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Priorities for government spending on net-zero aviation

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Summary

Decarbonizing international aviation could require up to $5 trillion in technology investments through 2050. As governments and the aviation industry pool resources into cleaner aircraft and fuels, questions about the split between public and private capital arise. This paper assesses how government fiscal support could address specific market shortcomings related to technological readiness and discusses why governments should consider prioritizing spending on clean aviation based on the maturity of that technology. This prioritization involves both timing and magnitude. Fiscal support is first and foremost needed for research and development (R&D) and first-movers' capital expenditure (CapEx); these should precede market subsidies that narrow cost gaps with fossil fuel alternatives. Governments should consider focusing market subsidies that help producers sell at more competitive prices on technologies that offer longer-term emission reduction potential, even if they scale more slowly than mature pathways.

Based on cost estimates from the International Civil Aviation Organization's 2050 net-zero goal feasibility study, this paper estimates the share of aviation's global decarbonization costs that should come from government spending. Under an effective financing structure that accelerates the development of advanced solutions, government spending would cover about 20% of total investments, totaling $0.8–1.4 trillion over 30 years, including $650 billion before 2035. Most spending would be in the form of market subsidies for emerging sustainable aviation fuel pathways, bringing them close to cost parity with fossil jet fuel. Nevertheless, a CapEx subsidy is a near-term priority, as advanced products may fail to reach market quickly without it, and mature technologies with limited emissions benefits may be over-subsidized in the meantime. The modelled CapEx subsidy totals $94 billion, with $81 billion needed before 2035.

As the technology pathways toward net-zero aviation become clearer, governments should consider planning spending in this area with long-term decarbonization goals in mind. Early investments in advanced technologies could not only accelerate decarbonization progress but also help maximize emissions reductions per government dollar spent.

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Introduction

In the past few years, aviation emissions have become an increasingly important topic in the discourse around climate change mitigation. Often considered a "hard to abate" sector, the aviation industry has, for many years, relied on purchasing carbon offsets from other sectors to reduce its emissions. Recently, however, as the world has made significant progress in decarbonizing other modes of transport, and as potential technologies to enable low-carbon flying have been identified, the aviation industry has finally moved towards in-sector mitigation.

An historic 2050 net-zero CO_2 goal for international aviation was announced in September 2022 at the International Civil Aviation Organization's (ICAO) 22nd Assembly. Prior to the meeting, a feasibility study of this long-term aspirational goal (LTAG) was conducted (ICAO, 2022). That LTAG report, along with decarbonization roadmaps developed by national governments, industry, and civil society, highlights the need for accelerated fuel efficiency improvements and wide adoption of renewable energy.

The decarbonization roadmaps also show that putting aviation on a 2050 net-zero pathway will require significant investment. The total cost of implementing the LTAG (on top of business-as-usual fuel efficiency gains) was estimated to be about $4.9 trillion dollars over 30 years, not counting investments for domestic aviation (the LTAG covers international aviation only). Other roadmaps have estimated around $5 trillion of capital investments, or $3.8 trillion infrastructure investment, for a net-zero compatible transition (ATAG, 2021; MPP, 2022). This 30-year investment is comparable to total global fossil fuel subsidies between 2010 and 2020, which added up to $4.4 trillion (IEA, 2020).

Who should bear the cost in this case? Past examples of clean energy transitions indicate a combination of public and private funding will be needed (Mazzucato & Semieniuk, 2018). However, government subsidies for clean technology are not the most economically efficient approach to reduce pollution (Freebairn, 2014; Hart, 2019), and a heavy use of subsidies contradicts the "polluter pays principle," which argues that pollution producers should bear the costs of mitigation (Barrett et al., 2019).

This study assesses how public funding can be most effectively used in relation to how mature a technology is. If a technology is still in its early stages, the private sector may underinvest due to the knowledge spillover effect and uncertainty of return (Popp, 2006). The spillover effect refers to how innovation by one company tends to benefit other companies without receiving proper return, leading to suboptimal levels of innovation. Instead, targeted government subsidies can spur innovation (Yong & McDonald, 2018). Facilitating innovation is especially important for the clean energy industry, because fossil fuel counterparts have higher knowledge stocks[1] and, therefore, are more profitable investments (Meckling et al., 2022). Policy interventions could also help correct other market failures associated with climate technologies, namely adoption externalities and incomplete information (Jaffe et al., 2005).

Research has highlighted the benefit of frontloading R&D subsidies and then introducing market-scaling subsidies when those technologies have reached maturity. Koseoglu et al. (2013) analyzed renewable energy policies in different countries and decomposed the factors that contribute to technology cost reduction. They found that R&D subsidies can help achieve levels of cost reduction that market subsidies cannot. Nevertheless, as the rate of learning through R&D slows for a certain technology (usually during the early commercialization stage), market subsidies are necessary to create demand pull and market stability. The authors argue that both should be stopped when a technology becomes competitive in the market without government support.

1 Defined as a cumulative function of the number of past energy patents used by each industry, adjusted for gradual decay and diffusion (Popp et al., 2010).

The authors also argue that a blanket policy emphasizing market expansion could have unintended consequences. One example, among others, is that current offshore wind and vehicle battery technologies rely heavily on rare earth materials, which has raised concerns about price and supply volatility, as well as exploitive and unsustainable mining practices (Bartekova, 2016; IEA, 2022a). These concerns are forcing producers to innovate and introduce a different, long-term solution. Subsidizing first-generation biofuels is likely to face the same set of challenges.

When a technology is fully developed but not yet at cost parity with its fossil fuel counterpart, governments can intervene with carbon pricing to close the price gap (Heggedal, 2015). This approach would be too costly for low-readiness technologies (Acemoglu et al., 2016), especially since aviation demand is less price elastic than other goods. Meanwhile, carbon pricing can scale mature technologies by aligning private benefits with social costs. Effective fiscal policy for the clean energy transition would combine carbon pricing with subsidies to help overcome market barriers and de-risk early investments (Fischer, Preonas, & Newell, 2017).

For sustainable aviation fuels (SAF), cost parity may be a stretch goal due to high costs associated with pretreatment demands for advanced pathways as well as limited feedstock availability for some biofuel pathways. In this case, market subsidies can be used to maximally reduce production costs in early years, but ultimately the cost gap needs to be closed by raising the price of fossil jet fuel through carbon pricing or taxation (IEA Bioenergy, 2020).

Therefore, we propose that governments consider using fiscal incentives to mature low-readiness technologies and then rely mostly on private investments (either voluntary or mandatory under carbon pricing) to scale deployment. However, governments should be careful not to over-subsidize mature technologies that do not offer long-term solutions. Subsidies may distort prices and favor options that have limited mitigation potential, low scalability, or both (for example crop-based biofuels). Meckling et al. (2022) argue that a certain level of “winner-picking” when funding clean energy is necessary, especially when both mature but less sustainable technologies (e.g., HEFA fuels) and emerging, high-mitigation-potential technologies (e.g., e-kerosene) are available. Too much subsidy for mature technologies could also draw “free riders” and hurt the economic efficiency of government spending.

After clarifying the role of government spending, this study examines the types of fiscal incentives applicable to clean aviation technologies (NREL, 2016; IATA, 2023). The most common incentive is a tax break. Tax subsidies can help reduce the upfront capital expenditure (CapEx), exemplified by the investment tax credits (ITC) for renewable energy in the United States. A subsidy could also enable producers to sell at a more competitive price, such as the renewable energy production tax credits (PTC), biodiesel production and blending tax credit, and the Inflation Reduction Act’s (IRA) SAF credits. The distinction between CapEx and market subsidies is important for the discussion in this paper.

A special type of market subsidy that can be used for low carbon fuels is contract for difference (CfD). This mechanism allows the government to intervene when a subsidized clean fuel price is still higher than the market rate; fuel producers return excess profit when subsidies bring the fuel price down too low. According to a previous analysis by the International Council on Clean Transportation (ICCT), CfD can be a more cost-effective policy than using subsidies alone (Pavlenko et al., 2017).

The other common cash incentive is grants, either for technology R&D or early-stage facility construction. This is tied to the spillover effect mentioned earlier, as well as the high risks associated with being a first mover. This kind of fiscal support can also take the form of rebates, but since aviation technologies are generally not going to be purchased directly by individual consumers, these are less applicable.

Government loan programs are another common financial support mechanism for emerging technologies. These can be direct loans for specific projects, lower interest rates through loan guarantees, or easier access to capital through credit enhancement. In this case, the same fiscal spending usually leverages a larger amount of private capital compared to grants and subsidies, as the support is provided through lending rather than cash incentives, unless the loan default rate is high.

Figure 1 summarizes our recommended use of these fiscal instruments at different technology readiness levels (TRL), as well as the distribution of the cost burden among government, industry, and consumers for each instrument. TRL is a commonly used metric for measuring the maturity of a technology (European Commission, 2014). Government spending discussed in this analysis differs from taxations and market mechanisms in both suitable TRL and cost distribution. The latter will be analyzed in detail in a future ICCT paper.

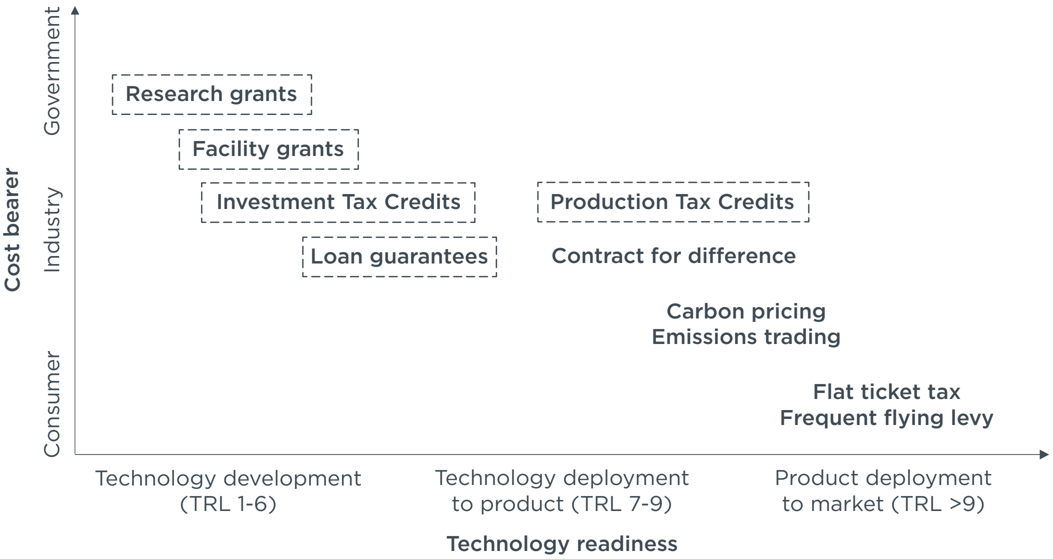

Figure 1. Typology of fiscal instruments for promoting clean aviation technologies by cost bearer and by technology readiness. Instruments analyzed in this study are outlined with dashed borders.

This study estimates the share of aviation's global decarbonization costs that must come from government spending, based on the cost assumptions used in the LTAG report. The following sections will discuss the methodology for breaking down LTAG cost estimates, the observations made from modeled results, and the implications for making fiscal policy related to aviation decarbonization.

Methodology

Breaking down LTAG cost estimates

To model the level of government spending, we first identified the emerging technologies from the LTAG report. The LTAG report included four Integrated Scenarios (numbered 0–3) to capture increasing levels of emissions reduction. This paper focuses on Integrated Scenario 3 (IS3), as it is net-zero compatible and includes the most advanced technologies.

For this study, we define emerging technologies as those with a TRL not greater than 6. A technology achieves TRL 6 when it has been demonstrated in a relevant environment (e.g., an engine running on a test bed), while TRL 7 can be reached when a system prototype has been demonstrated in an operational environment (e.g., an engine running in a car). Technologies are usually ready for commercialization when TRL 9 is reached, meaning that the actual system has been proven in operational environment. For low-carbon aviation, emerging technologies include advanced concept aircraft, advanced biofuels, and e-kerosene.

Table 1. Emerging technologies included in LTAG Integrated Scenario 3.

Decarbonization lever	Category	Aircraft type or feedstock*	TRL**
Aircraft	Advanced Concept Aircraft	Hydrogen planes	1–5
		Electric planes	1–5
Fuels	Advanced biofuel	Municipal solid waste	6
		Cellulosic energy crops	6
		Sugary/starchy crops	6
		Forest/agriculture residue	6
	E-kerosene	Point source	5–6
		Direct Air Capture	3–6

* Pathways using different feedstock may use the same processing technology, organized by feedstock here to match the level of detail in LTAG cost estimation.

** Source: European Commission, 2019; MPP, 2022

The next step is to summarize the total investments required for each emerging technology. All LTAG cost estimates are in constant 2020 dollars and are incremental to the baseline (Integrated Scenario 0), which assumes business-as-usual fuel efficiency improvements and no renewable energy deployment. The LTAG task group only quantified costs associated with international aviation (its regulatory purview). Cost estimates, therefore, include global aircraft and operations technology and clean fuel deployment on international flights only. Appendix A presents a version of the cost estimates inclusive of domestic aviation based on the global fuel volume data in the LTAG worksheet.

The LTAG task group applied high, medium, and low traffic projections to each Integrated Scenario. For this study, only the medium traffic growth case for each scenario was used, which assumes a 3.6% annual RPK growth rate between 2018 and 2050, and a COVID recovery to 2019 RPK level in 2024. Cargo operations are forecasted to grow 3.5% annually. The LTAG task group also developed high, medium, and low cases for the cost profile of each technology. We used the medium cost estimates for all technologies.

Costs of aircraft R&D and manufacturer non-recurring costs (NRC) were directly taken from the report. IS3 assumes a 2035 entry into service (EIS) year for advanced concept narrowbody aircraft, regional jets, and turboprops, and a 2050 EIS for widebody aircraft. The R&D and NRC for operational measures were only qualitatively discussed in the LTAG report. The global implementation cost by 2070 was estimated for each operational measure. We broke down the total costs into 10-year increments based on the implementation rates shown in the LTAG report and distributed the total cost per decade evenly to each year within.

In contrast to low carbon fuels, which are expected to remain more expensive than fossil jet fuel without government intervention, both aircraft technology and operational measures will help airlines reduce fuel costs; annual savings were estimated for each. While total fuel savings are higher than technology costs, we do not expect cost savings alone to incentivize the development of advanced concept aircraft. Therefore, we assume that manufacturer NRC could be balanced by fuel savings, but aircraft R&D would still require government support because of its uncertainty of return.

Costs of advanced biofuels and e-kerosene, on the other hand, were broken down into feedstocks based on our analysis of the LTAG datasheet and other data sources cited in the LTAG report. Given feedstock split each year and the total fuel volume that year, we calculated the annual fuel volume (thousand tonnes, or kt) by feedstock. We then took the unit CapEx and minimum selling price (MSP) from the ICAO SAF rule of thumb (RoT), both in dollars per liter, to calculate the total CapEx and incremental market cost for each feedstock annually. A flat $0.6 per liter price for fossil jet fuel was used in IS3 as the fuel price baseline. We also assumed that there would be 5–10 pioneer plants[2] worldwide for each pathway in the early years. They would operate for 15 years. Cost assumptions for pioneer plants from the RoT were applied to these plants.

LTAG accounts for SAF investment by fuel producers (i.e., total CapEx) and by airlines (i.e., total market cost when purchasing at MSP) separately. While the LTAG report highlights substantial overlaps between the two, it does not specify the exact amount. Therefore, we treat the market costs to airlines as the total SAF cost. However, we base our CapEx subsidy calculation on the total CapEx for fuel producers.

Because the LTAG report did not publish the feedstock split assumption between 2035 and 2050, we estimated the feedstock split in 2050 by manually adjusting the split until the weighted average fuel price and life-cycle emissions in 2050 was close to the values shown in the report. The feedstock split was then linearly interpolated between 2035 and 2050. In addition, the process described above was repeated for the less ambitious Integrated Scenario 2 for a sensitivity analysis. The values presented in this paper do not perfectly align with those published in the LTAG report because of this SAF annual breakdown process.

The ICAO SAF RoT does not provide future MSPs for different pathways. Estimation of future biofuel MSPs is complex because they depend heavily on feedstock and co-product prices; the LTAG task group, therefore, assumed constant MSPs for biofuels over time. In contrast, the MSP of e-kerosene does decrease in LTAG modeling, as the costs of renewable energy, its primary feedstock, is projected to fall over time.

Estimating government spending needed

While the LTAG report breaks down technology costs by stakeholders, the only government investment it quantified is R&D grants for advanced concept aircraft. The industry (including fuel producers, original equipment manufacturers, airlines, air navigation service providers, and airports) is assumed to incur the rest of the costs. The pass-through cost from stakeholders to consumers was not estimated, nor was any form of government incentive.

As discussed previously, we suggest that policymakers consider a financing structure where governments provide full or partial support for first movers in emerging technologies until a specific pathway reaches commercialization. Fiscal support can come in the form of grants, subsidies, or loan programs.

The first type of government spending modeled is research grants which typically precede industry investments. Government spending on aircraft R&D is estimated in the LTAG report. It equals a 5-year, forward-looking rolling average of 46% of manufacturers' NRC. The LTAG task group did not quantify clean fuel R&D funding. The report references some existing programs, including EU Horizon 2020 with €7.5 million for the Jet Fuel Screening and Optimization (JETSCREEN) project and €4 million for the cryogenic hydrogen (ENABLEH2) program. The U.S. Federal Aviation Administration also funds several programs, including the Aviation Sustainability Center (ASCENT), the Continuous Lower Emissions, Energy and Noise (CLEEN)

2 The number of pioneer plants varies by pathway because the size of a pioneer plant and the fuel volumes in early years differ.

program, and the FAST-SAF and FAST-Tech Grant Program under IRA Section 40007 (ICAO, 2022; USDOT, 2022).

For CapEx subsidies, we first assumed that government grants would cover upfront capital costs of pioneer plants for each pathway. In this case, 100% of the CapEx comes from public funding. Second, we modeled an investment tax credit (ITC) equal to 30% of n^{th} plant CapEx until the production of a specific fuel pathway reaches 3,000 kt.

Lastly, we modeled a government loan guarantee program based on a similar structure as the renewable energy loan program administered by the U.S. Department of Energy (DOE). The DOE loan program issued about $35 billion worth of guarantees between 2005 and 2011 (Alexander, 2020), which made up about 15% of total renewable energy investment in the United States in that period (Statista, 2019). The portfolio-wide default rate is about 3% to date. Therefore, we assume that for 15% of SAF investments from 2026–2032, 80% of the total CapEx would be government guaranteed. The default rate was assumed to be 5%, applied 5 years after the initial guarantees. The modeled loan guarantees do not distinguish between fuel pathways.

We modeled market subsidies using two approaches: a carbon price approach and a subsidy phase-out approach. For the carbon price approach, we applied mid- and long-term carbon price forecasts from various sources. The assumed carbon price starts at $6/tonne of CO_2 in 2020 and increases linearly to $75/tonne in 2030 (IMF, 2022). The price then climbs to $120/tonne in 2035 (EY, 2022). Finally, the carbon price reaches $230/tonne in 2040 and $280/tonne in 2050 based on modeling of a below 1.75 degree C pathway (Gambhir et al., 2019). This aligns with the $250/tonne in advanced economies in 2050 assumed in IEA net-zero modeling (IEA, 2022b). In this case, the carbon price approximates the industry's willingness to pay for mature clean technologies under the pressure of public policy. With the hypothetical carbon price in place, we modeled a market subsidy (i.e., production tax credit) that would close the remaining price gap to carbon-price-adjusted Jet A. We converted the carbon price into extra cost per liter of Jet A by multiplying the dollar per tonne of CO_2 with its full-lifecycle carbon intensity (88.5 gCO_2/MJ). Although many fuel pathways have non-zero lifecycle emissions, we assume they are exempted from carbon pricing because taxing alternative fuels in this case would lead to unnecessary subsidies.

The market subsidy would be highest at about $1.2 per liter in 2025 and gradually decrease to zero as carbon price increases (Figure 2). In reality, multiple market subsidies may exist simultaneously; a CfD may be put in place to more efficiently subsidize fuel producers as market price fluctuates.

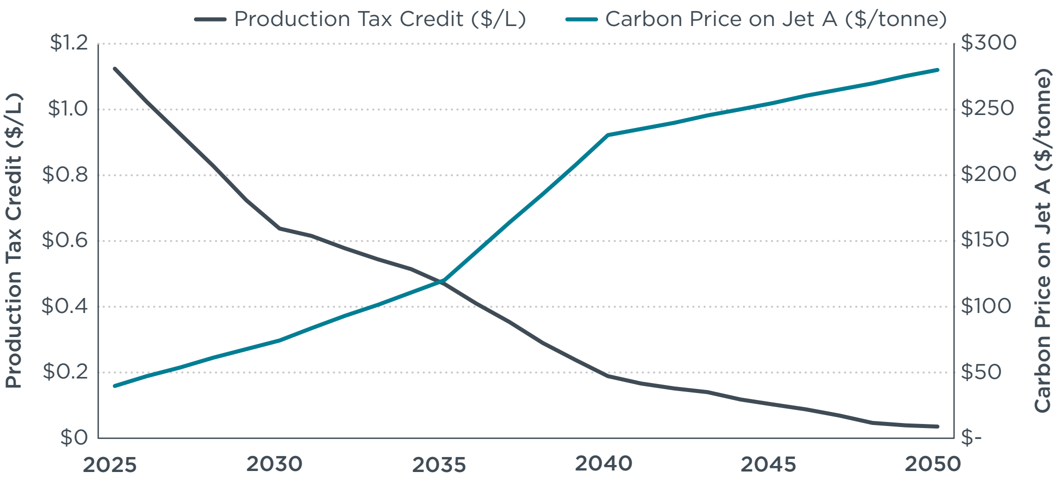

Figure 2. Modeled market subsidy and carbon price, 2025–2050.

The second approach, the subsidy phase-out approach, assumes that governments would cover all incremental fuel costs (using Jet A price as baseline) until a pathway reaches a 100-fold increase in cumulative production volume, relative to first-year production. The 100-fold increase was used because the rate of cost reduction through learning by doing slows past this point. Depending on the learning rate, the production cost of a pathway could be reduced by 30–70% after a 100-fold scale-up, but only 8–14% further until a 1,000-fold increase in cumulative capacity (IEA Bioenergy, 2020). We use production volume as a proxy for capacity here, as LTAG modeling assumes that the SAF share of product slate remains constant over time. LTAG modeling also uses a constant MSP for each pathway over time, except for e-kerosene. This is because even though economies of scale lower production costs, feedstock prices are likely to increase due to limited supply, and feedstock costs make up a large share of total operational costs for most SAF pathways (Pavlenko et al., 2019).

Once a 100-fold expansion is achieved, subsidies are gradually phased out until a 1,000-fold increase in volume is reached, in a linear fashion. Since the MSP of e-kerosene is expected to fall over time, the phase-out starts when the price reduction slows down around 2030; the subsidies completely phase out after 10 years. During and after the phase-out, the remaining cost gap between SAF and fossil jet fuel are assumed to be covered by private investments, which could be voluntary or mandatory through a carbon pricing mechanism.

Results

We first examined the total amount of investments required over 30 years for each technology (Figure 3). The biofuel pathways are categorized as either an emerging or mature pathway, based on TRL. E-kerosene would require the most funding, at $2.4 trillion for point source and direct air capture (DAC) pathways combined. Emerging biofuel pathways follow, totaling $1.3 trillion. The investments needed for mature biofuel pathways, meanwhile, would be smaller, at $368 billion. Hydrogen fuel and infrastructure are estimated to cost about $187 billion, and low carbon aviation fuel (LCAF)[3] would cost $73 billion. The lump-sum investment (without fuel savings) would be $4.9 trillion, while net cost would be $3.7 trillion (with fuel savings).

Aircraft technology and operational measures combined would cost about $640 billion, of which about $500 billion is for zero-emission planes (hydrogen and regional

3 The LTAG modeling included some fossil jet fuel produced with lower life-cycle emissions (at 80.1 gCO_2e/MJ, rather than 89 gCO_2e/MJ) through measures such as low carbon electricity use, control of methane leakages, minimization of flaring of associated gases, carbon capture of flue gases and use of low carbon hydrogen.

electric) and about $140 for operational measures. Therefore, within the LTAG cost estimation, about $4.2 trillion would be for emerging technologies, almost seven times the $700 billion estimated for mature technologies.

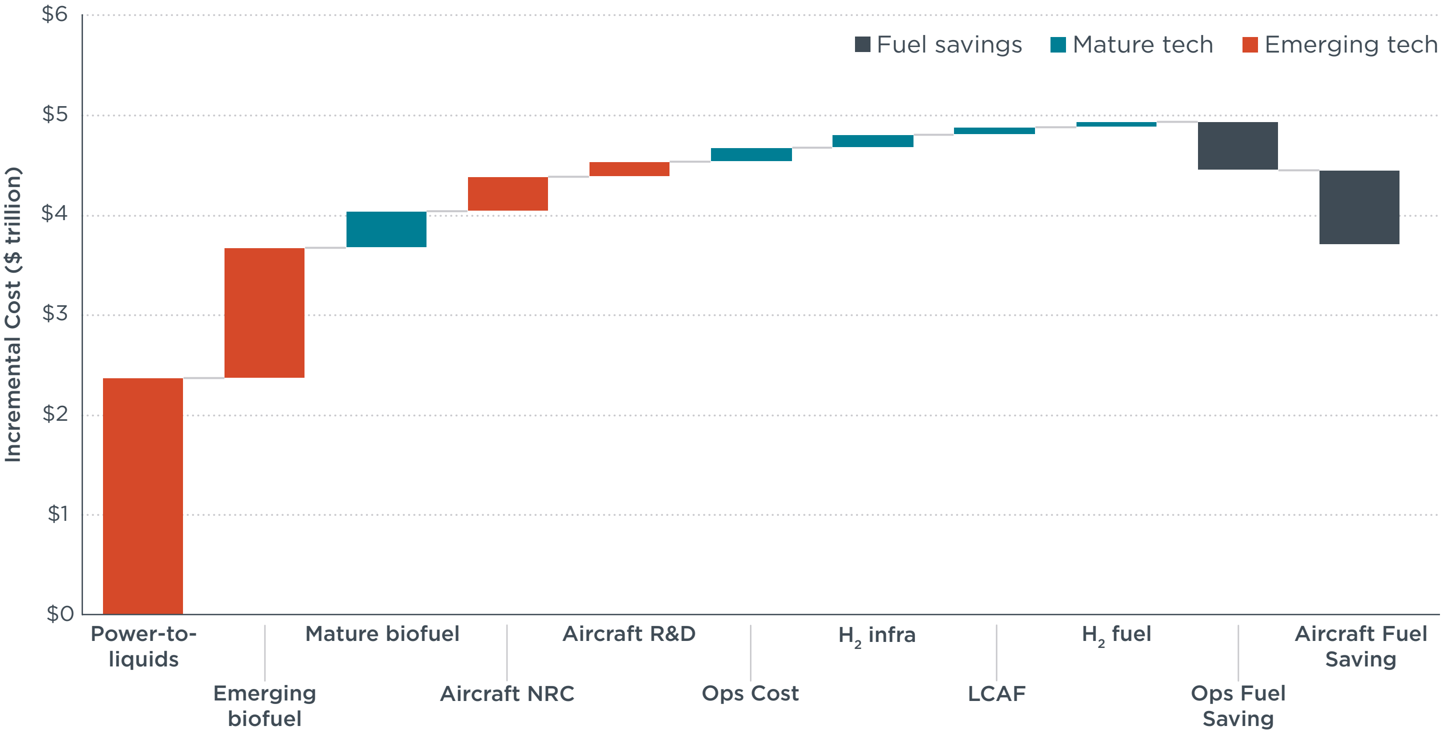

Figure 3. Total investment need (2020–2050) sorted by technology.

The investments for emerging technologies that require help from either fiscal support or policy intervention total about $4.3 trillion over 30 years, based on the assumed financing structure. Government support includes aircraft R&D grants, SAF facility grants, CapEx and market subsidies for advanced SAF, as well as potential losses from a SAF loan guarantee program.

Government spending will be key to the commercialization of various pathways in the current decade, before a gradual shift of the burden to industry starting in the 2030s (Figure 4). Modeled CapEx subsidies total about $94 billion over 30 years, while market subsidies total $590–1,100 billion depending on the modeling approach. Combined with the $152 billion for aircraft R&D, the total government spending is estimated to be $0.8–1.4 trillion, or 20% of the total technology investment. In the current decade, $350 billion in fiscal incentives are needed, while $650 billion is needed before 2035. The sensitivity of these key results to modeling assumptions are presented in Appendix B.

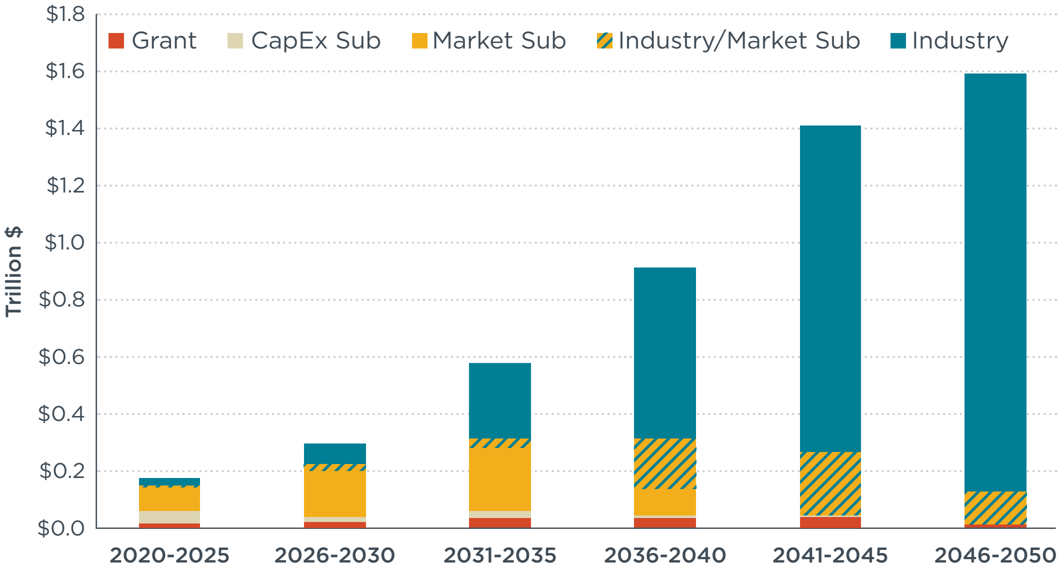

Figure 4. Annual technology investment by funding source. Dashed areas represent industry investment in the subsidy phase-out approach or government subsidies in the carbon price approach.

Using the methodology described above, we estimated the total CapEx subsidy that would likely be needed for each emerging technology (Table 2). DAC PtL (e-kerosene using carbon from DAC) would need the largest subsidy, at $19 billion or 22% of all CapEx subsidies. Residue-based fuels follow at $18 billion for the agricultural crop residue pathway and $17 billion for the forestry residue pathway. Fuels derived from sugary and starchy crops would require the smallest subsidy. Combining all pathways, governments would need to put $94 billion towards reducing the CapEx of SAF production.

Table 2. Government subsidy for SAF project CapEx by pathway through 2050, sorted from highest to lowest total subsidy.

	Government Spending (Billion $)			
Feedstock	**Pioneer Plant Grants**	**Investment Tax Credit**	**Loan Guarantees ***	**Total ****
DAC e-kerosene	2	17	2	19
Agricultural residues	6	12		18
Forestry residues	7	10		17
Municipal solid waste	5	7		12
Point source e-kerosene	0	10		10
Cellulosic energy crops	4	6		10
Hydrogen	0	6		6
Sugary crops	1	0.4		1.4
Starchy crops	1	0.3		1.3
Total	**24**	**68**	**2**	**94**

* Assumes 5% default rate of guaranteed projects regardless of fuel pathway.

** Feedstock totals exclude payments for defaulted loans.

With an assumed carbon price in place, the majority of market subsidies would be spent towards e-kerosene before 2040 (Figure 5). Of the total $1.1 trillion of market subsidies over 30 years, e-kerosene would require $790 billion, or 71%. These subsidies would consist of $523 billion for point source pathways and $267 billion for DAC pathways. Meanwhile, a small subset of the subsidy, about $18 billion, would be needed to support vegetable- or waste oil-based HEFA fuels until 2030. Among the advanced biofuel pathways, fuels derived from municipal solid waste (MSW) and energy crops (including lignocellulosic, sugary, and starchy crops) would require modest subsidization compared with e-kerosene, totaling about $132 billion. Residue-based fuels would require about half of the post-2040 subsidies as their production ramps up over time and as they maintain the highest MSP among all biogenic SAFs. The forestry residue and crop residue pathways combined would require $167 billion in market subsidies over 30 years.

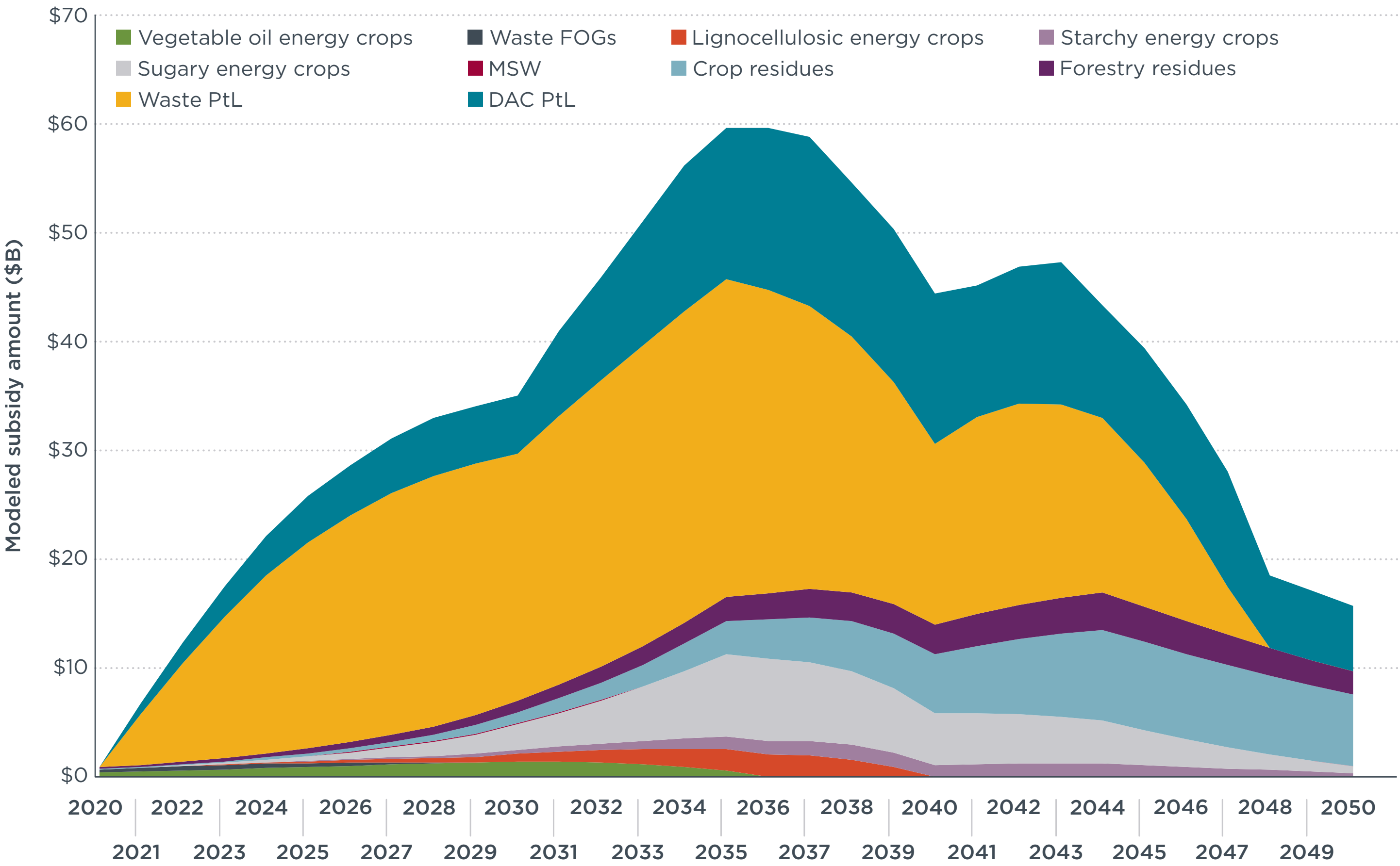

Figure 5. Modeled annual market subsidy needed by SAF pathway (carbon price approach).

Under the subsidy phase-out approach, in contrast, the government would provide a total of $589 billion in market subsidies, almost all of which would be distributed before 2040 (Figure 6). E-kerosene would receive 86% of subsidies, totaling $506 billion. Residue-based pathways would receive $27 billion in this scenario, less than in the carbon price scenario. These are the pathways with the highest MSPs and, therefore, the largest price gap with fossil jet fuel. Even with lower production costs, private investments would be needed to cover high feedstock costs. Subsidies for MSW and energy crop pathways would also be reduced to $42 billion. HEFA fuels would receive a similar amount of subsidy at $14 billion total.

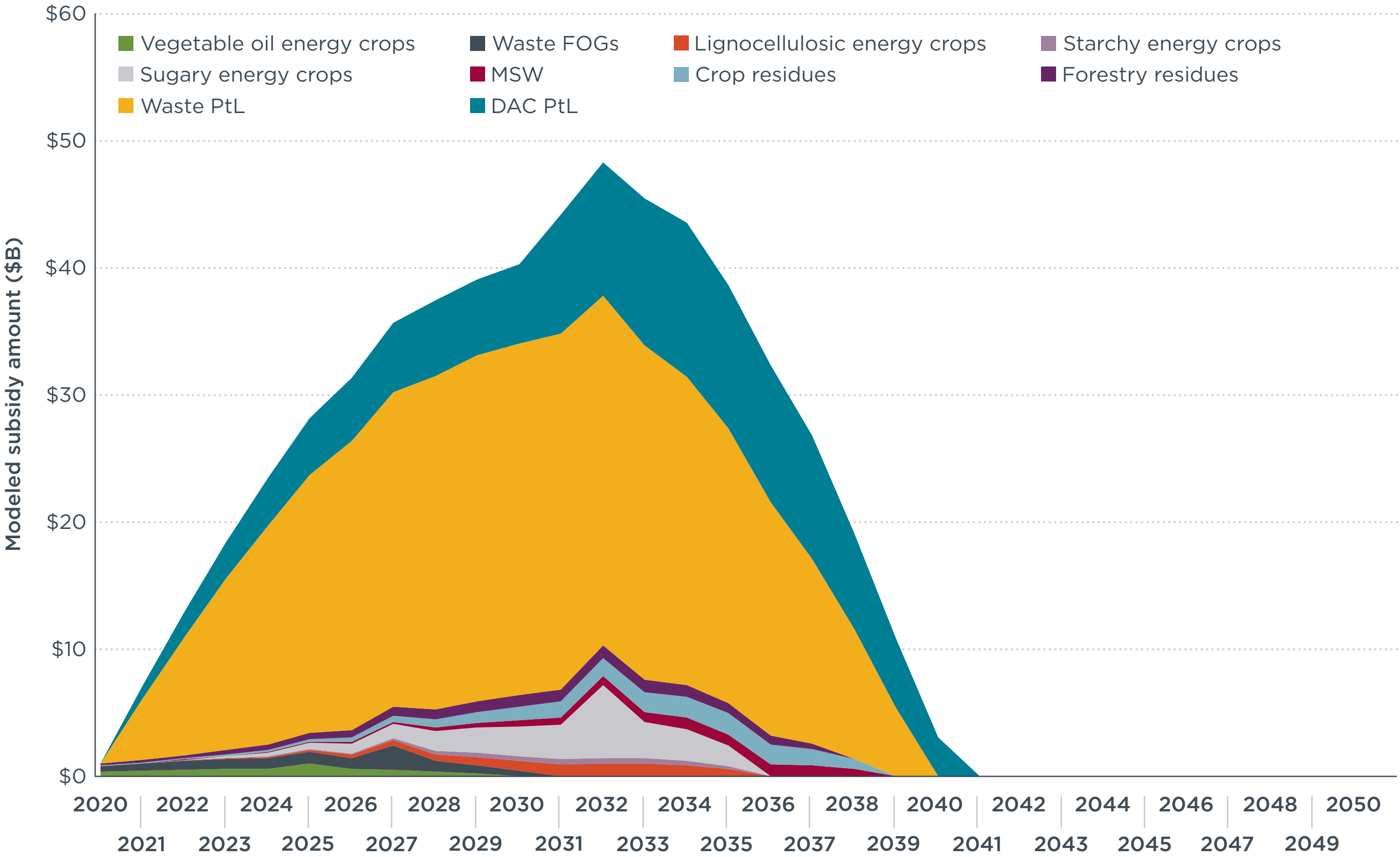

Figure 6. Modeled annual market subsidy needed by SAF pathway (subsidy phase-out approach).

Based on this analysis, Figure 7 summarizes the general financing structure envisioned for global aviation decarbonization in the form of a Sankey diagram. The left side shows investments by stakeholders; the right side shows investments by technology type as well as the total amount of $5 trillion. Fuel suppliers and airlines have significant cost overlap, as fuel producers will pass on their CapEx and OpEx to airlines with a certain profit margin.

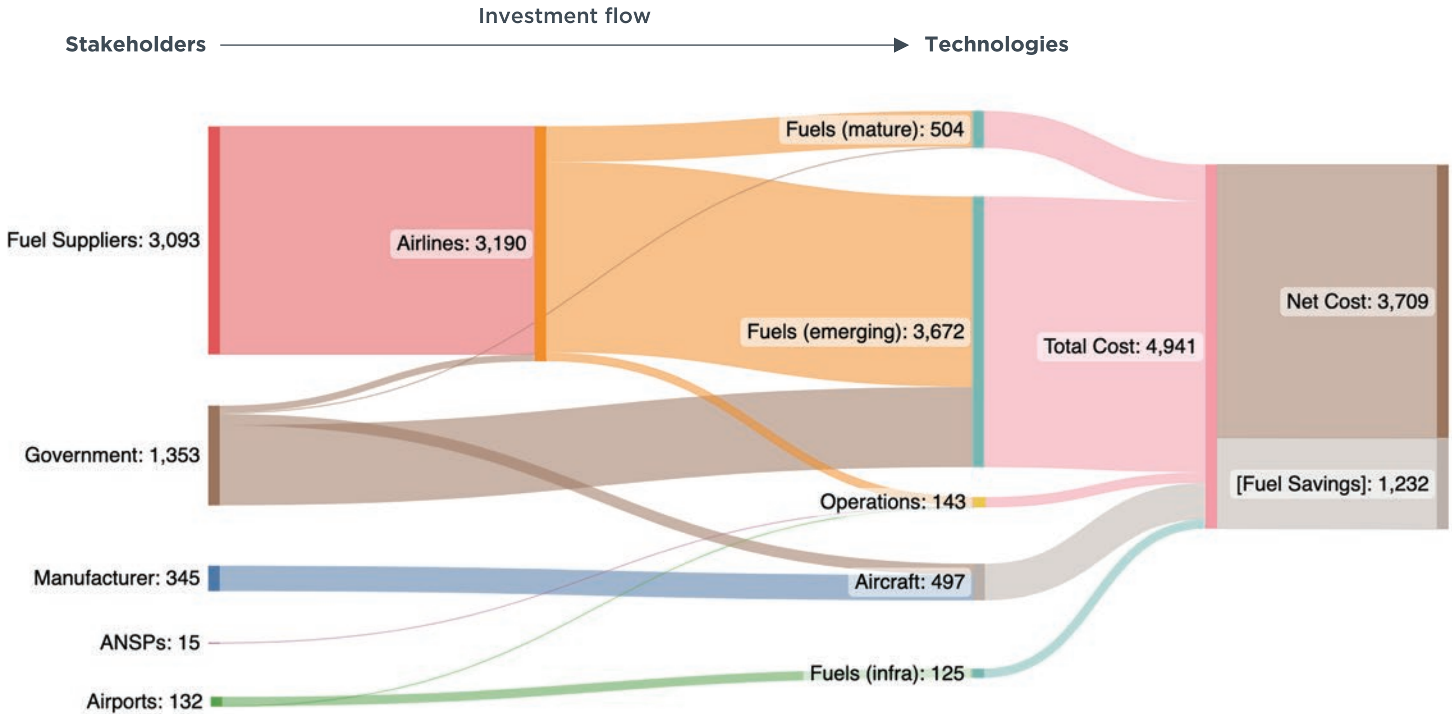

Figure 7. Modeled financing structure for decarbonizing international aviation using ICAO LTAG cost estimates (carbon price approach). All values are in million USD and represent either the amount spent by a stakeholder (on the left of the diagram) or the amount spent on a type a technology (on the right).

For the $1.4 trillion of government spending using the carbon price approach, most of it ($1.1 trillion) would be directed towards subsidizing emerging SAF pathways so that the cost gap with fossil jet fuel can be fully bridged. A smaller portion ($152 billion) would go to aircraft R&D, while $94 billion would cover some of the early-stage fuel plant CapEx. Market subsidies for mature fuel pathways would make up only about 1.3% of total spending, at $18 billion. A similar pattern can be observed when constructing the diagram using results from the subsidy phase-out approach, as presented in Appendix C.

Conclusion

Decarbonizing international aviation by midcentury requires $5 trillion in technology investments, or $4 trillion of net funding when considering cost savings from improved fuel efficiency. Fiscal support for clean energy will play a critical role in financing this transition, especially if focused on bringing low-readiness technologies to maturity.

We estimate a total of $0.8–1.4 trillion of government spending is needed between 2020 and 2050 for maturing emerging clean aviation technologies. This would make up about 20% of the $5 trillion total cost estimated by the ICAO. About $650 billion of the public investments need to happen before 2035, according to our analysis; $350 billion is needed for the current decade. To put this into perspective, global public investments in renewable energy totaled about $224 billion from 2012–2021 (IRENA, 2023). If governments can use the structure described in this paper to efficiently bring technologies to commercialization and rely more on private capital over time, the long-term fiscal burden from aviation decarbonization should be more manageable.

Within the $0.8–1.4 trillion potential spending, the CapEx subsidy takes up a small share (10%) at $94 billion, but it is crucial for de-risking pioneer plant development and attracting capital into early commercial plants. The bulk of spending ($0.6–1.1 trillion) would be for market subsidies focused on e-kerosene. The modeled subsidy amount gradually comes down starting in 2035 as private investment takes a larger share. Our modeling illustrates how ideal fiscal support would help overcome market barriers and shift cost burdens to the private sector over time. However, the exact amount of government spending would vary greatly depending on the mechanisms that incentivize or mandate the private sector to invest.

The trajectory of annual spending is closely tied to the optimistic e-kerosene timeline and the constant biofuel MSPs that LTAG modeling assumed. The actual investments into e-kerosene in the 2020s may be lower due to the slow development process, but the total amount of e-kerosene needed likely remains the same. For biofuel pathways where feedstock is neither a major cost driver nor substantially limited in supply, their MSPs are likely to decrease over time. Since this study focuses on the partitioning between public and private funding for decarbonization, rather than detailed recommendations for exact subsidy amounts, we chose not to modify the rate of deployment or the biofuel MSPs assumed in LTAG modeling. However, the scale of e-kerosene deployment will significantly affect the amount of government funding needed, as shown through the sensitivity analysis.

Case-by-case feedstock supply and fuel plant financial modeling would be needed to make specific recommendations for national or regional subsidy policies. The geographical distribution of these investments is also worth investigating, as the rate of aviation industry growth will be uneven across the world. In addition, revenues collected from an aviation carbon tax could be earmarked for subsidizing clean planes and fuels, making it revenue neutral for governments. We will discuss in-sector revenue recycling in detail in a subsequent study focusing on taxation and market mechanisms. Lastly, the interaction between fiscal support and other climate policies, such as blending mandates, will also be a key area of future research.

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Appendix A

The LTAG modeling only covered international aviation due to the ICAO's regulatory purview, which means cost estimates did not include clean fuel deployment for domestic aviation. To provide a general idea of the technology investments needed for achieving net-zero emissions globally, we scaled LTAG cost estimates based on projected global fuel volumes. The global drop-in fuel volume is approximately 1.6 times the fuel volume for international aviation only. Therefore, costs for drop-in fuels are scaled by 1.6 times (Table A1). The global hydrogen volume, however, is projected to be 3–4 times that of international aviation only, because hydrogen would mostly be deployed on short- and medium-haul flights, which are more prevalent in domestic markets. Investments in hydrogen thus also more than triple in the global scenario.

Table A1. Estimated costs by technology for international aviation only (LTAG scope) versus global aviation.

Technology	Estimated Cost (billion $)	
	LTAG	Global
E-kerosene	2,376	3,799
Emerging biofuel	1,296	2,071
Mature biofuel	368	591
Aircraft technology	498	498
Hydrogen	187	626
Operational measures	143	143
Low-carbon jet A	73	117
Total cost	4,941	7,846
Ops Fuel Savings	(493)	(493)
Aircraft Fuel Savings	(740)	(740)
Net cost	3,708	6,613

Appendix B

To capture the uncertainties in our assumptions about climate policy and clean energy deployment, we tested the sensitivity of pre-2035 government spending under the carbon price approach to four key modeling assumptions (Figure B1). The spending is most sensitive to the overall mitigation ambition. Pre-2035 fiscal support needed for the less ambitious Integrated Scenario 2 would be $130 billion lower than that for Integrated Scenario 3. Meanwhile, government spending from 2035–2050 for the two scenarios has a smaller gap, at $611 billion for IS2 and $701 billion for IS3.

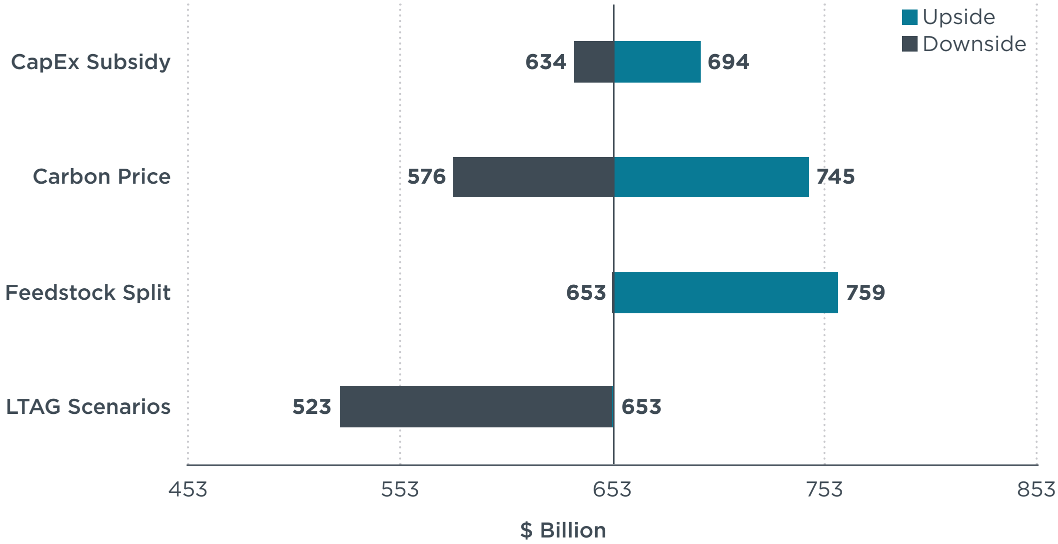

Figure B1. The sensitivity of pre-2035 government spending under the carbon price approach to four key modeling assumptions.

Spending is also sensitive to assumed feedstock split in 2035. Due to concerns about feedstock availability for HEFA pathways, the ICCT modeled a higher share of agricultural residue based fuels in 2035 in our decarbonization roadmap than the LTAG task group did in their modeling. Since residue-based fuels are more expensive, the amount of subsidy needed in early years could go up by about $100 billion.

We also varied the carbon price schedule by $50/tonne upwards and downwards to account for the uncertainty in future carbon price. Total spending could be $80 billion less or $90 billion more with these different carbon price schedules. This is a key assumption to consider when making specific policies, as the carbon price would vary from country to country depending on socio-economic dynamics and political environments.

Government spending is least sensitive to the length and magnitude of CapEx subsidies. Decreasing the investment tax credit from 30% of the total CapEx to 20% would lower government spending by about $20 billion. Increasing the penetration threshold from 3,000kt to 6,000kt would increase spending by about $40 billion.

Appendix C

Figure C1 shows the alternative financing structure diagram based on the subsidy-phase out approach. For the $836 billion of government spending using the subsidy phase-out approach, most ($576 billion) would be distributed to emerging SAF pathways. A smaller portion ($152 billion) would go to aircraft R&D, while $94 billion would be needed to cover some of the early-stage fuel plant CapEx. Market subsidies for mature fuel pathways would make up only about 1.7% of the total spending, at $14 billion. The priorities for spending do not differ from the carbon price approach.

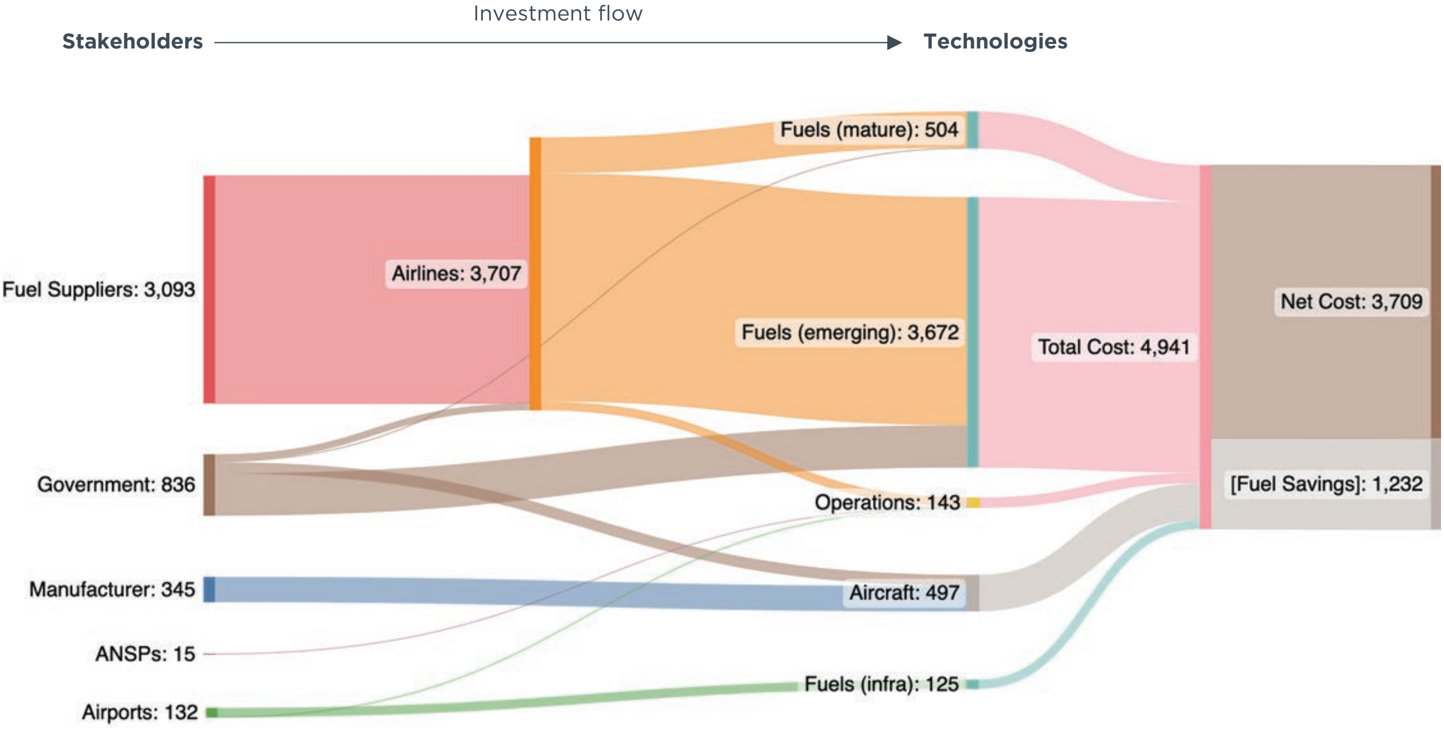

Figure C1. Modeled financing structure for decarbonizing international aviation using ICAO LTAG cost estimates (subsidy phase-out approach). All values are in million USD and represent the investments or spendings by each stakeholder.