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Transition policies for climatically sustainable aviation

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ABSTRACT
Emissions from aviation are expected to grow. With evidence that the International Civil Aviation Organization's Carbon Offsetting and Reduction Scheme for International Aviation is an inadequate mitigation mechanism, there is interest in upscaling the sector's climate-related policies. This paper reviews potential aviation emissions mitigation policies against the background of emerging complexities, such as the large share of radiative forcing not covered under any policy agreement, as well as highly skewed demand distributions. In total, 30 voluntary, market-based and regulatory "transition policies" are identified and evaluated with regard to their potential to reduce emissions from air passenger transport and to initiate the transition to new fuels and propulsion technologies. The paper also discusses the potential public acceptance of differing policies. It concludes that the removal of fossil fuel and related subsidies represents a priority, supported by policy mixes comprising levies (CO_2, frequent fliers, premium classes) and a feed-in quota for definitively established sustainable aviation fuels. To reduce flight emissions is feasible in principle, but will require policy initiatives at the national level or at the level of regional jurisdictions such as the European Union.

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1. Introduction

Worldwide emissions of greenhouse gases from aviation have grown continuously through to 2019, increasing by a factor of 6.8 between 1960 and 2018 to an estimated total of 1,034 Mt CO_2 (Lee et al., 2020). This, together with aviation's non-CO_2 contributions to global warming, makes the sector responsible for an estimated 3.5% of net anthropogenic effective radiative forcing from human sources in 2011. COVID-19 caused a very significant decline in air transport and associated emissions, though the sector expects a rebound and continued growth in emissions (ICAO, 2016a, 2020a). This will make it more difficult to limit global warming, as all sectors are expected to make contributions to mitigation and low-carbon goals (IPCC, 2018). The aviation industry's own Carbon Offsetting and Reduction

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Scheme for International Aviation (CORSIA; ICAO, 2016a) is unlikely to make significant and meaningful contributions to emission reductions (Becken & Mackey, 2017; Scheelhaase, Maertens, Grimme, & Jung, 2018). As the European Union Emissions Trading Scheme for aviation (EU ETS) constitutes the only significant alternative policy initiative (Efthymiou & Papatheodorou, 2019), this has led to a renewed interest in climate policies for aviation (Larsson, Elofsson, Sterner, & Åkerman, 2019; Larsson, Kamb, Nässén, & Åkerman, 2018; Larsson, Matti, & Nässén, 2020).

The definition of such policy alternatives is complex for legal, distributional and economic reasons (Gössling & Humpe, 2020; Larsson et al., 2018; Lyle, 2018; Schäfer et al., 2019). For example, a significant share of radiative forcing from air transport is not addressed under CORSIA, requiring additional policy interventions. Research has also highlighted vast differences in air transport demand between nations and individuals, underscoring the need to consider the role of specific regions, the contributions of the very frequent fliers, as well as premium class travel and private aircraft (Gössling & Humpe, 2020). Finally, it remains unclear how the sector will make the transition towards alternative propulsion technologies that are significantly more costly than conventional jet fuel (Larsson et al., 2019; Schäfer et al., 2019). Currently, there is very limited evidence of support from the aviation industry for any policy that would increase the cost of air transport, limit volume growth, or question subsidies (ICAO, 2020a).

Resistance to transport supply change is also evident in some consumer groups (Alcock et al., 2017; Hares, Dickinson, & Wilkes, 2010). Other significant barriers include technology myths (Peeters, Higham, Kutzner, Cohen, & Gössling, 2016), volume-growth focused destination models (Hall, 2008), identity-coevolution with highly mobile lifestyles (Cohen, Hanna, & Gössling, 2018), and political entanglement with the aviation system that involves personal benefits (Gössling & Scott, 2018). Policies can address these roadblocks indirectly, for instance through awareness raising, though underlying structures of provision and specific interests will remain barriers to change (Geels, 2014; Geels, Sovacool, Schwanen, & Sorrell, 2017).

Against this background, there is an urgent question as to how air transport decarbonisation policies should be designed to address demand distribution and growth, technology change, and policy support. The purpose of this paper is to review and discuss the cornerstones of an "effective" transition policy mix for global aviation. It sets out with a discussion of aviation's contribution to global warming; establishes the international policy context; outlines weaknesses of ICAO's CORSIA scheme; and underlines the role of different stakeholders in supporting the transition. The paper then introduces a methodology to identify the full range of aviation transition policies for climate change, which may be voluntary, market-based or regulatory, to then evaluate their effectiveness in supporting policy goals. This leads to the definition of transition policies principally suitable to embrace complexities.

2. Theoretical background

2.1. Situating aviation in context

Commercial, private and military aviation all contribute to emissions of greenhouse gases including CO_2 and short-lived "non-CO_2" (NO_x, H_2O) that cause additional radiative forcing at flight altitude (Lee et al., 2009; Lee et al., 2020). Taken together, these are responsible for an estimated 3.5% of effective radiative forcings from all anthropogenic sources for all sectors of the economy (Lee et al., 2020). In absolute numbers, it is estimated that the sector emits close to one Gt CO_2 annually (978 Mt CO_2 in 2017; IEA, 2019b; or 1034 Mt CO_2 in 2018; Lee et al., 2020). Out of this total, 71% fall on commercial passenger transport, and another 17% on freight. Military flights are an estimated 8% of global aviation emissions, and private flights 4% (Gössling & Humpe, 2020). There is an expectation of continued strong growth of the sector once the COVID-19 pandemic is over, causing emissions to double or even triple by 2050 (ICAO, 2020a).

Recent research has added an important dimension of demand distribution, as emissions from air transport are highly skewed on global, national and individual scales (Gössling & Humpe, 2020). It is likely that only 11% of humanity participated in air travel in 2018, and at most 4% flew internationally between any two countries. There is also an important regional concentration. Including emissions from both domestic and international aviation, the USA alone emits as much (240 Mt CO_2) as the next ten largest Annex I country emitters taken together (UK, Japan, Germany, France, Australia, Russian Federation, Canada, Spain Turkey and Italy). Data for the USA also highlights the importance of individual distributions, as some 53% of the US-population did not fly in 2018, while the 12% of the most frequent fliers took 68% of all flights (ICCT, 2019a). Gössling and Humpe (2020) conclude that on a global scale, and considering higher emissions associated with premium class flights, 1% of humanity is responsible for more than 50% of all emissions from commercial passenger air transport.

Gössling and Humpe (2020) also find that a significant share of radiative forcing from aviation is not covered by any treaty or agreement. Non-CO_2 emissions are not addressed in any agreement. Emissions not covered also include military and private flight. The estimate is that only 36% of aviation's overall contribution to radiative forcing are theoretically addressed under the aviation industry's CORSIA scheme and, as the following section discusses, CORSIA in itself must be considered inadequate.

2.2. A critical appraisal of CORSIA

The governance of aviation emissions mitigation is uniquely subject to differing international legal instruments. Subsequent to the adoption of the Kyoto Protocol to the UNFCCC[1] in 1997 emissions of aviation bunker fuels (those used in international operations) continue to be treated by States through the International Civil Aviation Organization (ICAO) despite the effective lapsing of the Protocol at the end of 2020 and all sectors now being *de facto* encompassed directly by the 2015 Paris Agreement. ICAO's governing 1944 Convention on International Civil Aviation contains provisions which proscribe nation-based discrimination[2] while the UNFCCC uses a "bottom up" model based on varying Nationally Determined Contributions (NDCs). For its primary emissions mitigation instrument, CORSIA, ICAO addressed the UNFCCC principle of Common But Differentiated Principles and respective capabilities by an approach of not imposing any reductions but rather of carbon offsetting of emissions above 2020 levels with exemptions for routes to and from Least Developed Countries (LDCs), Small Island Developing States (SIDS) and Landlocked Developing Countries (LLDCs). At the same time the Organization determined that CORSIA be the only global market-based measure applying to CO2 emissions from international aviation, thereby discouraging greater ambition by individual States.[3] Since ICAO received its mandate in 1997, CO_2 emissions from international aviation have doubled. ICAO's basket of emissions mitigation measures for international aviation will contribute *pro rata* much less than any of the first NDCs to which 186 Parties have committed.

CORSIA's weaknesses have been acknowledged in various publications and are summarised in Table 1. CORSIA's focus on "carbon neutral growth" means that only the amount of emissions *exceeding* an average annual CO_2 baseline will be addressed by the scheme (ICAO, 2016b). Annually, this will leave more than half a Gt CO_2 from international commercial air transport unaccounted for (Gössling & Humpe, 2020). Non-CO_2 warming is outside the scope of CORSIA (ICAO, 2016b). The scheme is designed to start a pilot (voluntary, non-obligatory) phase in 2021, and then move through a first implementation phase (again voluntary) between 2024 and 2027 that involves a "share" of airlines, becoming fully operational from 2027. In June 2020, the ICAO Council, in the context of the COVID-19 crisis and on the basis of majority vote rather than previous hard-won consensus on all CORSIA actions, further weakened CORSIA by agreeing to amend its baseline to 2019 (rather than the originally envisaged average of 2019/2020; ICAO, 2020a; ICAO, 2020c). The scheme will not have any significant effect for many years to come and does not reliably reduce emissions. As the future capacity of CORSIA to address emissions is uncertain, it is of interest to note that being based on ICAO Assembly Resolutions and implemented through ICAO Standards and Recommended Practices, the scheme is not binding under international law.

CORSIA's concentration on offsetting is another concern, as there is an ambition to identify price-effective projects to minimise the additional cost imposed on airlines. This is evident in ICAO's "recommendations on CORSIA eligible emission units", which indicates a focus on afforestation and reforestation (ICAO, 2020b). Offsetting approaches

Table 1. Shortcomings of CORSIA.

Issue	Critique	Reference
Non-CO_2 emissions	Focus on CO_2 emissions; ignoring for example methane, NO_x and contrails or cloud formation, which cause significant additional radiative forcing.	Lee et al. (2009)
Partial inclusion of aviation	Exceptions exist for routes to and from Least Developed Countries, Landlocked Developing Countries and Small Island Developing States. Only 80% of international air traffic expected to be covered.	EC (2017)
Focus on "carbon neutral growth"	The offsetting mechanism of CORSIA, relating only to growth beyond 2020, is expected to cover only 25% of international aviation's emissions over the period 2021–2035.	ICCT (2017a)
Voluntary character	Voluntary in both pilot (2021–2023) and first phase (2024–2026). Only by 2027 would most airlines participate.	Lyle (2018)
Scale of offsets needed	CORSIA will require offsetting at unprecedented scales, i.e. an estimated 142–174 Mt CO_2 by 2025, and 443–596 Mt CO_2 by 2035.	ICAO (2017)
Low cost forest projects	Offsetting likely to focus on low-cost projects. Some of these imply a considerable risk of carbon leakage (for example, forest fires).	Correa, van der Hoff, and Rajão (2019); Laing, Taschini, and Palmer (2016); ICCT (2016a)
New propulsion technology needed	Offsetting is more price-effective than the development and dropping in of alternative fuels, which means that new propulsion technologies will not be stimulated through CORSIA.	ICCT (2018a); IEA (2019a)

also include Reduced Emissions from Deforestation and Forest Degradation in Developing Countries (REDD+). Yet, with the anecdotal examples of major forest fires in the whole West coast of the USA, Brazil, and Australia, as well as in a range of other countries from Sweden to New Zealand in 2019 and 2020, all forest-based projects must be considered unreliable for carbon storage. Offsetting consequently implies high financial, regulatory and reputational risks (Scott, Gössling, Hall, & Peeters, 2016), as well as climate mitigation risks.

CORSIA's focus on offsets also has implications for innovation. New propulsion technologies or fuels will not be developed, because their market-viability depends on a significantly higher carbon price (Larsson et al., 2019). According to the International Energy Agency (IEA, 2019a), the production cost of fossil jet kerosene is US$0.3–0.6 per L, while the production cost of advanced aviation biofuels is US$1.0–2.5 per L, i.e. a factor 3–4 higher.

These weaknesses in the set-up of CORSIA may be contrasted with low-carbon technology options that exist in principle, for example electric propulsion (battery/electric fuel cell) and sustainable alternative fuels (hydrogen, biomass-derived, or synthetic fuels) (Herz, Reichelt, & Jahn, 2018; Perner & Bothe, 2018; Reimers, 2018; Schäfer et al., 2019; Schmidt, Batteiger, Roth, Weindorf, & Raksha, 2018). All have disadvantages in comparison to jet fuel, apart from their higher cost. For electric flight with batteries there are calculations that energy density would have to increase to 800 Wh/kg of battery weight to reach a range of 1200 km, i.e. three times the current energy density (Schäfer et al., 2019). Larsson et al. (2019) conclude that electric flight may help avoiding only up to 5% of the CO_2 emissions caused by global aviation, as it is in particular long-haul travel that contributes to the largest share of emissions. As a result of weight/volume considerations, electric fuel cell and hydrogen flight would imply that the proportional number of passengers that can be carried by an aircraft will decline. These options make additional flights necessary, with implications for slot availability, staff requirements, and hence cost. Fundamentally different aircraft designs will only emerge in decades, and fleet renewal will take even longer (Schäfer et al., 2019). There is also a need to accommodate alternative technologies at airports, such as storage and charging infrastructure.

Selected alternative fuels have the advantage that they can be used on a drop-in basis as part of existing infrastructure, while they also have higher energy intensities. However, studies of lifecycle emissions suggest that alternative jet fuels produced from sugar and starch feedstocks deliver small emission benefits, while vegetable oil-based feedstocks can have even higher carbon intensities than conventional jet fuel. The ICCT (2017b) concludes that only lignocellulosic and waste feedstocks will provide significant emission reductions, though their availability is restricted by competing uses.

Non-biogenic synthetic fuels, which require far lower water and land inputs than biofuels, seem to represent the most suitable option for a long-term jet fuel (IEA, 2019a). Their main disadvantage is that to produce these fuels, vast amounts of renewable energy are needed, implying a significant land cost (Gössling, Humpe, Fichert, & Creutzig, 2021). If non-biogenic sustainable fuels are to make a significant contribution to emission reductions, there is also a need to vastly increase production capacity. A problem with non-biogenic synthetic jet fuels is that these do not resolve the issue of non-CO_2 warming effects (Bock & Burkhardt, 2019). As this short review of the cornerstones for emission reductions suggests, demand growth and distribution, energy intensities, and technology options will all have to be weighed into the discussion of effective mitigation policies. CORSIA cannot be expected to make a significant contribution to emission reductions and propulsion technology changes, as even acknowledged by the scheme's proponents: Maertens, Grimme, and Scheelhaase (2020) conclude, for instance, that "the scheme's environmental effectiveness will be rather limited in the first years", which, notably, refers to 2027 and beyond.

2.3. Transition policies, regime actors, and policy mixes

The academic literature has paid considerable attention to transitions, i.e. processes in which society or industry undergoes significant changes within comparably short periods of time. Any transition is a power struggle, in which different "regime actors" have diverging and often competing interests in change or maintenance of the status quo (Geels, 2014). Within given economic structures, firms and industries may have limited interest in policies seeking to curb emissions, as changes in cost structures will have implications for profitability and business models. This may be specifically true for the aviation sector, as profit margins are small and airlines economically vulnerable to changes in demand (Doganis, 2005). In this situation, air transport regime actors can be expected to employ material, instrumental, discursive or institutional forms of power to resist more fundamental system change (Geels, 2014). This has indeed been shown by Peeters et al. (2016), who find that green technology narratives have been employed to deflect regulation, or Gössling, Fichert, and Forsyth (2017), who reveal the wide range of subsidies forwarded to the sector. Low-carbon transitions can thus be expected to face "socio-political struggles" (Geels, 2014, p. 37), calling for the consideration of the various regime actors, i.e. aviation industry, policy makers, as well as individuals in their role as either consumers or citizens.

System change in transportation requires consideration of technologies, infrastructures, organisations, markets, regulations and user practices (Geels et al., 2017): It has been emphasised that the low-carbon transition will not be achieved by technology innovation (Geels, 2014) or carbon pricing alone (Rosenbloom, Markard, Geels, & Fuenfschilling, 2020). This calls for more complex sets of transition policies, in which policy processes, policy mixes and socio-technical change are assessed (Kern & Rogge, 2018). The objective here is to identify an ideal mix of policies to achieve a given goal in principle (Kern, Rogge, & Howlett, 2019).

Rosenbloom et al. (2020) emphasise that transitions research should move from perspectives of market failure to system change; from efficiency to effectiveness; from optimisation to transforming; and from universal towards context-sensitive policies that also consider political realities. This mirrors observations that policy mixes not only address market failures, but also structural and transformational failures (Weber & Rohracher, 2012). As a new global policy regime to replace CORSIA is unlikely (Larsson et al., 2019), there is a need to also discuss the divergent roles of regime actors: Mitigation will require national and regional policy initiatives, which again depend on societal support. Research has found that political support for carbon policies is much greater than individual willingness to "sacrifice" consumption (Kantenbacher, Hanna, Cohen, Miller, & Scarles, 2018). This may have changed as a result of recent developments, such as the Fridays-for-Future movement and its outcomes for social norm change.

Just a few years ago, studies noted that few air travellers were concerned about their contribution to climate change (Alcock et al., 2017; Hares et al., 2010). More recent studies detected growing concern, with a share of fliers reporting to fly less, or pledging to even give up flying altogether (Gössling, Humpe, & Bausch, 2020; Larsson et al., 2020). Studies also highlight that individuals may not change consumption choices, though they will support mitigation policies in their roles as citizens (De Bakker & Dagevos, 2012).

In conclusion, transition policy mixes should consider the roles of all regime actors, as well as the mechanisms through which these influence the transition. This may be envisioned as a self-reinforcing process: consumer-citizens influence demand, through their choices and policy support, and they create society's wider social norms regarding the desirability of air travel. This increases pressure on policymakers to introduce low-carbon legislation, which then forces the aviation sector to embrace technology change. The cost of innovation influences demand, and affects the social norms surrounding air travel.

Apart from the role of the different regime actors, the transition towards low-carbon aviation will also have to consider four issues as outlined in the preceding sections. The first is *accountability*, in light of the aviation industry's own approaches' inadequateness to achieve emission reductions, and the need for alternative actors – consumers or nation states – to take responsibility. Second, *comprehensiveness* in addressing emissions refers to the inclusion of both CO_2 and non-CO_2 warming. Industry currently only addresses a share of CO_2 from commercial passenger transport, and it pays no attention to the distribution of emissions between regions such as the EU, nations and individuals. Third, *future-proofing* refers to the necessity to introduce new propulsion systems. Last, public acceptance in terms of *common goals* needs to include a significant share of the population.

3. Methodology

The preceding sections have revealed the complexity that has to be embraced by air transport transition policies. To assess policy options against this background requires the development of a specific methodology that here takes the form of a three-step procedure to (i) identify available mitigation policies that can be implemented by nation states (*accountability*), (ii) assess these policies' effectiveness in supporting system change (*comprehensiveness, future-proofing*), and (iii) evaluate their public acceptance (*common goals*). Policies were identified based on a systematic search of the peer-reviewed and grey literature. This search was based on a recent discussion of policy regimes by Larsson et al. (2019), as well as specific searches of databases (Google Scholar, Ebsco). To add further policy suggestions, documents by non-governmental organisations were also evaluated, including in particular the work of The International Council on Clean Transportation (ICCT).

In total, 30 policies were identified, including those deemed "immature" by Larsson et al. (2019, p. 791) for difficulty of implementation. The list is not necessarily exhaustive and includes only generic policy types, i.e. it excludes suggestions to add specific amounts in taxes to ticket prices, as well as incentives such as to subsidise fuel research. Likewise, the paper does not consider policies such as to require a minimum length of stay in the destination. Policies indirectly affecting aviation, such as an expansion of railway systems or the introduction of incentives for train travel are also omitted. Focus is on direct energy use (fuel), i.e. energy use of infrastructures such as airports is not considered, nor are life-cycle analysis perspectives. The issue of freight is not discussed separately, the general focus is on passenger travel. All policies are described in detail in a Supplemental file.

Policies identified in the process are divided into voluntary, market-based and regulatory legislation. This distinction helps to assess the relative importance of each category, specifically in the evaluation of *effectiveness*. This is the second step in the methodology, which evaluates whether a policy affects demand, technology or social norms, and assesses whether a policy's effectiveness to reduce emissions is high, medium, or low. Scores for "effectiveness" are symbolised by plusses, with one plus sign (+) denoting policies with small and insignificant implications for emission reductions, two plusses (++) the more significant policies, and three plusses (+++) the most effective policies with a high potential to transform the sector. As the effectiveness of each policy depends on its exact characteristics (for example, a carbon tax may be implemented at US$10 or US $1000 per ton), the assessment generally assumes a more ambitious and progressive framing. Theoretically, single policies can bring emissions to zero: For example, a feed-in quota forcing the sector to use 100% non-biogenic synthetic fuels could theoretically fully decarbonise aviation by 2050. Likewise, a non-tradable cap on emissions that declines to zero by mid-century would force the sector to identify and introduce new technologies.

The purpose of the effectiveness rating is to show that policies have different outcomes in principle, and that they address different aspects. Figure 1 illustrates this multi-dimensionality by arranging policies according to their effectiveness and in relation to demand, technology, and social norm change. There is no clear-cut boundary between these dimensions: For example, a carbon tax also affects technology change as alternative fuels become economically more viable. Where relevant, policies are thus placed "between" dimensions, depending on their relevance for the respective policy fields. While there can be little doubt that policies are not equally effective (consider the difference between a voluntary and a mandatory carbon offset, for example), evaluation is inherently subjective. For this reason, the initial organisation of policies by the authors was presented to three colleagues working with air transport governance, who were asked to reposition policies in Figure 1 if they felt the assigned position to be inaccurate. They were simultaneously asked to identify and add further policies. This process did not lead to the identification of new policies, but did lead to small shifts in the positioning of some policies in Figure 1. The overall approach to the effectiveness scoring is thus expert-based, though it remains inherently subjective and hence indicative only.

Finally, the issue of *common goals* is considered in the discussion of public acceptability, the last step in the evaluation process. Larsson et al. (2019) suggest to rule out policy designs with high levels of coercion and direct/indirect effects on individuals that may alienate consumers. While this is a valid observation in principle, an important question is by whom specific policies are rejected. Earlier studies have determined that air travellers are unlikely to assume responsibility for emissions (Alcock et al., 2017; Cohen, Higham, & Reis, 2013; Hares et al., 2010; Kantenbacher et al., 2018), and it may thus be impossible to not alienate specific groups, such as the very frequent fliers. In contrast, it is desirable to garner the support of the wider public. Depending on viewpoint, different stakeholders may have diverging perspectives. These are discussed on the basis of the available literature.

4. Results: transition policies for aviation

Table 2 provides an overview of all policies that were identified, and sorted by policy type (voluntary, market-based, regulatory) and recipient (individual/society or aviation sector). The table illustrates that most policies would apply to the aviation sector and fall into the "market-based" and "regulatory" categories. Policies are not equally effective, though it needs to be noted that for many (carbon taxes, APD, emissions levy), their effectiveness will depend on the level at which these are set. Some represent transformative measures, others have modest or small effects.

Interrelationships are illustrated in Figure 1, which situates each policy within the field of demand, technology and social norm change. For instance, a quota for sustainable fuels will affect the carbon-content of propulsion systems (technology change); a carbon tax will reduce demand as the price of air travel increases (demand change); governmental communication strategies on energy-intense consumption will affect views of air transport as desirable (social norm change). Yet, as many policies have relevance for more than one of these dimensions, their location is indicative. For example, a progressive frequent flier tax will affect demand because of price increases, but it will also change views regarding the justifiability of the travel patterns (a social norm change). The closer to the outer ring of the model the policy is situated, the more effective it is considered in terms of its potential to reduce emissions.

Figure 1 indicates that most policies would primarily affect demand, even though some would also have relevance for technology change. Few – all of them voluntary policies – are directly relevant for social norm change. Voluntary policies are also the least effective in reliably contributing to emission reductions. Yet, policies such as carbon labels on air tickets are relevant in that they underline that climate change is real, while also supporting social norm change by increasing carbon literacy (Babakhani, Ritchie, & Dolnicar, 2017).

Effective policies to reduce emissions include air passenger duties, emission levies and carbon taxes (Falk & Hagsten, 2019). There is some evidence that price signal changes would have to be very significant in order to lead to negative growth (Markham, Young, Reis, & Higham, 2018; see also Mayor & Tol, 2010). Other measures that would likely have a reasonable effect for emission reductions are the introduction of a value added tax on all air travel, or a significant low-cost carrier duty. Removing VAT and fuel tax exemptions will have a similar effect, as all of these measures increase the cost of air travel. Market-based policies designed to consider distributional issues, such as the share of emissions caused by frequent fliers or the far higher emissions incurred in premium-class travel, can make more significant contributions to emission reductions. Minimum load factors have some potential to reduce emissions.

Highly effective measures include in particular those that limit the air transport system's expansion. For example, an annual reduction in overall emissions from an airline would reliably force the sector into greater efficiency (higher load factors, faster renewal of fleets, development of new propulsion systems). Carbon allowances or maximum flight quotas to address the very frequent fliers should also have very

Table 2. Policies for the transformation of the aviation sector.

Policy type[a]	Individual/society	Aviation sector
Voluntary	• Voluntary carbon offsets+ • Option to purchase SAF flight+ • Governmental communication++	• Carbon labels on tickets++
Market-based	• Emission levy++ • Air passenger duty++ • Progressive frequent flier tax++	• VAT for all air travel++ • Minimum fare rule++ • Assigning slots based on efficiency++ • Carbon-related landing charges++ • Fossil fuel carbon tax+++ • Staying financial aid, loans and tax relief+++ • Removing subsidies+++
Regulatory	• Mandatory carbon offsets+ • Removal of loyalty programs++ • Maximum flight quotas+++ • Personal carbon allowances+++	• Banning air transport advertisement++ • Speed reductions++ • Phasing out short-haul flights++ • Staying airport expansions++ • Minimum load factors++ • Faster replacement of inefficient aircraft+++ • Private flight synthetic fuel specification++ • Denser premium seating layouts+++ • Flight path changes+++ • Feed-in quota+++ • Annual reduction in emissions+++

Source: Babakhani et al. (2017); Larsson et al. (2018, 2019, 2020); Gössling et al. (2020); ICCT (2016b, 2018b, 2019); Jagers, Löfgren, and Stripple (2010); own policy designs.
[a]Policies apply to individuals, society, or different actors in aviation (manufacturers, airlines, airports, fuel suppliers); their effectiveness is assessed as low (+), medium (++), or high (+++) as described in the Methodology.

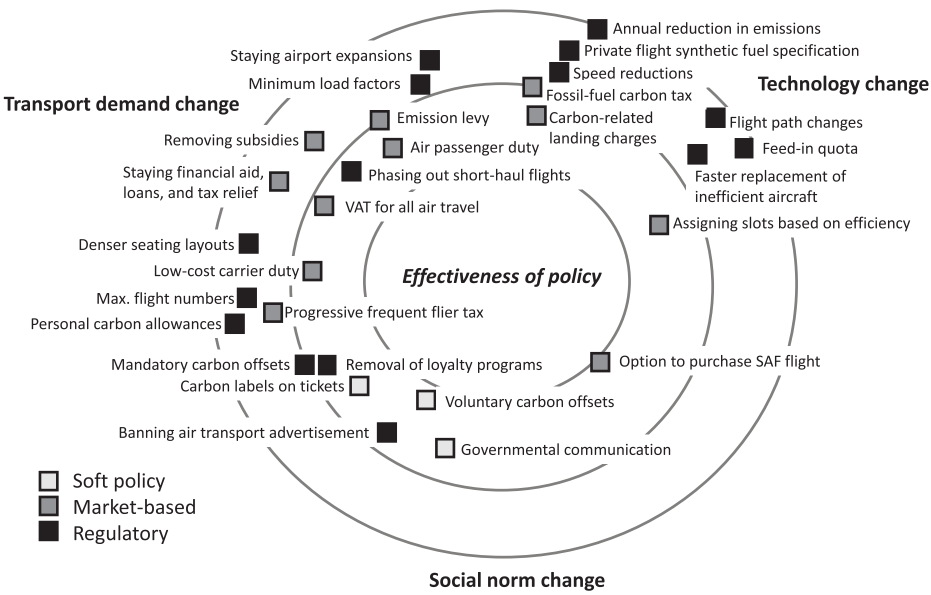

Figure 1. Policy dimensions and their relative effectiveness. *The further outside the concentric rings a policy is located, the more effective it is considered. See Methodology for further information on the positioning process.

significant and immediate effects on emissions. A feed-in quota forcing the transition from fossil to non-biogenic synthetic fuels until 2050 is another effective measure to bring about technology change. Less developed conceptually, though potentially with significant effects is a synthetic fuel specification for private aircraft, forcing the very wealthy to lead the transformation towards sustainable fuels. Likewise, a denser premium class seating layout requirement is an option with considerable potential to reduce emissions. Other effective measures include the removal of subsidies, the faster replacement of inefficient aircraft, speed reductions, the staying of airport expansions, the phasing out of old aircraft, or the limitation of slot numbers for inefficient aircraft. Flight path changes to avoid contrail formation is potentially an avenue to avoiding radiative forcing, with a potentially marginal increase in fuel use (Teoh, Schumann, Majumdar, & Stettler, 2020). Equity issues may be covered by policies reducing "non-essential" flights, limiting the frequent fliers, or addressing private air travel. The wide range of options to implement policies can be narrowed down to a combination of effective transition policies (Table 3).

Some policies in the mix overlap, or have similar, mutually self-reinforcing effects on demand. They can be implemented in addition to existing frameworks, such as the EU Emissions Trading Scheme for aviation. All are *supportive* of transitions towards national low-carbon trajectories for aviation, though they will only become significant if they are implemented at a globally relevant scale. As a much simplifying alternative, countries may debate whether it is possible to mandate a non-tradable annual reduction in overall emissions from the sector, as this measure would make the need for additional policies redundant and leave it to the market to devise the best way forward. As most emissions from aviation occur in North America (in both absolute and per capita terms), policies in this country will potentially make more significant contributions to mitigation.

While some studies have implied disinterest to fly less and resistance to any policy increasing the cost of air travel (Cohen, Higham, & Cavaliere, 2011; Kantenbacher et al., 2018; Randles & Mander, 2009), more recent studies affirm more complex interrelationships (Cohen et al., 2018; Gössling et al., 2020; Larsson et al., 2020). For example, there is evidence that some very effective measures to reducing emissions are contested, as

Table 3. Transition policies effectively addressing complexity.

Issue covered	Policy example	Mechanism
Non-CO_2 (notably contrail) forcing	Flight path changes	Regulatory, technology
Curbing growth	Carbon tax	Market-based, demand
Domestic emissions from aviation	Phasing out of domestic flights	Regulatory, demand
Frequent fliers	Progressive frequent flier tax	Market-based, demand
	Carbon labels on air tickets	Voluntary, social norm
Energy intensities – inefficient aircraft (high emissions per pax.)	Faster replacement of inefficient aircraft	Regulatory, technology
		Market-based, technology
Energy intensities – premium classes	Airport slots assigned on efficiency basis	
Energy intensities – private flight		Market-based, demand
	Air passenger duty for premium classes	Regulatory, demand
	Synthetic fuel specification	
Technology change	Removal of subsidies and State aid	Regulatory, technology
	Feed-in quota for synthetic fuels	Market-based, demand

both Larsson et al. (2020) and Gössling et al. (2020) find that policies budgeting or limiting air travel have lower support in the population. Yet, Larsson et al.'s (2020) Likert-scale data also reveals that there is a concentration of negative views regarding frequent flier taxes, perhaps by those profiting from the current system. Larsson et al. conclude that "fairness and effectiveness appear to be crucial aspects for the design of new policies" (Larsson et al., 2020, p. 1). This raises the question whether "fair" and "effective" are mutually exclusive, or whether "fair", from wider societal viewpoints, implies a need to take on the high emitters.

While these interrelationships require further research, existing studies suggest that much air transport is induced, while transition policies are sanctioned by the public. Studies have demonstrated that many flights lack importance in the view of the air travellers themselves, and that even frequent business travellers may wish to fly less (Cohen et al., 2018). There is significant support for a biofuel quota and carbon labels (Larsson et al., 2020), as well as regulatory policies to curb emissions from aviation and to remove subsidies (Gössling et al., 2020).

5. Conclusions

It is likely that emissions from aviation will continue to grow, unless new policy regimes are implemented. To start this discussion, the paper has summarised evidence that current policies to tackle climate change, devised by industry, are inadequate to address mitigation needs. They also ignore distributional issues, as well as the need to phase out fossil fuels. New, comprehensive policy regimes are needed that are characterised by accountability (a regime actor assumes responsibility for emissions), comprehensiveness (covering all radiative forcing from aviation), future-proofing (leading to a transition in propulsion systems), and common goals (being supported by the public). Using a transition policy framework, the paper discussed distributional and technology challenges, concluding that new policy regimes will have to be established nationally or regionally, and in considering the respective roles of regime actors.

In reviewing 30 voluntary, market-based and regulatory policies, the paper concludes that not all of these are equally effective. Transition policies complementing and exceeding CORSIA or the EU ETS would ideally embrace all flight emissions, curb air transport demand and force the sector to consider alternative propulsion technologies. More complex policy regimes would also consider social norm change, for instance by introducing information on emissions on tickets. Even if countries implement policy mixes that vary in their scope and approach, they will all be relevant in trialling different strategies while learning from the outcomes.

Notes

1. https://unfccc.int/resource/docs/convkp/kpeng.pdf, Article 2-2.
2. ICAO Doc7300, for example Articles, 11, 12 and 15.
3. ICAO Doc 10140, Assembly Resolutions in Force (as of 4 October 2019), Resolution A40-19, pp I-80 to I-85.

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