option ($/ton)	(Implicit) Tax	-	278.5	1973	-	-	52	1203	718.5	2437.5
	Subsidy	-	-	-	304.5	2799.3	247	796	1482	1428
CO_2e Emissions (Million ton CO_2e)		54.8	53.2	47.7	54.3	49.6	54.1	48.1	48.0	39.7
CO_2e Emissions Reduction (%)		-	-3%	-13%	-1%	-10%	-1%	-12%	-12%	-28%
Average Emissions Intensity (ton CO_2e/ton fuel)		3.5	3.4	3.1	3.4	3.15	3.4	3.1	3.1	2.6

Policy Scenario	Baseline	Scenario A		Scenario B		Scenario C		Scenario D	
		Tax		Subsidy		Blending Mandate		Blending Mandate	
		I	II	I	II	I	II	I	II
Abatement Cost per CO_2e Avoided ($/ton CO_2e)	-	38.7	598.7	203.0	944.4	909.8	2818.2	1501.9	2310.6

Source: Author's Calculation

Table 34. Estimated Results When Jet Fuel Price Elasticity is -0.35

Policy Scenario		Baseline	Scenario A		Scenario B		Scenario C		Scenario D	
			Tax		Subsidy		Blending Mandate		Blending Mandate	
			I	II	I	II	I	II	I	II
Total Demand (Million Ton)		15.8	14.8	11.1	15.8	15.8	15.5	12.0	12.3	11.0
Total Demand Reduction (%)		-	-6%	-30%	0%	0%	-2%	-24%	-22%	-30%
SAF (Million Ton)	Waste Oil SAF	0.7	0.9	2.2	0.7	3.2	0.8	2.4	1.6	3.9
	Virgin Oil SAF	2.1	2.1	-	2.5	-	2.2	-	2.7	-
SAF Demand Percentage (%)		18%	20%						35%	
Jet Fuel Price ($/ton)		723.5	866	2003.5	723.5	723.5	766	1588.5	1513	2032
Jet Fuel Price Increase (%)		-	20%	177%	0%	0%	6%	120%	110%	181%
Policy Option ($/ton)	(Implicit) Tax	-	142.5	1280	-	-	42.5	865	756.5	1308.5
	Subsidy	-	-	-	304.5	2799.3	210	572	510	1349

Policy Scenario	Baseline	Scenario A		Scenario B		Scenario C		Scenario D	
		Tax		Subsidy		Blending Mandate		Blending Mandate	
		I	II	I	II	I	II	I	II
CO_2e Emissions (Million ton CO2e)	54.8	50.6	34.7	54.3	49.6	52.7	37.7	37.5	28.9
CO_2e Emissions Reduction (%)	-	-8%	-37%	-1%	-10%	-4%	-31%	-32%	-47%
Average Emissions intensity (ton CO_2e/ton fuel)	3.5	3.4	3.1	3.4	3.15	3.4	3.1	3.0	2.6
Abatement Cost per CO_2e Avoided ($/ton CO_2e)	-	18.4	240.4	203.0	944.4	270.0	721.4	467.7	674.9

Source: Author's Calculation

Results assuming a jet fuel price elasticity of -0.03

When the jet fuel price elasticity is -0.03 as shown in Table 33, policy impact on fuel demand is minimal, with all reductions falling below 5%. Among the scenarios targeting a 20% share, scenario A-I (tax with all types of SAF available) requires the lowest abatement cost but achieves only a modest environmental impact, reducing total CO_2e emissions by just 3%. On the other hand, Scenarios A-II (tax with waste oil-based SAF only) and C-II (blending mandate with waste oil-based SAF only) yield the most substantial environmental benefits, reducing total CO_2e emissions over 10%, with scenario A-II having 5 times lower abatement cost than scenario C-II.

Implementing tax (scenario A) and a blending mandate (scenario C) would increase jet fuel prices, while stricter policy constraints could boost jet fuel prices by nearly 3 to 4 times. Subsidy (scenario B), however, would have a negligible impact on jet fuel prices, because unlike the other policy scenarios, the additional cost of SAF was paid for by the government, rather than fuel consumers and/or producers.

These three policy instruments achieve the objective of a 20% SAF share but the magnitude of policy instruments varies. Under the first constraint (I), implementing a tax (scenario A-1) incurs modest abatement costs at $38.7/ton CO_2e. In the subsidy scenario (scenario B-I), the abatement cost rises to $203.0/ton CO_2e. The blending mandate scenario (scenario C) is the most costly, with the abatement cost of $ 909.8/ton CO_2e. Under constraint (II), in which virgin oil based SAF is not permitted, the abatement costs increase significantly. The abatement cost of the tax (scenario A-II) is the lowest, at about $598.7/ton CO_2e. In contrast, the abatement cost of the blending mandate (scenario C-II) exceeds that of both the tax and subsidy, reaching \$2818.2/ton CO_2e—about 5 times the cost.

If the target share is 35%, the abatement cost of the blending mandate under constraint I (scenario D-I) increases by about 65% compared to scenario C-I. However, under constraint II, the abatement cost is about 18% lower than scenario C-II. Scenario D can generate substantial environmental benefits. Even under a lax policy restriction (scenario D-I), CO_2e emissions would decrease by 12%, ten times more than in scenario C-I. Under a strict policy restriction (scenario D-II), CO_2e emissions would decrease by 28%. However, there would also be a significant increase in jet fuel prices due to the implicit tax.

Results assuming a jet fuel price elasticity of -0.35

When the jet fuel price elasticity is -0.35 as shown in Table 34, the policy impact on fuel demand can be substantial, but it has less impact on jet fuel prices. For instance, when targeting a 20% share, the largest reduction in total demand reaches about 6% under constraint I and 30% under constraint II. With a 35% target share, reductions of 22% to 30% are observed. The largest price is almost three times the fuel price in the baseline scenario, which is about 36% lower than the maximum price observed in Table 8 with a jet fuel price elasticity of -0.03.

Among the 20% SAF target share scenarios, the tax variant (scenario A) has the best environmental effectiveness and cost-effectiveness. If the target share is 35%, a blending mandate can effectively reduce CO_2e emissions by about 50%. Compared to scenario C-II, scenario D-II achieves a 1.5 times greater reduction in emissions at a lower abatement cost (\$674.9/ton CO_2e).

In conclusion, the overall social abatement costs under each policy scenario are smaller when the jet fuel price is more elastic. A tax variant shows the best environmental effectiveness and cost-effectiveness. The blending mandate can be costly if jet fuel demand is less price elastic (e.g. with a price elasticity of -0.03 compared to -0.35). However, with a more elastic jet fuel price elasticity (e.g., with a price elasticity of -0.35 compared to -0.03), a blending mandate is the second-best both in cost-effectiveness and environmental effectiveness. In addition, the blending mandate option would have less impact on total demand and jet fuel price compared to the tax option. Notably, a blending mandate that limits the use of SAF types shows better cost-effectiveness and environmental effectiveness with a more ambitious target. In this scenario, the abatement cost is lower, and CO_2e emissions reduction is nearly doubled. The abatement cost of scenario D decreases by 70% when the jet fuel price elasticity is -0.35 compared to that of scenario D when the jet fuel price elasticity is -0.03. However, it's important to note that such implementation could lead to a significant reduction in demand, potentially by up to 30%. Increasing the use of SAF can indeed be a relatively expensive method for reducing CO_2 emissions, especially under a single policy instrument, however until other methods for deep decarbonization of air travel emerge, such as zero-emission aviation, SAF remains the primary scalable tool to achieve critical GHG targets.

It is important to note that this analysis omits consideration of equity or distributional impacts of these policies. Quantification of these impacts is complex and outside the scope of this report. At a qualitative level, aviation's environmental impacts tend to disproportionately fall on poorer communities and those with a higher fraction of non-white residents, who are more likely to live in proximity to airports and so are exposed to the noise, air, and water pollution associated with commercial aviation. Air travel is also disproportionately consumed by more affluent people, so cost impacts are likely to be more strongly felt among this income strata, however, increases in ticket prices could put air travel beyond the financial reach of lower-income consumers entirely. Further work is warranted to better understand the distributional impacts of any proposed SAF policy.

Conclusion

The path that transitioning to a cleaner California aviation sector might be a bumpy road. The analysis has shown that using an exclusive policy to transform the aviation sector into a more sustainable one could be costly. Thus, a more comprehensive plan needs to be proposed.

For the short term, SAF is the only useful tool available. The analysis indicates that by 2030, the estimated demand will meet the supply of SAF for intrastate flights while keeping total vegetable oil-based fuel consumption below 500 million gallons/year. However, to make California well-positioned in aviation decarbonization over the short and long, further policy incentives need to be allocated as the current LCFS design is inadequate.

The impacts and relative merits of policies to promote SAF depend on the price elasticity of demand for fuel. While intuition may suggest that jet fuel demand is inelastic, there is reason to believe that in the longer run, when airlines have the ability to adjust their fleets and consumers their travel patterns, the price elasticity is more pronounced. Policy roll-outs with long time horizons may enable a greater price elasticity, which would in turn lead to lower increases in aviation fuel prices from a given policy. The dynamics and magnitudes of airline responses to fuel price changes, and their implications of aviation decarbonization policy, should be a priority area for future research.

While the long-term technological solutions for achieving complete decarbonization may remain uncertain. Electric and hydrogen power technologies for aviation applications are just in the initial stages of development. The technology readiness level of both applications is 3-4, according to the ETP Clean Energy Technology Guide (IEA, 2022).

Electrifying intrastate flights using battery aircraft is feasible but challenging. Transferring all intrastate flights' energy demands to electric power would only require a relatively small percentage (about 1%) of the overall electricity generation in the state. However, the lower speed and significantly heavier weight could make the commercial deployment struggle and impediment. On average, the battery-electric aircraft is roughly 1.8 times heavier and 23% slower than the conventional jet.

LH_2-powered aircraft would also face the problems of increased weight and shorter flight range. The results showed that LH_2-powered aircraft have an average 21% increase in total fuel system weight and a 23% increase in operational empty weight.

The state has acknowledged the potential of zero-emission technologies, such as battery and hydrogen-powered aircraft, and has set a goal of replacing 20 percent of its fuel needs with these technologies. However, further policy programs are still in limbo. Apart from grants and funding for research and development, tax exemptions represent another potential policy instrument. The cost and effectiveness of the tax exemption policy require further examination.

With its ambitious climate goal, California decision makers must consider how much emphasis to give to alternative fuel aviation (AFA) adoption in developing policies. Until a well-defined and structured plan for achieving sustainability in this sector is established, it will be difficult to turn this goal into a tangible reality and to effectively steer the sector towards a cleaner future.

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