BRIEFING

JANUARY 2023

A roadmap for decarbonizing California in-state aviation emissions

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California is currently developing a plan to reach net zero greenhouse gas (GHG) emissions by 2045 and is aggressively pursuing revisions to its array of climate policies. California has made progress in deploying alternative fuels and electric vehicles in the road sector, but aviation emissions remain a challenge due to a combination of technical, economic, and legal barriers. Although direct regulation of aviation emissions by California could be preempted by Federal laws, there are still steps that the state can take to reduce its own intra-state aviation emissions.

This briefing paper assesses the opportunities for decarbonizing California's in-state aviation by 2035. We assess the contribution of passenger civil aviation to California's aviation sector emissions and evaluate the potential GHG reductions that could be achieved through emerging aviation decarbonization technologies, including sustainable aviation fuel (SAFs) and zero emission planes (ZEPs). Lastly, we assess the policy changes necessary to stimulate the deployment of these technologies.

BACKGROUND

California's aggressive climate policies have helped to reduce the state's overall climate impact, resulting in an over 10% decrease in statewide GHG emissions from 2000 to 2019, even as the state's population and economy have grown. California is currently evaluating its progress towards the target of reaching a 40% reduction in statewide GHG emissions relative to 1990 levels and is developing a plan for reducing dependency on petroleum and reaching a goal of statewide carbon neutrality by 2045.[1]

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[1] California Air Resources Board (CARB), "Draft 2022 Scoping Plan Update," (2022), https://ww2.arb.ca.gov/sites/default/files/2022-05/2022-draft-sp.pdf.

Acknowledgments: This work was generously supported by the ClimateWorks Foundation. Thanks to Dan Rutherford (ICCT), Ethan Elkind, and Katie Segal (UC Berkeley) for helpful reviews.

Mitigating aviation emissions at the state level is extremely challenging due to the risk of exceeding state jurisdiction. Emissions standards for aircraft, for example, are established at the federal level and therefore preempt state action.[2] The 2022 Scoping Plan for California's AB 32 climate policy identifies aviation as an important sector for further decarbonization and proposes that 10% of aviation fuel demand be met with electricity and hydrogen in 2045, with the remaining demand met via liquid SAFs.[3] To promote the deployment of SAFs, California Governor Newsom has urged the California Air Resources Board (CARB) to adopt a 20% SAF blending target.[4] In the State Legislature, AB 1322 proposes that CARB develop a plan to increase SAF production to 1.5 billion gallons by 2030 and deploy an unspecified quantity of zero-emission aviation technologies, such as electric and hydrogen-powered planes.[5]

California is already a global leader in SAF production, with the world's first commercial-scale SAF production site and approximately 8 million gallons of SAF produced in 2021.[6] The California Low-Carbon Fuel Standard (LCFS), amended to include aviation as an optional, opt-in compliance pathway, offers SAF producers one of the most lucrative markets for their product. Multiple airlines operating in California have signed offtake agreements to supply SAF at its two busiest airports in Los Angeles and San Francisco, ensuring a growing stream of SAF consumption in the state.[7] However, the total impact of SAF on California's aviation emissions is negligible—it comprised less than 1% of annual jet fuel consumption in the state in 2021. The opt-in status of aviation fuels under the LCFS is a potential barrier to wider adoption of SAFs, as SAF production is not cost-effective relative to the cost of producing drop-in renewable diesel for compliance with road sector fuels policies.[8] Further, opt-in compliance with SAFs may also push some of the costs of decarbonizing aviation onto the road sector.

On the Federal level, the SAF Grand Challenge announced in 2021 raises the ambition of domestic SAF production to 3 billion gallons by 2030 and sets a long-term target of 35-billion gallons by 2050.[9] The 2022 Inflation Reduction Act includes a tax credit of up to $1.75 per gallon of SAF produced through 2027, which can be combined with existing financial incentives provided under the federal Renewable Fuel Standard (RFS) and the California LCFS.[10]

Intra-state, short-haul flights are a promising target for decarbonization efforts, as these routes are typically served by smaller, less-efficient aircraft and the short flight

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[2] 42 U.S.C. § 7573 ("No State or political subdivision thereof may adopt or attempt to enforce any standard respecting emissions of any air pollutant from any aircraft or engine thereof unless such standard is identical to a standard applicable to such aircraft under this part."); 49 U.S.C §§ 40101, 41713.

[3] California Air Resources Board (CARB), "Draft 2022 Scoping Plan Update."

[4] Office of Governor Gavin Newsom, "Letter to the California Air Resources Board," July 22, 2022. https://www.gov.ca.gov/wp-content/uploads/2022/07/07.22.2022-Governors-Letter-to-CARB.pdf?emrc=1054d6.

[5] Robert Rivas and Al Muratsuchi, AB-1322 California Global Warming Solutions Act of 2006: Aviation greenhouse gas emissions reduction plan., Pub. L. No. AB 1322. Accessed August 23, 2022. https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=202120220AB1322.

[6] California Air Resources Board (CARB), "LCFS Data Dashboard," Accessed August 23, 2022, https://ww2.arb.ca.gov/resources/documents/lcfs-data-dashboard.

[7] Sapp, Meghan. "New SAF Collaboration to Provide Permanent Supplies for Private Aviation at SFO and London-Luton," *Biofuels Digest*, September 28, 2020. https://www.biofuelsdigest.com/bdigest/2020/09/28/new-saf-collaboration-to-provide-permanent-supplies-for-private-aviation-at-sfo-and-london-luton/.

[8] Graham Noyes, "Proposed LCFS Regulations Pertaining to Alternative Jet Fuel," Public Comment on 2018 LCFS Rulemaking, 2018.

[9] Department of Energy, Department of Transportation, and U.S. Department of Agriculture, "Memorandum of Understanding: Sustainable Aviation Fuel Grand Challenge," (2021) https://www.energy.gov/sites/default/files/2021-09/S1-Signed-SAF-MOU-9-08-21_0.pdf

[10] Inflation Reduction Act of 2022, Pub. L. No. H.R.5376

distances are suitable for less energy-intensive transport modes or zero-emission aircraft.[11] Commercial interest in zero-emission planes (ZEPs) has increased in recent years, with battery-electric aircraft of varying passenger capacities under development. The Velis Electro is the first, and currently only, certified electric aircraft and can sustain a two-person flight for 50 minutes.[12] Eviation and Heart Aerospace are targeting the commuter market with 9- and 19-passenger aircraft, respectively, and both companies intend to enter the market as early as 2024.[13] The biggest challenge for battery electric aircraft is the weight of the batteries. ICCT research suggests that current battery technology would only allow 9-passenger aircraft to fly routes up to 140 km.[14] If battery technology improved to store double the amount of energy per unit mass as is currently possible, that would allow 19-passenger aircraft to complete routes that are 300 km or less.[15]

Hydrogen-powered aircraft, on the other hand, promise larger payload and range capability if brought into service. Hydrogen provides three times the energy per unit mass than fossil jet fuel, produces zero carbon emissions on usage, and can be used to generate electricity through fuel cells or combusted to power gas turbine-based aircraft propulsion systems. When used in fuel cells, the only exhaust is water, whereas combusting hydrogen in a gas turbine generates nitrogen-oxide (NOx) emissions as well. Project Fresson is retrofitting 9-seater Britten-Norman Islander aircraft to be powered by fuel cell propulsion systems.[16] ZeroAvia is taking a tiered approach, starting with retrofitting a 10- to 20-seat aircraft, with future plans to retrofit a 40- to 80-seat aircraft.[17] Universal Hydrogen is taking a slightly different approach, selling a conversion kit for larger turboprops like the ATR 72 and the De Havilland Canada Dash-8 Q300.[18] The power output currently achievable from hydrogen fuel cells limits the size of the aircraft that can be converted. The large volume taken up by hydrogen limits the amount that can be carried on-board and, consequently, limits the payload and range capability of the aircraft. The bigger fuel-cell powered aircraft are likely to be limited to 600 km routes, when using gaseous hydrogen (GH_2). Hydrogen combustion aircraft would provide even longer range—up to 1400 km for regional turboprops and up to 3400 km for narrowbody turbofans—but are not expected to enter into service before 2035.[19] Fuel cell aircraft with 40 to 70 seats are expected to enter the market slightly later than electric aircraft, with the the first set of electric aircraft manufacturers aiming for 2026 for deliveries.

A key barrier to the successful deployment of SAFs and ZEPs is the steep cost gap between alternative fuels and airframes and the relatively lower cost of existing fuels.

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[11] Brandon Graver, Dan Rutherford, and Sola Zheng. "CO_2 Emissions from Commercial Aviation: 2013, 2018, and 2019." (Washington, DC: ICCT, 2020), https://theicct.org/sites/default/files/publications/CO2-commercial-aviation-oct2020.pdf.

[12] "Velis Electro EASA TC – Pipistrel Aircraft," Pipistrel Aircraft, accessed April 5, 2022, https://www.pipistrel-aircraft.com/aircraft/electric-flight/velis-electro-easa-tc/.

[13] Eviation, "Aircraft – Eviation,"accessed June 28, 2022. https://www.eviation.co/aircraft/; Heart Aerospace, "Electrifying Regional Air Travel," accessed November 11, 2021. http://heartaerospace.com/.

[14] Jayant Mukhopadhaya and Brandon Graver, "Performance Analysis of Regional Electric Aircraft," (Washington DC: ICCT, 2022), https://theicct.org/publication/global-aviation-performance-analysis-regional-electric-aircraft-jul22/.

[15] Jayant Mukhopadhaya and Brandon Graver, "Performance Analysis of Regional Electric Aircraft."

[16] "Project Fresson to Deliver World's First Truly Green Passenger Carrying Airline Services Using Hydrogen Fuel Cell Technology," Cranfield Aerospace, May 12, 2021. https://www.cranfieldaerospace.com/2021/project-fresson-hydrogen/.

[17] ZeroAvia,"First Practical Zero Emission Aviation Powertrain," accessed June 28, 2022, https://www.zeroavia.com.

[18] "Product-Universal Hydrogen", Universal Hydrogen, accessed June 28, 2022, https://hydrogen.aero/product/.

[19] Jayant Mukhopadhaya and Dan Rutherford, "Performance Analysis of Evolutionary Hydrogen-Powered Aircraft," (Washington, DC: ICCT, 2022), https://theicct.org/publication/aviation-global-evo-hydrogen-aircraft-jan22/.

Though California's ability to mitigate aviation emissions through more traditional regulatory instruments run the risk of federal preemption, the state can opt to motivate new technologies through fiscal incentives and the support of pilot projects. At smaller scales, California may be able to providing financing and support for these emerging technologies before they are suitable for wider-scale adoption. These approaches could also leverage existing financial incentives such as the LCFS, the RFS, and federal tax credits. California's large geographic size, substantial renewable energy potential, and relatively high quantity of intra-state, short-haul routes offer a sizeable pool of possible ZEP flight corridors to decarbonize. Because these flights would occur solely within California, the state may address technological and economic barriers to widespread use of ZEPs through targeted financial incentives for the fueling infrastructure and fuel supplied to these planes along selected in-state flight corridors.

Decarbonizing California's aviation sector will likely require a mix of different policies and technologies. As many of these technologies have not yet been commercialized, deploying them quickly enough to reduce emissions significantly by 2045 will prove challenging. Most critically, the largest share of the state's aviation emissions fall outside its jurisdiction to regulate. Therefore, a key role component of the state's aviation decarbonization strategy is to provide a proving ground for technology adoption in other states and to influence federal policy.

A PROFILE OF CALIFORNIA'S AVIATION EMISSIONS

California accounts for 15% of domestic jet fuel consumption, and the state's commercial carriers emitted approximately 32.5 million tonnes CO_2 in 2019 from fuel combustion.[20] This estimate doesn't include emissions from general aviation, which typically includes smaller aircraft for business travel and recreation, nor from dedicated freight; nationally, general aviation jet fuel consumption comprised approximately 20% of the fuel consumed by the larger, domestic commercial aviation sector.[21] Using ICCT's Global Aviation Carbon Assessment (GACA) model to determine the airport origin, destination, and route distance, as well as emissions attributable to each route, we disaggregate California's 2019 emissions in Figure 1 below. The blue bars illustrate emissions from intra-state flights grouped by distance range, whereas the brown bars illustrate the combined emissions from interstate flights, as well as the emissions from flights departing from California. Intra-state emissions are approximately 2 million tonnes CO_2, with the bulk of these emissions attributable to flights from 400 to 800 km. However, flights leaving the state comprise approximately 94% of the state's aviation emissions.

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[20] California Air Resources Board (CARB), "California Greenhouse Gas Emissions for 2000 to 2019 Trends of Emissions and Other Indicators" (2021), https://ww2.arb.ca.gov/ghg-inventory-data

[21] U.S. Environmental Protection Agency, "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020," (2022), https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2020.

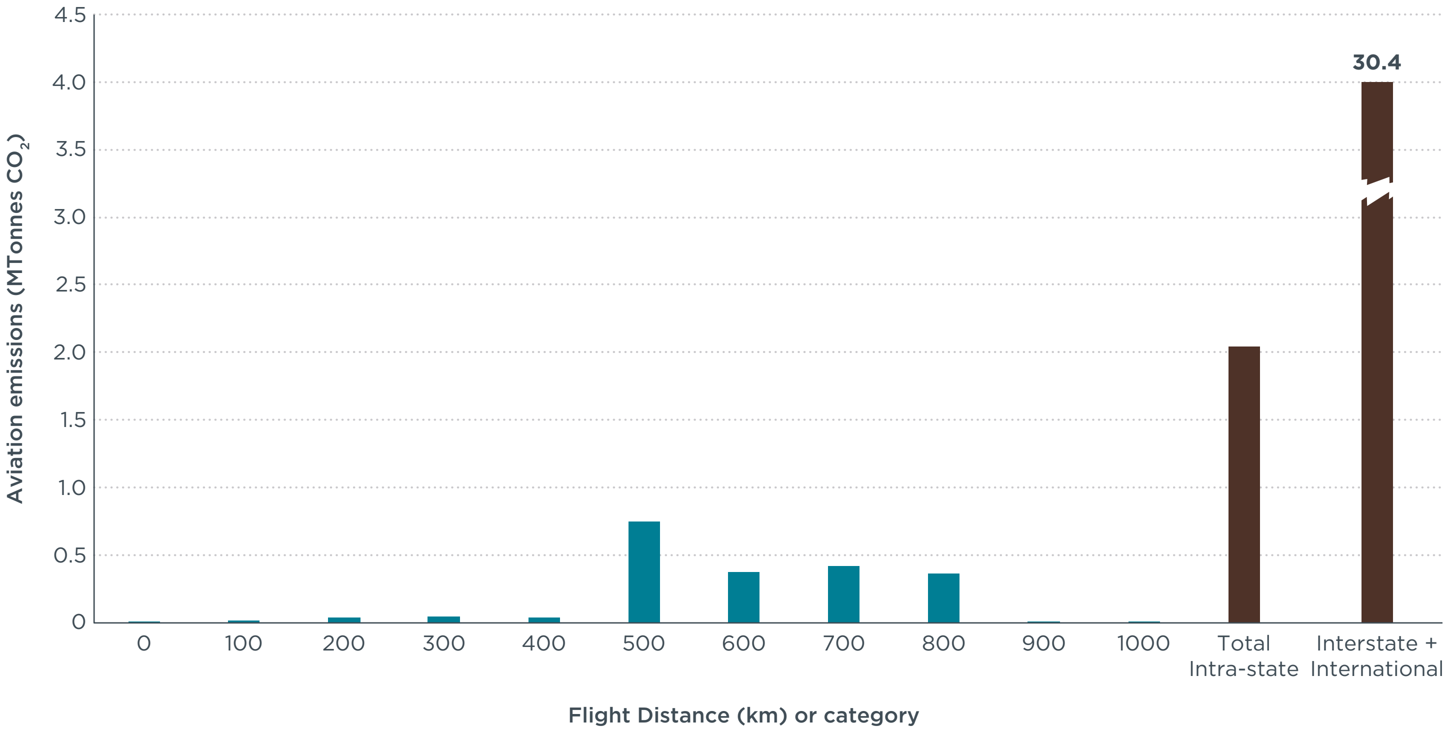

Figure 1. Disaggregation of California aviation sector emissions, 2019

In its GHG Emission Inventory, the California Air Resources Board (CARB) attributes 4.4 million tonnes of CO_2-equivalent emissions (Mt CO_2e) to intrastate aviation. This corresponds to roughly 1% of the total 418 Mt CO_2e emissions reported in California in 2019. These numbers are based on the sale of aviation fuels and so include non-commercial aviation and freight operations. Based on the heat content of in-state aviation fuel sales (reported as 6×10^{13} BTU) and reported intrastate aviation emissions, we calculate that CARB uses a carbon intensity factor of 3.0 kg of CO_2 per kg of aviation fuel used.[22] This is lower than 3.16 kg of CO_2 per kg of aviation fuel used by the International Civil Aviation Organization (ICAO).[23] We compare the California GHG Inventory estimates to emission estimates for commercial passenger aviation in ICCT's GACA database in Table 1 below.[24] Since the GACA database only uses commercial airline route data to estimate fuel consumption for passenger aviation, the jet fuel usage values estimated will be necessarily lower than those reported by CARB. However, this discrepancy is partially offset as the GACA database uses slightly higher carbon intensity than the values assumed by CARB.

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[22] California Air Resources Board, Fuel Activity for California's Greenhouse Gas Inventory by Sector & Activity (Fuel usage data, last updated July 2021, accessed August 2022), https://ww3.arb.ca.gov/cc/inventory/data/tables/fuel_activity_inventory_by_sector_all_00-19.xlsx

[23] International Civil Aviation Organization (ICAO), *2019 Environmental Report: Aviation and the Environment*, (Montreal: 2019), https://www.icao.int/environmental-protection/pages/envrep2019.aspx.

[24] Brandon Graver, Daniel Rutherford, and Sola Zheng, "CO_2 Emissions from Commercial Aviation: 2013, 2018, and 2019."

Table 1. 2019 Jet fuel usage and GHG emissions reported by CARB compared to those estimated by the ICCT

	Jet A usage (tonnes)		CO_2 emissions (Mt CO_2e)	
	CARB	ICCT	CARB	ICCT
California aviation totals	1.3×10^7	1.0×10^7 (-23%)	38	32.5 (-14%)
Intra-state flights	1.5×10^6	6.0×10^5 (-60%)	4.4	2.0 (-55%)

To evaluate the potential future impacts of aviation decarbonization technologies in California, we also assess the potential growth in aviation demand and emissions in California up to 2035. This analysis does not factor in a demand disruption associated with the Covid-19 pandemic. Starting from a 2019 baseline, this analysis assumes a 1.7% annual increase in aviation demand in conjunction with a 0.5% annual efficiency improvement consistent with the Projection of Aviation Carbon Emissions (PACE) model.[25] Assuming that this growth is evenly distributed across routes, we therefore assume that emissions from intra-state flights increase to approximately 2.5 Mtonnes CO_2 and the statewide total increases to approximately 39.3 Mtonnes. Assuming that the demand is met solely through fossil jet fuel, this would be equivalent to approximately 1 and 15.7 million liters of fossil jet, respectively.

PROMOTING SAFS THROUGH THE LOW-CARBON FUEL STANDARD

The 2019 amendments to the LCFS expanded the program to include alternative aviation fuels as an "opt-in" compliance pathway.[26] With this amendment, SAFs could generate credits when blended in California, though fossil-derived aviation fuels could continue to be imported and produced without generating deficits; this change expanded the opportunities for compliance credit generation within the program, without increasing the quantity of deficits. In practice, this gives fuel producers generating a mixed slate of alternative fuels the ability to receive credits for their aviation fuels, even as the majority of their production is dedicated to drop-in, renewable diesel production.[27]

Obligating conventional aviation fuels within the LCFS, as with efficiency standards, poses a risk of running afoul of federal preemption.[28] Similarly, aviation is excluded from California's cap and trade program due to concerns over federal preemption.[29] However, California may have the flexibility to expand the LCFS to include the share of aviation fuels consumed for intra-state travel, driving SAF deployment in a smaller sub-set of the aviation sector. There remains substantial legal ambiguity on the regulation of fuels' life-cycle emissions rather than point-source vehicle emissions, as well as whether states can regulate life-cycle emissions from in-state flights. Obligating the in-state share of aviation fuel emissions in the LCFS would be the first regulatory

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[25] International Council on Clean Transportation, "Projection of Aviation Carbon Emissions (PACE) Model," https://theicct.github.io/PACE-doc/.

[26] California Low Carbon Fuel Standard Regulation, CCR 17 § (n.d.)

[27] Gladstein, Neandross & Associates, "Sustainable Aviation Fuel: Greenhouse Gas Reductions from Bay Area Commercial Aircraft." (Bay Area Air Quality Management District, 2020), https://www.baaqmd.gov/-/media/files/planning-and-research/research-and-modeling/saf-report-final-for-distribution-to-baaqmd-pdf.pdf?la=en.

[28] Graham Noyes, "Proposed LCFS Regulations Pertaining to Alternative Jet Fuel."

[29] Fred Ghatala, "Sustainable Aviation Fuel Policy in the United States: A Pragmatic Way Forward," (Atlantic Council, 2020).

measure that could boost SAF deployment in California. However, we note that the additional compliance deficits created from fossil jet fuel use would not necessarily be fully offset by credits generated by blending SAFs; for example, high renewable diesel blending and over-compliance on the diesel pool in California is used to offset a share of deficits generated by fossil gasoline.[30]

To assess the scale of expanding the LCFS to aviation fuels, we evaluate the potential obligation on fuel suppliers of intra-state fuel volumes through 2035. As shown in Figure 2, starting from a fossil fuel baseline of 89.37 gCO_2e/MJ of fuel, the GHG intensity standard for jet fuel (orange line) aligns with the declining standard for diesel (blue line) starting in 2023 and declines to 80.36 gCO2e/MJ in 2030 in the LCFS regulation. The total deficits for aviation fuels in the program, in units of thousand tonnes CO_2e, are shown in the blue bars. We extrapolate the mandated GHG intensity reduction out to 2035 for this analysis, as shown in the dotted orange line, to 74.35 gCO2e/MJ in 2035—a 16% decline relative to the fossil baseline by 2035. Fuels with a carbon intensity above the declining standard generate deficits, whereas fuels with a carbon intensity below the standard generate LCFS credits.

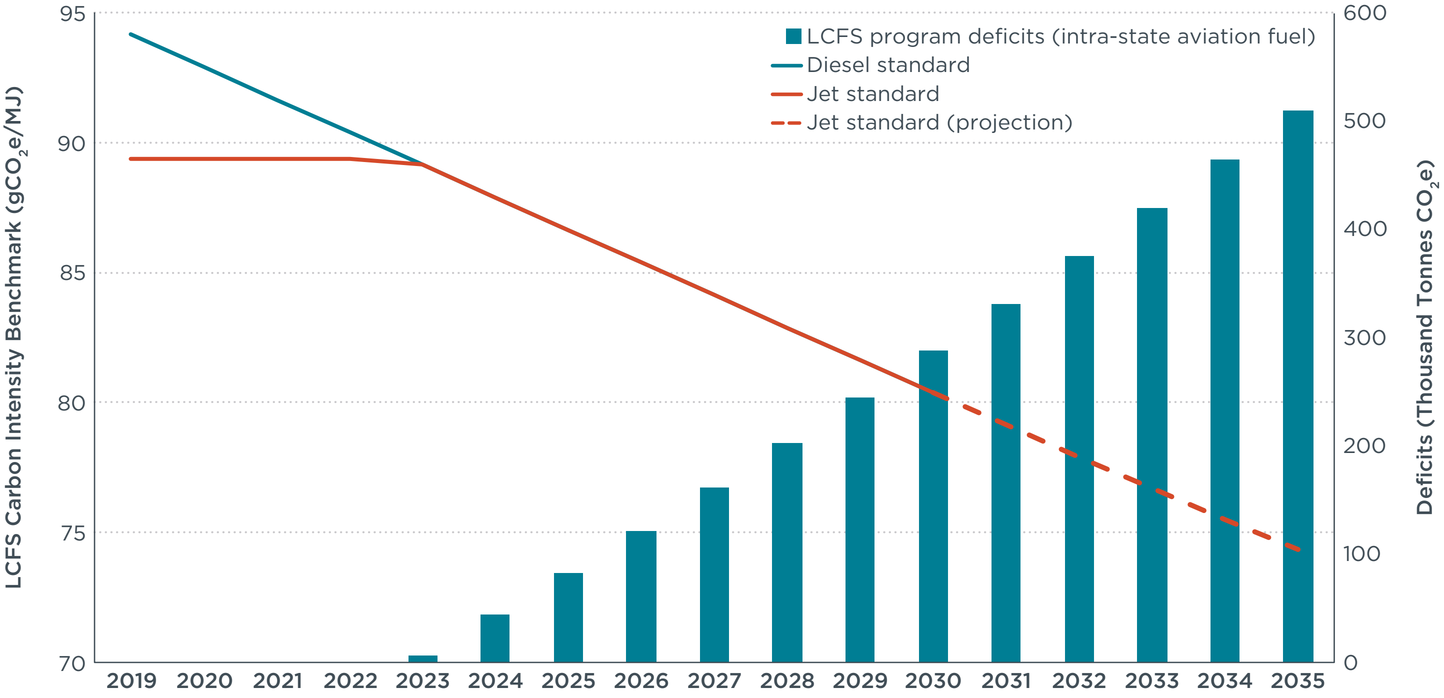

Figure 2. Projected carbon intensity standard for jet fuel and total obligation from fuel consumed for intra-state flights in the California LCFS

Obligating intra-state fuel consumed within civil aviation would generate a small but growing share of aviation-sector deficits within the LCFS. Based on our assumed fuel consumption growth rate described above, in conjunction with a strengthened GHG standard, we estimate that the LCFS deficits generated by aviation fuel consumed on intra-state flights would grow from approximately 6 thousand tonnes CO_2e in 2023 to over 500 thousand tonnes by 2035, as shown by the blue bars in Figure 2. This would comprise a miniscule share of overall LCFS program obligations in 2021, which in total

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[30] California Air Resources Board (CARB), "LCFS Data Dashboard," https://ww2.arb.ca.gov/resources/documents/lcfs-data-dashboard.

exceeded 18 million tonnes CO_2e of deficits. Based on 2021 SAF consumption data reported to CARB, the total compliance already achieved from blending SAFs in 2021 would greatly exceed the deficits from expanding the obligation in 2023.[31] By 2025, however, the continued decline in the carbon intensity benchmark, in conjunction with projected growth in intra-state fuel consumption, would necessitate additional fuel blending. Assuming the average carbon intensity of SAFs remains the same as in 2021, the deficits from intra-state aviation in 2035 would necessitate blending approximately 113 million gallons of SAFs, though we note that the deficits may also be offset via other compliance pathways outside the aviation sector, such as those from road biofuel blending or electric vehicle charging.

Given the risk of federal preemption, as well as the inherent compliance flexibility of the LCFS program, expanding the program to obligate only fuels consumed for intra-state flights would likely have a minor impact on the deployment of SAFs from 2023 to 2035. The 113 million gallons of SAF required to offset deficits falls far short of the 1.5-billion-gallon target envisioned by California's legislature and governor. Together, this suggests that additional SAFs could be generated through either a higher GHG reduction target for the LCFS, or an expansion of the program's obligation to cover a larger share of California's aviation sector.

If California opts to only regulate the carbon intensity of all aviation fuels consumed in-state, the LCFS would only obligate compliance from approximately 6% of the state's aviation fuel sector. Despite this constraint, the LCFS could still be a valuable tool whose value can be leveraged in conjunction with separate, more targeted policies. The state can distribute upfront grants or financial incentives for individual SAF producers to boost in-state SAF production and reduce the cost barrier of entry to the market; regardless of whether fuel is consumed on intra-state flights, it will still qualify for LCFS credits. Similarly, the state can act as a facilitator for offtake agreements between interested airports and airlines and emerging fuel producers. Establishing offtakes for a fixed quantity of fuel production at a set price would reduce the risk and uncertainty for new producers by ensuring a market for their finished fuel. As these types of programs would be voluntary, rather than binding requirements, they would not risk federal preemption but would still capture the value that the LCFS provides to each gallon of fuel.

Beyond the question of the quantity of SAFs that could be incentivized by the LCFS is the question of their quality. Previous analyses have highlighted the disappointing scale-up of lignocellulosic or second-generation biofuels in California, compared to expectations of their future contribution at the outset of the LCFS.[32] As the carbon intensity target has continued to decline, LCFS compliance has instead come from the rapid expansion of dairy manure biogas and hydrotreated lipid production.[33] This presents an important warning sign for the future of SAFs under the LCFS, as the growing volumes of lipids (i.e., virgin vegetable oils, waste fats, oils and greases) used to produce drop-in, renewable diesel could be easily diverted to the aviation sector using existing, commercialized conversion pathways. A key risk to the integrity

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[31] Based on the LCFS dashboard, the average CI of alternative jet fuel was 36.2 gCO2e/MJ and 8.1 million gallons gasoline-equivalents were consumed in 2021, generating approximately 51,000 tonnes CO_2e of LCFS credits.

[32] Julie Witcover, "What Happened and Will Happen with Biofuels? Review and Prospects for Non-Conventional Biofuels in California and the U.S.: Supply, Cost, and Potential GHG Reductions," (2021). https://doi.org/10.7922/G26W98D7.

[33] Julie Witcover, "What Happened and Will Happen with Biofuels? Review and Prospects for Non-Conventional Biofuels in California and the U.S.: Supply, Cost, and Potential GHG Reductions."

of any SAF policy is the opportunity for existing renewable diesel producers—who already supply over 800 million gallons of renewable diesel—to shift their product slate towards jet fuel. Lipids such as soybean oil and waste oil present important sustainability risks for the LCFS, including food price increases, deforestation and indirect emissions from virgin vegetable oils, and the possibility of waste oil fraud in the case of imported waste oils.[34] The ongoing capacity expansions and refinery retrofits to produce hydrotreated lipids—up to 5 billion gallons of new capacity by 2024—suggest that California may already be on a trajectory to ramp up lipid consumption drastically absent policy changes.[35]

To avoid the potential impacts of shifting potentially unsustainable feedstocks from the road sector to the aviation sector, targeted support for SAFs could be limited to second-generation pathways with higher GHG savings. Previously, CARB has noted that if ultralow-carbon fuel pathways do not reach sufficient volumes under the current structure of the program, "special provisions in the regulation may aid in their development."[36] Examples of how to implement this for SAFs could include awarding certain types of fuels, such as lignocellulosic biofuels, bonus LCFS credits if they meet certain sustainability and technology criteria. An alternative approach, based off the recent provisions for electric vehicle charging, would be to provide advance LCFS credits for second-generation SAF producers based on their production capacity, thereby reducing the impact of high upfront expenses for more challenging technologies. Alternatively, as part of efforts to facilitate offtake agreements, California could opt to provide a guaranteed LCFS credit price for new producers, similar to a contract for difference approach.[37] This could cost-effectively enable new production by mitigating the downside risks for investors; California could guarantee a minimum LCFS credit price for a set period of time (e.g., 10 years) and pay the difference whenever the price drops below the level specified in the offtake. In all these cases, policymakers could utilize discretion when awarding incentives, limiting support only to pathways that offer a minimum GHG savings (e.g., 80%) such as synthetic fuels produced from renewable electricity or biofuels produced using only certain feedstocks, such as lignocellulosic wastes and residues.

AMENDING THE LOW-CARBON FUEL STANDARD TO INCLUDE ZERO-EMISSION AVIATION PATHWAYS

As a technology-neutral performance standard that already incentivizes the deployment of hydrogen and electric powertrains in the road sector, the LCFS can also promote zero-emission technologies in the aviation sector. This approach is well precedented in the road sector, where LCFS credits provide a valuable complement to separate incentives and mandates for zero-emission vehicles. To credit hydrogen and electric-drive vehicles on a consistent basis with internal combustion engine

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[34] Jane O'Malley, Nikita Pavlenko, Stephanie Searle, and Jeremy Martin. "Setting a Lipids Fuel Cap under the California Low Carbon Fuel Standard,." (Washington, DC: ICCT, 2022). https://theicct.org/publication/lipids-cap-ca-lcfs-aug22/.

[35] Chris Mallins and Cato Sandford. "Animal, Vegetable or Mineral (Oil)? Exploring the Potential Impacts of New Renewable Diesel Capacity on Oil and Fat Markets in the United States." (Washington, DC: ICCT, 2022), https://theicct.org/publication/impact-renewable-diesel-us-jan22/.

[36] R. Corey, M. Buffington, and L. Hatton, "Low Carbon Fuel Standard 2011 Program Review Report" (California Air Resources Board, 2011), https://dokumen.tips/documents/low-carbon-fuel-standard-2011-program-review-report-08122011-low-carbon-fuel.html.

[37] Nikita Pavlenko, Stephanie Searle, Chris Malins, and Sammy El Takriti. "Development and Analysis of a Durable Low-Carbon Fuel Investment Policy for California." (Washington, DC: ICCT, 2016), https://theicct.org/publication/development-and-analysis-of-a-durable-low-carbon-fuel-investment-policy-for-california/.

(ICE) vehicles, the LCFS utilizes energy economy ratios (EERs) to normalize the emissions savings per unit energy of fuel across powertrains with different efficiencies. For example, the EER of an electric light-duty vehicle is 3.4, signifying that 1 MJ of electricity displaces approximately the same quantity of energy as 3.4 MJ of liquid fuels. Crediting ZEPs within the LCFS would require developing an assessment of the propulsion efficiency across conventional and zero-emission aviation powertrains to develop a new set of EERs for aviation.

Here we focus on the EERs for emerging battery-electric and fuel cell aircraft likely to be commercially available before 2035. However, we note that hydrogen combustion in gas turbines can power larger aircraft. A recent study by the ICCT suggests that liquid hydrogen (LH_2) combustion designs could service intra-state routes within California.[38] However, large technical challenges remain regarding the design, testing, and mass production of LH_2-powered gas turbine engines. Since 2035 is the last year considered in this assessment and the LH_2-powered aircraft would take time to get adopted into airlines' fleets, we do not assess their contribution to decarbonizing intra-state aviation in California.

For aircraft, the overall efficiency of a propulsion system is the product of the thermodynamic efficiency of the energy conversion system and the propulsive efficiency of the thrust generation system. Using a turboprop aircraft as an example, the energy conversion system is the gas turbine, and the thrust generation system is the propeller. While ZEPs may use different energy conversion systems, the thrust generation systems are identical to fossil-fueled aircraft and will have the same propulsive efficiencies. Therefore, the energy efficiency ratios will be purely dependent on the thermodynamic efficiencies of the energy conversion systems.

Gas turbines are the dominant energy conversion system for hydrocarbon fueled aircraft. The thermodynamic efficiency of a gas turbine engine varies based on the size of the engine and the related optimizations. Large turbofan engines that are optimized for fuel efficiency typically achieve thermodynamic efficiencies of 45%–55% depending on the engine's maximum power output.[39] In contrast, smaller turboprop engines which are optimized for weight reduction and durability across more landings and takeoffs, typically achieve more modest thermodynamic efficiencies of 25%–35%.

The boundary of the energy conversion system for electric aircraft goes from the battery to the motor shaft. Energy losses in the electrical wires, motors, and gearbox are expected to be 10% (90% efficiency).[40] Including the energy lost during the battery charging process (15% lost to heat and the controller),[41] the efficiency of the electric energy conversion system is expected to be 75%.

For hydrogen fuel cell aircraft, the charging losses are replaced by the thermodynamic efficiency of the fuel cell itself. This varies between types of fuel cells, but the industry-

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[38] Jayant Mukhopadhaya and Dan Rutherford, "Performance Analysis of Evolutionary Hydrogen-Powered Aircraft."

[39] National Academies of Sciences, Engineering, and Medicine, "Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions", (2016), https://doi.org/10.17226/23490.

[40] Raymer, Daniel, *Aircraft Design: A Conceptual Approach, Sixth Edition*. (American Institute of Aeronautics and Astronautics, 2018), https://doi.org/10.2514/4.104909.

[41] Georg Bieker, "A Global Comparison of the Life-Cycle Greenhouse Gas Emissions of Combustion Engine and Electric Passenger Cars," (ICCT: Washington, DC, 2021), https://theicct.org/publication/a-global-comparison-of-the-life-cycle-greenhouse-gas-emissions-of-combustion-engine-and-electric-passenger-cars/.

leading standard is the Proton Exchange Membrane (PEM) fuel cell.[42] These fuel cells operate at 50% thermodynamic efficiency.[43] Including the electrical losses, the efficiency from hydrogen fuel to shaft power is expected to be 45%.

To calculate EERs, we use hydrocarbon combustion gas turbines as the baseline thermodynamic efficiency. Since there is a significant difference in the thermodynamic efficiencies of turboprop and turbofan systems, we calculate separate EERs for each, similar to what is done under the LCFS for light-duty and heavy-duty vehicles. The baseline efficiency of a gas turbine running on Jet A is set at 30% for a turboprop and 50% for a turbofan. The EERs for different fuel and engine combinations are listed in Table 2. Since fuel cells and batteries are unlikely to power aircraft requiring turbofans in the timeline considered in this work, they are omitted from the Turbofan category of EERs. The two near-term technologies likely to see commercial use by 2035, hydrogen fuel cell and battery-electric turboprops, both offer an EER higher than conventional liquid fuels; electricity and hydrogen supplied to these aircraft could therefore receive a multiplier for its contribution.

Table 2. Energy economy ratios for different fuel and engine combinations

Turboprop		Turbofan	
Fuel/Engine combination	**Energy economy ratio**	**Fuel/Engine combination**	**Energy economy ratio**
Jet A/Gas turbine	1.0	Jet A/Gas turbine	1.0
SAF/Gas turbine	1.0	SAF/Gas turbine	1.0
H_2/Gas turbine	1.0	H_2/Gas turbine	1.0
H_2/Fuel Cell	1.5		-
Electricity/Battery	2.5		-

PILOT PROJECTS FOR ZERO-EMISSION AVIATION CORRIDORS

Similar to the role that California may take in supporting pilot projects with SAF producers and facilitating offtake agreements with SAF buyers, the state may also consider supporting ZEPs through pilot projects on selected routes. These "ZEP corridors" could serve as a testing ground and demonstration for other jurisdictions. Furthermore, their introduction could be financed in part through LCFS credits for supplying fuel and fueling infrastructure.

To identify the most promising ZEP corridors, we use the GACA database to estimate the airports with the greatest quantity of annual, short-haul (<1,500 km) passenger departures, including flights leaving the state. Using the performance characteristics of a 9-seat battery electric aircraft and the 90-seat fuel cell aircraft, we calculate the share of the intra-state aviation market that can be replaced by ZEPs. Figure 3 illustrates California's intra-state routes as dots, based on seating capacity on the Y-axis and distance on the X-axis. It then overlays the ZEP performance capabilities,

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[42] U.S. Department of Energy, "Alternative Fuels Data Center: Fuel Cell Electric Vehicles," accessed June 29, 2022, https://afdc.energy.gov/vehicles/fuel_cell.html.

[43] John Minnehan, and Joseph Pratt, "Practical Application Limits of Fuel Cells and Batteries for Zero Emission Vessels." (Military Academic Collaboration (MAC) Program, Sandia National Laboratories, 2017), https://doi.org/10.2172/1410178.

based on range and expected aircraft size as blue and orange lines, with the suitable routes shown as green dots serviceable by ZEPs. We find that electric aircraft are suitable for few routes, but that fuel cell aircraft can replace nearly one-third of intrastate departures.

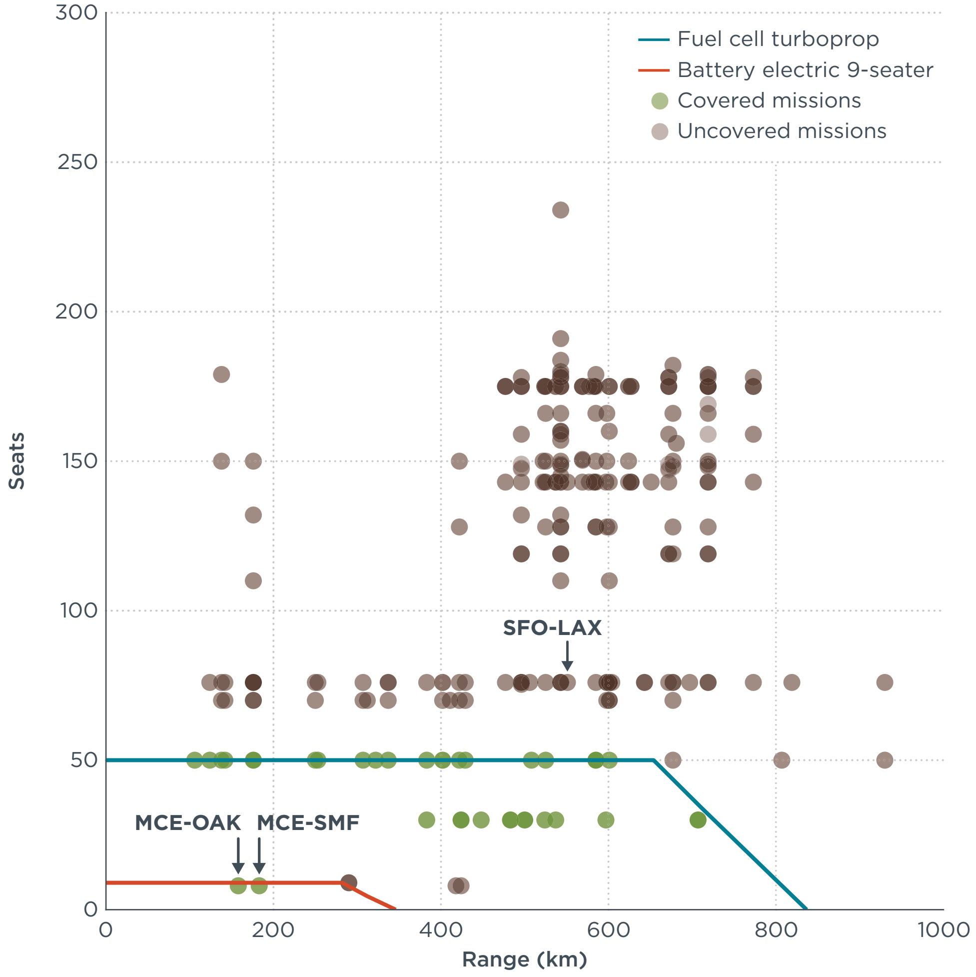

Figure 3. Overview of California airline routes by range and seating; routes serviceable by near-term, zero-emission planes indicated by lines

Figure 4 illustrates the most promising ZEP corridors identified in this analysis including San Francisco International Airport to Los Angeles International Airport (SFO–LAX), and Merced Yosemite Regional Airport to Oakland International Airport and Sacramento International Airport (MCE–OAK–SMF). The former route is approximately 600 km and is serviced by a variety of airlines using different aircraft with different seating capacities; we focus solely on the those flown on turboprop aircraft to align with the expected type of fuel cell hydrogen aircraft. Likewise, flights from MCE to either SMF or OAK occur daily or semi-daily on small aircraft suitable for battery-electric powertrains.

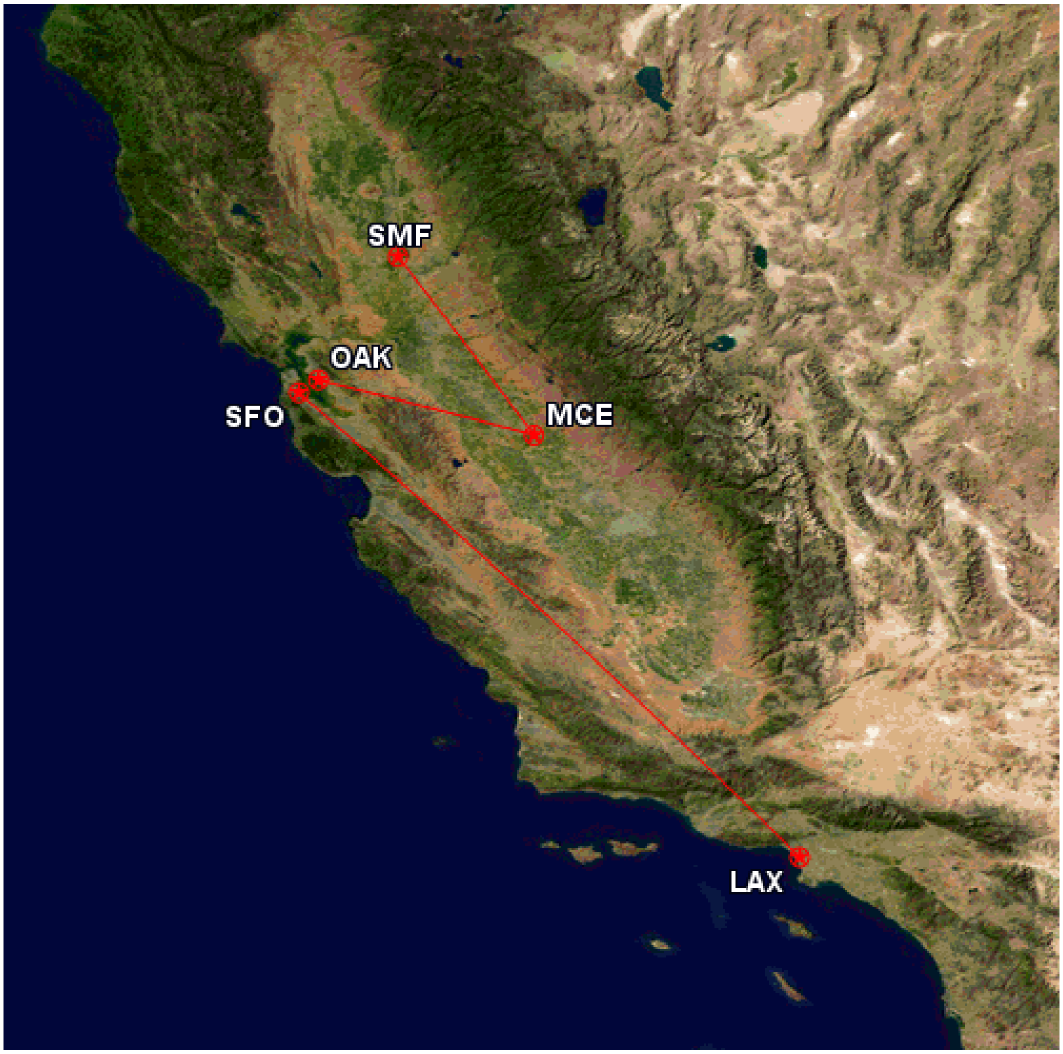

Figure 4. Illustration of potential ZEP corridors in California for battery electric (OAK-MCE-SMF) and hydrogen fuel cell (SFO-LAX) routes

Based on the GACA model for flights on these routes, we can then extrapolate the energy needs and GHG emissions reductions from the use of ZEPs on these flights, as shown in Table 3. Based on the energy consumption for a short-haul turboprop hydrogen plane estimated by Mukhopadhaya (2022), SFO–LAX would require approximately 4.7 million kg of hydrogen annually.[44] Likewise, a battery electric plane servicing routes to OAK and SMF from MCE would consume approximately 150,000 kWh of electricity at MCE.[45] Displacing even a small share of SFO–LAX flights could yield significant GHG savings; assuming the use of average hydrogen certified under the LCFS in 2021 (56 gCO_2e/MJ), approximately 44,000 tonnes of CO_2e could be abated annually from this route alone. The GHG savings from MCE–SMF–OAK are substantially smaller, as it comprises fewer flights and shorter distances; the combined GHG savings is approximately 157 tonnes annually.

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[44] *Performance Analysis of Evolutionary Hydrogen-Powered Aircraft*.

[45] Flights to SMF would occur nearly daily, whereas flights to OAK would occur every other day. Therefore, the energy consumption at SMF and OAK would be approximately 103,000 and 45,000 kWh, annually.

Table 3. Estimated energy demand and emissions savings from deploying zero-emission planes on selected California routes

Route	Technology	Annual energy demand	Petroleum displacement (thousand gallons, kerosene-equivalent)	GHG Reduction (tonnes CO_2e)	Number of departures
SFO-LAX	Hydrogen fuel cell	4,700,000 kg H_2	6,517	44,101	5,060
MCE-SMF	Battery electric	205,556 kWh	14	109	608
MCE-OAK	Battery electric	89,444 kWh	6	47	306

Beyond supplying energy and new aircraft, deploying ZEPs on these routes would also require installing new fueling infrastructure at airports. Hydrogen fueling infrastructure—particularly on the scale necessary to supply commercial aviation—can be extremely costly. To fuel the SFO–LAX route, the combined airports would need to fuel approximately 6,400 kg of hydrogen daily. Whether supplied via a single fueling station or multiple sites for redundancy, this would be at the upper end of present-day planned and existing hydrogen fueling stations.[46]

The high cost of installing new infrastructure would be compounded by the cost of building fueling stations capable of high fueling speeds; at an expected capacity of 500 kg H_2 for a short-haul flight, it would take approximately 8 hours to refuel a hydrogen ZEP at prevailing fueling rates in light-duty fuel cell vehicles (1 kg H_2/min). For fuel cell planes to have a suitable turnaround time for short-haul flights, airports would need to provide fast-flow hydrogen fueling stations currently being developed for the heavy-duty vehicle sector, which can offer peak fueling rates approaching 10 kg/min on average.[47]

To offset the cost of building new fueling stations, airports could implement pilot projects in conjunction with the California Energy Commission. Upfront capital grants to offset the cost of hydrogen fueling stations in California, awarded via the California Energy Commission's Clean Transportation Program (GFO-19-602), averaged approximately $847 per kg/day fueling capacity starting in 2020.[48] California is continuing to provide substantial policy support to expand California's hydrogen fueling network, with $279 million in funding planned to reach a goal of over 100 hydrogen fueling stations, with an increasing focus on large fueling stations for heavy-duty vehicles.[49]

The high battery capacity of emerging electric airplane designs will also necessitate the deployment of fast chargers to minimize turnaround times. Even direct current fast charging (DCFC) speeds, which range from 50 kW to 350 kW for light-duty vehicles would be insufficient for the needs of even small battery-electric aircraft, which may require 800 kWh of capacity and use approximately half that on a routine flight.[50] In order for these routes to maintain a turnaround time of under an hour, ultra-fast chargers with speeds of 1 MW and above will likely be necessary.

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[46] California Air Resources Board (CARB), "2021 Annual Evaluation of Fuel Cell Electric Vehicle Deployment," (2021), https://ww2.arb.ca.gov/sites/default/files/2021-09/2021_AB-8_FINAL.pdf

[47] Jean Baronas, Belinda Chen, Elizabeth John, Mark J Wenzel, Hannon Rasool, and Drew Bohan. "Joint Agency Staff Report on Assembly Bill 8: 2021 Annual Assessment of Time and Cost Needed to Attain 100 Hydrogen Refueling Stations in California," (California Energy Commission, California Air Resources Board, 2021), https://www.energy.ca.gov/sites/default/files/2021-12/CEC-600-2021-040.pdf.

[48] California Air Resources Board (CARB), "2021 Annual Evaluation of Fuel Cell Electric Vehicle Deployment," (2021), https://ww2.arb.ca.gov/sites/default/files/2021-09/2021_AB-8_FINAL.pdf

[49] Jean Baronas, Belinda Chen, Elizabeth John, Mark J Wenzel, Hannon Rasool, and Drew Bohan. "Joint Agency Staff Report on Assembly Bill 8: 2021 Annual Assessment of Time and Cost Needed to Attain 100 Hydrogen Refueling Stations in California."

[50] California Low Carbon Fuel Standard Regulation, CCR 17 §

Fuels supplied to ZEPs can benefit significantly from the value of LCFS credits; these credits would be generated by the fuel supplier at the airport and could offset the cost of deploying ZEPs. Grid-average California electricity supplied in 2021, with an average of 75.9 gCO_2e/MJ, would be subsidized from $0.05 to $0.11 per kWh.[51] Renewable electricity would generate an even higher incentive, generating $0.08 to $0.16 per kWh. Hydrogen fueling could also generate significant LCFS revenues for airports, depending on the type of hydrogen supplied. The 2021 average hydrogen supplied under the LCFS with a carbon intensity of 56 gCO_2e/MJ would generate from $0.60 to $1.20/kg H_2, whereas zero-emission hydrogen produced from renewable electricity could theoretically generate $1.50 to $3.00/kg H_2, depending on the LCFS credit price. For fast charging infrastructure, the LCFS offers five years of infrastructure crediting for fast charging installations up to 2.5 MW (or 6 MW with approval), based on the difference between installed capacity, uptime, and electricity dispensed.[52] Hydrogen refueling infrastructure also qualifies for this incentive for up to 15 years, but the capacity limit of 1,200 kg/day may be too low for airport applications. As ZEP charging infrastructure is anticipated to be highly utilized, these installations may not qualify for LCFS infrastructure credits.

CONCLUSIONS

Though California's authority to regulate the emissions of aviation fuels remains uncertain, the state can still implement a variety of voluntary incentives to drive the adoption of zero-emission aviation and support the scale-up of SAF production. Currently, California's LCFS offers a valuable financial incentive for SAF production, though SAFs are not mandated. We find that expanding the obligation of the LCFS to include fuel consumed on intra-state flights would only expand the LCFS program by approximately 5%, although it wouldn't necessarily send a strong signal for SAF production. Additionally, this approach would burden other sectors with the cost of decarbonizing aviation with SAFs, instead of putting the cost of SAF deployment on the aviation sector. Despite these limitations, however, the LCFS can play a significant role in boosting the value for SAFs delivered via other, more targeted programs.

To address the larger barriers to second-generation alternative fuels, California can supplement the LCFS with policies such as upfront grants for new producers to offset capital expenses and additional production incentives. To avoid the unintended consequences of creating demand for vegetable oils in the aviation sector, this policy support can be ring-fenced for a subset of fuels with high GHG savings and with novel conversion technologies. For these pathways, the state can facilitate offtake agreements between SAF producers and customers, guaranteeing a minimum LCFS credit value for SAF producers, allowing for cost-effective SAF support. The LCFS could also provide a significant value to the deployment of ZEPs by crediting them for efficiency and incentivizing every unit of hydrogen and electricity consumed.

The abundance of short-haul, intra-state airline routes in California creates a ripe opportunity for introducing the first-generation of evolutionary ZEP designs. There are several potential ZEP corridors where the distances and passenger capacities of existing routes could be replaced by hydrogen and battery-electric planes by 2035. Pilot projects to deploy ZEPs on these routes could be implemented via grants for charging and fueling infrastructure, backstopped by the continued value for electricity and hydrogen supplied to aviation via the LCFS.

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[51] Assuming a range of $100-$200 per tonne CO_2e in the LCFS, and an EER of 2.5 for BEV ZEPs, and an EER of 1.5 for fuel cell H_2 ZEPs

[52] California Low Carbon Fuel Standard Regulation, CCR 17 §