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Turbulence Ahead: Economic Policies for Decarbonizing Aviation

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Turbulence Ahead: Economic Policies for Decarbonizing Aviation

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We study the design of climate policy for hard-to-abate sectors, focusing on global aviation. We build a spatial equilibrium model that links ticket booking data, the global airline network, and climate-regulated airlines' choices in imperfectly competitive air transport markets. We find that sustainable aviation fuel (SAF) quotas outperform carbon pricing, delivering equal emissions cuts at 46–66% of the welfare cost. Ignoring market structure understates the cost of price-based Pigouvian instruments when fuel-capital substitution is limited. SAF quotas are more robust to regulatory scope, cause less carbon leakage, and—when layered with existing carbon pricing—increase abatement while lowering welfare cost. Relying on carbon offsets risks locking in fossil jet fuel, whereas cost-effective in-sector abatement hinges on substantial SAF uptake. (JEL: Q58, H23, L93, R48, C63)

Hard-to-abate industries—steel, cement, chemicals, aluminum, shipping, and aviation—account for roughly 40% of global greenhouse gas emissions (World Economic Forum, 2024) and are thus central to achieving decarbonization objectives. These industries typically exhibit two defining characteristics. First, they depend heavily on fossil fuels, with only limited possibilities for substituting carbon-intensive inputs with clean capital, reflecting the lack of scalable clean alternatives under current technology. Second, they are highly capital-intensive, with long asset lifetimes and substantial barriers to entry, which often result in oligopolistic market structures.

How should climate policy be designed for hard-to-abate sectors? Low substitutability implies that Pigouvian price signals from market-based environmental regulation (Pigou, 1920; Baumol and Oates, 1988) induce only limited abatement, while market power allows firms to pass carbon costs on to consumers, generating welfare-reducing contractions in demand.[1] By contrast, command-and-control

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[1]For example, Fabra and Reguant (2014) find that emissions costs are passed through almost fully to

measures—such as technology or performance standards and fuel-blending quotas—can directly mandate the adoption of cleaner technologies. They are, however, often viewed as less cost-effective because they can sustain inefficiently high demand for carbon-intensive goods and services and distort relative prices of clean and dirty inputs (Fullerton and Metcalf, 2001; Holland, Hughes and Knittel, 2009). On the other hand, market-based instruments achieve least-cost abatement only under idealized conditions (Montgomery, 1972; Goulder et al., 1999; Metcalf, 2009), including perfectly competitive output markets (Buchanan, 1969; Barnett, 1980) that are not characteristic of many hard-to-abate industries.

This paper shows that, in hard-to-abate sectors, command-and-control regulation can outperform market-based instruments. Technology and clean fuel standards implicitly subsidize output; in imperfectly competitive output markets, this subsidy component mitigates pre-existing output distortions and thus yields a welfare advantage. Because carbon-intensive inputs and capital are only weakly substitutable in hard-to-abate sectors, market-based approaches—such as carbon taxes—generate relatively modest gains in abatement efficiency. The combination of market power and limited input substitutability therefore overturns conventional wisdom: the welfare cost per ton of emissions reduced is lower under command-and-control regulation than under market-based policy. It also implies that, when these conditions are ignored, the welfare cost of price-based Pigouvian instruments is systematically understated. Our findings therefore have first-order implications for climate policy design in hard-to-abate sectors.

This paper situates climate policy design in hard-to-abate sectors by examining the decarbonization of global aviation. Aviation markets are characterized by oligopolistic structures, driven by high fixed costs, regulatory barriers (e.g., airport slot allocations), and price-inelastic demand. Because aircraft require high energy-density fuels, electrification via batteries is infeasible, leaving fuel combustion as the only viable option and severely limiting input substitutability. Sustainable aviation fuels (SAF) are currently emerging as a low-carbon alternative to conventional jet fuel (CJF), but are not yet cost-competitive. Climate policy is thus essential to decarbonize aviation. As in other hard-to-abate sectors, the fundamental choice is between market-based and command-and-control regulation. Current climate policy frameworks in aviation employ both carbon pricing and SAF quotas.

We make three main contributions. First, we extend the second-best theory of instrument choice to a hard-to-abate industry, showing that both the absolute welfare costs and the relative ranking of climate policy instruments depend critically on the interaction between oligopolistic distortions and limited substitutability between fossil and non-fossil inputs. Second, we present the first economic analysis of global aviation decarbonization by assessing the welfare effects of market-based and command-and-control regulation. To this end, we develop a quantitative spatial equilibrium model that captures airlines' responses to climate regulation through input choices—between carbon-based CJF, SAF, and capital inputs—and output decisions in oligopolistic markets on a constrained global route network linking

electricity prices. More broadly, Alexeeva-Talebi (2011) and de Bruyn et al. (2015) document substantial cost pass-through in products and sectors covered by the EU Emissions Trading System (EU ETS).

origin and destination airports. Third, we provide novel quantitative evidence on the costs and feasibility of deep decarbonization in aviation by evaluating existing and planned climate policies at the global and sub-global level, including CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation) carbon offsets, the EU Emissions Trading System (EU ETS), and the EU SAF mandate.

We develop our analysis in several steps. We present a stylized theoretical model to build intuition for the economic mechanisms at play. In a symmetric Cournot oligopoly of airlines producing air transport services with fuel and capital inputs, we characterize the first-best climate policy and recover the standard result (Buchanan, 1969; Barnett, 1980) that with imperfectly competitive output markets a carbon tax alone cannot implement the social optimum. We then show that a SAF quota is equivalent to an implicit emissions tax combined with an output subsidy, thereby partially correcting the oligopoly distortion. Market power magnifies this implicit subsidy, which mitigates underproduction but also raises the cost of output distortions. With imperfect competition and low input substitutability, the subsidy's surplus effect can outweigh the carbon tax's marginal-efficiency advantage. Thus, the welfare ranking of the two instruments depends critically on market power and the degree of substitutability of inputs—core features of aviation as a hard-to-abate sector—and further varies with policy and market primitives such as quota stringency, the divergence between true emissions damages and the implicit tax, and the price difference between dirty CJF and clean SAF prior to the introduction of climate policy.

In a second step, we quantify these effects empirically. We develop a spatial network equilibrium model of the global aviation market that recovers supply and demand conditions—including market power and limited input substitutability—and allows us to characterize the responses to, and welfare effects of, market-based and command-and-control climate regulation. Full-service network carriers (FSNCs) and low-cost carriers (LCCs) compete under Cournot competition on a constrained route network shaped by the *Freedoms of the Air* and observed traffic flows. Airlines choose between CJF, SAF, and non-fuel capital, and supply differentiated air transport services across origin-destination markets. Demand is modeled at the region–airport level with substitution across airlines, routes, and an outside option. To bring the theory to the data, we calibrate the model using detailed global booking records from the pre-COVID year 2019, covering 96% of worldwide flights with airline- and route-specific passenger flows, ticket prices, carrier types, and flight distances. The resulting benchmark equilibrium replicates observed data, providing a disciplined foundation for analyzing policy counterfactuals and evaluating welfare.

Summary of Results: We find that in the aviation sector climate regulation that embeds implicit output support can outperform price-based Pigouvian instruments by several orders of magnitude. With carbon pricing—whether via CORSIA offset prices, a plain carbon tax, or the EU ETS—costs are passed through to consumers as higher ticket prices, so most CO_2 abatement arises from reduced demand for air transport services. By contrast, an SAF blending mandate implicitly subsidizes output, leading to much smaller ticket-price increases from climate regulation. Relative to carbon pricing, this helps avoid further exacerbation of the output distortions that arise from airlines' oligopolistic behavior. For emissions-reduction targets consistent with the industry's ambitious goals over the coming decades, we estimate that a global SAF quota can deliver the same emissions cuts at only 46–66% of the welfare cost of global carbon pricing. Relatedly, this suggests that ignoring market structure severely underestimates the welfare cost of price-based Pigouvian instruments when substitutability between carbon-based fuel inputs and capital is low.

The reversal in the welfare ranking between market-based and command-and-control instruments hinges critically on market power and input substitutability. We therefore take care not to overstate market power, adopting conservative assumptions in identifying airlines' markups and allowing for differential pro-competitive effects via entry and exit in response to regulation. Similarly, we show that the result remains robust when assuming fuel-efficiency improvements that markedly exceed the gains realized by the global aviation industry in the past. Carbon pricing outperforms an SAF quota only when market power is implausibly low relative to what is observed in real-world aviation markets. Moreover, the welfare-cost advantage of an SAF quota narrows only at highly stringent abatement levels (beyond those relevant for the sector's transition in the coming decades) because, at that point, either regulatory approach requires substantial uptake of clean SAF.

We apply our framework to examine climate regulation in the EU. We derive several novel insights for designing real-world aviation climate policy. First, instrument overlap—adding the EU SAF quota on top of the EU ETS—improves performance rather than undermining it. The EU SAF quota will largely render the EU ETS for aviation redundant: it both substantially increases sectoral emissions reductions and lowers the welfare cost per ton abated. Importantly, the opposite conclusion would follow under the (incorrect) assumption of perfectly competitive aviation markets.

Second, we show that an SAF quota is far less sensitive to regulatory scope, while expanding the scope of carbon pricing does not necessarily lower costs. Spatial heterogeneity in market power explains this: a narrow ETS targets routes with lower markups, whereas broader coverage shifts abatement to higher-markup routes, making carbon pricing costlier through stronger output distortions. In contrast, an SAF quota reduces emissions mainly through fuel substitution, so variation in market power matters little. Hence, under imperfect competition, scope is far more consequential for carbon pricing, and broader coverage can even raise welfare costs.

Third, we find that instrument choice, not scope, is the main driver of carbon leakage. SAF blending mandates produce leakage rates roughly half those under carbon pricing by moderating price effects and focusing abatement on fuel switching. In contrast, an explicit carbon price triggers route and carrier switching, which tends to increase leakage.

Fourth, exploring "net-zero emissions growth" for global aviation, we find that abatement costs are substantial and depend critically on instrument choice. If CORSIA offsets work as intended, costs remain moderate; if they are "hot air," costs increase sharply and emissions fall only marginally because abatement comes mainly from reduced demand. Since offset prices do not trigger SAF adoption, heavy reliance on CORSIA risks locking the sector into fossil jet fuel, whereas SAF mandates shift the fuel mix with smaller output distortions.

Our findings challenge the view that price-based Pigouvian instruments are superior to command-and-control regulation. In aviation, SAF mandates emerge as a cost-effective tool for deep decarbonization. Because many hard-to-abate industries share similar features—imperfect competition, heavy reliance on fossil fuels, and limited substitution possibilities—our results have broader relevance for instrument choice and climate-policy design in these sectors.

Related Literature: Our study relates to several literatures. First, it contributes to a literature on environmental regulation under market power. Foundational contributions show that Pigouvian taxes can reduce welfare by exacerbating pre-existing output distortions (Buchanan, 1969) and that optimal corrective taxes must internalize both the pollution externality and the market-power distortion (Barnett, 1980). By contrast, Oates and Strassmann (1984) argue that the welfare gains from Pigouvian taxation are likely to dwarf potential losses from uncorrected non-competitive behavior. Subsequent theoretical and empirical work has explored implications for policy design when output markets are imperfectly competitive, including the choice between emissions taxes and permits (Requate, 1993; Mansur, 2013), the interaction of market structure with endogenous technological change (Fischer, Parry and Pizer, 2003), the effects of incomplete regulation and carbon leakage (Fowlie, 2009), and the choice between emissions-intensity standards and Pigouvian taxes (Holland, 2009). Fowlie, Reguant and Ryan (2016) show that cap-and-trade programs that incorporate design features to mitigate the exercise of market power and emissions leakage—such as grandfathered allowance allocations that bolster production incentives—can deliver welfare gains by reducing output distortions when carbon damages are large. We provide the first comparison of Pigouvian taxes and alternative command-and-control designs for hard-to-abate sectors, i.e. when output markets are imperfectly competitive and capital-fuel substitution is limited. Moreover, we contribute the first quantitative evidence for aviation that welfare differences between these regulatory paradigms are first-order.

Second, we relate to a burgeoning literature on decarbonizing hard-to-abate sectors, including industry and transportation (Gillingham et al., 2025). Recent work has begun to focus on climate-policy design in steel, cement, and shipping (Clausing et al., 2025; Cavalett et al., 2024; Cristea et al., 2013), complementing research on the effectiveness and design of climate regulation spanning multiple energy-intensive sectors (Böhringer, Lange and Rutherford, 2014; Aldy and Pizer, 2015; Colmer et al., 2025). We contribute by providing the first analysis of climate-policy instrument choice and design in a hard-to-abate sector, which explicitly incorporates market structure. We are also the first to examine these issues for the aviation sector.

Third, we contribute to the literature on aviation climate policy. Prior work largely relies on ex-post evaluations and single-instrument or single-market analyses—for example, the emissions effects of the EU ETS (Fageda and Teixidó, 2022; Kang et al., 2022) and airport charges in Europe (Fageda and Flores-Fillol, 2025), the impacts of fuel taxes and biofuels on fuel use and emissions in the US (Fukui and

Miyoshi, 2017; Winchester et al., 2015), and a potential cash-for-clunkers program for the US airline industry (Brueckner, Kahn and Nickelsburg, 2024). On instrument choice, Jiang and Yang (2021) and Mayeres et al. (2023) find carbon taxes typically more cost-effective than SAF mandates, whereas Proost (2024) argues that SAF quotas—though less efficient—may be politically feasible and should be paired with R&D subsidies. Crucially, these comparisons abstract from market structure. Our approach also relates to foundational research on strategic behavior and market power in aviation.[2] In climate-policy contexts, Albers, Bühne and Peters (2009) and Brueckner and Zhang (2010) show how emissions taxes shape network structure and fleets. Ovaere and Proost (2025) study optimal fossil-fuel taxes and efficiency standards when producers (but not airlines) have market power. Cardoso (2023) estimate second-best carbon taxes for the oligopolistic US domestic aviation market, focusing on a short-run perspective that abstracts from fuel substitution and SAF. We contribute the first analysis of global aviation climate policy and the first welfare comparison of market- and non-market-based instruments in aviation that explicitly takes market structure into account.

Outline: Section I provides industry and climate-policy context for the global aviation. Section II develops simple theory and qualitative insights on climate policy design under imperfect competition. Section III presents our quantitative framework, with data and calibration in Section IV. Sections V–VII present our main quantitative results, covering (hypothetical) global and EU climate policies for aviation as well as the prospects for net-zero emissions growth in global aviation. Section VIII concludes. Several appendixes contain proofs, additional information on data, and additional quantitative exercises.

I. Industry and Policy Context

Before introducing our model, we outline salient features of the global aviation market that guide our modelling choices and climate policy focus. Specifically, we briefly review the challenges of decarbonizing aviation, existing climate policies, airline business models, the structure of the global aviation network, and market competition.

A. Technological Barriers to Decarbonizing Aviation

Decarbonizing aviation is particularly challenging: battery-electric propulsion is infeasible for most commercial use due to weight constraints, and hydrogen aircraft would require large-scale investments in airport infrastructure, hydrogen production, and complete fleet renewal. Although commercial aircraft achieved substantial fuel efficiency gains in the late twentieth century, progress has since plateaued, with improvements typically below 1% per five-year interval since 1985.[3]

[2] Brueckner (2001, 2002) show that airlines' pricing and network choices depend on competition, and mergers and alliances are shown to affect fares and capacity (Luttmann, 2019; Ciliberto, Murry and Tamer, 2021; Bilotkach and Hüschelrath, 2019; Bontemps, Remmy and Wei, 2022).

[3] From 1968–2014, fuel burn of new commerical jets fell by about 45%, with the steepest gains in the 1980s (Kharina, Rutherford and Zeinali, 2015; Rutherford, Zheng and Graver, 2021). Subsequent progress

As technological advances alone cannot deliver net-zero by 2050 (van der Sman et al., 2025), economic instruments and policy support for SAF adoption are considered essential.

B. Climate Policies in Aviation

Existing climate policies for aviation comprise price- or market-based regulations (e.g., carbon pricing and carbon offsets) and "command-and-control" technology policies (e.g., SAF quotas), and they differ in terms of their geographic scope.

CORSIA: GLOBAL CARBON PRICING.—The current regulatory framework governing aviation emissions remains highly fragmented. In an effort to establish a global market-based mechanism, the International Civil Aviation Organization (ICAO) introduced the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). This initiative requires airlines to offset all CO_2 emissions exceeding a specified threshold, set at 85% of 2019 emission levels. Offsets can be broadly purchased on international offset markets, effectively without restrictions on eligibility.[4]

EU EMISSIONS TRADING.—The European Emissions Trading System (EU ETS) is a cap-and-trade mechanism that endogenously determines the price of emission allowances. As the cap will decrease over time, prices are expected to rise. As part of the EU Green Deal and the Fit for 55 initiative, revised regulations for the EU ETS in the aviation sector have been introduced (European Commission, 2024). The free allocation of emission certificates will be fully phased out by 2026 (i.e., moving to full auctioning). Until 2027, the EU ETS will apply only to flights within the EU, as well as those between the EU and Switzerland or the United Kingdom. After this period, flights to third countries that do not implement CORSIA will also be included in the EU ETS. The effectiveness of CORSIA will be assessed to determine the future geographical scope of the EU ETS in aviation beyond 2027.

EU SAF QUOTA.—As part of the EU Green Deal, the EU seeks to promote the adoption of SAF through the ReFuelEU initiative (European Council, 2023). The new regulations impose obligations on fuel suppliers, aircraft operators, and airports to facilitate the transition to SAF. Fuel suppliers must provide SAF blends at EU airports in accordance with quota requirements, while aircraft operators are required to refuel only the necessary fuel for their flights to prevent tankering. Additionally, airports must ensure their infrastructure is compatible with SAF. The SAF mandate, which took effect in 2025, applies to all flights departing from EU airports, regardless of their destination. The required SAF share increases progressively over time, from

slowed due to longer aircraft certification cycles (Rutherford and Zheng, 2023; International Energy Agency, 2023) and diminishing returns after major technology steps (McKinsey & Company, 2023; Transport& Environment, 2023). Operational changes, such as denser seating and higher load factors, reduced fuel per revenue passenger kilometer by about 2.5% annually (International Energy Agency, 2020), but long aircraft lifespans (25–30 years; EASA 2025) and slows fleet turnover limit fleet-wide gains. With 4% annual fleet replacement, even a 1% improvement every five years lifts fleet efficiency by only 0.008% per year.

[4] CORSIA is structured into three phases: a pilot phase (2021–2023), a first phase (2024–2026), and a second phase (2027–2035). Participation becomes mandatory for certain countries from the second phase onward. However, the scheme lacks an enforcement mechanism to sanction non-compliant airlines, raising concerns about its overall effectiveness. The measure undergoes a review every three years, with a comprehensive evaluation in 2032 determining whether CORSIA will be extended or discontinued.

2% in 2025 to 20% in 2035 and 70% in 2050.

Notably, emissions from SAF are exempt from both CORSIA and the EU ETS.

C. Airline Types

Since the 1970s, liberalization and deregulation in the aviation sector (Sun et al., 2024) have given rise to distinct airline business models, primarily low-cost carriers (LCCs) and full-service network carriers (FSNCs). LCCs typically operate point-to-point routes, minimizing network complexity by focusing on direct connections. By avoiding reliance on major hub airports with higher landing fees they achieve lower operational cost. Compared to hub-and-spoke airlines, their disadvantage is limited connectivity and lower capacity utilization. Examples of LCCs include Ryanair, easyJet, and Wizz Air. Some LCCs, such as AirAsia X, have attempted to expand into the long-haul market, though with limited success.

In contrast, FSNCs use hub-and-spoke networks, consolidating demand from smaller regional airports through feeder flights to major hubs. This structure enhances aircraft utilization, increases departure frequencies, and broadens destination options. Notable FSNCs include Air France, Lufthansa, and United Airlines, which operate mega-hub airports such as Paris-Charles de Gaulle, Frankfurt/Main, and Chicago O'Hare, respectively. Within this category, certain airlines, often referred to as "hourglass network carriers", specialize in connecting hub airports beyond their home countries via a stopover at their central hub. Examples include Qatar Airways, Emirates, and Turkish Airlines, which leverage their geographic positioning to facilitate seamless transfers. In both FSNC subcategories, the hub-based model enables a wide range of origin-destination pairs with a single layover.

D. Freedoms of the Air and Mode of Competition

The *Freedoms of the Air*, established under the Chicago Convention of 1944, continue to shape modern airline networks. These freedoms define various rights, such as flying over a foreign country without landing, refueling in a foreign country, operating flights between one's home country and another, and transporting passengers between two foreign countries with a stopover in the airline's home country. While some freedoms have been granted through multi- or bilateral agreements, others impose significant restrictions on airline network design.[5] Beyond regulatory constraints, airport capacity limits (e.g., slot allocations at congested airports) and high fixed entry cost restrict the number of airlines per route and thus per market. Empirical studies indicate that conduct is closer to Cournot (quantity) than Bertrand (price).[6]

[5] Appendix B provides further detail, in particular on the *Freedoms of the Air* used to identify the effective air transport network in this study.

[6] Brander and Zhang (1990) find no evidence of Bertrand behavior on duopoly routes, and Oum, Zhang and Zhang (1993) similarly conclude that Cournot competition better fits observed conduct. Accordingly, Cournot is widely used in theory (Verhoef, 2010; Barbot et al., 2014) and in simulations/empirical work (Nava et al., 2018; Basso, 2008; Chin and Zhang, 2013; Gong et al., 2023). Some studies assume Bertrand mainly for tractability (Betancourt et al., 2022; Bilotkach, 2005; Bontemps, Remmy and Wei, 2022; Bontemps, Gualdani and Remmy, 2023).

II. Theory and Qualitative Results

We begin with a simple conceptual model to clarify the mechanisms and welfare effects of market-based versus command-and-control regulation of aviation emissions under airline market power. The insights carry over to the quantitative-empirical framework we develop in Section III to evaluate current and prospective climate policies in global aviation in Sections V–VII.

A. Basic setup

BASIC SETUP.—Consider a symmetric oligopoly with N airlines, each producing homogeneous air transport services q_i using a constant-returns-to-scale production technology $f_i(k_i, z_i; \sigma_i)$ combining inputs of capital (k_i) and aviation fuels (z_i). σ_i measures the elasticity of substitution between inputs. Airlines take input prices for capital (p_k) and aviation fuel (p_z) as given. Aviation fuel can be sourced from clean fuel (c_i) and dirty fuel (d_i). Both fuels are supplied perfectly elastically at respective prices (net of regulatory charges) p_c and p_d. Throughout, we assume that prior to regulation $p_c > p_d$ (or, equivalently, $\Delta p \equiv p_c - p_d > 0$).[7] From the perspective of airlines (i.e., aircraft engine technology), the clean and dirty fuels are perfect substitutes: $z_i = c_i + d_i$. Only dirty fuels cause CO_2 emissions. θ_i measures the emissions per quantity of dirty fuel.

Under symmetry, $q_i = q$ and total output in the market is given by $Q = Nq$. Consumers derive utility $U(Q)$ from air travel services, where $U' := \partial U/\partial Q > 0$ and $U'' := \partial^2 U/\partial Q^2 < 0$. $P(Q) = U'(Q)$ gives the inverse demand function. Each airline chooses output q taking other airlines' choices as given. The standard Cournot pricing condition, indicating that price exceeds marginal cost is given by:

$$U'(Q)[1 - \Lambda(N)] = \frac{dC(q; \mathbf{p})}{dq}\,. \tag{1}$$

where $C(q; \mathbf{p}) = \min_{k,z} p_k k + p_z z + F$ subject to $f(k, z; \sigma)$ represents the airline's cost function minimizing the cost of producing output q using technology $f(k, z; \sigma)$ given input prices $\mathbf{p} = (p_k, p_z)$. $F > 0$ represent the fixed cost of a firm. $\Lambda(N) \geq 0$ represents the markup over marginal cost which we assume to decline with entry or the number of airlines, i.e. $\partial\Lambda(N)/\partial N < 0$. Hence, the greater the number of airlines, the smaller is the ability of each airline to charge a price above marginal cost. We also assume $\Lambda(N) \to 0$ as $N \to \infty$.

Airlines freely enter and exit the market such that each airline's profits π are driven to zero, i.e. the number of firms in equilibrium is determined by equalizing markup revenues with fixed cost:

$$\pi = U'(Nq)q - C(q; \mathbf{p}) = 0 \quad \Longleftrightarrow \quad P(Q)\Lambda(N)q = F\,. \tag{2}$$

Each airline chooses the cost-minimizing combination of capital and aviation

[7]If clean aviation fuels were already cheaper ($\Delta p < 0$), the problem of climate regulation becomes trivial, i.e. climate regulation is obsolete and the airlines are already decarbonized.

fuels, such that the marginal rate of technical substitution is equal to ratio of input prices (assuming interior solutions):

$$\frac{\partial f}{\partial k} p_z = \frac{\partial f}{\partial z} p_k \,. \tag{3}$$

Emissions from dirty aviation fuels are subject to climate regulation $\mathbf{\Theta}$, which can take various forms. A carbon tax t increases the user price of the dirty fuel in proportion to its carbon content: $\hat{p}_d = p_d + t\theta$, where p_d denotes the producer price of the dirty fuel. Airlines will always choose the cheaper fuel. Consequently, the price of the perfect-substitute aviation fuels under a carbon tax is given by:

$$p_z = \min(p_c, p_d + t\theta)\,, \tag{4a}$$

where p_c denotes the producer price of the clean fuel. If clean aviation fuels are initially more expensive (i.e., $\Delta p > 0$) and the carbon tax is insufficient to offset this price difference, then the price of aviation fuels will be equal to the tax-inclusive price of the dirty fuel: $p_z = \hat{p} < p_c$. The price of the clean fuel always serves as an upper limit (i.e., a "backstop") for the price of aviation fuels. Hence, if the carbon tax is large enough to offset the price difference, then $p_z = p_c < \hat{p}_d$.

A clean fuel quota mandates that a minimum share, γ, must come from clean fuels:

$$\frac{c}{z} \geq \gamma\,. \tag{4b}$$

With a binding clean fuel quota, the effective user price of the perfect-substitute aviation fuel is thus given by:

$$p_z = p_c\gamma + p_d(1-\gamma) \tag{4c}$$

COMPETITIVE EQUILIBRIUM.—Given climate policy choices $\mathbf{\Theta} = \{t, \gamma\}$, exogenous input prices $\mathbf{p}$ and producer prices of fuels p_c and p_z, the equilibrium is characterized by airlines' output choices q, the number of airlines N, the fuel-capital ratio (i.e., the fuel efficiency) z/k, and the price of the perfect-substitute aviation fuel p_z, as determined by the system of equations in (1), (3), and either (4a) or (4c) for the case of a carbon tax or clean fuel quota, respectively.

THE POLICY PROBLEM.—The regulator seeks to maximize welfare by choosing a climate policy $\mathbf{\Theta}$, where welfare equals economic surplus net of the environmental cost from CO_2 emissions.

$$W = \underbrace{\int_0^{Q=Nq} U'(y)dy}_{\text{Benefits}} \quad - \quad \underbrace{C(q;\mathbf{p})N - \delta\theta dN}_{\substack{\text{Social cost}\\ \text{=Private cost + Environmental cost}}} \quad . \tag{5}$$

Marginal damages resulting from emissions are assumed to be constant and denoted by δ, implying that total environmental cost due to emissions are $\delta\theta dN$.[8]

B. Optimal and constrained-optimal climate policy

FIRST-BEST POLICY.—As a benchmark, we describe the first-best policy, i.e. how a regulatory authority would approach the problem of regulating aviation emissions without restrictions on the policy instruments available.

PROPOSITION 1: *In an economy characterized by a symmetric oligopoly in the output market, endogenous markups $\Lambda(N)$, constant-returns-to-scale production technology, and a carbon externality ($\delta > 0$), the social optimum can be achieved through a policy consisting of: (i) an output subsidy $s^* = U'(Q)\Lambda(N) > 0$ and (ii) a carbon tax $t^* = \delta$. The optimal policy instruments are independent of each other and the optimal carbon tax does not depend on the equilibrium number of firms N.*

Proof: See Appendix A.1. □

Proposition 1 implies that a carbon tax alone cannot implement the social optimum in the presence of market power. It also implies that under perfect competition (i.e., $\Lambda(N) = 0$), the optimal policy consist of pricing carbon at the rate $t^* = \delta$, which is the standard Pigouvian pricing rule internalizing a carbon externality.

To compute the optimal output subsidy s^*, the regulator must know the equilibrium mapping $N(Q)$, which in principle requires detailed information on cost and demand functions as well as the market entry condition—making implementation in practice challenging. This motivates our focus on feasible climate policy rules, such as the SAF quota, and the extent to which they can approximate first-best outcomes under realistic informational constraints. Crucially, the information challenge applies to the output subsidy, not the carbon tax: the latter corrects a well-defined marginal externality and depends only on the marginal environmental damage δ, an economic primitive rather than a market outcome. Thus, even if s^* cannot be implemented precisely, the carbon tax $t^* = \delta$ remains a relatively robust policy component. We therefore turn to the analysis of constrained-optimal climate policy, assuming the regulator can employ either a carbon tax or an SAF quota, but not an independent output subsidy.

CONSTRAINED-OPTIMAL CLIMATE POLICY: CARBON TAXES VS. SAF QUOTA.—To understand the different abatement channels incentivized by a carbon tax and an SAF quota, we begin by showing that an SAF quota can be equivalently conceived as the combined effect of two price-based instruments: an input tax and an output subsidy. Importantly, this perspective is useful to understand the relative abatement efficiency implications of the two instruments for climate policy.

PROPOSITION 2: *A clean fuel quota $c/z \geq \gamma$, which mandates that a minimum share $\gamma \in (0, 1)$ of aviation fuels must come from clean fuels, is equivalent to a*

[8]Marginal damages, δ, can be interpreted as the social cost of carbon. Alternatively, if climate policy targets the quantity of emissions, $\overline{E}$, such as through an emissions trading system, δ represents the (shadow) price of carbon corresponding to the market-clearing constraint $\delta\theta dN \leq \overline{E}$.

blended emissions policy involving both (i) an implicit emissions tax $\hat{t}(\gamma, \Delta p, \theta)$ and an (ii) implicit per-unit output subsidy $\hat{s}(\gamma, \Delta p, MRT_{q,z})$. The magnitudes of these implicit policy instruments are determined by the quota stringency γ, the pre-policy price difference between clean and dirty fuels Δp, the carbon intensity of dirty fuel θ, and the marginal rate of transformation $MRT_{q,z}$ between output and fuel inputs.

Proof: See Appendix A.2. □

By showing that a clean fuel quota can be equivalently represented by a tax-subsidy policy combination $(\hat{t}, \hat{s})$, Proposition 2 provides valuable economic intuition to elucidate the mechanisms by which a clean fuel quota influences airline behavior, and, ultimately, the efficiency of climate regulation. Appendix A.2 shows that the implicit emissions tax under the quota is given by:

$$(6) \qquad \hat{t} = \underbrace{\gamma(p_c - p_d)}_{\substack{= \text{Extra cost per unit of dirty} \\ \text{fuel induced by the quota}}} \times \Big[\underbrace{\theta(1-\gamma)}_{\substack{= \text{Emissions per unit of} \\ \text{total fuel } z \text{ given quota fuel blend} \\ \text{and carbon intensity of dirty fuels}}} \Big]^{-1}.$$

Equation (6) reveals the hidden penalty per unit of CO_2 that airlines face as a result of being required to blend expensive clean fuel with cheaper dirty fuel, even without a direct carbon price. The term $\gamma(p_c - p_d)$ is the extra fuel cost per unit dirty fuel that the quota imposes. This can be interpreted as the implicit tax the airline pays on each unit of dirty fuel, simply to comply with the quota. The term $\theta(1-\gamma)$ translates the extra cost per unit dirty fuel into an implicit cost per unit emissions.[9] Importantly, however, the quota creates an implicit price on emissions that applies to the average, but not the marginal, emissions resulting from expanding output. Under a quota, increasing output expands the allowable emissions proportionally, so airlines can emit more as they produce more, without facing an additional cost for marginal emissions. In contrast, a carbon tax charges for every additional unit of emissions, ensuring that both average and marginal emissions are equally penalized.

Appendix A.2 shows that implicit per-unit output subsidy under the quota is given by:

$$(7) \qquad \hat{s} = \underbrace{\gamma(p_c - p_d)}_{\substack{= \text{Implicit subsidy per unit} \\ \text{of fuel } z \text{ used}}} \times \underbrace{\frac{dz}{dq}}_{\substack{= \text{Inverse of marginal rate of} \\ \text{transformation btw output and fuels } (\text{MRT}_{z,q})}}.$$

Equation (7) reveals that the implicit per-unit output subsidy generated by the clean fuel quota is equivalent to an implicit subsidy on each marginal unit of fuel consumed—arising from the absence of a marginal emissions penalty—multiplied by the marginal fuel requirement associated with additional output. Under the quota, the marginal cost of fuel at the mandated blend is lower at the margin

[9] Only dirty fuel produces emissions (at rate θ per unit), and the quota limits dirty fuel to a share $1-\gamma$ of total fuel use. So, for every unit of emissions, the firm must have used $1/\theta$ units of dirty fuel, and only $1-\gamma$ share of total fuel can be dirty.

than it would be under a carbon tax. This lack of a penalty for increased fuel use (since expanding output allows for greater emissions and increased consumption of conventional fuel under the quota) effectively functions as a subsidy for each additional unit of fuel consumed, as captured by the first term, $\gamma(p_c - p_d)$. The second term, $\frac{dz}{dq}$, represents the additional amount of fuel required to produce one more unit of output, reflecting the firm's technology and chosen input mix. This decomposition underscores that the quota effectively subsidizes output expansion by subsidizing marginal fuel use, despite the higher average fuel cost due to the required blend.

Proposition 2 also shows that the magnitude of the $\hat{t}$ and $\hat{s}$ depend on the quota stringency γ, the pre-policy fuel price difference Δp, and on technology $\mathrm{MRT}_{q,z}$. For a given quota and price wedge, the output subsidy is larger the more fuel is required at the margin to produce extra output (i.e., when $dz/df = 1/f_e = 1/\mathrm{MRT}_{q,z}$ is large). Thus, $\partial\hat{s}/\partial(dz/df) > 0$. If the production technology is fuel-intensive at the margin (i.e., output is highly dependent on additional fuel or, equivalently, the production technology exhibits a small fuel-efficiency at the margin), the implicit output subsidy under the quota is large. If fuel can easily be substituted with capital or if marginal returns to fuel are diminishing rapidly, the subsidy is smaller. The stricter the clean fuel quota (the higher γ), the more expensive it becomes to use dirty fuel, so the implicit subsidy for expanding output $\hat{s}$ is larger ($\partial\hat{s}/\partial\gamma > 0$), reflecting the greater benefit from being allowed to increase cheaper, dirty fuel use as output rises. The greater the cost gap between clean and dirty fuels, the more costly it is for the firm to comply with the clean fuel quota, which translates into a higher implicit tax on emissions (via the quota's effect on fuel cost, so $\partial\hat{t}/\partial\Delta p > 0$) and a correspondingly larger implicit subsidy for expanding output (since the quota relaxes for each additional unit produced, so $\partial\hat{s}/\partial\Delta p > 0$). For a given quota and fuel price difference, if dirty fuel is more carbon-intensive (high θ), the quota spreads the price wedge over more emissions per unit fuel, so the implicit tax per unit CO_2 is lower ($\partial\hat{t}/\partial\theta < 0$). The output subsidy $\hat{s}$ is a function of fuel use, not emissions, so θ does not enter directly ($\partial\hat{s}/\partial\theta = 0$).[10]

Given that a clean fuel quota implicitly entails both an emissions tax and an output subsidy, it is natural to ask whether such a quota can achieve the social optimum—an outcome that, as demonstrated by Proposition 1, is implemented through the appropriate combination of these two instruments. This, however, is not the case.

COROLLARY 1: *When airlines possess market power ($\Lambda(N) > 0$) and demand is elastic ($U'(Q) > 0$), neither a carbon tax nor a clean aviation fuel quota is sufficient to implement the social optimum.*

By Proposition 1, the social optimum under market power requires both a carbon tax at the marginal damage ($t^* = \delta$) and an output subsidy reflecting the markup ($s^* = U'(Q)\Lambda(N)$). For example, a carbon tax set below the Pigouvian level would

[10]If γ is set to target a specific emissions intensity or emissions level (so γ is a function of θ), then θ does indirectly affect $\hat{s}$.

raise output by reducing marginal cost just enough to offset the Cournot distortion. This would, however, under-internalize the carbon externality as marginal damages are not priced correctly: the firm equates private marginal cost with a tax below the true social cost, implying that emissions would be too high. By Proposition 2, a clean fuel quota delivers both an implicit emissions tax and an implicit output subsidy, but these are both jointly determined by the quota share γ and thus cannot be set independently by a regulator. Therefore, neither a carbon tax nor a clean fuel quota alone can generally implement the social optimum when market power is present.[11,12]

We now compare a carbon tax and an SAF quota under real-world conditions, imperfect competition in the aviation sector and price-elastic demand for air transport services.

PROPOSITION 3: *Compare a clean aviation fuel quota with stringency γ to a carbon tax set at the equivalent implicit emissions price $\hat{t}(\gamma)$. The quota yields higher welfare if, for additional output induced by the implicit output subsidy $\hat{s}(\gamma)$, the combined surplus from market power correction and inframarginal resource (fuel and capital) cost savings exceeds the unpriced marginal external cost of additional emissions.*

Proof: See Appendix A.3. □

Appendix A.3 derives an intuitive condition for when the clean aviation fuel quota dominates the equivalent implicit carbon tax:

$$\underbrace{(\delta - \hat{t})\,\frac{de}{dq}}_{\substack{\text{Unpriced marginal harm} \\ \text{per unit of output}}} \quad < \quad \underbrace{Q_{\text{tax}}(1-\Lambda_{\text{tax}})\,|U''|}_{\substack{\text{Inframarginal resource} \\ \text{cost savings}}} \; + \; \underbrace{\frac{\Lambda_{\text{tax}}\,MC_{\text{tax}}}{1-\Lambda_{\text{tax}}}}_{\substack{\text{Gains from correcting} \\ \text{market power distortion}}} \quad . \tag{8}$$

The LHS measures unpriced marginal harm from expanding output under the quota. If $\delta > \hat{t}$, society values a ton of CO_2 more than the implicit charge the quota induces. So every extra ton emitted because the quota nudges output up is undercharged by $(\delta - \hat{t})$, capturing the social cost per extra unit of output that is not internalized by the quota's implicit emissions pricing.

[11]This is reminiscent of the well-known Tinbergen (1952) rule, known as the targeting principle, which states that for effective economic policy, each distortion should be addressed with a separate policy instrument.

[12]For completeness, we present results for several important special cases arising from our model that nest well-established findings in the literature. First, under perfect competition, a Pigouvian tax implements the social optimum (Pigou, 1920; Baumol and Oates, 1988). This follows from Proposition 1, as $t^* = \delta$ and $s^* = 0$ when $\Lambda(N) = 0$. Second, still under perfect competition, for any given emissions target, a carbon tax achieves the minimum possible social cost; that is, a clean fuel quota cannot outperform an explicit, price-based carbon instrument (Goulder, Parry and Burtraw, 1997; Holland, Hughes and Knittel, 2009). This also follows from Proposition 1, since $s^* = 0$ when $\Lambda(N) = 0$, in contrast to Proposition 2, which indicates that under a binding clean fuel quota, $\hat{s}(\gamma) > 0$. Third, in the case of perfect competition with perfectly elastic demand ($U'(Q) = 0$), an appropriately set clean fuel quota can achieve the same emissions reduction at the same social cost as a Pigouvian tax (see Holland (2012) for the case of an emissions intensity standard and Abrell, Rausch and Streitberger (2019) for the case of a clean energy standard). Intuitively, with inelastic demand, output is fixed regardless of policy, so the only margin of adjustment is emissions per unit of output. It is therefore possible to choose a quota stringency γ^* that implements an implicit emissions tax equal to the Pigouvian rate—specifically, by setting $\hat{t}(\gamma^*) = \gamma^*(p_c - p_d)/(\theta(1-\gamma^*)) = \delta$.

The RHS expresses the gains produced by the quota (relative to the tax) from reducing marginal cost due to the implicit output subsidy. It comprises two terms. First, the $Q_{\text{tax}}(1-\Lambda_{\text{tax}})\,|U''|$ represents inframarginal resource (capital and fuel) cost savings. A larger output under tax makes the quota's per-unit marginal cost cut ($\hat{s}$) generate a bigger inframarginal gain $Q_{\text{tax}}\hat{s}$. $(1-\Lambda_{\text{tax}})|U''|$ captures sensitivity with respect to quantity. Since $\Delta Q \approx \hat{s}/[(1-\Lambda)|U''|]$, steeper inverse demand (larger $|U''|$) and lower markups (larger $1-\Lambda$) dampen ΔQ and thus the induced emissions. Second, the term $\Lambda_{\text{tax}}MC_{\text{tax}}$ represents the gain from easing underproduction associated with the market power wedge, i.e. the gap between price and MC at the tax outcome.

If $\delta > \hat{t}$, the quota beats the equivalent tax whenever the unpriced marginal harm per unit of output (LHS) are small relative to the gains (RHS).[13] This is likely to be the case under the following conditions. First, a higher quota stringency γ raises the implicit price $\hat{t}(\gamma) = \gamma\Delta p/\theta(1-\gamma)$ and lowers marginal emissions intensity $\frac{de}{dq} = \theta(1-\gamma)\,\frac{dz}{dq}$ (both directly via the clean share and indirectly as a higher user fuel price reduces dz/dq). Together this shrinks the LHS $(\delta-\hat{t})\,\frac{de}{dq}$, making condition (8) easier to satisfy. Second, a larger fuel price gap $\Delta p = p_c - p_d$ increases $\hat{t}(\gamma)$ and tends to reduce dz/dq. Both effects lower $(\delta-\hat{t})\,\frac{de}{dq}$, again working in favor of the quota. Third, when producing extra output needs little additional fuel (more fuel-efficient technology, low dz/dq), $\frac{de}{dq} = \theta(1-\gamma)\,dz/dq$ is small. The unpriced marginal harm per unit of output $(\delta-\hat{t})\,\frac{de}{dq}$ is therefore small, so the quota's gains can outweigh the damage term more easily. Fourth, greater market power and steeper demand (large Λ_{tax} and $|U''|$ increases the RHS: more market power creates more underproduction to correct, and steeper inverse demand attenuates the quantity response (so emissions only moderately increase), both pushing the threshold up.

In real-world climate policy, policymakers often seek the least-cost way to meet a given emissions target. Next, we thus adopt a cost-effectiveness perspective and identify the conditions under which an SAF quota achieves the target at lower welfare cost than a carbon tax.

PROPOSITION 4: *At a fixed level of carbon emissions, a clean fuel aviation quota yields higher welfare than a carbon tax when output markets are imperfectly competitive ($\Lambda > 0$), provided that airlines' fuel requirement satisfies $\frac{dz}{dq} > \bar{z}_q$, that is, if substitution between capital and aviation fuels is limited. Greater market power amplifies the welfare advantage of the quota and implies that a smaller fuel requirement (higher input substitutability) suffices.*

Proof: See Appendix A.4. □

At fixed emissions, any quota advantage can only come from its implicit output subsidy through correcting underproduction. But when substitution is large (the marginal fuel need is small), the implicit output subsidy is small. Thus, any such

[13]If $\delta \leq \hat{t}$, the inequality holds trivially and the quota strictly dominates the equivalent, implicit carbon tax. Intuitively, because the tax is too stringent relative to true damages, raising emissions (and output) under the quota actually moves the economy toward the social optimum.

advantage vanishes as the output subsidy gets small, while leaving the tax's cost edge intact. By contrast, the tax works on the marginal emissions channel and achieves any target intensity at (weakly) lower unit cost than a blend of aviation fuels; that cost gap does not go away with substitutability.

In general, the SAF quota dominates once market power (Λ) is large enough, but only if the fuel requirement (dz/dq) is large enough (or, equivalently, substitution between capital and fuels is limited) to provide a sufficiently strong output subsidy. To build intuition, it is useful to distinguish the following cases. First, in a near-perfect competition market (low Λ), the carbon tax already induces near-optimal output. A quota introduces an implicit output subsidy that is unnecessary unless the firm's marginal fuel requirement is very large (i.e., high $\frac{dz}{dq}$). Only then does the quota offset its cost from distorted input choices by significantly boosting output. Similarly, when Λ and $\frac{dz}{dq}$ are small, output is already efficient under the tax, and the quota's implicit subsidy is weak. The quota adds distortion without delivering offsetting gains, and thus the tax dominates. Second, at the other extreme, when market power distortions are strong, output is underprovided. Even a modest output correction, enabled by a small but nonzero $\hat{s}$, can produce significant welfare gains. Hence, the quota dominates even when $\frac{dz}{dq}$ is not especially large. Third, the most favorable case for the quota is when strong market power creates a large wedge between marginal cost and price, and a high marginal fuel need magnifies the quota's implicit output subsidy. The quota then delivers substantial output correction and dominates strongly.

While the theoretical results build intuition, it is ultimately an empirical question to what extent imperfect competition and limited input substitutability in real-world air transport service markets shapes the choice and design of climate-policy instruments. We therefore turn to quantitative, empirical analysis.

III. Quantitative Framework

To study the welfare effects of current and prospective climate policies in the aviation sector, we develop a quantitative-empirical spatial equilibrium model of the global aviation market that captures the market effects of airlines' responses to regional and global climate regulation. While the quantitative model encapsulates key features of the simple model in Section II, it incorporates additional key features of the global aviation market, as summarized in Section I. These include varying geographic scope of climate policy instruments, airlines with major differences in network operation (FSNCs vs. LCCs), constraints on the effective global air traffic network imposed by the *Freedoms of the Air*, endogenous fuel efficiency improvements, and price-elastic supply of aviation fuels. Airlines compete in markets defined by origin and destination airports (including direct and indirect routes). Given climate regulation, airlines choose output and inputs of (clean and dirty) aviation fuels and capital, maximizing their profits under static Cournot competition.

A. *Air Transport Network*

AIRPORTS, MARKETS, AND REGIONS.—Airports, indexed by $i, j \in \mathcal{I}$, represent the nodes in a global air traffic network. δ_{ij} denotes the geographical distance between two airports. The network of airports is given and fixed. Each i is either a hub airport or a non-hub airport.[14] Markets for air transportation services, indexed by $m(i,j) \in \mathcal{M}$, are defined by unique pairs (i,j), indicating the origin i and destination j airports, respectively. A market can contain both direct and indirect routes from i to j, where an indirect route involves travel with one or more intermediate stops.[15] $\mathcal{A}_{m(i,j)}$ denotes the set of all direct and indirect routes contained in market $m(i,j)$. While airports and connections between them completely define the network, a second geographical layer defines regions (countries or country aggregates), indexed by $r \in \mathcal{R}$. The set $\mathcal{B}_{r(i)}$ identifies the airports i located in region r. The set $\mathcal{G}_{r(m)}$ denotes the markets m that serve region r either as origin or destination.

MODEL OF NETWORK OPERATION.—Airlines, indexed by $f \in \mathcal{F}$, operate within the network according to two distinct models that characterize the global aviation industry: the hub-and-spoke model, typically used by FSNCs, and the point-to-point model, commonly associated with LCCs. Hub-and-spoke airlines transport passengers from their departure airport to a central hub, where they are then connected to their final destination alongside passengers originating from various locations but traveling to the same endpoint. In contrast, point-to-point airlines do not rely on centralized hubs; instead, they operate direct flights between non-hub airports. Furthermore, each airline is assigned a home region, reflecting real-world international aviation constraints governed by the *Freedoms of the Air*.

EFFECTIVE NETWORK.—The freedoms of the air, together with the airline types and airlines' home regions limit the air traffic network. The effective network identifies the routes between airports i and j contained in market m and operated by airline f:

$$\mathbb{J}_{ijmf} = \begin{cases} 1, & \text{if } ijmf \in \mathcal{A}_{m(i,j)} \times \mathcal{M}_{m(f)} \\ 0, & \text{otherwise}, \end{cases} \tag{9}$$

where $\mathcal{M}_{mf} \subset \mathcal{M}$ denotes all markets m served by airline f. Through mapping f to routes ij, $\mathbb{J}_{ijmf}$ implicitly defines the network type, indexed by $n \in \mathcal{N} = \{\text{FSNC}, \text{LCC}\}$ and the home region of an airline f. For instance, the route topology of an airline operating a hub-and-spoke network with a hub in a specific region differs from that of other hub-and-spoke airlines based in different regions, as well as from point-to-point airlines within the same region. In our quantitative model, we employ $\mathbb{J}_{ijmf}$ to capture the network's sparsity, ensuring consistency with observed air traffic flows at the route, market, and airline-type levels while adhering to regulatory constraints imposed by the *Freedoms of the Air*.

[14] The definition of hub airports is not necessarily driven by the airport being the main hub of an airline but rather covers main connecting airports. Non-hub airports in contrast are smaller airports with few to no connecting passengers.

[15] For example, all trips departing from Frankfurt and ending in Tokyo are included in a given market, regardless of whether they are direct flights or have one or multiple stopovers.

B. Preferences and Endowments

Each region is inhabited by a continuum of households that all have constant elasticity of substitution (CES) preferences (or the economy admits a representative household with preferences) over air travel T_r and an outside good Y_r:

$$(10) \qquad U_r(T_r, Y_r) = \left[\nu \underbrace{\left(\sum_{m \in \mathcal{G}_{r(m)}} \alpha_{mr} \, Q_m^{\frac{\gamma-1}{\gamma}} \right)^{\frac{\gamma}{\gamma-1}}}_{\substack{=:T_r \\ \text{Utility from air transport services}}}{}^{\frac{\epsilon-1}{\epsilon}} + (1-\nu)\, Y_r^{\frac{\epsilon-1}{\epsilon}} \right]^{\frac{\epsilon}{\epsilon-1}} .$$

ν is a distribution parameter. ϵ is the elasticity of substitution between air travel T_r and the outside good Y_r. Utility from air travel T_r is a nested CES utility composite that aggregates air transport services provided by airlines at multiple layers, reflecting households' preferences for departure and destination locations, routes, and additional attributes of air travel (such as time, stopovers, product quality).

On the first layer, households trade-off air transportation Q_m among markets for which the origin or destination airports are geographically located in region r, i.e. $m \in \mathcal{G}_{r(m)}$, according to observed travel patterns, captured by the distribution parameters α_{mr}, with $\sum_{m \in \mathcal{G}_{r(m)}} \alpha_{mr} = 1$, and an elasticity of substitution parameter γ. On the second layer, transportation services in a given market (i.e., with identical origin and destination locations) Q_{mf} are differentiated between services provided by FSNCs and LCCs from different regions:

$$(11) \qquad Q_m = \left(\sum_f \beta_{mf} Q_{mf}^{\frac{\rho-1}{\rho}} \right)^{\frac{\rho}{\rho-1}} .$$

$\beta_{mf} \in (0,1)$, with $\sum_f \beta_{mf} = 1$, are distribution parameters. ρ is the elasticity of substitution. Our formulation reflects that hub-and-spoke airlines tend to have higher ticket prices, shorter travel time (e.g., more direct routes and fewer stopovers), and higher quality (e.g., better on-board and on-ground services) as compared to point-to-point airlines.[16]

On the third layer, air transport services Q_s^{mf} offered by a continuum of symmetric

[16] Given that our quantitative model covers the global air transport services market and resolves representative airlines by region and network type, we abstain from modelling time and other product attributes (such as quality) explicitly. At such a level of aggregation, it is hardly possible to define and measure reasonable empirical counterparts for these attributes. However, by calibrating the model to actual ticket prices and observed air travel flows, our model implicitly captures households' preferences for these product attributes. Performing counterfactual analyses then implies that *changes* in the underlying attributes based on this benchmark do not influence the behaviour of households.

airlines s of type f in a given market m enter utility:[17]

$$Q_{mf} = \left[\int_{s=0}^{N_{mf}} \left(Q_s^{mf}\right)^{\delta} ds \right]^{\frac{1}{\delta}} , \qquad 0 < \delta \leq 1 \,. \tag{12}$$

s indexes the different airlines supplying market segment *mf*.[18] N_{mf} is the endogenous number of airlines s in market segment *mf*. $\sigma = 1/(1-\delta)$ is the elasticity of substitution among the transportation services supplied by airlines in that market segment. Transportation services supplied in a given market segment are perfect substitutes if $\delta = 1$, implying $\sigma \to \infty$. $\delta < 1$ represents the case of imperfect substitutes.

Households in region r are endowed with shares of global capital $\overline{K}_r$ and global resources used to produce aviation fuels $\overline{R}_{rt}$, $t \in \mathcal{T} = \{CJF, SAF\}$ which are supplied inelastically. Households maximize utility subject to the income constraint:

$$P_r^U \, U_r \leq M_r = P^K \overline{K}_r + P_t^R \sum_t \overline{R}_{rt} + \Upsilon_r \,. \tag{13}$$

P_r^U, P^K, and P_t^R are the prices of regional utility, global capital and global fuel-specific resources, respectively. Υ_r is income received from rebates of carbon tax revenues. Both initial endowments and tax redistribution can differ across regions. Pre-policy income in region is given by $\overline{M}_r$.

C. Airlines

BEHAVIOR, PROFITS, ENDOGENOUS MARKUPS.—Airlines supply air transport services under imperfect competition, taking the effective air transport network $\mathcal{J}_{ijmf}$ on which they operate as given. We assume Cournot competition, with airlines symmetric in technology within each market segment. Each airline s produces a differentiated variety, maximizes profits by choosing output while taking the outputs of rivals as given. Cournot profits Π_s^{mf} for airline s in market segment *mf* are defined as:

$$\Pi_s^{mf} = P_s^{mf}(Q_s^{mf}, \overline{Q}_{-s}^{mf}) Q_s^{mf} - C_s^{mf} Q_s^{mf} - F_s^{mf} \,. \tag{14}$$

$\overline{Q}_{-s}^{mf}$ denotes the vector of outputs of all competitors of airline s. P_s^{mf} is the inverse demand function for airline s. C_s^{mf} and F_s^{mf} represent marginal and fixed cost of airline s, respectively.

Profit maximization yields the familiar markup-pricing formula, equating marginal

[17]For example, households can choose among several hub-and-spoke airlines (full-service network carriers) to fly from an origin airport in Europe to a destination airport in the US.

[18]We define market segment *mf* as that segment of market m that is served by the representative airline f. For notational simplicity, we suppress *mf* when indexing airlines across market segments, i.e. $s(mf) \triangleq s$.

revenue and marginal cost for airline s in market segment mf:

$$P_s^{mf}\left(1-\Lambda_s^{mf}\right)=C_s^{mf}\,. \tag{15}$$

Markups are endogenous and depend inversely on an airline's perceived own-price elasticity of demand η_s^{mf}. η_s^{mf} itself depends on equilibrium quantities (the airline's market share ψ_s^{mf} and price elasticity of demand in the market segment ε^{mf}) so that markups in market segment mf are given by (see Appendix C for the derivation):

$$\Lambda_s^{mf}=\frac{1}{\eta_s^{mf}(\psi_s^{mf},\varepsilon^{mf})}=\frac{1}{\varepsilon^{mf}N_{mf}}\,. \tag{16}$$

The second equality follows from the assumption of symmetry: within a market segment, each airline's market share is simply $\psi_s^{mf}=1/N_{mf}$, $\forall s$. Given the nested utility specification in (10)–(12), ε^{mf} is determined by taste parameters and expenditure shares which effectively capture how much consumers depend on air transport services offered in a given market segment.[19]

Airlines can freely enter and exit any market segment, so the number of active airlines N_{mf} in equilibrium is pinned down by the zero-profit condition in that segment:

$$N_{mf}\,\Pi^{mf}=0 \quad ,\forall\ m,f\,. \tag{17}$$

TECHNOLOGY.—Airlines produce transportation services by combining inputs of aviation fuels F_{mf} and capital K_{mf}^Q according to the CES form (dropping the s subscript for clarity):

$$Q^{mf}=G(K_{mf}^Q,F_{mf})=\left[\mu\left(F_{mf}\right)^{\frac{\chi-1}{\chi}}+(1-\mu)\left(K_{mf}^Q\right)^{\frac{\chi-1}{\chi}}\right]^{\frac{\chi}{\chi-1}}\,. \tag{18}$$

$\mu\in(0,1)$ is a distribution parameter. The elasticity of substitution between fuel and capital inputs is χ. Capital employed comprises all non-fuel-related (variable) inputs used by an airline in the provision of air transport services. The main component of physical capital is the aircraft itself. We call an aircraft fuel-saving (fuel-using) when fuel and capital are gross substitutes with $\chi>1$ (gross complements with $\chi<1$). When $\chi=0$, the fuel efficiency, defined by the ratio of capital to fuel inputs, is fixed and solely determined by μ. When $\chi>0$, fuel efficiency is endogenous.

The fuel input to transport passengers from an origin to a destination airport in

[19] Intuitively, a smaller market share (larger number of firms) implies a lower markup. In the limit, as $\psi\to 0$ ($N\to\infty$), $\Lambda_s=0$, corresponding to perfect competition. At the other extreme, $\psi=1$ ($N=1$) denotes monopoly, with the markup fully determined by the inverse of the price elasticity of demand. For a given market share, markups decrease with higher demand elasticity. Demand is more elastic when consumers view services across market segments as closer substitutes (high ρ) or when substitution to the outside good is easier (high γ). Conversely, markups increase with the expenditure share of consumers on air transport services in a given market segment: the larger this share, the more dependent consumers are on travel in that segment, and the less willing they are to substitute away, which makes demand relatively inelastic. Appendix C derives an explicit expression for ε^{mf}.

market m reflects the non-substitutable, distance- and efficiency-adjusted quantity of fuel burned $\hat{F}_{ijf}$ on each of the individual legs of the possible route in this market (taking into account the network and type of network operation adopted by airline f):

$$F_{mf} = \sum_{ij \in \mathbb{J}_{ijmf}} \delta_{ij} \theta \hat{F}_{ijf} \,. \tag{19}$$

θ is a fuel efficiency parameter (for example, the quantity of aviation fuel needed to transport Q_{mf} passengers over a unit distance). The Leontief technology implies that in equilibrium and for any pair of airports ij which is part of an active route served by airline f, $F_{mf} = \delta_{ij}\theta\hat{F}_{ijf} = \delta_{i'j'}\theta\hat{F}_{i'j'f}$, $\forall i, i', j, j' \in \mathbb{J}_{ijmf}$.

$\hat{F}_{ijf}$ is the quantity of aviation fuels required by airline f to transport passengers between airports ij. From an engineering perspective of fueling an aircraft (and ignoring CO_2 emissions), conventional jet fuel and SAF are perfect substitutes[20], implying that:

$$\hat{F}_{ijf} = \hat{F}^{\text{CJF}}_{ijf} + \hat{F}^{\text{SAF}}_{ijf} \quad ,\forall\ i, j, f \,. \tag{20}$$

As the choice among aviation fuel types is not restricted by airline technology, equilibrium fuel choice depends solely on relative prices.

Airlines are assumed to have identical technologies for producing air transportation services. Profit maximization subject to technology, represented by (18)–(20), implicitly defines marginal cost:[21]

$$C^{mf}_{s}(\underbrace{P^K, P^F_{mf}[P^t_{ij}]}_{\substack{\text{Capital and}\\ \text{fuel cost}}};\ \underbrace{\mu, \chi, \theta}_{\substack{\text{Technology}\\ \text{parameters}}}\ ,\ \underbrace{\delta_{ij}, \mathbb{J}_{ijmf}}_{\substack{\text{Distance and}\\ \text{network}}}) \,. \tag{21}$$

Airlines pay P^t_{ij} per unit of aviation fuel t, which includes regulatory charges due to climate regulation. Indexing the user price of aviation fuels by ij, enables representing airport-, route- and region-specific climate regulation. Given (19) and (20), the fuel cost to produce air transport services offered in market segment mf depend on fuel prices, the distance between two airports δ_{ij}, the feasible network $\mathbb{J}_{ijmf}$, and fuel efficiency θ:

$$P^F_{mf}[P^t_{ij}] = \theta \sum_{ij \in \mathbb{J}_{ijmf}} \left(\delta_{ij} \min\{P^{\text{CJF}}_{ij}, P^{\text{SAF}}_{ij}\} \right) \,. \tag{22}$$

[20]The current generation of bio-based SAF achieves the same performance as fossil aviation fuels and thus complies with the international standards that define approved aviation fuels (IATA, 2024c), including key dimensions such as energy density, thermal oxidation stability, the freezing point, and the flash point (the lowest temperature at which a volatile liquid can vaporize to form an ignitable mixture in air).

[21]Formally, $C^{mf}(\cdot)$ is the unit expenditure function which solves:

$$C^{mf}(P^K, P^F_{mf}; \mu, \chi, \theta, \delta_{ij}, \mathbb{J}_{ijmf}) = \min_{K^Q_{mf}, F_{mf}: G \geq 1} P^K K^Q_{mf} + P^F_{mf} F_{mf} \,.$$

CO$_2$ EMISSIONS.—The carbon emissions E_{mf} caused by air travel in market segment mf are the by-product of the combustion of aviation fuels and are given by:

$$E_{mf} = \sum_{ij \in \mathbb{J}_{ijmf}} \sum_{t} \zeta_t \hat{F}^t_{ijf}. \tag{23}$$

ζ_t is the carbon intensity of aviation fuel of type t (measured in tons of CO_2 per litre of fuel burned). In general, $\zeta_{\text{CJF}} > \zeta_{\text{SAF}}$; depending on whether life-cycle emissions are taken into account or not $\zeta_{\text{SAF}} > 0$ or $\zeta_{\text{SAF}} = 0$.

D. *Closing the Model: Supply of Aviation Fuels and Outside Good*

Aviation fuels F_t are produced at the global level combining a fuel-specific resource factor R^F_t, that is supplied inelastically, and capital K^F_t in a CES formulation:

$$F_t = \left[\omega \left(R^F_t \right)^{\frac{\varphi-1}{\varphi}} + (1-\omega) \left(K^F_t \right)^{\frac{\varphi-1}{\varphi}} \right]^{\frac{\varphi}{\varphi-1}}. \tag{24}$$

$\omega \in (0,1)$ is a distribution parameter. The elasticity of substitution between resource and capital inputs is φ.[22]

Macro production combines inputs of capital K^Y and fuels F^Y_t (not used to produce air transport services) according to a Cobb-Douglas formulation:

$$Y = \left(K^Y \right)^{1-\sum_t \xi_t} \prod_t \left(F^Y_t \right)^{\xi_t}. \tag{25}$$

$\xi_t \in (0,1)$, with $\sum_t \xi_t < 1$, is the value share of fuel t in macro production. Including the production of the macro good serves two purposes. First, it enables representing substitution possibilities for air travel as in (10) (i.e., holding the level of aggregate consumption fixed, consumers may switch to the outside good if the relative price of air transport services increases). Second, we can evaluate climate policies for decarbonizing aviation in terms of aggregate-economy welfare effects.

E. *Climate Policies*

The two major market-based policy approaches to regulate carbon emissions from the combustion of aviation fuels in global aviation are (1) carbon pricing, either introduced as a carbon tax (in the case of CORSIA) or through emissions trading (in the case of the EU ETS), and (2) an SAF quota.

Both instruments drive a regulatory wedge between the producer price per unit

[22] Modelling fuel production according to (24), and assuming that the resource-specific factor is in fixed supply, provides a convenient way of formulating price-elastic fuel supply in general equilibrium. The elasticity of substitution φ can be calibrated to imply an own-price elasticity of fuel supply ι^{fuel}_t according to: $\varphi_t = \iota^{\text{fuel}}_t \omega/(1-\omega)$. Rents from fuel production accrue to owners of capital and resources.

of aviation fuel type t, P_t^F, and the corresponding user price P_{ij}^t:

(26) $$P_{ij}^t = P_t^F + \mathbf{\Theta}_{tij}\,.$$

The regulatory wedge $\mathbf{\Theta}_{tij}$ is indexed by tij to allow the scope of regulation to vary depending on airport, route, and region.

CARBON TAX.—If the regulator imposes a price τ_{ij} on CO_2 emissions from aviation fuels burned on flights between airports ij, the regulatory wedge is:

(27) $$\mathbf{\Theta}_{tij} = \tau_{ij}\,\zeta_t\,.$$

SAF QUOTA.—An SAF quota mandates that a given, minimum share $\kappa \in [0,1]$ of total fuel burned needs to come from SAF:

(28) $$\underbrace{\sum_{ij\in\mathbb{S}_{ij}}\sum_f \hat{F}_{ijf}^{\mathrm{SAF}}}_{\substack{=\text{ Supply of}\\ \text{SAF credits}}} \geq \kappa \underbrace{\sum_t \sum_{ij\in\mathbb{S}_{ij}}\sum_f \hat{F}_{ijf}^t}_{\substack{=\text{ Demand for}\\ \text{SAF credits}}} \qquad (P^{\mathbb{S}_{ij}})\,.$$

$\mathbb{S}_{ij}$ denotes the regulatory scope of the SAF policy and can be chosen to represent alternative policy designs of an SAF quota. For example, if the SAF quota applies to flights originating from airports located in a given region r and regardless of airline type f (as is the case under EU regulation where the SAF quota applies to all flights originating from EU airports), $\mathbb{S}_{ij} = 1$ if $ij \in \mathcal{B}_{r(i)}$, $\forall f$, and 0 otherwise. Alternatively, $\mathbb{S}_{ij}$ can also represent a destination- or route-specific SAF quota.

As shown in Proposition 2 an SAF quota translates into an implicit output subsidy and an implicit carbon tax. A SAF quota is by construction revenue-neutral (within the regulated entity): expenses for the implicit subsidies are fully financed through implicit input taxes. The output subsidy on each liter of SAF equals the shadow price of the quota$P^{\mathbb{S}_{ij}}$. The implicit per-unit tax on CJF is: $\kappa P^{\mathbb{S}}$. The regulatory wedge for aviation fuel type t is then given by:

(29) $$\mathbf{\Theta}_{tij} = (\kappa - \mathbb{I})P^{\mathbb{S}_{ij}}\,,$$

where $\mathbb{I}$ is an indicator variable which equals 0 if the aviation fuel is fossil-based ($t = CJF$) and 1 otherwise. Since $\kappa \in [0,1]$, it is straightforward to see that an SAF quota effectively subsidizes SAF consumption and taxes CJF consumption.

F. Markets and Pricing

To define the decentralized equilibrium, we need additional market clearing conditions. The producer price of aviation fuels of type t (net of climate regulatory charges), P_t^F, clears the respective global market:

(30) $$F_t = F_t^Y + \sum_{mf} \hat{F}_{mf}^t\,.$$

The price of capital clears the market for capital:

$$\sum_r \overline{K}_r = K^Y + \sum_{mf} K^Q_{mf} + \sum_t K^F_t \,. \tag{31}$$

The price of the fuel-specific resource factor P^R_t, used to produce fossil-based and SAF, is determined by the following market clearing condition:

$$\sum_r \overline{R}_{rt} = R^F_t \,. \tag{32}$$

G. Competitive Equilibrium

Given climate policy choices $\{\tau_{ij}, \kappa, \mathbb{S}_{ij}\}$ and the effective air transport network $\mathbb{J}_{ijmf}$, a competitive equilibrium is characterized by quantities $\{Q_m, Y_r, Q_{mf}, Q^{mf}_s, N_{mf}, F_{mf}, K^Q_{mf}, \hat{F}^t_{ijf}, R^F_t, K^F_t, K^Y, F^Y_t\}$ and prices $\{P^K, P^F_t, P^{mf}_s, P_{tij}, P^{\mathbb{S}_{ij}}, P^R_t\}$ such that: *(i)* $\{Q_m, Y_r, Q_{mf}, Q^{mf}_s\}$ maximize utility (10) subject to the resource constraint (13), *(ii)* $\{Q^{mf}_s, F_{mf}, K^Q_{mf}, \hat{F}^t_{ijf}\}$ maximize airlines' profits (14) subject to technologies (18) and (19), (20), *(iii)* $\{R^F_t, K^F_t\}$ and $\{K^Y, F^Y_t\}$ maximize profits of aviation fuel producers and firms producing the macro good given technologies (24) and (25), respectively, *(iv)* the number of firms N_{mf} is determined by (17), *(v)* the price of capital P^K clears the capital market (31), *(vi)* the producer price of aviation fuels P^F_t clears the respective global market (30) *(vii)* the market-based regulatory wedge $\mathbf{\Theta}_{tij}$ depending on policy choices $\{\tau_{ij}, \kappa, \mathbb{S}_{ij}\}$ is given by (27), (29), respectively, and connects the producer price to consumer price of aviation fuel type t, P_{tij}, according to (26), *(viii)* the price of SAF credits $P^{\mathbb{S}_{ij}}$ clear the market (28) *(ix)* P^R_t the price of the fuel-specific resources to produce aviation fuels clear the market (32), *(x)* the price of air transport services P^{mf}_s in market segment mf is given by the markup pricing equation (15) with endogenous markups Λ^{mf}_s determined by (16).

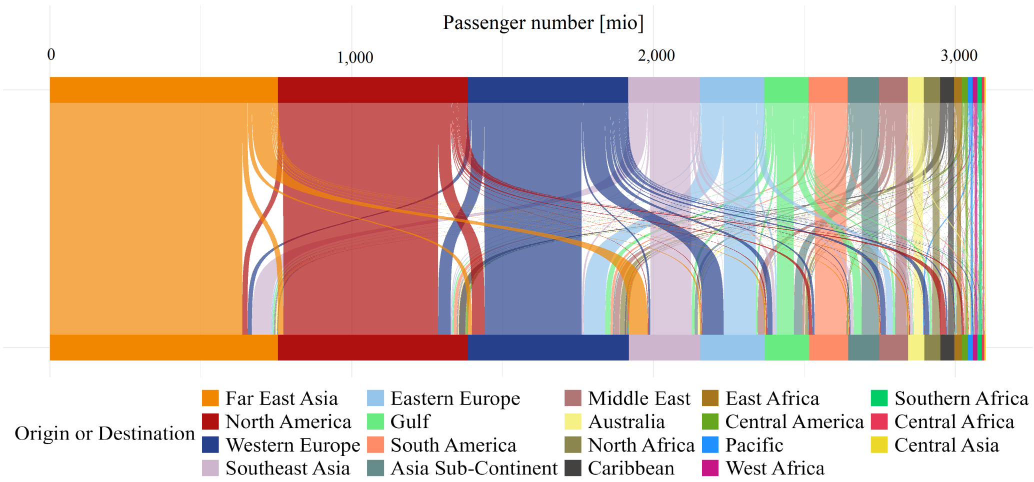
IV. Data and Calibration

This section describes how our quantitative model is mapped to data. We first describe our data sources and provide summary statistics. We then explain our strategy for model calibration and computing counterfactual policy experiments.

A. Data

PASSENGER AND TICKET PRICE DATA.—We use proprietary ticket booking data from SABRE (2019) on ticket prices and the number of tickets booked, with the latter providing information on the number of passengers. In its raw form, the data comprises information on the universe of worldwide airline ticket bookings for commercial passenger flights in 2019 for individual airlines between origin and destination airports, including stopovers. The data covers 3.80 billion passengers, representing approximately 96% of all global (commercial) flights observed by IATA

Figure 1. **Matrix of origin-destination passenger flows between model regions**



Notes: The Sankey diagram illustrates passenger flows between global regions $\overline{Q}_{rr'}$, with the top representing origin regions and the bottom representing destination regions. The width of each line reflects the volume of passengers traveling between regions, while the color denotes the origin region. Passenger numbers are based on all commercial passenger flights worldwide from January 1 to December 31, 2019, based on data from SABRE (2019). The regions are ordered from left to right in descending order according to the total volume of within-region passenger flows.

(2023a) that reports 3.97 billion origin-destination passengers in 2019.[23] We have access to a version of these data which gives us information on quantities $\overline{Q}_{rr'a}$ and prices $\overline{P}_{rr'a}$ of tickets by airline a, aggregated at the region level r.The regional aggregation comprises 19 regions (listed in Figure 1). We use data from 2019, the year before the COVID-19 crisis, to exclude impacts of pandemic-related travel restrictions from our analysis.

Figure 1 visualizes the scale of passenger flows between regions. The largest markets are intra-regional, with 637 million passengers traveling within Far East Asia, 513 million within North America, and 332 million within Western Europe. The largest inter-regional flow is between Western and Eastern Europe (71 million passengers). Passenger volumes vary widely across regions: Far East Asia, North America, and Western Europe dominate global traffic, while regions such as Africa and Central Asia play a comparatively smaller role in the global aviation network.

ROUTE DISTANCES.—To obtain route distances $\delta_{rr'}$, we use SABRE data on individual flights, which represent the passenger-weighted average of all observed flight distances between the respective regions. Mapping airports to regions, we translate $\overline{\delta}_{rr'}$ into δ_{ij}, which in turn provides the flight distance for each leg ij

[23]SABRE relies on data obtained through their booking software, which is mainly used for indirect ticket bookings made through online travel agencies and global travel retailers. To create comprehensive datasets for the global aviation market, SABRE enriches these data with external sources and proprietary models. Rigorous validation and cross-checking ensure consistency and representativeness (Soliman, O'Connell and Tamaddoni-Nezhad, 2022). Due to its high level of detail and numerous parameters, SABRE data is widely used in both research and commercial applications (Maertens, Grimme and Bingemer, 2020; Iacus et al., 2020).

operated by airline f to serve market m.

EFFECTIVE NETWORK.—To define $\mathbb{J}_{ijmf}$ in equation (9), we rely on the rules outlined in the *Freedoms of the Air* (ICAO, 1944) and incorporate assumptions about how LCCs and FSNCs operate across different airport types. LCCs are assumed to serve only non-hub to non-hub connections via direct flights. In contrast, FSNCs always route connections through the hub airport in their home region. For markets connecting airports outside their home region, these airlines are assumed to operate through a stopover at their hub airport within their home region (hub-hub-hub connection). FSNCs can connect their local hub airport to hub airports of other regions or to non-hub airports within the same region. Additionally, to account for code-sharing in airline alliances, $\mathbb{J}_{ijmf}$ allows an FSNC to connect a foreign hub to a foreign non-hub airport, provided passengers originate from or are traveling to their respective home region. In sum, this pins downs empirically the 0-1 pattern of $\mathbb{J}_{ijmf}$, providing a real-world approximation of airlines' networks for our model. Appendix B.1 provides additional detail.

TRANSLATING BOOKING DATA TO MODEL STRUCTURE.—To bring the data in the structure needed for model calibration, we carry out the following steps. We convert the SABRE (2019) data with information on airline-by-region bookings and fares into the model's airport–market structure with representative carriers (FSNC/LCC) per region. Concretely, individual airlines are mapped to a home region (IATA codes) and to a carrier type (LCC via ICAO (2017) list; for others, we gather and analyze publicly available information provided by each airline to determine its network type), then aggregated to representative airlines. Fares are passenger-weighted averages. Region-pair flows are disaggregated to airport-pair markets using our effective network $\mathbb{J}_{ijmf}$: LCCs serve non-hub-to-non-hub routes directly; FSNCs from third regions connect hubs via their home hub; FSNCs from the origin or destination region are split across different hub/non-hub pairings consistent with the network. In sum, these steps translate raw data ($\overline{Q}_{rr'a}$, $\overline{P}_{rr'a}$) to passenger flows $\overline{Q}_{mf}$ and ticket prices $\overline{P}_{mf}$ which serve as inputs for model calibration. Appendix B.2 provides additional details.

DIMENSIONALITY: AIRPORTS, AIRLINES, MARKETS, AND FLIGHTS—The model structure accounts for one representative hub airport and one representative non-hub airport per region. With 19 regions, this yields $I = 38$ airports, all observed in the data. Each region has two representative airline types, FSNCs and LCCs, for a total of 36 representative airlines (19 FSNCs and 17 LCCs). Markets are defined as unique origin-destination airport pairs ij, with a theoretical maximum of $I(I-1) = 1406$ markets; in our data, we observe 1002 served markets, with missing cases due to SABRE's limitation to single-ticket bookings which do not account for self-hubbing. Individual flights, one or more of which may be used by an airline to serve a given market, have the same theoretical maximum (1406 number of flight connections), but only 796 observed in the data. The fact that just 56% (=796/1406) of direct connections are utilized reflects the efficiency of hub-and-spoke networks, allowing airlines to serve many origin-destination pairs with fewer flights. This also underscores the need, addressed in our model, to distinguish between markets, flights and the routes airlines use to connect them.

Table 1. Booking data: Summary statistics

Data	Parameter name	Mean	Std. dev.
Aggregate: global or by region			
Total number of flights by passengers [mio.]	$\sum_{ij} \overline{Q}_{ij}$	3,101.2	–
Total number of bookings [mio.]	$\sum_{mf} \overline{Q}_{mf}$	2,449.0	–
Distance between airports [km]	δ_{ij}	7406.4	4899.0
Passenger flow by origin region [mio.]	$\overline{Q}_r$	163.2	225.1
By market			
Passenger flow by market [mio.]	$\overline{Q}_m$	2.4	17.0
By airline			
Passenger flow by airline [mio.]	$\overline{Q}_f$	68.0	144.9
Passenger flow by LCC [mio.]	$\overline{Q}_{LCC}$	13.6	20.0
Passenger flow by FSNC [mio.]	$\overline{Q}_{FSNC}$	116.7	187.5
By market by airline			
Passenger flow by market and airline [mio.]	$\overline{Q}_{mf}$	1.0	10.8
Ticket prices by market and airline [$]	$\overline{P}_{mf}$	542.3	368.3

Notes: Mean and standard deviation based on the SABRE (2019) data. Passenger flow is defined by booked tickets. Mean distance between airports is not passenger weighted. ^{a}: The coefficient of variation (CV) is defined as the ratio of the standard deviation of prices within a market to the mean price in that market.

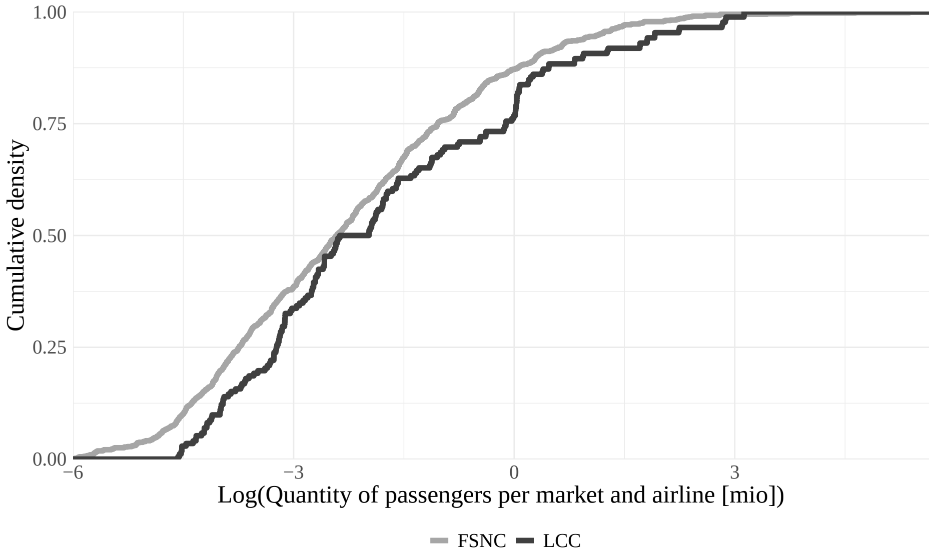
B. *Booking Data: Summary Statistics*

Table 1 reports ticket prices ($\overline{P}_{mf}$), passenger flows ($\overline{Q}_{mf}$), and geographical distances between airports (δ_{ij}) from the SABRE (2019) booking data. In 2019, the cleaned dataset covers 3.1 billion passenger flights, corresponding to 2.5 billion bookings, an average of 1.3 flights per ticket sold. The mean airport–airport distance is 7,406 km with a standard deviation of 4,899 km. Passenger volumes vary widely across markets and airlines indicating substantial heterogeneity: the mean flow per market is 2.4 million with a standard deviation of 17.0 million; FSNCs average 116.7 million passengers, compared to 13.6 million for LCCs.

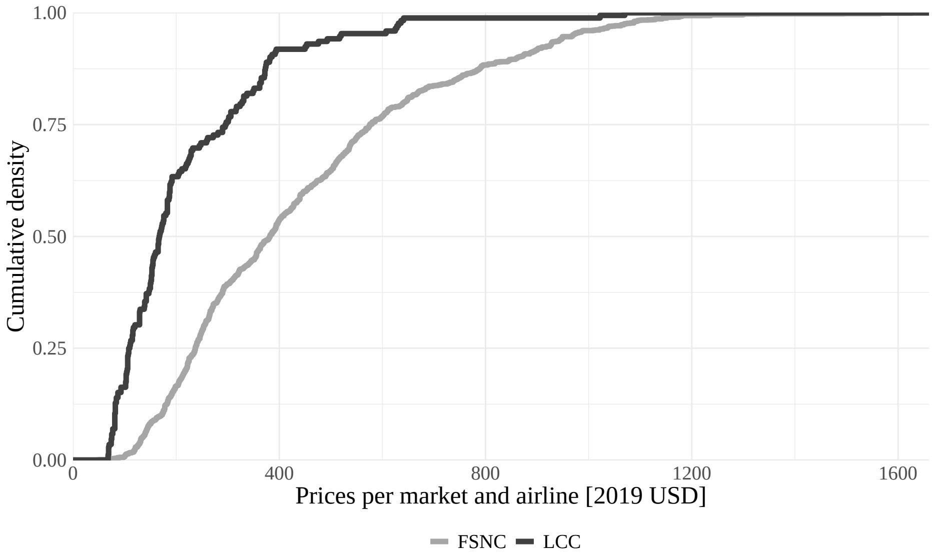
Figure 2(a) further illustrates the heterogeneity in $\overline{Q}_{mf}$ using empirical cumulative density functions (CDFs) of passenger numbers by market and airline. Over 90% of market segments have volumes below 5 million, while a small share accounts for much larger traffic. The dark green line for LCCs lies below that for FSNCs, indicating that markets with lower demand are primarily served by FSNCs. Since FSNCs serve most of total demand, the combined distribution closely mirrors that of FSNCs.

Table 1 and Figure 2(b) document substantial variation in ticket prices. The mean price per market and airline $\overline{P}_{mf}$ is $542.3 with a standard deviation of $368.3, with clustering around specific values such as $250 and $425, while prices above $1,200 are rare. Just over half of all market segments served by FSNCs have average prices at or below $400, for LCCs, 90% of market segments fall within this range. Figure 3 shows that also within markets (i.e., across airlines in the same market) ticket price variation is substantial. On average, the standard deviation of ticket prices equals 22% of the mean ticket price (CV = 0.22). About 12% of markets are served by only one representative airline, yielding a CV of zero, and 45% have a

Figure 2. **Distribution of passenger flows and ticket prices by market and airline type**



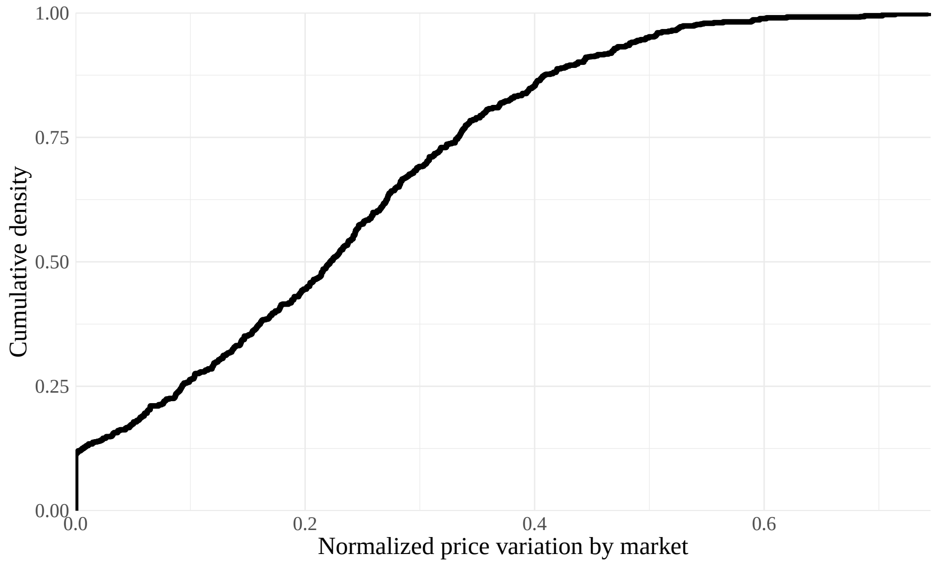
(a) Quantities ($\overline{Q}_{mf}$): number of passengers (=number of tickets)



(b) Prices ($\overline{P}_{mf}$): ticket prices

Notes: The empirical cumulative density distributions represent quantity and price variables for all global flights that occurred between January 1 and December 31, 2019, based on the SABRE (2019) booking data. FSNC=Full-service network carriers. LCC=Low-cost carriers.

Figure 3. **Within-market ticket price dispersion**



Notes: The plot shows the within-market distribution of ticket prices $\overline{P}_{mf}$ for all bookings between January 1 and December 31, 2019, based on SABRE (2019) data. The x-axis reports the coefficient of variation (CV), the standard deviation of ticket prices in market m divided by the mean price in that market, as a measure of normalized price variation. In markets served by only one representative airline, the mean price equals the single observed fare, yielding a CV of zero.

CV of 0.2 or less, while only a small fraction exceed 0.6.

In sum, substantial heterogeneity in ticket prices and passenger flows exists both between and within markets and across airline types. Distinguishing airlines serving the same market via different routes is a key feature of the global air transport network. Ignoring these patterns risks misrepresenting how a carbon tax versus an SAF quota affects prices, demand, and fuel use and CO_2 emissions, and may bias the comparison of their relative welfare effects.

C. Calibration

To develop a quantitative version of our theory, we calibrate the model's equilibrium conditions in the absence of climate policy to a factual benchmark situation that rationalizes observed booking, market, and aviation technology data. The benchmark reflects 2019 conditions.[24] We proceed in five steps. First, we seed the air transport network with our effective network and geographical distances between airport pairs. Second, we use the booking data to calibrate passenger demand, supply, and ticket prices in each market by airline type. Third, we derive estimates for airlines' marginal cost and markup parameters consistent with the model structure. Fourth, we specify consumer preferences and build demand for air transport services (including an outside good). Fifth, we parametrize aviation fuel

[24]Given that the climate policies of interest, SAF quotas and carbon pricing, were either absent or implemented only at minor levels, this year provides a clean baseline for evaluating policy counterfactuals.

Table 2. Parameter values

Parameter	Source/Value
Effective air transport network: $\mathbb{J}_{ijmf}$	Sparsity based on *Freedoms of the Air* and passenger-flow data (SABRE, 2019)
Air transport markets	
Ticket prices [\$]: $\overline{P}_{mf}$	Booking data: SABRE (2019)
Number of passengers: $\overline{Q}_{mf}$	Booking data: SABRE (2019)
Pre-policy markup: $\overline{\Lambda}^{mf}$	Booking data: SABRE (2019)
Geographical distance btw airports: δ_{ij}	Booking data: SABRE (2019)
Preferences and demand	
Share of aviation expenditure on airline f: β_{mf}	Booking data: SABRE (2019)
Share of total aviation expenditure: ν	0.01[a]
Share in regional demand: α_{mr}	World Bank (2024)
EOS air travel btw airlines f: ρ	0.7[b]
EOS btw different markets m: γ	0.5[b]
EOS btw air travel and outside good: ϵ	0.2[b]
Aviation technology and macro production	
Cost share aviation fuels: $\overline{\mu}$	0.25[c]
Fuel efficiency [l/PAX km]: θ	0.0294[d]
EOS aviation fuels vs. capital: χ	0–.1[e]
Carbon intensity of CJF [tCO_2/l]: ζ_{CJF}	0.00258[f]
Carbon intensity of SAF [tCO_2/l]: ζ_{SAF}	Conditional on policy treatment of life-cycle emissions
Cost share of aviation fuel in macro good: ξ_t	0.005[g]
Aviation fuel markets	
Pre-policy aviation fuel prices [\$/l]: $\overline{P}_t^F$	IATA (2023b), World Economic Forum (2020)[h]
Production of aviation fuel t: ω, φ_t	Own assumptions[i]

Notes: EOS=elasticity of substitution. [a]:Based on Statista (2023) and World Bank (2024). [b]: Based on Brons et al. (2002), InterVistas (2007), Berry and Jia (2010), and Mayor and Tol (2007). [c]:Based on IATA (2018). [d]:Based on Graver and Rutherford (2017). PAX=passengers. [e]:Baseline model assumes 0. [f]:Based on Graver (2013). [g]:Own assumption, based on World Input-Output database (Woltjer, Gouma and Timmer, 2021). [h]:Baseline model assumes 0.5\$/l and 1.5\$/l for CJF and SAF, respectively. [i]:The cost share of the fuel resource input (ω) and the EOS between resource and capital inputs (φ_t) are calibrated to match an own-price elasticity of supply of 0.2 and 1.5 for CJF and SAF, respectively.

markets by calibrating pre-policy prices and quantities of SAF and CJF, together with price-elastic supply.

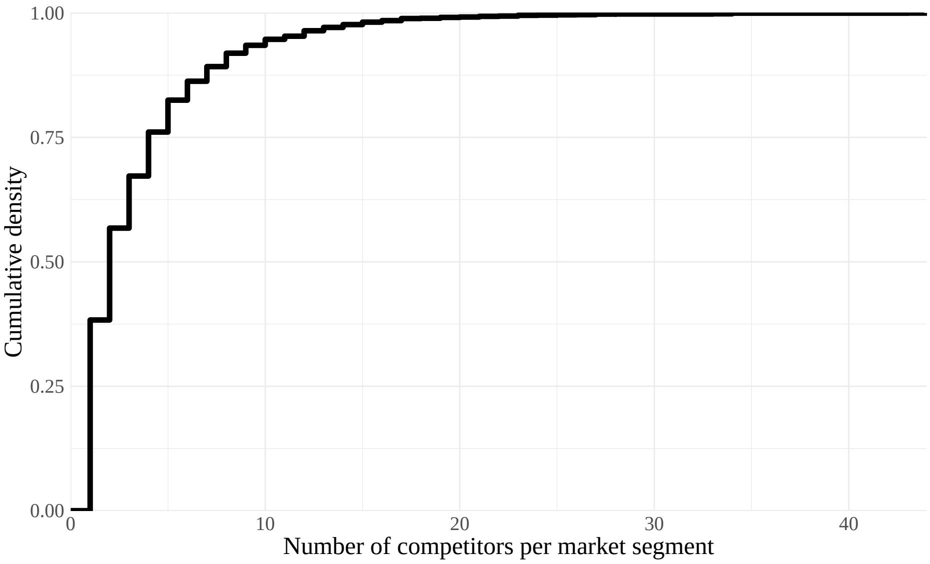
Table 2 summarizes the parameters used in the calibration along with their data sources. We now describe each step of the model calibration in detail.

NETWORK SPARSITY AND BENCHMARK QUANTITIES AND PRICES—All feasible connections between airports and their mapping to markets are captured by the effective network $\mathbb{J}_{ijmf}$, with geographical distances denoted by δ_{ij}. Since $\mathbb{J}_{ijmf}$ was used to translate raw booking data into the prices and quantities employed for model calibration (see Section IV.A), its sparsity pattern is consistent with that of $\overline{Q}_{mf}$ and $\overline{P}_{mf}$.

We use standard techniques to calibrate CES functions to observed prices and quantities in the pre-policy benchmark.[25] The advantage of this approach is that the benchmark pre-policy equilibrium exactly replicates the observed levels and patterns of passenger flows and ticket prices from the SABRE (2019) booking data.

[25]For example, the CES technology for Q_m in equation (11) can be globally characterized through its

Figure 4. **Empirical distribution of number of competitors by market segment**



Notes: The plot shows the number of competitors observed per market segment *mf*, computed from the SABRE (2019) booking data using definitions of representative markets and airlines.

MARGINAL COST AND TECHNOLOGY—Airline marginal cost is not directly observable at the resolution of our model. Moreover, given its global coverage and aggregation, many factors influencing airline cost, even if observable, cannot be represented in a model of this scale.[26] We therefore construct marginal cost "bottom-up", drawing on observables such as fuel and capital cost, technology parameters, geographic distance, and network structure—all of which are measurable and aligned with how airline decisions are represented in the model.

To derive an empirical counterpart of marginal cost in (21), we proceed in four steps. First, we compute the total route distance for a given market m and airline f, defined as the sum of segment distances $\sum_{(i,j)\in\mathbb{J}_{ijmf}}$ across all direct and indirect flight segments in the effective network $\mathbb{J}_{ijmf}$. Second, following Graver and

dual unit cost function:

$$c_m(P^{\mathrm{mf}}) = \overline{Q}_m \left[\sum_f \theta^{mf}\left(\frac{P_{\mathrm{mf}}}{\overline{P}_{mf}}\right)^{1-\rho}\right]^{1/(1-\rho)},$$

where $c_m(P^{\mathrm{mf}})$ is calibrated to data using observed values for passenger flows at the market and market-segment level ($\overline{Q}_m$, $\overline{Q}_{mf}$), ticket prices by market segment ($\overline{P}_{mf}$), and by calibrating the input value shares according to

$$\theta^{mf} := \frac{\overline{P}_{mf}\overline{Q}_{mf}}{\sum_{f'}\overline{P}_{mf'}\overline{Q}_{mf'}}.$$

For a detailed derivation, see Rutherford (2002). This calibration approach is standard practice in applied general equilibrium modelling, with applications in Harrison, Rutherford and Tarr (1997), Böhringer, Carbone and Rutherford (2016), Goulder, Hafstead and Williams III (2016), Bretschger et al. (2017), and Chen et al. (2022) among others.

[26] Examples include seat density and utilization, labor contracts, airport and airspace charges (landing, slots, overflight), local taxes and security fees, and scale effects from hub utilization.

Rutherford (2017), we set fuel burn at $\theta = 0.0294$ liters per PAX-km. Third, in the pre-policy equilibrium airlines use only CJF, for which we set the fuel price at $\overline{P}^F_{CJF} = 0.5\,[\$/\mathrm{l}]$ (IATA, 2023b). Based on current aviation fuel prices (World Economic Forum, 2020), our baseline model assumes that SAFs are three times more expensive than CJFs. In our robustness checks, we vary this initial fuel price gap. Combining route distance, fuel burn, and fuel price yields marginal fuel cost per unit of output (PAX-km). Fourth, fuel accounts for about 25% of total marginal cost (IATA, 2018), which implies $\overline{\mu} = 0.25$ and enables us to infer the capital cost component accordingly. Our baseline model sets fuel efficiency constant ($\chi = 0$). We then allow for endogenous improvements ($\chi > 0$), consistent with historical efficiency gains in aircraft propulsion (Section I.A).

Under carbon pricing policies, marginal cost also depend on the carbon intensity of CJF multiplied by the prevailing CO_2 price. Following Graver (2013), we set the carbon intensity of CJF to $\zeta_{CJF} = 0.00258$. Unless life-cycle emissions of SAF are explicitly accounted for, $\zeta_{SAF} = 0$. Alternative policy cases with differential treatment of life-cycle emissions, where $\zeta_{SAF} > 0$, are discussed below.

In sum, marginal cost in our model are determined by distance- and efficiency-adjusted fuel cost and capital cost with policy-dependent charges on carbon emissions, while SAF cosst are reflected directly in its user price.

Market shares and markups—We face two main challenges in empirically identifying the markup parameter in a model with global coverage. First, airlines' (marginal) cost is not directly observable. Second, while ticket prices are available, the information is coarse: we only observe $\overline{P}_{rr'a}$ for airline a between aggregated regions r and r'. Hence, markups cannot be inferred directly from observed prices and cost. Instead, we infer market shares from the observed number of competitors in each market segment. First, we use the network topology $\mathbb{J}_{ijmf}$ to map observed trips between regions r and r' and actual airlines a into market segments mf. Second, we recover the price elasticity of demand in segment mf, ε^{mf}, from expenditure shares in the factual equilibrium and the preference parameters (see Appendix C). Third, we derive effective competitor numbers $\overline{N}_{mf}$ by counting the airlines a serving segment mf in both the data and the effective network $\mathbb{J}_{ijmf}$. Fourth, assuming that airlines a represented by a common type f supply homogeneous services, we compute market shares as $\psi^{mf} = 1/\overline{N}_{mf}$.

Figure 4 summarizes the distribution of the number of competitors by market segment mf. About 37% of market segments are effective monopolies, while markets in larger or coarser-grained regions typically have five or more competitors. Passenger-weighted mean markup equals $\overline{\Lambda}_{avg} = 0.35$ (standard deviation 0.27) with a median of 0.60, varying substantially by airline origin (see Figure E.1 in Appendix C). Overall, our parametrization is deliberately conservative to ensure that we do not exaggerate the relative advantage of SAF quotas over carbon pricing. By inferring market shares from observed competitor counts and aggregating carriers across sub-markets, we understate competition intensity and thus avoid overstating markups. Accordingly, our effective-competition estimates are lower than those reported in the literature, yet remain consistent with benchmark ranges (Berry and Jia, 2010; Koopmans and Lieshout, 2016; Ennen, Allroggen and Malina, 2019; Bet, 2021).

CONSUMER PREFERENCES AND DEMAND.—To pin down consumers' utility function, we need to calibrate share parameters (β_{mf}, α_{mr}, ν) and elasticity of substitution parameters (γ, ϵ, ρ). The share parameters β_{mf} are directly calibrated from the SABRE (2019) booking data (see footnote 25). α_{mr} shares are determined by allocating market-level demand Q_m across regions in proportion to average per-capita income, using data from World Bank (2024). This avoids double-counting demand when markets span multiple regions and reflects evidence that income is a strong predictor of air travel propensity (Zheng, 2022; Graham and Metz, 2017). We set $\nu = 0.01$, reflecting the fact that air transport services constitute only a small share of total consumption, as indicated by data from (Statista, 2023; World Bank, 2024). Empirical estimates of substitution elasticities are notoriously difficult to obtain and, at best, provide out-of-model references that indicate plausible ranges and relative magnitudes. Based on a review of the literature (see Table 2 for sources), our baseline model assumes $0 < \epsilon < \gamma < \rho < 1$. The elasticity of substitution between air transport and non-aviation consumption is set low ($\epsilon = 0.2$), consistent with meta-analyses showing that overall demand for air travel is relatively inelastic (Brons et al., 2002; InterVistas, 2007).

Air transport services within a market are closer substitutes than those across airport pairs. Empirically, firm-specific elasticities on a given route are larger in magnitude, indicating stronger substitution among carriers on the same route, whereas national or pan-regional elasticities are smaller, reflecting weaker substitution across destinations (InterVistas, 2007; Berry and Jia, 2010; Mayor and Tol, 2007). Accordingly, we set $\gamma = 0.5$ for within-market substitution and $\rho = 0.7$ for cross-market substitution, both below unity to reflect inelastic demand.

COMPUTATIONAL STRATEGY.—We formulate the model as a mixed complementarity problem associating quantities with zero-profit and prices with market-clearing conditions (Mathiesen, 1985; Rutherford, 1995). We use the General Algebraic Modeling System (GAMS) software together with the PATH solver (Dirkse and Ferris, 1995) to compute the equilibrium.

V. Welfare Effects of (Hypothetical) Global Policies for Aviation

This section presents our first set of quantitative results. We compare the welfare and market effects of global climate policies—a market-based carbon tax versus a command-and-control SAF quota. Although such global policies for aviation are largely hypothetical, the exercise is useful: it provides a benchmark for assessing sub-global policies, and it offers a quantitative complement to Section II, disentangling mechanisms and the roles of imperfect competition and limited input substitutability in climate policy design.

A. Welfare Measurement

When assessing global policies, we employ a utilitarian aggregation of regional welfare and define the global welfare change as:

$$\Psi = \sum_{r} \Delta W_r \times \big[\sum_{r'} \overline{M}_{r'}\big]^{-1} . \tag{33a}$$

ΔW_r denotes the Hicksian equivalent variation in region r associated with consumers' utility in (10) due to imposing a climate policy, expressed as a monetized change evaluated at pre-policy income $\overline{M}_r$. Dividing Ψ (expressed in monetary terms, \$) by the quantity of emissions reduced (in tons of CO_2) yields the average welfare cost of abatement (AWC) in \$ per ton of CO_2 abated:

$$\Psi^{\text{average}}(\Delta E) = \frac{\Psi}{\Delta E} , \tag{33b}$$

where $\Delta E := E - \sum_{mf} \overline{E}_{mf}$ represents the change in emissions between the policy counterfactual ($E = \sum_{mf} E_{mf}$) and the pre-policy baseline ($\overline{E}_{mf}$), aggregated over market segments. To evaluate the cost of achieving incremental emissions reductions at a given distance from pre-policy emissions, ΔE, we define the marginal welfare cost of abatement (MWC) as:[27]

$$\Psi^{\text{marginal}}(\Delta E) = \left.\frac{\partial \Psi}{\partial E}\right|_{\Delta E} . \tag{33c}$$

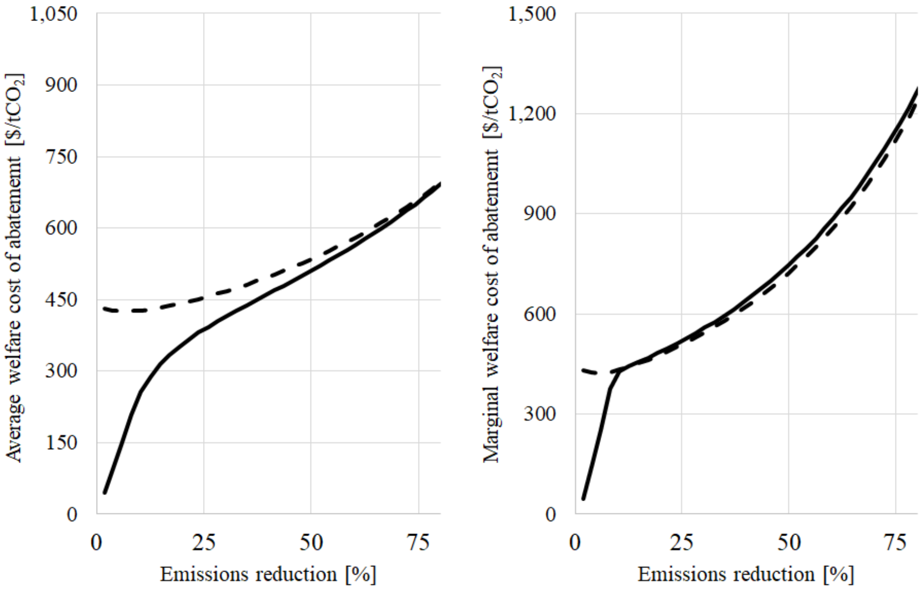
B. Welfare and Market Impacts of Global Instruments

CLIMATE REGULATION UNDER PERFECT COMPETITION.—Climate policy instruments are typically evaluated under perfectly competitive output markets. Assuming perfectly competitive air transport service markets, Figure 5(a) reproduces the standard result in our model—consistent with Proposition 1: a carbon tax minimizes abatement cost and outperforms a command-and-control SAF quota instrument. For modest reductions, when the tax-inclusive user price of CJF remains below the SAF price, the MWC is far higher under the quota than under the tax (upper-right panel). Once the target is stringent enough that further abatement occurs entirely via fuel substitution to SAF, the instruments' MWC converge.[28] These MWC differences translate into first-order differences in AWC: at low abatement, the quota is multiple orders of magnitude more expensive than the tax (upper-left panel). The

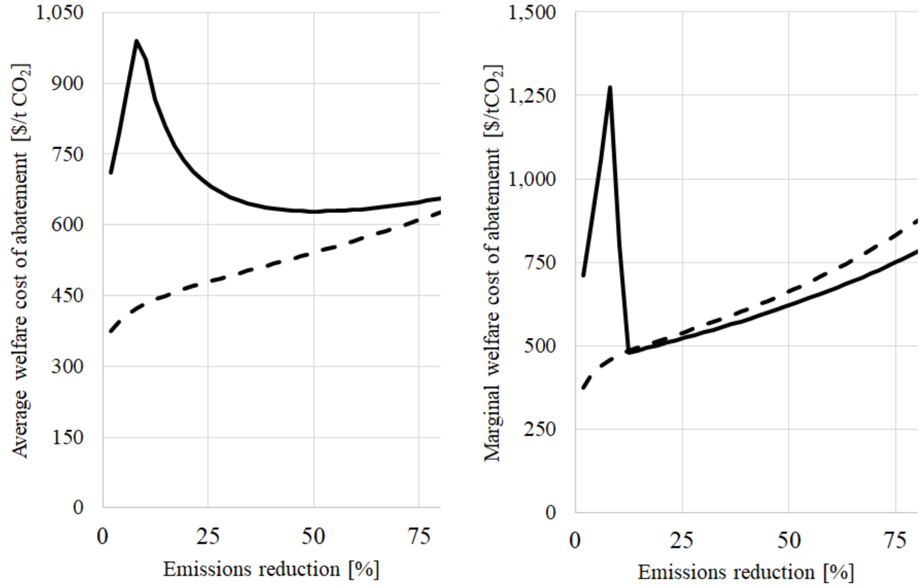
[27]We approximate $\Psi^{\text{marginal}}(\Delta E)$ numerically by computing the discrete difference $\Psi^{\text{average}}(\Delta E + \epsilon) - \Psi^{\text{average}}(\Delta E)$ where ϵ is a small increment of abated emissions.

[28]Under perfect competition, after the fuel switch is complete the MWC is slightly lower under the SAF quota. At the margin, both policies abate by using more SAF, but the quota relied less on demand reduction at low abatement, so a given fuel-cost increase implies a smaller welfare loss from reduced demand. This reflects path dependence in our general-equilibrium MWC. If each incremental reduction were evaluated around the same local equilibrium (i.e., "re-benchmarked"), MWC would be identical under both instruments.

Figure 5. **Average and marginal welfare cost of abatement of global climate policies**



(a) Perfectly competitive air transport service markets

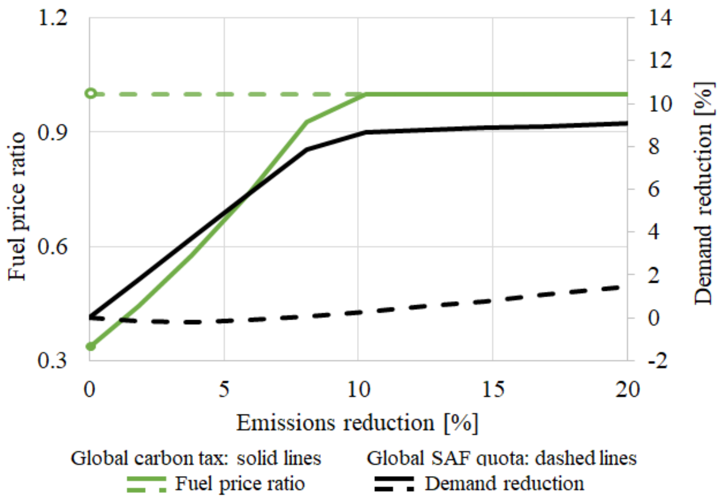


(b) Oligopolistic air transport service markets

Global carbon tax   Global SAF quota

Notes: The graph plots the average and marginal global welfare cost of abatement ($\Psi^{\text{average}}(\Delta E)$, $\Psi^{\text{marginal}}(\Delta E)$) for two policy instruments: a "*Global carbon tax*" and a "*Global SAF quota*". Results are shown across a range of global emissions-reduction targets ΔE under two market-structure settings (perfect competition, Cournot oligopoly with $\overline{\Lambda}_{avg} = 0.35$).

Figure 6. **Abatement channels by reduction target: aviation fuel substitution and ticket demand**



Notes: The graph plots changes in the relative fuel price, defined as the user-price ratio of CJF to SAF, and in ticket demand for a "*Global carbon tax*" and a "*Global SAF quota*". All changes are measured relative to the pre-policy equilibrium, and refer to the baseline model with Cournot competition. Initially, SAF is three times more expensive than CJF (see Section IV); hence the CJF/SAF price ratio before policy intervention is 1/3, indicated by the green dot on the left-hand axis. The hollow circle at a price ratio of CJF/SAF of 1 indicates that a binding SAF quota immediately eliminates the fuel price gap from the first unit of emissions reduction by implicitly subsidizing SAF over CJF.

AWC gap narrows with more stringent targets and eventually converges. But, as we show next, the perfect-competition benchmark severely misstates both absolute and relative welfare cost, reversing standard conclusions about policy instrument choice.

OLIGOPOLISTIC AIRLINE MARKETS.—With oligopolistic markets for air transport services, the welfare ranking reverses (see Figure 5(b)): for a given emissions target, the SAF quota attains the same abatement at a substantially lower AWC than the carbon tax (lower-left panel), consistent with Proposition 2. The mechanism is the composition of different abatement channels incentivizing substitution between clean and dirty aviation fuels and demand conservation (Figure 6). For low reductions—while the CJF user price with the carbon tax is still below the SAF price—the tax mainly cuts emissions by suppressing ticket demand, whereas the quota leaves demand roughly unchanged. By eliminating the fuel-price gap from the first unit of abatement (an implicit subsidy to SAF relative to CJF), the quota raises the SAF share to the mandate without materially affecting demand. As the emissions reduction tightens, the required carbon tax to deliver the emissions reduction becomes effectively capped at the SAF price (which acts as a "backstop"), after which abatement comes primarily from aviation fuel substitution and ticket demand is largely unaffected.

The two instruments induce similar price and quantity changes under perfectly and imperfectly competitive output markets (Table 3). Their welfare and efficiency

Table 3. Welfare and market effects of (hypothetical) global climate policies for aviation

	Air transport service markets are...			
	perfectly competitive		oligopolistic	
	Carbon tax	SAF quota	Carbon tax	SAF quota
Welfare and carbon cost				
Average abatement cost [\$/tCO_2]	150 (416)	426 (469)	886 (659)	410 (492)
Marginal abatement cost [\$/tCO_2]	251 (560)	423 (546)	1056 (540)	438 (561)
Carbon price [\$/tCO_2]	311 (569)	–	263 (486)	–
Abatement channel: demand				
Ticket demand [% change]	-6 (-10)	0 (-3)	-6 (-10)	0 (-3)
Ticket prices [% change]	36 (68)	0 (18)	24 (45)	0 (10)
Abatement channel: fuel substitution				
Market share of SAF in aviation fuels [%]	0 (23)	6 (28)	0 (22)	6 (28)
(Implicit) CO_2 charge on CJF [\$/l]	0.80 (1.47)	0.07 (0.46)	0.68 (1.25)	0.07 (0.37)
Implicit subsidy on SAF [\$/l]	–	1.10 (1.18)	–	1.0 (0.95)
Competition effects				
Number of airlines [% change]	–	–	6 (11)	-0.1 (3)
Markup [% change]	–	–	-6 (-11)	0.1 (-3)

Notes: The table reports welfare and market effects of a "*Global carbon tax*" and a "*Global SAF quota*" under two market structures (perfect competition, Cournot oligopoly with $\overline{\Lambda}_{avg} = 0.35$) for two emissions targets (6% and 30%; values in parentheses are for 30%).

effects, however, diverge sharply, in line with Proposition 4: with pre-existing market power, abating emissions through curbing demand is extremely costly (Figure 5, bottom-right panel). Under a carbon tax, the MWC at small reductions ranges from \$750 to \$1,200 per ton of CO_2, orders of magnitude above the SAF quota, which remains below \$500 per ton. This yields AWC advantages for the quota at low-medium targets. At a 6% abatement, for example, the tax's AWC is about 2.2 times the quota's (886/410; Table 3). This reflects the "policy mix" of an implicit output subsidy, an implicit carbon price, and the pass-through to ticket prices: at 6%, the quota implies an output subsidy of \$1.00/l and an implicit carbon charge of \$0.07/l, whereas the tax must impose \$0.68/l to achieve the same cut; ticket prices rise 24% under the tax but remain flat under the quota.

As emission targets tighten and the tax brings SAF to the market, its MWC falls until the CJF user price exceeds the SAF price and the fuel switch is complete; beyond that point, the MWC rises for both instruments. Accordingly, the AWC gap narrows with stringency: at 30% abatement, the AWC ratio is still 1.3, and only at very high targets ($\approx$ 75% and higher) does it approach one (Figure 5, lower-left panel). For a gradual transition, arguably the relevant real-world policy path, climate policy instrument choice is therefore first-order.

Beyond the reversal in the welfare ranking, our analysis bears out a second key insight: welfare-cost estimates are highly sensitive to market structure. Evaluating an oligopolistic sector with a misspecified perfect-competition model severely understates the cost of a market-based instrument (the carbon tax) relative to a command-and-control instrument (the SAF quota), because the tax transmits a stronger demand-conservation signal. In Figure 5, the AWC of the carbon tax under Cournot competition is 15.6, 3.7, and 1.6 times the perfect-competition estimates at 2%, 10%, and 30% reductions, respectively. By contrast, the quota mitigates the markup distortion, so ignoring market power overstates its cost at low to medium abatement.

C. *Imperfect Competition and Limited Input Substitutability: How Important?*

Like other hard-to-abate sectors, aviation features imperfectly competitive output markets and limited scope for substituting carbon-intensive inputs. As empirical measures of market power and input substitutability (and their mapping to our model) are inherently imprecise, we examine how sensitive the reversed welfare ranking of policy instruments is to these features. Drawing on empirical evidence, we bound plausible parameter ranges and assess the robustness and relevance of our quantitative findings.

DEGREE OF MARKET POWER.—Figure 7(a) plots the AWC ratio (SAF quota/carbon tax) across abatement targets, varying pre-policy markups (red markers). Our baseline model features a mean markup of 0.35 (standard deviation of 0.27) in the benchmark equilibrium before climate policy—calibrated from the empirical distribution of competitors and demand elasticities (Sections IV.C and Appendix C).

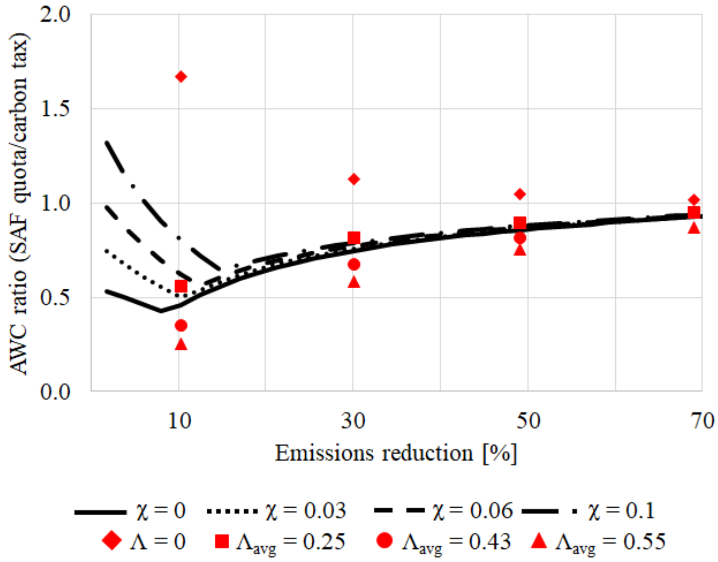
Two key insights emerge. First, with imperfectly competitive output markets the SAF quota dominates the carbon tax at all abatement targets, and the gap widens as market power increases. Given empirical ranges, our baseline average markup of 0.35 appears conservative, suggesting that the reversal of the instrument ranking relative to perfect competition is a policy outcome one should reasonably expect in actual aviation markets. Second, as policy stringency rises, the instrument ranking becomes less sensitive to market power, reflecting that at high abatement both instruments rely primarily on substitution between clean and dirty aviation fuels.

We adopt a conservative stance not only in parametrization but also in modeling imperfect competition. Allowing free entry and exit lets the model capture medium- to long-term competitive adjustments that can differentially shape each instrument's welfare effects. As Table 3 shows, the carbon tax is more pro-competitive: its larger regulatory wedge induces stronger entry and lowers markups. Under the SAF quota, the implicit output subsidy offsets part of the wedge, raising marginal cost less, weakening entry incentives, and yielding smaller markup reductions. Importantly, even after accounting for these stronger pro-competition effects under a carbon tax, the SAF quota still dominates; with a fixed number of airlines, the AWC gap would be even larger.

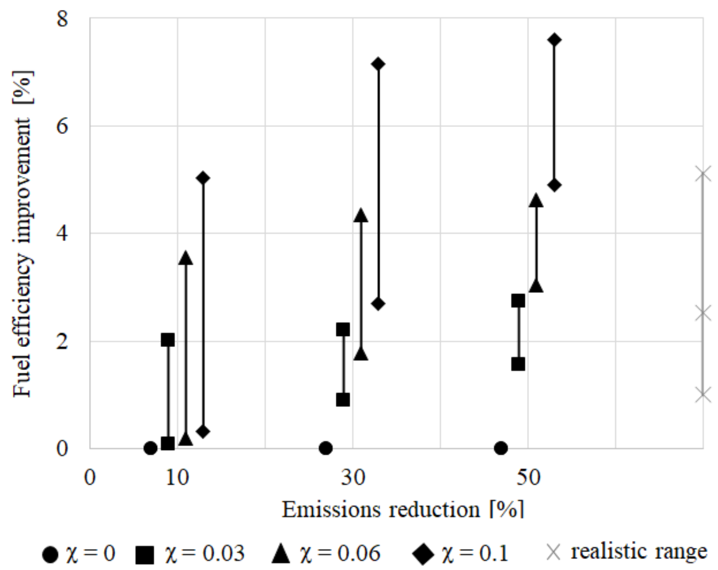
INPUT SUBSTITUTABILITY AND ENDOGENOUS FUEL EFFICIENCY.—Figure 7(a) plots the AWC ratio (SAF quota/carbon tax) across abatement targets while varying the capital-fuel elasticity of substitution, χ. Greater substitutability makes marginal fuel use cheaper to replace, favoring the carbon tax: by pricing marginal emissions, it induces substitution toward capital along the least-cost margin. The SAF quota, by imposing an average blend price without pricing marginal emissions, cannot fully exploit this channel; as χ rises, its market-power-correction advantage erodes.

For the same instruments and targets, Figure 7(b) reports endogenous fuel-efficiency improvements for different χ implied by the model and benchmarks them

Figure 7. **Robustness of welfare-instrument ranking to market power and input substitution between capital and aviation fuels**



(a) AWC ratio



(b) Implied equilibrium fuel efficiency and comparison to historic improvements

Notes: Panel (a) plots the AWC ratio (global SAF quota/global carbon tax) across emissions targets, varying χ (capital-fuel elasticity) and market power (summarized by the average markup $\overline{\Lambda}_{avg}$. The baseline assumes $\overline{\Lambda}_{avg} = 0.35$; perfect competition corresponds to $\overline{\Lambda} = 0$). Variations in χ hold $\overline{\Lambda}_{avg} = 0.35$ fixed; variations in $\overline{\Lambda}_{avg}$ hold $\chi = 0$. Ratios < 1 imply the SAF quota is more efficient. Panel (b) reports fuel-efficiency improvements (fuel per passenger-km) under each instrument. With $\chi = 0$, efficiency is fixed; for $\chi > 0$, it adjusts endogenously to policy-induced relative prices. Results are compared with a "realistic range" of historical gains: assuming 4% annual fleet-renewal rate, the lower (upper) bound corresponds to a global fleet efficiency improvement of 0.04% (0.2%) per year, or about 1% (5.1%) cumulatively over 25 years. Values of $\chi > 0.1$ imply implausibly high efficiency gains absent major aircraft propulsion breakthroughs.

Table 4. Design of counterfactual experiments: policy instruments and regulatory coverage

Counterfactual	Policy instrument		Geographical scope
	Carbon tax	SAF quota	of regulation (τ_{ij} or $\mathbb{S}_{ij}$)
Hypothetical global climate policies			
Global carbon tax	Yes	No	All flights worldwide
Global SAF quota	No	Yes	All flights worldwide
Current and prospective climate regulation			
EU regulation: EU ETS[a]	Yes	No	Flights within EU
EU regulation: SAF quota[b]	No	Yes	Only take-offs from EU airports
EU regulation: Combined	Yes	Yes	As under *EU ETS* and *SAF quota*
Global regulation: CORSIA[c]	Yes	No	Flights not covered by EU ETS
Global regulation: CORSIA-tax[d]	Yes	No	Flights not covered by EU ETS
EU regulation and CORSIA-tax	Yes	Yes	As under *EU regulation: Combined* and *CORSIA-tax*

Notes: Names of policy counterfactuals are italicized. [a]In addition to the EU ETS in its actual scope (covering all intra-EU flights), we define *EU regulation: EU ETS (quota scope)*, which aligns its scope with the SAF quota, i.e. it covers all departures from EU airports, regardless of destination (EU or non-EU). [b]In addition to the EU SAF quota in its actual scope (covering all departures from EU airports), we define *EU regulation: SAF quota (ETS scope)*, which aligns its scope with the EU ETS, i.e. it covers only intra-EU flights. [c]Under current CORSIA rules, airlines pay a carbon charge (purchase offsets) only on emissions exceeding 85% of 2019 levels. [d]This scenario assumes airlines pay a carbon charge on all emissions for flights regulated under CORSIA, not only the portion above 2019 levels. Regulatory scope is modeled through τ_{ij} for the carbon tax in eq. (27) and $\mathbb{S}_{ij}$ for the SAF quota in eq. (28).

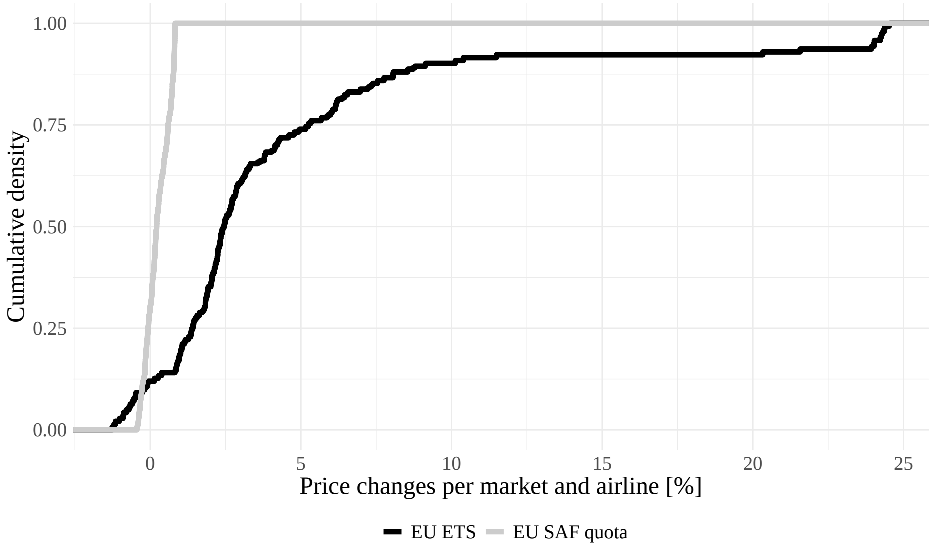
against historically observed gains. Even when χ is calibrated to imply efficiency improvements that exceed historical rates (e.g., $\chi = 0.1$), the AWC ratio remains well below 1 at low-to-medium targets. Thus, absent a major breakthrough in aircraft propulsion technology, regulating aviation emissions in a sector with market power and limited capital-fuel substitutability is considerably more cost-effective under an SAF quota than under a carbon tax.

Other robustness checks.—Appendix D examines robustness to the price elasticity of ticket demand, the pre-policy fuel-price gap, and differential accounting of life-cycle CO_2 emissions of SAF. The level of welfare cost varies with assumptions, but the qualitative welfare ranking of the two instruments remains unchanged.

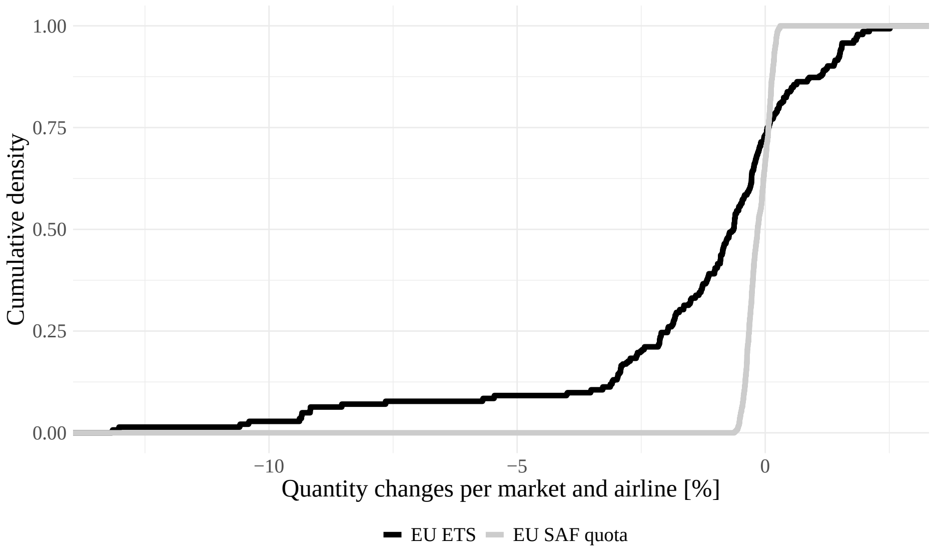
VI. Evaluating EU Climate Policies for Aviation

This section presents our second set of quantitative results. Motivated by the fact that the EU is the only continent with a comprehensive, binding regime that both prices aviation emissions (EU ETS) and mandates SAF uptake (EU SAF quota), we examine EU policies for aviation. Building on the policy context described in Section I.B, Table 4 lays out our policy counterfactuals. We assess welfare and emissions impacts and examine how instrument choice, instrument overlap, and geographic coverage affect CO_2 abatement efficiency, market outcomes, environmental performance, and distribution between regulated and non-regulated regions.

Figure 8. **Ticket price and passenger impacts for emissions-equivalent EU ETS and EU SAF quota**



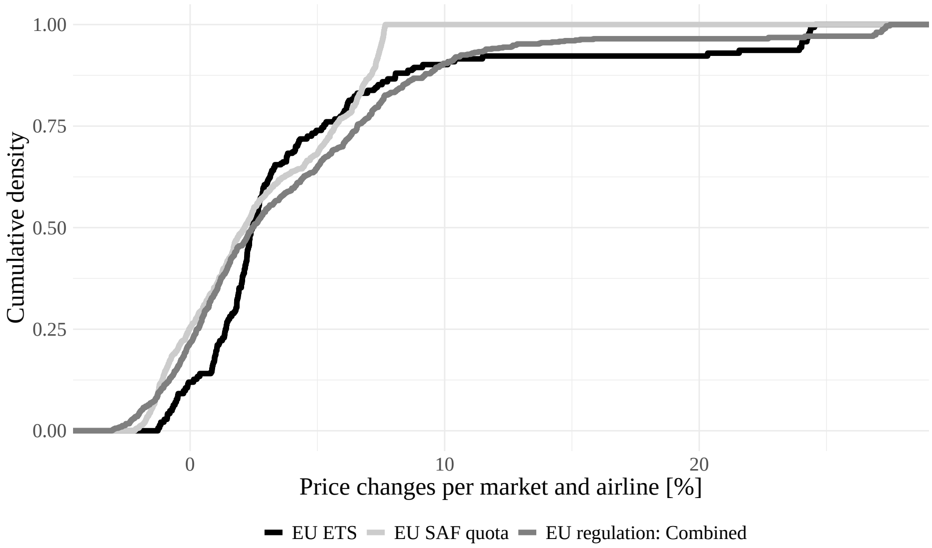
(a) Ticket prices ($\overline{P}_{mf}$)



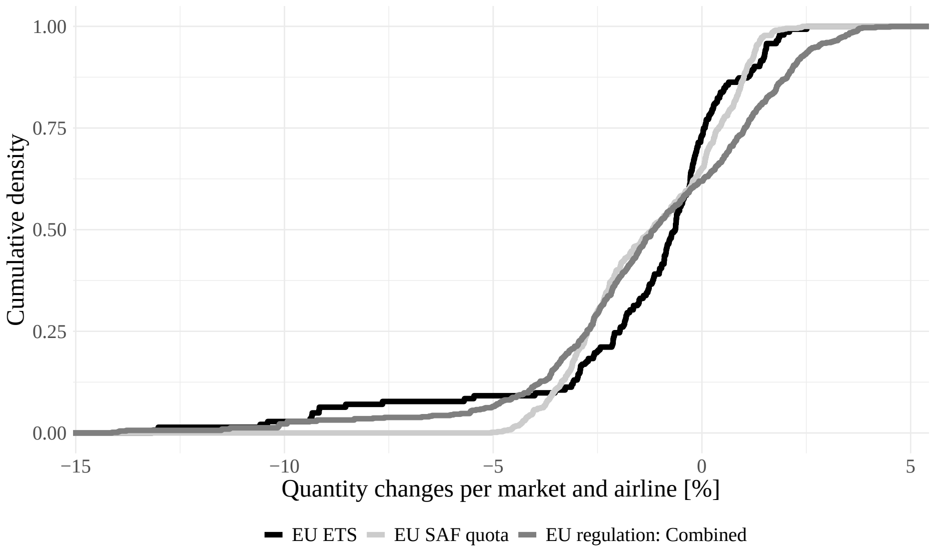
(b) Passengers $\overline{Q}_{mf}$ (=number of tickets)

Notes: Simulated CDFs of percentage changes in (a) ticket prices and (b) quantities of markets including regulated flights under emissions-equivalent EU ETS and EU SAF quota, relative to the no-policy baseline. Geographical coverage of the regulations are summarized in Table 4. *EU ETS* applies a carbon price τ_{ij} = \$200 per ton of CO_2 on intra-EU flights; *EU SAF* imposes a κ = 2.8% blending mandate for departures from EU airports (regardless of destination). Both policies deliver a 7% emissions reductions.

Figure 9. **Ticket price and passenger impacts of standalone and combined EU climate policies for aviation**



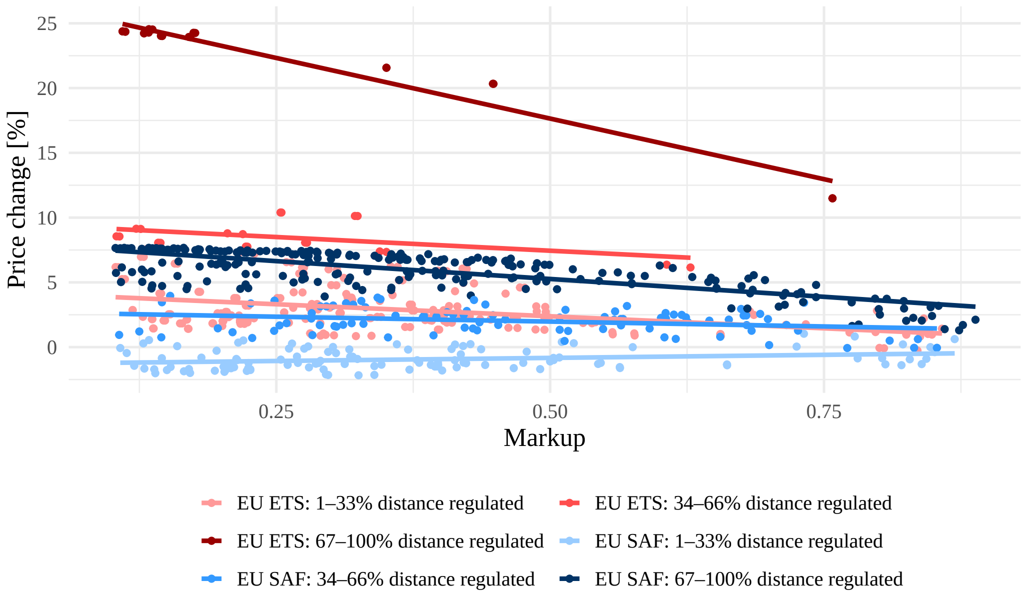
(a) Ticket prices ($\overline{P}_{mf}$)



(b) Passengers $\overline{Q}_{mf}$ (=number of tickets)

Notes: Simulated CDFs of percentage changes in (a) ticket prices and (b) quantities of markets including regulated flights under alternative EU aviation climate policies, relative to the no-policy baseline. The policy instrument mix for each scenario is summarized in Table 4. Policy stringency reflects planned EU regulation for 2035: *EU ETS* applies a carbon price τ_{ij} = \$200 per ton of CO_2 on regulated flights, *EU SAF* imposes a $\kappa = 20\%$ blending mandate, and *EU Combined* implements both policies. Notably, the emissions reductions under the EU ETS and SAF quota differ markedly (i.e., 7% and 22%, respectively).

Figure 10. **Ticket price changes and markups by market segment, climate policy instrument, and fraction of regulated route distance**



Notes: Scatter plot of market-segment price changes from EU aviation policies (EU ETS with carbon price \$200/tCO$_2$, EU SAF quota with 20% blending mandate) against market-segment markups. For each climate policy instrument, colors denote the fraction of regulated route distance in the entire route. Example: "EU ETS: 1–33%" indicates that up to one third of the route's total distance is subject to climate regulation, leaving at least two thirds unregulated. Solid lines show within-distance category OLS fits; slopes indicate the correlation between markups and price changes by distance category.

A. *Ticket Price and Passenger Impacts*

Figure 8 shows the simulated CDFs of percentage changes in ticket prices and quantities for markets including regulated flights under the EU ETS and EU SAF quota. To compare price and quantity impacts cleanly, we consider an EU ETS regime that levies \$200/tCO$_2$ on intra-EU flights and an emissions-equivalent EU SAF regime (implying a 2.8% blending mandate for all departures from EU airports, regardless of destination).[29] Differences between the two instruments are striking. First, the price-based EU ETS raises ticket prices far more than the EU SAF quota, owing to the quota's implicit output subsidy (mean and standard deviation under ETS (SAF quota): 4.5%, 6.1% (0.2%, 0.4%). Second, the SAF quota yields much less dispersion in price impacts across markets and airlines. With the SAF mandate, ticket prices are nearly unchanged; by contrast, under the EU ETS the distribution shifts: the median increase exceeds 2.5%, and 25% of market segments see increases above 5%. Impacts on passenger numbers mirror these price effects. Hence, relative to carbon pricing, the command-and-control approach produces

[29]The implied blending mandate is therefore comparable in magnitude to the EU's SAF quota of 2% adopted in 2025.

smaller cross-market variation in prices and quantities.

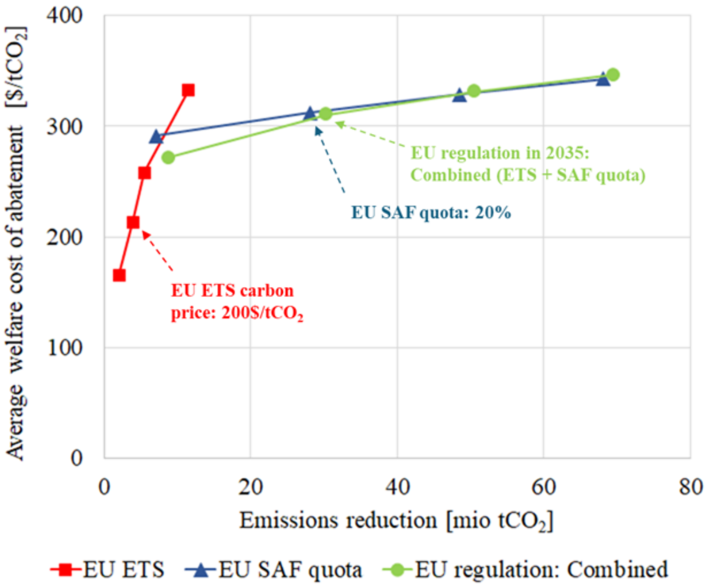
Figure 9 reports the same CDF plots of percentage changes in ticket prices and passengers for EU climate aviation policies envisaged for 2035: an EU ETS price of $200 per ton of CO_2 and an SAF blending mandate of 20%. Crucially, for similar-sized increases in ticket prices and declines in passenger numbers, emissions abatement is 3.1 larger under the SAF quota. Framed as a regulatory wedge, the EU ETS amounts to an explicit levy on CJF of 0.5$/l. Under the SAF quota, the implicit tax on CJF is only 0.2$/l, while SAF are implicitly subsidized by about 0.7$/l. The ETS carbon price is not high enough to pull SAF into the market; under SAF quota, however, 20% of total aviation fuel on regulated flights is sourced from SAF. Thus, on output prices and quantities, the SAF quota is markedly less intrusive yet delivers the same emissions reduction.

Figure 10 helps explain the heterogeneity in ticket-price responses to climate policy shown in Figure 9. First, the price-based EU ETS generates larger ticket price increases (up to 25%), whereas the SAF quota, which embeds an implicit output subsidy, limits increases (below 7.5%). Second, price effects scale with the regulated share of route distance (given that fuel consumption is proportional to distance): the EU ETS yields particularly large increases on intra-EU routes where more than two thirds of the distance is regulated (brown dots), and smaller increases on feeder-plus-long-haul itineraries (dark and light red dots). The SAF pattern is analogous: the smaller the regulated distance fraction, the smaller the price increase (blue dots). Third, conditional on instrument type and distance coverage, variation in ticket price increases aligns closely with market power across segments: lower markups (more competition) imply less scope to absorb input-cost shocks and thus higher pass-through to consumer prices (consistent with the downward-sloping within-distance category OLS fits). Figure 10 also underscores that a spatial representation of routes and markets, with explicit flight segments constituting a route, is essential to capture heterogeneous price (and quantity) responses to aviation climate policy, and, hence, to evaluate welfare.

B. Cost-Effectiveness

Figure 11 reports the emissions impacts and AWC of current and prospective EU climate policies for aviation. As with the (hypothetical) global policies, the cost-effectiveness ranking among sub-global EU aviation climate policies clearly favors the SAF quota over carbon pricing. The abatement-efficiency gap widens quickly with stringency: under the EU ETS, AWC rises steeply from $180/t$CO_2$ for low levels of abatement to $340/t$CO_2$ at 16% emissions reduction, whereas under the EU SAF quota AWC remains comparatively flat, about $300/t$CO_2$ at 8% and not exceeding $350/t$CO_2$ even at 70% reduction. As European airlines compete in oligopolistic output markets, the SAF quota's implicit output subsidy curbs costly abatement via demand contraction. By contrast, under the EU ETS, putting a carbon price on CJF raises the cost of flying relative to the SAF quota, reducing demand more and thereby exacerbating the pre-existing output distortion associated with imperfect competition.

Figure 11. **Cost-effectiveness of EU climate policies for aviation**



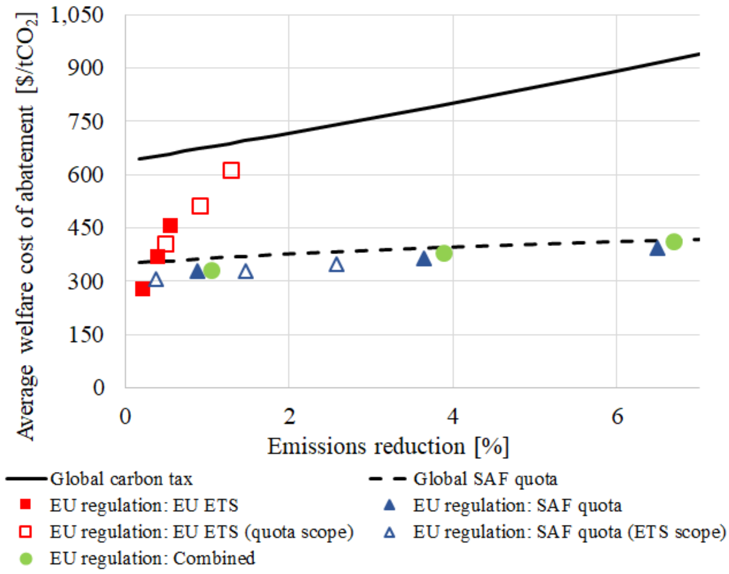
Notes: The graph shows the AWC and emissions impacts of EU climate policies for aviation. Welfare cost is measured as Hicksian equivalent variation in European regions. Reduced emissions refer to the absolute change in emissions compared to the baseline without policy measures, with the *EU regulation: EU ETS* and the *EU regulation: SAF quota* differing in terms of geographical coverage (see Table 4). For each policy, markers from left to right denote increasing stringency: for EU ETS scenarios, carbon prices τ_{ij} of \$100, \$200, \$300, and \$400 per ton of CO_2; for SAF-quota scenarios, blending mandates κ of 5%, 20%, 35%, and 50%.

C. Policy Design

The welfare-cost advantage of command-and-control over market-based policy under market power has important implications for climate-policy design. According to the standard view, compliance cost rise sharply when where-flexibility is limited, for example, when sectoral or regional scope is restricted. In addition, overlapping policies that layer technology or fuel mandates onto carbon pricing typically undermine cost-effectiveness by displacing low-cost abatement with higher-cost measures. However, when output markets are imperfectly competitive, several non-standard results emerge.

INSTRUMENT OVERLAP.—Aviation has been included in the EU ETS since 2012. In 2025, the EU added an SAF quota, thereby creating an overlapping regulatory framework. Figure 11 shows that instrument overlap need not be costly when output markets are imperfectly competitive; it can markedly improve policy performance. Adding the EU SAF quota to the ETS increases CO_2 abatement efficiency, reducing the AWC while raising total abatement. With a binding EU SAF quota calibrated to the 2035 mandate, the EU ETS becomes largely redundant for aviation emissions: it adds only marginal abatement by slightly raising ticket prices and depressing demand, whereas the bulk of CO_2 abatement comes from fuel switching to SAF

Figure 12. **Regulatory coverage and cost-effectiveness of EU climate policies for aviation**



Notes: The graph shows the welfare cost and emissions impacts of EU climate policies for aviation and for global instruments (carbon tax, SAF quota). Reduced emissions refer to the absolute change in global emissions compared to the baseline without policy measures. The instrument mix for each EU regulation is detailed in Table 4. For each policy, markers from left to right denote increasing stringency: for EU ETS scenarios, carbon prices τ_{ij} of \$100, \$200, and \$300 per ton of CO_2; for SAF-quota scenarios, blending mandates κ of 5%, 20%, and 35%. By 2035, the EU SAF quota requires a blending mandate of $\kappa = 20\%$. *EU regulation: Combined* pairs the low, medium, high configurations of the EU ETS with those of the EU SAF quota.

induced by the quota. Taken together, cost-effective and sizable CO_2 abatement hinges on including an SAF quota in the policy mix when output markets are imperfectly competitive.

FLIGHT COVERAGE AND GEOGRAPHICAL SCOPE.—The coverage of flight segments is a central design feature of aviation climate policy. Figure 12 compares the price-based ETS and the SAF blending mandate in their sensitivity to changes in regulatory scope, i.e. which flights are covered. Not surprisingly, extending ETS scope to match the broader SAF quota raises abatement (red filled vs. hollow squares). Despite the broader scope, however, the AWC increases. Spatial heterogeneity in market power explains this: a narrow ETS concentrates reductions on intra-EU markets with lower airline power; broader coverage shifts reductions to routes with non-EU segments, where stronger market power makes abatement costlier through added output distortions. By contrast, SAF-quota welfare cost is largely insensitive to scope (blue filled vs. hollow triangles): abatement is mainly through fuel switching, so demand changes are small and markup heterogeneity matters little. Thus, under imperfectly competitive output markets, regulatory scope matters more for carbon pricing than for the command-and-control blending mandate.

SUBGLOBAL VS. GLOBAL POLICIES.—Similarly, a narrow, sub-global climate policy need not be more costly than a broad, global policy when market power varies spatially across output markets. Figure 12 shows that the EU ETS (red filled squares) delivers modest abatement at lower cost than a global carbon tax (solid black line) because EU-covered carriers operate with lower markups than non-EU competitors (see Figure E.1). As abatement deepens, the EU ETS's narrower geographic scope drives cost up sharply, making a sub-global carbon price ill-suited for ambitious reductions in global aviation emissions. By contrast, a sub-global command-and-control policy performs well: since an SAF quota cuts emissions mainly via fuel substitution rather than demand reductions, spatial heterogeneity in market power has little effect on AWC. Consequently, the EU SAF quota (blue filled triangles) closely tracks the cost of a global SAF quota (dashed black line).

CARBON LEAKAGE.—A central risk of spatially limited climate policy is carbon leakage, defined as the ratio of emissions increases in unregulated regions to emissions reductions in regulated regions. We find that instrument choice, not scope, is the dominant driver of leakage.[30] The EU ETS, whether confined to intra-EU flights or extended to all EU departures, yields leakage rates of 31-34%. By contrast, the SAF quota produces markedly lower leakage of 15-20%. The intuition is the regulatory wedge each instrument creates: the ETS levies a high per-unit emissions cost, raising fares in regulated markets and inducing route substitution and carrier switching that push up emissions elsewhere. The SAF quota mainly changes the fuel mix rather than output, keeping price effects small and limiting evasion incentives even as coverage varies. Thus, spatially limited carbon pricing is more prone to spillovers, whereas the quantity-based SAF mandate is comparatively robust.

VII. Toward Sustainable Aviation: Net-Zero Emissions Growth

Can global aviation grow and go green? Decarbonizing aviation under current technology and passenger demand is already highly challenging, projected passenger growth in the near future further strains the sector's decarbonization. Driven by a growing global middle class and increased globalization, annual growth rates of 3.1–4.0% are plausible (ICAO, 2019; ATAG, 2021; Airbus, 2024; Boeing, 2024), implying roughly a 143% increase in passenger numbers by 2050. Against this backdrop, "net-zero growth" has been adopted as the near-term feasible pathway at global scale.[31]

We study scenarios that stabilize net emissions, accounting also for CORSIA offsets, at 2019 levels, mirroring CORSIA's requirement that airlines compensate emissions above 85% of 2019 CO_2 emissions. We ask: What are the welfare cost of achieving net-zero emissions growth with alternative policy instruments at sub-global and global scales? And how do emissions outcomes differ if CORSIA offsets

[30] In our model, carbon leakage arises from changes in the fuel market for CJF and from shifts in demand for air transport across and within markets. Appendix E details within-market effects as passengers substitute between carriers serving the same origin-destination pair via alternative routes, some of whose segments are not covered by EU regulation.

[31] The global aviation industry contends that this pathway is politically and administratively feasible, leverages existing monitoring-reporting-verification (MRV) and offsetting infrastructure via CORSIA (ICAO, 2024; EASA, 2022; IATA, 2024a), and serves as a bridge while in-sector abatement options, such as SAF, aircraft efficiency, operational improvements, scale up and long-lived fleets turn over (ATAG, 2021; IATA, 2024b).

Table 5. Welfare and emissions impact of policies to achieve net-zero emissions growth in global aviation by 2050

	Emissions [mio tCO_2]	Emissions reduction [%]	AWC [$/$tCO_2$]	Demand reduction [%]	Policy stringency
No policy 2050	1,589	–	–	–	–
No policy 2019	655	59	–	59	–
Global carbon tax	655	59	954	16	856$/$tCO_2$
Global SAF quota	655	59	766	11	53%
EU regulation + CORSIA					
Offsets are real	556	65	113	3	110$/$tCO_2$
Emissions are not offset	1,357	15	505	3	110$/$tCO_2$
EU regulation + CORSIA-tax	655	59	858	15	964$/$tCO_2^a$

Notes: [a]CORSIA-tax on each ton of CO_2 under geographical scope of CORSIA, not only on emissions above 85% of 2019 levels. EU policies: EU ETS 300$/$tCO_2$ and EU SAF quota 70%. Global quota, global tax and CORSIA-tax stringency is endogenously calculated to meet the net-zero-growth target of stabilizing emissions at 2019 levels. Demand changes and emissions reductions are given in relation to the 2050 no-policy benchmark.

are environmentally robust versus "hot air" due to integrity concerns?

GLOBALLY UNIFORM ACTION.—To the extent abatement must be generated within the sector, achieving net-zero emissions is highly costly—both absolutely and, at a minimum, relative to abatement in other sectors: we estimate an AWC for a global carbon tax of 954$/$tCO_2$ (Table 5). Consistent with our earlier analysis under imperfect competition, the tax's AWC exceeds that of a global SAF quota (766$/$tCO_2$). Reaching 2019 emission levels would require either a carbon tax of 856$/$tCO_2$ or an SAF blending mandate of 53%. Both policies induce SAF adoption, but the carbon tax depresses passenger demand more (-16%) than the quota (-11%). Compared with scenarios without passenger growth where emissions fall by 59% at AWC of 632$/$tCO_2$ (carbon tax) and 565$/$tCO_2$ (SAF quota), AWC is substantially higher because absolute abatement is larger.

CORSIA OFFSETS.—We also study the welfare and emissions effects of CORSIA, the international offsetting scheme, in combination with the EU ETS and the EU SAF quota at future stringency. We consider three cases. First, a functioning offset market with an exogenous price of 110$/$tCO_2$, capturing both price and offset effects. Offsets compensate emissions by financing external projects that reduce or remove CO_2 elsewhere, allowing airlines to maintain operations without direct abatement. Second, offset are "hot air" and provide no real emissions reductions.[32] Treating such offsets as equivalent to direct abatement can thus overstate environmental effectiveness. In this scenario, our modelling only captures the price effect. Third, a "CORSIA-tax" that applies a uniform carbon price to all emissions covered by the geographical scope of CORSIA. The difference from the two other cases is that, in this scenario, abatement must be achieved entirely within the sector.

Our results indicate that, if offsets function as intended, CORSIA could achieve net-zero growth at relatively low cost, with an AWC of 113$/$tCO_2$. At an offset price of 110$/$tCO_2$, total emissions would decline by 65%, surpassing the 59%

[32]The environmental integrity of CORSIA offsets is highly uncertain: up to 87% of global offsets across all sectors are considered high-risk and may not deliver additional reductions (Trencher et al., 2024).

reduction seen in no-growth scenarios, while demand would fall modestly by just 3%, partly due to overlapping EU policies. If the offset mechanism fails, AWC rises to 505\$/tCO_2 and emissions fall by only 15%, as demand declines somewhat due to the pass-through of offset cost into ticket prices. Importantly, the offset price does not create any incentive for SAF uptake and hence abatement takes place via the demand channel. Thus, reliance on an environmentally ineffective CORSIA also risks locking the aviation sector into a carbon-intensive CJF pathway. Unsurprisingly, welfare cost is highest when abatement must be achieved entirely within the sector. Under a CORSIA tax combined with EU policies, achieving net zero requires a carbon price of 964\$/tCO_2 and yields an AWC of 858\$/tCO_2. This policy mix yields lower AWC than the global tax but still implies a 15% demand decline.

VIII. Conclusion

Decarbonizing hard-to-abate industries—such as aviation—is central to meeting global climate targets. These sectors rely heavily on fossil fuels, offer limited substitution away from fuel inputs (dirty or clean), and operate in imperfectly competitive output markets. Using a granular spatial-equilibrium model of global aviation, we show that these features have first-order welfare implications for policy design: command-and-control regulation in the form of SAF quotas outperforms price-based Pigouvian instruments. Ignoring market structure understates the costs of carbon pricing when substitution is limited. SAF quotas are more robust to regulatory scope, generate less carbon leakage, and—when layered with existing carbon pricing—increase abatement while lowering welfare costs. Our results suggest that cost-effective decarbonization in aviation hinges on substantial SAF uptake, for which an SAF quota is the appropriate instrument.

Our analysis leaves room for future research. First, data constraints limit the granularity of empirically-derived markups. We infer markups from the observed number of airlines per region pair and a representative carrier, which likely overstates the number of firms per market and therefore yields conservative markup estimates. However, higher markups would only reinforce the superiority of SAF quotas over carbon pricing. Second, regional aggregation restricts the detail with which we can model economies of scale, scope, or density at the airline, market, or airport level. Yet, this aggregation makes a global representation of aviation tractable. Finally, our findings focused on one command-and-control instrument that is highly relevant for the decarbonization of aviation—SAF quotas. The specific context of other hard-to-abate sectors may call for different policy instruments and designs. To the extent that these instruments create explicit or implicit production incentives, our findings may still be useful for informing policy design in hard-to-abate sectors outside of aviation.

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Turbulence Ahead: Economic Policies for Decarbonizing Aviation

Supplementary material (for online publication)

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Appendix A. Proofs

Appendix A1: Proof of Proposition 1

Let $q = Q/N(Q)$. From (5), welfare is defined as:

$$W(Q) = \int_0^Q U'(y)\,dy - N(Q)\cdot C\left(\frac{Q}{N(Q)}\right) - N(Q)\cdot \delta\theta \cdot d\left(\frac{Q}{N(Q)}\right). \tag{A.1}$$

The social planner maximizes welfare by choosing Q:

$$\begin{aligned}\frac{dW}{dQ} &= U'(Q) - \frac{d}{dQ}\left[N(Q)\cdot C\left(\frac{Q}{N(Q)}\right)\right] - \frac{d}{dQ}\left[N(Q)\cdot \delta\theta\cdot d\left(\frac{Q}{N(Q)}\right)\right] \\ &= U'(Q) - \left[C'(q)\cdot \frac{dq}{dQ}\cdot N(Q) + C(q)\cdot\frac{dN}{dQ}\right] - \delta\theta\left[d'(q)\cdot\frac{dq}{dQ}\cdot N(Q) + d(q)\cdot\frac{dN}{dQ}\right].\end{aligned}$$

Using the derivative

$$\frac{dq}{dQ} = \frac{d}{dQ}\left(\frac{Q}{N(Q)}\right) = \frac{1}{N} - \frac{Q}{N^2}\cdot\frac{dN}{dQ} = \frac{1}{N} - \frac{q}{N}\cdot\frac{dN}{dQ},$$

and substituting back yields:

$$\begin{aligned}\frac{dW}{dQ} &= U'(Q) - C'(q)\cdot\left(\frac{1}{N} - \frac{q}{N}\cdot\frac{dN}{dQ}\right)\cdot N - C(q)\cdot\frac{dN}{dQ} \\ &\quad - \delta\theta\left[d'(q)\cdot\left(\frac{1}{N} - \frac{q}{N}\cdot\frac{dN}{dQ}\right)\cdot N + d(q)\cdot\frac{dN}{dQ}\right] \\ &= U'(Q) - \left[C'(q) + \delta\theta d'(q)\right] + \frac{dN}{dQ}\cdot\left[qC'(q) - C(q) + \delta\theta(qd'(q) - d(q))\right].\end{aligned}$$

This gives three effects: the benefit from extra output ($U'(Q)$), the social marginal cost ($C'(q) + \delta\theta d'(q)$) and the effects from entry caused by changes in average cost and average emissions due to N. To see the last effect, note that $C(q)$ is the cost of a typical airline and $qC'(q)$ is the marginal cost scaled by output per airline. So their difference approximates how average cost changes as airline size shrinks. Given constant-returns-to-scale, airlines' cost minimization is homogeneous of degree 1 and the fuel mix is determined by relative prices, not scale, which implies that input ratios (and hence emissions per unit of output) are scale-invariant, too. The entire last term thus drops out. The planner's optimality condition then becomes:

$$U'(Q) = C'(q) + \delta\theta d'(q). \tag{A.2}$$

To decentralize the social optimum when airlines face an output subsidy s and carbon tax t^{CO2}, note that the airlines FOCs in (1) become:

$$U'(Q)[1 + \Lambda(N)] = \frac{dC(q;\mathbf{p}, t^{CO2})}{dq} - s. \tag{A.3}$$

Note that if $s > 0$, it is a true subsidy, pushing up output (as the subsidy reduces the cost of producing an additional unit).[b] To obtain an expression for $dC(q; \mathbf{p}, t^{CO2})/dq$, note that with a carbon tax airlines solve:

$$C(q; t^{\mathrm{CO2}}) = \min_{k,c,d} \left\{ p_k k + p_c c + (p_d + t^{CO2}\theta)d \,\middle|\, f(k, c+d) = q \right\} .$$

Since the carbon tax only affects the cost via dirty fuel use, and assuming the firm optimally chooses input mix according to (3), we obtain:

$$\frac{dC(q; \mathbf{p}, t^{CO2})}{dq} = \frac{\partial C(q; \mathbf{p}, t^{CO2})}{\partial q} = C'(q) + t^{CO2} \cdot \theta \cdot \frac{dd}{dq} ,$$

where the first equality follows from the envelope theorem. Inserting this into (A.3) and comparing the resulting condition with (A.2) shows that $t^* = t^{CO2} = \delta$ and $s^* = U'(Q)\Lambda(N) > 0$ implement the social optimum.

Because $t^{CO2} = \delta$ targets a marginal distortion in the input choice and not a distortion in scale or output, it holds whether or not N is endogenous.

Even though both instruments enter the firm's cost structure, they target distinct margins. $t^{CO2} = \delta$ affects the fuel mix via input prices and condition (3). It changes p_z, which affects the MRTS and hence the optimal capital-fuel ratio and emissions intensity. s^* affects the firm's output choice by shifting the perceived marginal revenue, without affecting input prices or the MRTS. From the envelope theorem, we have: (i) at the optimum, the marginal impact of the carbon tax on marginal cost is entirely captured by its direct effect on the cost of emissions, and (ii) input re-optimization induced by the tax does not affect the derivative of cost with respect to output at the margin (i.e., the firm already optimally adjusts the input mix). Optimal policy thus only needs to correct the direct distortions, implying that the two instruments can be set independently. $\square$

Appendix A2: Proof of Proposition 2

Proceed as follows: *(a)* demonstrate that the implementation of a clean fuel quota effectively regulates the average emissions intensity per unit of aviation fuel consumed; *(b)* derive, from the airline's cost-minimization problem, the implicit tax on emissions that is induced by the quota; and *(c)* identify the implicit output subsidy by comparing the marginal cost of output under the quota to the marginal cost of output under a policy regime which only involves the quota-induced implicit emissions tax.

(a)—Define emissions as $e = \theta d$. Noting that $z = c + d$, the clean fuel quota $c/z \geq \gamma$ can be re-stated as an effective emissions intensity standard per unit of fuel z used: $e/z \leq \theta(1-\gamma)$, i.e. the emissions per unit of aviation fuel consumed must not be greater than $\theta(1-\gamma)$.

(b)—Given a binding emissions intensity constraint $e/z = \theta(1-\gamma)$, the Lagrangian

[b] Alternatively, s could be added to marginal revenue in which case $s < 0$ would represent a true subsidy. The former sign convention is more intuitive as it gives a positive subsidy value.

for the airline's problem is: $\mathcal{L} = p_k k + \tilde{p}_z z + \lambda[q - f(k,z)] + \mu[e - \theta(1-\gamma)z]$, where the Lagrangian multipliers λ and μ correspond to the production constraint and the emissions intensity constraint, respectively. From the FOCs (differentiating with respect to k and z) and re-arranging, we obtain: $\lambda = \frac{p_k}{f_k} = \frac{\tilde{p}_z - \mu\theta(1-\gamma)}{f_z}$, where $f_k := \partial f/\partial k$ and $f_z := \partial f/\partial z$ denote the respective marginal product (or marginal rate of transformation). To force the same fuel blend as the quota, the shadow price of emissions μ must equate the cost of fuel under a quota and under a tax: $\tilde{p}_z = p_d + \mu\theta(1-\gamma)$. Given binding the quota, $\tilde{p}_z = \gamma p_c + (1-\gamma)p_d$. Solving for μ yields the shadow price of emissions under the quota or the implicit emissions tax under the quota as shown in equation (6): $\hat{t}(\gamma, \Delta p, \theta) = \mu = \frac{\gamma(p_c - p_d)}{\theta(1-\gamma)}$.

(c)—The implicit subsidy per unit of output under quota is obtained as the difference between marginal cost of output under the quota and marginal cost of output under an emission tax only (which is set at the level implied by the quota). From the envelope theorem, $\frac{\partial \mathcal{L}}{\partial q} = \lambda$, i.e. marginal cost of output at the airline's optimal decision are given by λ. This implies that the implicit subsidy per unit of output under the quota can be obtained as: λ^{quota}: $\hat{s} = \lambda^{\text{tax}} - \lambda^{\text{quota}}$. If only an emissions tax is used, $\mu = 0$ (i.e., the quota constraint does not bind). Hence, from the FOCs derived under *(b)*, $\lambda^{\text{tax}} = \frac{\tilde{p}_z}{f_z}$. Under a binding quota, it holds that $\mu > 0$, and hence $\lambda^{\text{quota}} = \frac{\tilde{p}_z - \mu\theta(1-\gamma)}{f_z}$. The implicit per-unit output subsidy is then given by: $\hat{s} = \lambda^{\text{tax}} - \lambda^{\text{quota}} = \frac{\mu\theta(1-\gamma)}{f_z}$. Substituting for μ yields the implicit per-unit output subsidy under the quota as in equation (6) $\hat{s}(\gamma, \Delta p, \text{MRT}_{q,z}) = \frac{\gamma(p_c - p_d)}{\theta(1-\gamma)} \frac{\theta(1-\gamma)}{f_z} = \frac{\gamma(p_c - p_d)}{f_z} = \gamma(p_c - p_d)\frac{dz}{dq}$, where $\text{MRT}_{q,z} \equiv \frac{dq}{dz}$. Since the airline's marginal cost is identical under both the clean fuel quota (an emissions intensity standard per unit of fuel z used) and the equivalent tax-subsidy policy $(\hat{t}, \hat{s})$, i.e., $\frac{dC(p_k, \gamma p_c + (1-\gamma)p_d)}{dq} = \frac{dC(p_k, p_d + \hat{\tau})}{dq} - \hat{s}$, the airline's FOC from (1) is also identical across both policy regimes. In other words, under the quota, the airline behaves as if it receives a per-unit output subsidy $\hat{s}$ and faces an emissions tax $\hat{\tau}$, even though these are not explicitly imposed. □

Appendix A3: Proof of Proposition 3

Let equilibrium output and emissions under the quota and tax be $(Q^{\text{quota}}, E^{\text{quota}})$ and $(Q^{\text{tax}}, E^{\text{tax}})$, respectively, and marginal cost $\text{MC}^{\text{tax}} := \partial C(q, \mathbf{p})/\partial q$. Based on equation (5), the welfare difference under the two policy regimes $\Delta W = W^{\text{quota}} - W^{\text{tax}}$ is:

(A.4)

$$\Delta W = \underbrace{\int_{Q_{\text{tax}}}^{Q_{\text{quota}}} P(Q)\, dQ}_{\substack{\text{A:= Change in consumer} \\ \text{surplus}}} - \underbrace{\left[Q^{\text{quota}}\text{MC}^{\text{quota}} - Q^{\text{tax}}\text{MC}^{\text{tax}}\right]}_{\substack{\text{B:= Change in resource} \\ \text{cost}}} - \underbrace{\delta(E_{\text{quota}} - E_{\text{tax}})}_{\substack{\text{C:= Change in social} \\ \text{cost of emissions}}}.$$

A clean fuel quota thus yields higher welfare than a carbon tax (or, equivalently, get closer to the first-best) if: $\Delta W > 0$, or, equivalently $A - B > C$. To derive a local sufficient condition for when the quota yields higher welfare than the tax, first derive a linearized quantity response under the quota at the tax. The difference in airlines' FOC is $(1-\Lambda_{\text{tax}})\big[P(Q_{\text{quota}})-P(Q_{\text{tax}})\big] = MC_{\text{quota}} - MC_{\text{tax}} = -\hat{s}$. A first-order Taylor series expansion in ΔQ yields $\Delta Q \approx \frac{\hat{s}}{(1-\Lambda_{\text{tax}})\,|U''|}$.

Second, derive second-order expansions for A, B, and ΔE. A Taylor expansion around Q_{tax} gives

$$A \;\approx\; P(Q_{\text{tax}})\,\Delta Q \;+\; \frac{1}{2}U''\,(\Delta Q)^2 \,.$$

Using $MC_{\text{quota}} = MC_{\text{tax}} - \hat{s}$ and $Q_{\text{quota}} = Q_{\text{tax}} + \Delta Q$:

$$B \;=\; Q_{\text{quota}}MC_{\text{quota}} - Q_{\text{tax}}MC_{\text{tax}} \;=\; -\,Q_{\text{tax}}\hat{s} \;+\; \Delta Q\,(MC_{\text{tax}} - \hat{s})\,.$$

The change in emissions change is given by:

$$\Delta E \;\approx\; \frac{de}{dq}\,\Delta Q \;=\; \frac{\hat{s}}{\hat{t}}\,\Delta Q \;=\; \frac{\hat{s}^2}{\hat{t}\,(1-\Lambda_{\text{tax}})\,|U''|}\,.$$

Next, write $A - B \;=\; Q_{\text{tax}}\hat{s} \;+\; \Delta Q(P - MC_{\text{tax}} + \hat{s}) \;+\; \frac{1}{2}U''(\Delta Q)^2$, and note $P - MC_{\text{tax}} = \dfrac{\Lambda_{\text{tax}}}{1-\Lambda_{\text{tax}}}MC_{\text{tax}}$. Substituting terms from above yields:

$$A - B \;\approx\; Q_{\text{tax}}\hat{s} \;+\; \frac{\Lambda_{\text{tax}}MC_{\text{tax}}}{(1-\Lambda_{\text{tax}})^2|U''|}\,\hat{s} \;+\; \frac{\hat{s}^2}{(1-\Lambda_{\text{tax}})|U''|} \;-\; \frac{1}{2}\frac{\hat{s}^2}{(1-\Lambda_{\text{tax}})^2|U''|}\,.$$

Rewrite the welfare change in (A.4) as:

$$\Delta W \;\approx\; (A-B) \;-\; \delta\,\Delta E \;=\; \big[(A-B) - \hat{t}\,\Delta E\big] \;-\; (\delta - \hat{t})\,\Delta E\,.$$

Note that $(A-B) - \hat{t}\,\Delta E \;\approx\; Q_{\text{tax}}\hat{s} \;+\; \frac{\Lambda_{\text{tax}}MC_{\text{tax}}}{(1-\Lambda_{\text{tax}})^2|U''|}\,\hat{s} \;-\; \frac{1}{2}\frac{\hat{s}^2}{(1-\Lambda_{\text{tax}})^2|U''|}$, since the $+\hat{s}^2/[(1-\Lambda)|U'']$ term cancels with $\hat{t}\,\Delta E$. Divide by $\hat{s}$ and let $\hat{s}\to 0$: $\lim_{\hat{s}\to 0}\frac{\Delta W}{\hat{s}} \;=\; \Big[Q_{\text{tax}} + \frac{\Lambda_{\text{tax}}MC_{\text{tax}}}{(1-\Lambda_{\text{tax}})^2|U''|}\Big] \;-\; (\delta - \hat{t}) \times \frac{\Delta E}{\hat{s}}$ where we used $\Delta E/\hat{s} = \dfrac{de}{dq}\dfrac{\Delta Q}{\hat{s}} = \dfrac{de}{dq}\dfrac{1}{(1-\Lambda_{\text{tax}})|U''|}$. Multiplying both sides by $(1-\Lambda_{\text{tax}})|U''| > 0$ gives the condition (8) shown in the text:

$$\underbrace{(\delta - \hat{t})\,\frac{de}{dq}}_{\substack{\text{Unpriced marginal harm}\\ \text{per unit of output}}} \;<\; \underbrace{Q_{\text{tax}}(1-\Lambda_{\text{tax}})\,|U''|}_{\substack{\text{Inframarginal resource}\\ \text{cost savings}}} \;+\; \underbrace{\frac{\Lambda_{\text{tax}}\,MC_{\text{tax}}}{1-\Lambda_{\text{tax}}}}_{\substack{\text{Gains from correcting}\\ \text{market power distortion}}}\,.$$

□

Appendix A4: Proof of Proposition 4

DERIVING THE THRESHOLD CONDITION.—With emissions held fixed, the welfare difference arises from differences in consumer surplus and resource cost:

$$\Delta W = \int_{Q_{\text{tax}}}^{Q_{\text{quota}}} P(y)\,dy - \left[C(Q_{\text{quota}}) - C(Q_{\text{tax}})\right] .$$

Using a Taylor expansion around Q_{tax}:

$$\Delta W = \left[P(Q_{\text{tax}}) - MC(q_{\text{tax}})\right] \Delta Q - \frac{1}{2}\left[C'' + |P'(Q_{\text{tax}})|\right] \cdot (\Delta Q)^2 .$$

From the airlines' FOCs, $P(Q_{\text{tax}})(1-\Lambda) = MC(q_{\text{tax}})$ or $P(Q_{\text{tax}}) - MC = \Lambda P(Q_{\text{tax}})$, we get $P'(Q_{\text{tax}}) = -\frac{P(Q_{\text{tax}})}{Q_{\text{tax}}\varepsilon}$, with $\varepsilon := -\frac{P(Q)}{Q \cdot P'(Q)} > 0$. Substituting terms yields:

$$\Delta W = \Lambda P(Q_{\text{tax}}) \cdot \Delta Q - \frac{1}{2}\left[\frac{P(Q_{\text{tax}})}{Q_{\text{tax}}\varepsilon} + C''\right] \cdot (\Delta Q)^2 .$$

The quota imposes an implicit per-unit output subsidy: $\hat{s} = \gamma(p_c - p_d) \cdot \frac{dz}{dq}$. The airline's equilibrium output responds to the per-unit subsidy $\hat{s}$ according to the airline's FOC to:

$$P(Q) + qP'(Q) + \hat{s} = MC(q) ,$$

so the airline behaves as if the market price has risen by $\hat{s}$, encouraging greater output. This FOC implicitly defines the airline's optimal output $q(\hat{s})$ as a function of the subsidy. To examine its curvature, we totally differentiate the FOC with respect to $\hat{s}$. Let $Q = Nq$, and define the FOC as:

$$F(q, \hat{s}) = P(Nq) + Nq \cdot P'(Nq) + \hat{s} - MC(q) .$$

Then:

$$\frac{dq}{d\hat{s}} = -\frac{\partial F/\partial \hat{s}}{\partial F/\partial q} = \frac{1}{MC'(q) - N^2 P'(Nq) - N^2 q \cdot P''(Nq)} .$$

Given convex cost ($MC'(q) > 0$), downward-sloping demand $P'(Q) < 0$, and weakly concave or linear demand curvature $P''(Q) \le 0$, the denominator is positive. Hence, $\frac{dq}{d\hat{s}} > 0$, i.e. output increases with the subsidy. Convexity follows from:

$$\frac{d^2 q}{d\hat{s}^2} = \frac{d}{dq}\left(\frac{1}{\partial F/\partial q}\right) \cdot \left(\frac{dq}{d\hat{s}}\right)^2 = -\frac{\partial^2 F/\partial q^2}{(\partial F/\partial q)^3} .$$

Taking the second derivate of the FOC $F(q, \hat{s})$, we obtain:

$$\frac{\partial^2 F}{\partial q^2} = -MC''(q) - N^3 P''(Nq) - 2N^2 P'(Nq) < 0 ,$$

given $MC''(q) > 0$, $P'(Q) < 0$, and $P''(Q)$. Thus, $\frac{d^2 q}{d\hat{s}^2} > 0$: the airline's output is convex in the subsidy. This implies that output grows faster than linearly in $\hat{s}$. Since the subsidy is itself proportional to the marginal fuel requirement, $\hat{s} \propto \frac{dz}{dq}$, output is also convex in $\frac{dz}{dq}$. This convexity means that, for sufficiently high $\frac{dz}{dq}$, the quota-induced surplus gain from correcting Cournot underproduction outweighs the rising resource cost, leading to net welfare gains from the quota relative to the tax.

Let the total output increase under the quota be $\Delta Q = \phi(\hat{s})$, with $\phi' > 0$, $\phi'' > 0$, and define $\eta := \phi'(\hat{s})\gamma(p_c - p_d)$. The change in output can then be written as: $\Delta Q \approx \eta \frac{dz}{dq}$. Substituting into ΔW yields:

$$\Delta W = \Lambda P(Q_{\text{tax}})\eta \cdot \frac{dz}{dq} - \frac{1}{2}\left[\frac{P(Q_{\text{tax}})}{Q_{\text{tax}}\varepsilon} + C''\right]\eta^2 \left(\frac{dz}{dq}\right)^2$$

This is a quadratic in $\frac{dz}{dq}$, so the quota yields higher welfare than the tax at fixed emissions (i.e., $\Delta W > 0$) if and only if:

$\frac{dz}{dq} > 2\Lambda P(Q_{\text{tax}})\left[\eta\left(\frac{P(Q_{\text{tax}})}{Q_{\text{tax}}\varepsilon} + C''\right)\right]^{-1} := \bar{z}_q$, which holds when inputs are hard to substitute, i.e. with high $\frac{dz}{dq}$. This shows the condition $\frac{dz}{dq} > \bar{z}_q$ stated in the proposition.

INTERPRETATION OF THE THRESHOLD CONDITION.—We define the following composite object, which summarizes the marginal resistance to output expansion:

$$\Psi := \frac{P(Q_{\text{tax}})}{Q_{\text{tax}}\varepsilon} + C''.$$

This bundles the slope of marginal revenue (price sensitivity; $\frac{P(Q_{\text{tax}})}{Q_{\text{tax}}\varepsilon}$), and marginal cost curvature (production sensitivity; C'') into a single measure of output resistance. The threshold can then be written as:

$$\bar{z}_q(\Lambda) = \frac{2\Lambda P(Q_{\text{tax}})}{\eta\Psi}.$$

The nominator measures the "output distortion under the tax". The denominator measures the "output correction strength of the quota": $\eta\Psi$ captures how effectively the quota's implicit output subsidy translates into welfare gains. The term η measures the quantity response to the quota, while Ψ reflects how much marginal surplus is created when output expands.

GREATER MARKET POWER AMPLIFIES WELFARE ADVANTAGE.—We show that although the threshold fuel intensity $\bar{z}_q$ increases linearly in the markup Λ, the welfare gain from the quota increases faster in Λ at low levels, making the quota more likely to dominate the tax as market power rises. We derive the welfare difference between a quota and a tax (holding emissions fixed) as:

$$\Delta W = \Lambda P(Q_{\text{tax}})\Delta Q - \frac{1}{2}\Psi \cdot (\Delta Q)^2$$

where $\Delta Q = \eta\hat{s}$ and the implicit output subsidy under the quota is given by

$\hat{s} = \Lambda\kappa\frac{dz}{dq}$. Substituting, we obtain: $\Delta Q = \eta\Lambda\kappa\frac{dz}{dq}$

$$\Delta W(\Lambda) = \Lambda^2 \left(P(Q_{\text{tax}})\eta\kappa\frac{dz}{dq} - \frac{1}{2}\Psi\eta^2\kappa^2 \left(\frac{dz}{dq}\right)^2 \right) .$$

The welfare gain grows with market power at rate:

$$\frac{d}{d\Lambda}\Delta W(\Lambda) = 2\Lambda \left(P(Q_{\text{tax}})\eta\kappa \cdot \frac{dz}{dq} - \frac{1}{2}\Psi\eta^2\kappa^2 \cdot \left(\frac{dz}{dq}\right)^2 \right) .$$

The threshold increases at constant rate:

$$\frac{d}{d\Lambda}\bar{z}_q(\Lambda) = \frac{2P(Q_T)}{\eta\Psi} .$$

We are now in the position to compare the rate at which the welfare gain from using a quota increases with market power Λ to the rate at which the threshold fuel requirement increases, how they behave depending on the level of $\frac{dz}{dq}$: *(i)* for a low fuel requirement (small $\frac{dz}{dq}$), the welfare gain derivative grows slowly with Λ, as the output correction is small. In this region, the threshold $\bar{z}_q(\Lambda)$ may rise more quickly than the welfare benefit, making it harder for the quota to dominate; *(ii)* for moderate to high fuel requirements (moderate $\frac{dz}{dq}$), the welfare gain derivative grows more rapidly and may outpace the threshold growth. As Λ increases, the quota becomes increasingly favorable because the gain from correcting market power distortion grows faster than the increase in the fuel switching cost; and *(iii)* for high fuel requirement (large $\frac{dz}{dq}$), the welfare gain derivative continues to grow with Λ, but at a diminishing rate, as the cost of inducing output expansion becomes larger. Even though the threshold rises, the increasing welfare gain can still dominate, provided fuel substitutability remains low enough.

In summary, the quota's welfare advantage grows more strongly with market power when the fuel requirement is not too small. This reinforces that a quota is more likely to dominate a tax in the presence of both low substitutability and significant market power. This proves the first part of the second sentence in the proposition.

GREATER MARKET POWER ALLOWS QUOTA TO DOMINATE AT LOWER FUEL REQUIREMENT.——As derived above, the welfare gain from using the quota is:

$$\Delta W(\Lambda) = \Lambda^2 \left(P(Q_{\text{tax}})\eta\kappa\frac{dz}{dq} - \frac{1}{2}\Psi\eta^2\kappa^2 \left(\frac{dz}{dq}\right)^2 \right) .$$

Solving the inequality $\Delta W(\Lambda) > 0$ gives:

$$\frac{dz}{dq} < \frac{2P(Q_{\text{tax}})}{\Psi\eta\kappa} .$$

This expression defines an upper bound on the fuel requirement such that the quota remains welfare-superior. Now observe the following: *(i)* the lower bound for quota dominance, $\bar{z}_q(\Lambda)$, increases linearly in Λ; *(ii)* the feasible interval for fuel requirements that satisfy the dominance condition is:

$$\left(\bar{z}_q(\Lambda),\ \frac{2P(Q_{\text{tax}})}{\Psi\eta\kappa}\right)\ ;$$

(iii) the size of this interval shrinks with Λ, but remains nonempty as long as $\Lambda < 1/\kappa$. Now fix a fuel requirement $\frac{dz}{dq} = z^*$. Then, if $z^* < \bar{z}_q(\Lambda_1)$, the quota does not dominate at Λ_1. But since $\bar{z}_q(\Lambda)$ is increasing in Λ, for any $z^* > 0$, there exists a higher $\Lambda_2 > \Lambda_1$ such that: $z^* > \bar{z}_q(\Lambda_2)$, which implies $\Delta W(\Lambda_2) > 0$.

Hence, for any fixed level of fuel substitutability, there exists a high enough level of market power such that the quota dominates the tax. Thus, greater market power allows the quota to dominate at a lower fuel requirement, because the welfare benefit from correcting underproduction increases more than proportionally with Λ. This proves the second part of the second sentence in the proposition.

DEGENERATE CASE: PERFECT COMPETITION.—When $\Lambda = 0$, i.e. under perfect competition, the threshold condition $\frac{dz}{dq} > \bar{z}_q$ becomes $\frac{dz}{dq} > 0$, which is trivially satisfied. However, the threshold condition is derived under the assumption $\Lambda > 0$. In the limiting case of $\Lambda \to 0$, the welfare expansion simplifies to:

$$\Delta W = -\frac{1}{2}\Psi(\Delta Q)^2 < 0,$$

where $\Delta Q > 0$ is the output expansion induced by the quota's implicit subsidy. Since the first-order benefit of correcting the output distortion vanishes ($\Lambda = 0$), the second-order welfare loss from excessive output dominates. Thus, under perfect competition, the quota strictly reduces welfare relative to the tax. We therefore condition Proposition 4 on $\Lambda > 0$. □

Appendix B. Effective Air Transport Network and Data Processing

This appendix complements Section IV.A by detailing (1) the empirical construction of the effective global air transport network $\mathbb{J}_{ijmf}$ and (2) the processing of the raw data on ticket prices and passengers flows for model calibration.

Appendix B1: Freedoms of the Air and effective air transport network

The effective network $\mathbb{J}_{ijmf}$ specifies the feasible routes available to airlines within specific markets. These routes are constrained by the regulatory framework of the *Freedoms of the Air* (ICAO, 1944). In constructing $\mathbb{J}$*ijmf*, we incorporate the following *Freedoms of the Air*:

(i) the *First Freedom Right* ("the right [...] granted by one State to another State or States to fly across its territory without landing"),

(ii) the *Third Freedom Right* ("the right [...] granted by one State to another State to put down, in the territory of the first State, traffic coming from the home State of the carrier"),

(iii) the *Fourth Freedom Right* ("the right [...] granted by one State to another State to take on, in the territory of the first State, traffic destined for the home State of the carrier"), and

(iv) the *Sixth Freedom Right* ("the right [...] of transporting, via the home State of the carrier, traffic moving between two other States (not incorporated into any widely recognized air service agreements").

To account for code sharing, we additionally allow for the following *Freedoms of the Air*:

(v) the *Fifth Freedom Right* ("the right [...] granted by one State to another State to put down and to take on, in the territory of the first State, traffic coming from or destined to a third State")

(vi) the *Eighth Freedom Right* ("the right [...] of transporting cabotage traffic between two points in the territory of the granting State on a service which originates or terminates in the home country of the foreign carrier (not incorporated into any widely recognized air service agreements").

Although countries differ in the air traffic rights they grant, and variations exist beyond the freedoms discussed here, our assumptions are reasonable within the regional aggregation of our quantitative framework. The first five *Freedoms of the Air* are widely recognized internationally, whereas the sixth to ninth freedoms rely primarily on bilateral or multilateral agreements.

In addition to the *Freedoms of the Air*, we incorporate explicit assumptions regarding flight operations by FSNC and LCC airlines. Here, we closely follow standard assumptions in the established literature on modelling air transport networks (Efthymiou and Christidis, 2023; Števárová and Badánik, 2018). Specifically, we assume that FSNCs (a) operate flights between a hub airport and a non-hub airport within their home region, (b) flights between a hub airport in their home region and a hub airport in a foreign region, and (c) between a hub and a non-hub airport in a foreign region, provided that the overall itinerary originates or terminates in the FSNC's home region (in this way we account for code sharing). LCCs are assumed to operate point-to-point flights between non-hub airports, with one airport in the home region of the respective airline.

Appendix B2: Data processing

We process the raw data on ticket prices and passenger flows for model calibration in four main steps.

FILTERING AND AGGREGATION.—The data are initially filtered to retain only airline-region pairs ($rr'a$) for which annual passenger volumes exceed 100 and average fares are at least \$40. We then aggregate passenger data from individual airlines to representative airlines ($rr'a$ to $rr'f$) by summing across all airlines assigned to a given representative carrier f.

MAPPING TO REPRESENTATIVE AIRLINES.—The assignment of individual airlines a to representative airlines f follows a two-step procedure, which comprises: (1) regional matching (each airline is matched to its home region based on its IATA code), and (2) carrier type classification (airlines included in the LCC list by ICAO (2017) are assigned to the LCC group; for remaining airlines, classification is conducted manually using publicly available sources). Each airline is either classified as an LCC, a FSNC, or excluded from the dataset if reliable classification is not possible. This defines a many-to-one mapping from airline a to airline f.

AGGREGATION OF QUANTITY AND PRICE INFORMATION.—Using this mapping, we derive from $\overline{Q}_{rr'a}$ the aggregated passenger numbers between region by airline f, $\overline{Q}_{rr'f}$. To obtain prices consistent with this aggregation $\overline{P}_{rr'f}$, we compute the passenger-weighted average price based on $\overline{P}_{rr'a}$. After aggregation, a second filtering step is applied to ensure that only representative airlines f serving region pairs (r, r') with more than 10,000 annual passengers $\overline{Q}_{rr'f}$ are retained for further analysis.

MAPPING TO MARKETS.—The data gives us information on booked tickets in a market m defined by a region pair rr'. The challenge is now to transform $\overline{Q}_{rr'f}$ to $\overline{Q}_{mf}$. We start by mapping airport pairs ij to markets m. Origin airport i and destination airport j are connected along different routes by different airlines f. Using the effective network $\mathbb{J}_{ijmf}$, we first establish that if airline f is a LCC from region r or r', the observed demand $\overline{Q}_{rr'f}$ is between non-hub airports of the respective regions. The airline f serves market m that connects ij in regions r and r' directly without intermediate stops. Second, according to the effective network $\mathbb{J}_{ijmf}$ if $\overline{Q}_{rr'f}$ involves an FSNC from a third country, it links hub airports in regions r and r' via the carrier's home hub airport. Third, when airline f serving $\overline{Q}_{rr'f}$ is an FSNC from the origin region r or the destination region r', the effective network $\mathbb{J}_{ijmf}$ does not provide additional insights. We therefore assume that $\overline{Q}_{rr'f}$ in that case is equally split between $\overline{Q}_{mf}$, $\overline{Q}_{m'f}$, $\overline{Q}_{m''f}$, and $\overline{Q}_{m'''f}$, where m connects ij, m' connects $i'j$, m'' connects ij', and m''' connects $i'j'$. Here, i and j represent hub airports, while i' and j' are non-hub airports. In all four cases, the local FSNC f connects the regions through their respective hub airports.

Appendix C. Markup-Pricing Formula and Calibration

Appendix C1: Derivation of Markup-Pricing Formula

This appendix derives the markup-pricing formula in (16). In market segment mf, airline s chooses Q_s^{mf} to maximize profits Π_s^{mf} as defined by (14). Taking standard

FOCs yields:

$$\begin{aligned}\frac{\partial \Pi_s^{mf}}{\partial Q_s^{mf}} &= P_s^{mf} + Q_s^{mf}\frac{\partial P_s^{mf}}{\partial Q_s^{mf}} - C_s^{mf} \\ &= P_s^{mf} + P_s^{mf}\underbrace{\left(\frac{Q_s^{mf}}{P_s^{mf}}\frac{\partial P_s^{mf}}{\partial Q_s^{mf}}\right)}_{=:\eta_s^{mf}} - C_s^{mf} = 0\,.\end{aligned}$$

Rearranging gives the markup rule in (15):

$$P_s^{mf}\Big(1 - \Lambda_s^{mf}\Big) = C_s^{mf}\,,$$

where the markup is given by:

$$\Lambda_s^{mf} = \frac{1}{\eta_s^{mf}}\,.$$

η_s^{mf} is the airline's perceived own-price elasticity of demand.

Assuming symmetric airlines and homogenous products in a market segment, let the total quantity in market segment mf be $Q_{mf} = \sum_j Q_j^{mf}$ and let $P_s^{mf}(\cdot) = P_{mf}(Q_{mf})$ denote the common price. Then, $\frac{\partial P_s^{mf}}{\partial Q_s^{mf}} = \frac{dP_{mf}}{dQ_{mf}}$. Plugging this into the inverse elasticity term yields:

$$\frac{1}{\eta_s^{mf}} = \frac{Q_s^{mf}}{P_{mf}(Q_{mf})}\frac{dP_{mf}}{dQ_{mf}} = \underbrace{\frac{Q_s^{mf}}{Q_{mf}}}_{\psi_s^{mf}}\ \underbrace{\frac{Q_{mf}}{P_{mf}(Q_{mf})}\frac{dP_{mf}}{dQ_{mf}}}_{-\frac{1}{\varepsilon_{mf}}} \ = \ -\frac{\psi_s^{mf}}{\varepsilon_{mf}},$$

where

$$\varepsilon_{mf} \equiv -\frac{dQ_{mf}}{dP_{mf}}\frac{P_{mf}}{Q_{mf}} > 0$$

is the market-segment mf price elasticity, and ψ_s^{mf} is airline s' market share in segment mf (which is equal to the quantity share under a common price). With N_{mf} symmetric Cournot competitors, $\psi_s^{mf} = 1/N_{mf}$. Hence

$$\Lambda_s^{mf} = \frac{1}{N_{mf}\,\varepsilon_{mf}}\,,$$

which gives (16).

Appendix C2: Price Elasticity of Demand ε_{mf}

To derive ε_{mf}, we assume airlines consider two levels of the nested CES demand system (10)–(12): (i) substitution within a market m across segments mf (corresponding to (11)), and (ii) substitution between markets m within total air transport demand T_r (corresponding to (10)). When evaluating the price elasticity of demand, airlines thus abstract from substitutability with the outside good and from general-equilibrium income effects. While it is technically feasible to incorporate these broader responses into airlines' quantity-setting decisions, it is reasonable to assume that firms only "look two layers up", since both the share of air travel in overall consumption (T_r relative to Y_r) and general-equilibrium income effects are sufficiently small. Put differently, airlines perceive demand as primarily local to their competitive environment rather than shaped by the entire economy.

Using the CES aggregation in (11), let

$$P_m = \left(\sum_f \beta_{mf} \, P_{mf}^{1-\rho} \right)^{\frac{1}{1-\rho}}$$

denote the price index of aggregated air transport services in market m. Using the CES aggregation for T_r in (10), let

$$P_r^T = \Big(\sum_{m \in \mathcal{G}_{r(m)}} \alpha_{mr} \, P_m^{1-\gamma} \Big)^{\frac{1}{1-\gamma}}$$

denote the price index of total air transport services T_r.

The inverse demand function for air transport services in market segment mf can be written as a function of the top-level aggregates:

$$P_{mf} = P_r^T (\alpha_{mr})^{1/\gamma} \left(\frac{Q_m}{Q_T} \right)^{-1/\gamma} (\beta_{mf})^{1/\rho} \left(\frac{Q_{mf}}{Q_m} \right)^{-1/\rho} . \tag{C.1}$$

Taking logs and differentiating with respect to Q_{mf} gives:

$$\frac{1}{\varepsilon_{mf}} := - \frac{\partial \ln P_{mf}}{\partial \ln Q_{mf}} . \tag{C.2}$$

Using the expenditure shares

$$e_{mf} \equiv \frac{P_{mf} Q_{mf}}{P_m Q_m}, \qquad \hat{e}_m \equiv \frac{P_m Q_m}{P_r^T T_r}$$

and (C.1), the RHS of (C.2) yields an explicit expression for ε_{mf}:

$$\frac{1}{\varepsilon_{mf}} = \rho \, (1 - e_{mf}) + \gamma \, e_{mf} \, (1 - \hat{e}_m) \ .$$

Thus, the market segment-level inverse elasticity can be expressed as a weighted sum of the higher-level elasticities, where the first term captures substitution across market segments within the same market and the second captures substitution across markets.

Appendix D. Robustness Checks: Welfare-Instrument Ranking

This section presents additional robustness checks of the welfare ranking between the global carbon tax and the global SAF quota, focusing on the price elasticity of ticket demand, the pre-policy fuel price gap, and the treatment of life-cycle emissions from SAF.

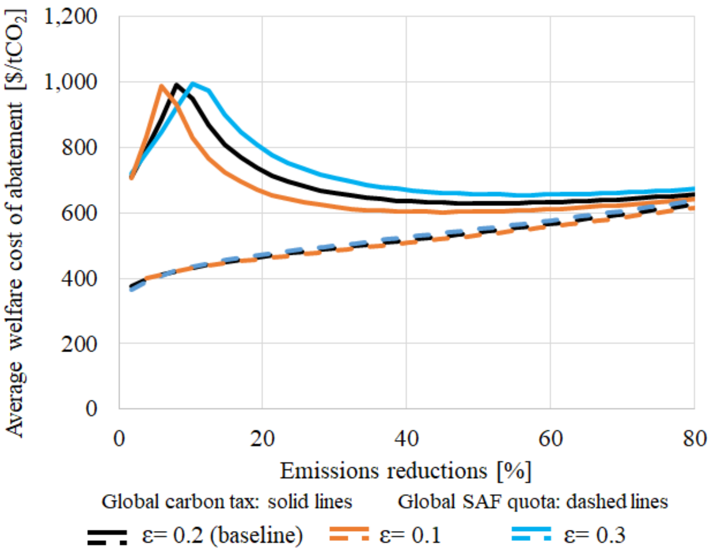
PRICE-ELASTICITY OF TICKET DEMAND.—When ticket demand is less elastic, consumers reduce ticket purchases less in response to higher prices. Under a carbon tax, much of the abatement—especially when SAF is relatively expensive—comes from contracting demand. If demand is inelastic, the tax must be set higher to achieve the same emissions reduction, pushing ticket prices up further. This magnifies welfare losses because prices rise sharply while quantities fall only modestly, inflating the AWC. By contrast, the SAF quota achieves most abatement through fuel substitution rather than demand contraction, and its implicit output subsidy cushions ticket prices. As a result, changes in demand elasticity have a smaller impact on both prices and quantities under the quota, making its AWC less sensitive to elasticity. Since both instruments' AWCs increase as demand becomes less elastic—though more steeply for the carbon tax—the quota maintains its cost advantage across the full elasticity range, leaving the welfare ranking unchanged (see Figure D.1(a)).

PRE-POLICY FUEL PRICE GAP.—A higher pre-policy fuel price gap, Δp, i.e. a higher initial SAF price relative to CJF, makes the fuel-substitution channel more costly. Under a quota, the higher Δp raises the implicit output subsidy, increasing output. To meet the same emissions target, the SAF share must therefore rise or demand must contract more sharply. Both adjustments increase resource cost: blending more SAF at a higher unit cost or incurring a larger deadweight loss from reduced demand. Consequently, AWC rises with Δp, despite the larger output subsidy. Under a carbon tax, the higher initial SAF price similarly increases the marginal cost of using SAF to reduce emissions intensity or forces greater reliance on demand contraction, both of which raise cost. Since both instruments are exposed to this channel, higher Δp increases AWC for each, while leaving their relative ranking largely unchanged (see Figure D.1(b) in the Appendix).

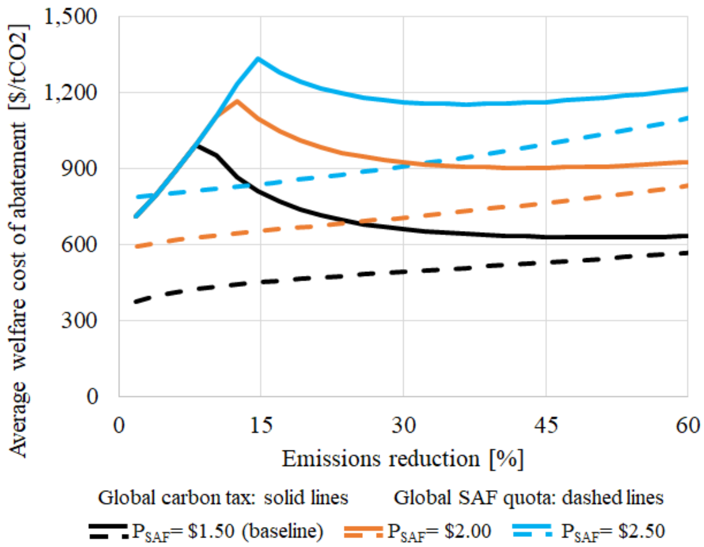
LIFE-CYCLE EMISSIONS ACCOUNTING OF SAF—While SAF is fully exempt from regulatory measures such as the EU ETS and CORSIA, it does generate emissions during combustion. SAF encompasses a range of fuel types, reaching from synthetic fuels to refined vegetable oils, with life-cycle emission reduction potentials varying widely, from approximately 50% to 90% (Braun, Grimme and Oesingmann, 2024). To evaluate the impact of SAF life-cycle emission values, we vary ζ_{SAF} assess whether this variation affects the welfare ranking when comparing a global carbon tax and a global SAF quota. Using Equation 22 we introduce different fuel intensities ζ_{SAF} for SAF. The main specification assumes that SAF cause no CO_2 emissions, i.e. $\zeta_{\mathrm{SAF}} = 0\frac{tCO_2}{l}$, while $\zeta_{\mathrm{CJF}} = 0.00258\frac{tCO_2}{l}$. Our robustness checks consider SAF carbon intensities of 25%, 50%, and 70% of CJF. For example, the 70% case assumes $\zeta_{\mathrm{SAF}} = (1-0.7)\,\zeta_{\mathrm{CJF}} = 0.000774\frac{tCO_2}{l}$, implying that, per liter of aviation fuel, SAF causes only 30% of the CO_2 emissions of CJF.

Figure D.2 reports the AWC ratio (global SAF quota/global carbon tax) across

Figure D.1. **Average welfare cost of abatement for global carbon and SAF quota: sensitivities**



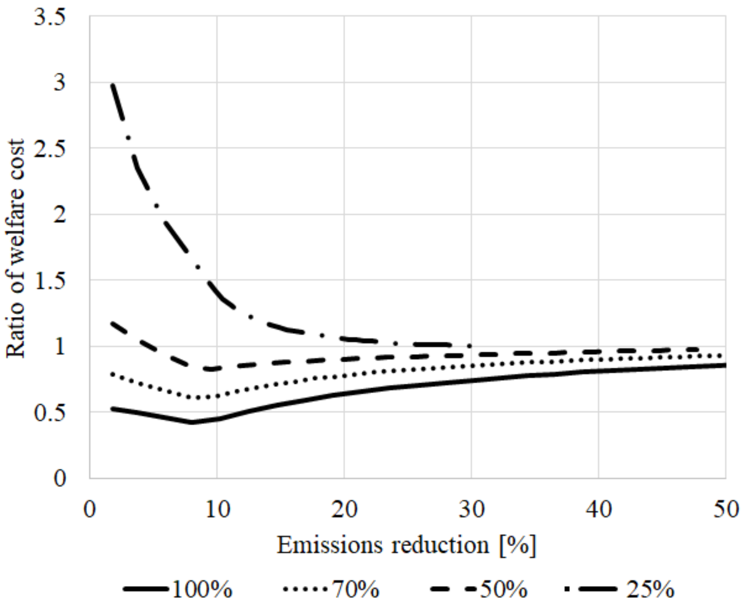
(a) Elasticity of demand for air transport services



(b) Pre-policy fuel price gap

Notes: The graph shows the average welfare cost of abatement under a global carbon tax (solid line) and a global SAF quota (dashed line) across emissions-reduction targets. Panel (a) presents sensitivity to the elasticity of demand for air transport. The main case (black) assumes $\epsilon = 0.2$ for switching away from aviation to the outside good; alternative cases assume $\epsilon = 0.1$ and $\epsilon = 0.3$. Panel (b) varies the pre-policy fuel price gap. The main case assumes SAF is three times more expensive than CJF (i.e., $\overline{P}^F_{SAF}/\overline{P}^F_{CJF} = 1.5/0.5$; see Table 2). Additional cases set $\overline{P}^F_{SAF} = 2.0\,\$/l$ and $2.5\,\$/l$, holding the pre-policy price of CJF constant. Note that aviation fuel prices adjust endogenously in equilibrium; this sensitivity pertains to variations in pre-policy benchmarks.

Figure D.2. **Welfare ranking of global SAF quota to global carbon tax for varying assumptions about carbon-neutrality of SAF**



Notes: This figure plots the AWC ratio (global SAF quota/global carbon tax) across emissions targets under Cournot competition varying the assumption about life-cycle emission reductions of SAF. The baseline model assumes 100% emissions reduction from SAF ($\zeta_{\text{SAF}} = 0\frac{tCO_2}{l}$). The alternative cases assume that SAF retains 70%, 50%, and 25% of the CO_2 content of conventional jet fuel (CJF), respectively.

emissions targets varying the assumption about life-cycle emission reductions of SAF. Assuming policy instrument choice does not systematically influence the selection of different types of SAF, the relative ranking of instruments is qualitatively robust for life-cycle reductions of 100-70%. When life-cycle emissions reductions are only 50%, the carbon tax outperforms the SAF quota at low abatement targets, while the SAF quota remains superior for reductions larger than 5%. If SAF's carbon intensity is only 25% below that of CJF, the welfare ranking reverses, regardless of policy stringency. Such fuels, however, are generally not considered SAF but low-carbon alternatives, highlighting the importance of eligibility rules that ensure sufficient climate benefits.

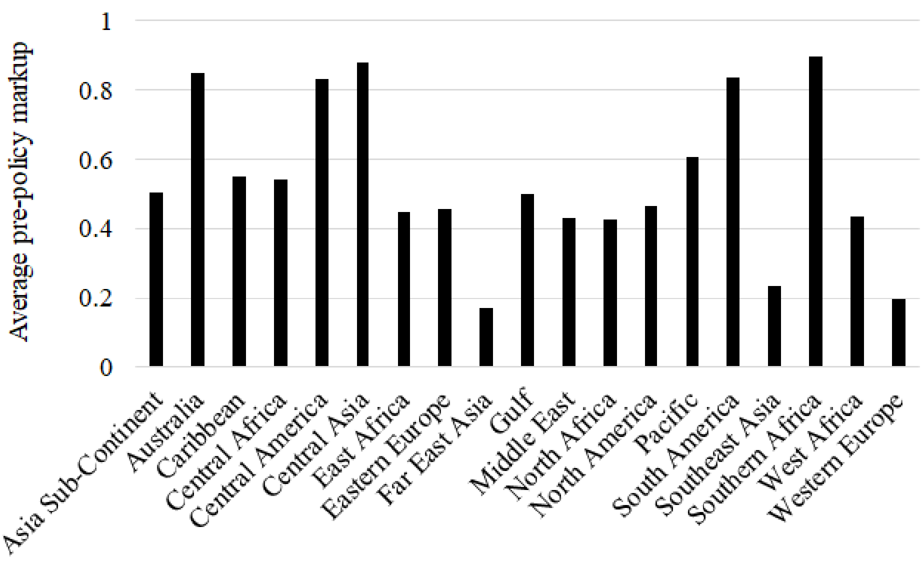
Appendix E. Additional Graphs and Tables

WEIGHTED AVERAGE PRE-POLICY MARKUP PER AIRLINE ORIGIN REGION.—Figure E.1 reports the estimated weighted average pre-policy markups per airline origin across all markets.

WITHIN-MARKET DEMAND SHIFTS IN RESPONSE TO CLIMATE REGULATION.—By mapping representative airlines to specific markets and defining the routes along which airlines operate via $\mathbb{J}_{ijmf}$, our quantitative model introduces an additional layer of heterogeneity. Some routes, and with that the airlines serving a market, are subject to sub-global regulations, while others remain unregulated or are only partially regulated along certain flight segments. As a result, the effects on prices and quantities vary across routes. Passengers are free to choose among airlines serving a given market, and this flexibility can amplify carbon leakage.

Table E.1 reports the changes in passenger demand by airline within a representative market connecting a hub airport in Eastern Europe with a hub in the Asian subcontinent, relative to the benchmark. Under the EU ETS, only the connection via the Western European hub is regulated. Consequently, the Western European FSNC experiences a decline in demand, while all other airlines benefit. By contrast, the EU SAF quota applies to all flights departing from the EU. Both direct connections (operated by the FSNCs based in Eastern Europe and the Asian Sub-Continent) are therefore fully regulated. The route via the Western European hub faces regulation on both segments, Eastern Europe to Western Europe and Western Europe to the Asian subcontinent, whereas routes transiting through Gulf or Middle Eastern hubs are regulated only on the first segment (Eastern Europe to the respective home hub). We find that regulation reduces demand for the affected airlines. The example market illustrates a broader pattern: in markets where geographic routing allows passengers to bypass regulated segments, demand tends to shift toward unregulated carriers, increasing the potential for carbon leakage.

Figure E.1. **Weighted average pre-policy markup per airline origin region**



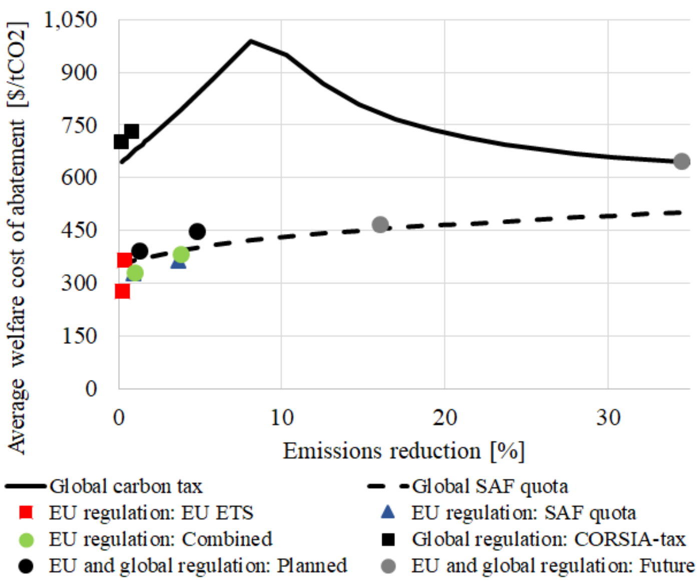
CURRENT AND PROSPECTIVE EU AND GLOBAL POLICIES ASSUMING NO PASSENGER GROWTH.—Figure E.2 reports the AWC and emissions impacts of current and prospective EU and global policies under the assumption that there is no growth in demand, i.e. passenger numbers is calibrated at the 2019 levels (but change in response to policy-induced relative price changes and income).

Table E.1. Within-market shift in air transport demand due to climate regulation for an exemplary market

	EU ETS	EU SAF quota
Direct flights		
FSNC Asia Sub-Continent	1.3	-2.5
FSNC Eastern Europe	1.6	-0.1
Connections with multiple segments		
FSNC Gulf	1.1	-0.5
FSNC Middle East	1.6	1.4
FSNC Western Europe	-2.1	-6.0

Notes: The table presents the percentage changes in passenger demand for the EU ETS and the EU SAF quota at 2035 stringency levels in the market connecting the hub airport in Eastern Europe with the hub-airport in Asia Sub-Continent. FSNC=Full Service Network Carriers. The FSNC from Asia Sub-Continent and Eastern Europe offer direct connections, the FSNCs form the Gulf, the Middle East and Western Europe serve the market via hub airports in their respective home regions.

Figure E.2. **Welfare cost and emissions impact of current and prospective EU and global climate policies for aviation assuming no passenger growth**



Notes: This figure reports the average welfare cost of abatement under imperfect competition for a global carbon tax (solid line) and a global SAF quota (dashed line) across a range of emissions reduction targets. These global policy outcomes are benchmarked against current and future climate regulation. We consider: (i) the EU ETS ; (ii) the EU SAF quota; (iii) a combined policy package of the EU ETS and the SAF quota; (iv) the CORSIA-tax; (v) a combined policy package of the EU policy bundle and the CORSIA-tax (at planned and possible future stringency) . For the EU ETS, we evaluate carbon prices of $100 and $200 per ton of CO_2. For the CORSIA-tax we consider prices of $10 and $40. For the SAF quota, we assess two levels of stringency: 5% and 20% SAF blending mandates. The first future policy bundle (”Future I”) assumes an EU ETS price of 500$/t CO_2, an SAF quota of 70% and a CORSIA-tax of 40$/t CO_2. The second future policy bundle (”Future II”) assumes the CORSIA-tax to increase to 500$/t CO_2. Demand for air transport services is calibrated at the observed 2019 levels on all markets and routes in the modeled network.

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