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A Win-Win Solution to Abate Aviation CO_2 Emissions

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This reprint is intended to communicate research results and improve public understanding of global environment and energy challenges, thereby contributing to informed debate about climate change and the economic and social implications of policy alternatives.

—Ronald G. Prinn and John M. Reilly,
Joint Program Co-Directors

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A Win-Win Solution to Abate Aviation CO_2 emissions

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Abstract: We outline a benchmark carbon dioxide (CO_2) intensity system with tradable permits for the aviation industry that will incent in-sector emission abatement opportunities that cost less than the social cost of carbon (SCC). The system sets benchmark emission intensities (CO_2 emissions per revenue ton kilometer) by route group and facilitates flexibility in meeting the benchmarks by allowing airlines to sell permits if they operate more efficiently than the benchmarks, and buy permits if they do not meet the benchmarks. The CO_2 benchmark system could operate concurrently with existing measures to mitigate aviation CO_2 emissions, will reduce the number of offsets needed to achieve carbon-neutral growth, and provide another (optional) lever to address fairness issues in climate regulations. Moreover, by providing a blueprint for other industries to price marginal emissions at the SCC, a CO_2 benchmark system could preserve the 'carbon budget' for use by high-cost abatement industries such as the aviation industry.

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1. Introduction

In 2009, the International Air Transport Association set goals to achieve carbon neutral growth from 2020 onwards and to reduce emissions in 2050 by 50% relative to the 2005 level (IATA, 2009). As the industry growth rate is expected to outstrip efficiency improvements, global aviation emissions are projected to grow by 322% between 2006 and 2050 under optimistic technology and operational improvement assumptions, and by 347% under moderate improvement assumptions (ICAO, 2009).

To help achieve its emission reduction goals, the 39th ICAO Assembly agreed to a market based measure known as the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) in 2016 (ICAO, 2016a). For the period 2021 to 2035, the CORSIA sets out requirements for airlines to fund reductions in CO_2 emissions elsewhere to compensate for aviation CO_2 emissions above the 2020 level through the purchase of carbon offsets. The proposed formula to determine the number of offsets that an airline must purchase is a weighted average of the growth factor for that airline and the industry-wide growth factor.

Although the CORSIA is a step in the right direction to abate greenhouse gas (GHG) emissions, it will not result in an efficient level of emissions abatement from either the perspective of the aviation industry or society. From an industry point of view, the level of abatement is efficient when the cost of the last unit abated is equal to the price of offsets. However, as the costs of each airline's emissions are partially borne by other airlines under the CORSIA, the agreement will not incent airlines to implement all abatement options that cost less than the price of offsets until 2030 at the earliest and perhaps not at all.

As is well-established in economic theory (Pigou, 1920), a socially efficient level of emissions abatement occurs when the marginal cost of abatement is equal to the marginal benefit of avoided damages, which is approximated by the social cost of carbon (SCC). This will not occur under the CORSIA for two reasons. First, the price of offsets, especially in the near to medium term, is likely to be much less than the SCC. Second, even if the price of offsets was equal to the SCC, as noted above, airlines will not exercise all abetment options that cost less than the offset price.

In this paper, we outline a benchmark CO_2 intensity system with tradeable permits that incents a socially efficient level of emissions abatement from international aviation. The proposed system sets benchmark levels of CO_2 emissions per revenue ton kilometer (RTK) for aviation route groups. Airlines that operate below the benchmark intensities are awarded permits and airlines that emit more CO_2 per RTK than set out by the benchmark are required to purchase permits. Trade in permits among airlines will lead to a market permit price, and the stringency of the benchmarks are set so that permit price is equal to the SCC. This system can operate simultaneously with the CORSIA and other aviation mitigation measures.

The proposed benchmark CO_2 intensity system applies the SCC to a fraction of each airline's emissions rather than all emission. Accordingly, an aviation benchmark CO_2 intensity system provides a blueprint for efficient emissions abatement elsewhere that is more palatable to industry groups than other policies that apply the SCC to all emissions, such a carbon tax. As aviation emission abatement options are expensive relative to those in other sectors (Winchester *et al.*, 2013), the aviation industry has a strong incentive to 'lead the way' in imposing a socially efficient carbon price and ultimately preserve the Earth's limited capacity to absorb GHG emissions for its own use. Other benefits from a benchmark CO_2 intensity system include: (i) it provides an (optional) additional lever to address 'fairness' concerns in assigning emission abatement obligations to airlines, (ii) it reduces the number of offsets required for the industry to achieve carbon neutral growth; and by pricing emissions at the SCC it may (iii) improve the aviation industry's relationship with consumers and investors, and (iv) prevent governments from imposing more costly policies on the aviation industry in the future.

This paper has four further sections. The next Section highlights incentives to reduce emissions under the CORSIA and outlines why this scheme will not result in an efficient level of emissions abatement. Section 3 discusses the motivation for the aviation industry to price marginal emissions at the SCC. Section 4 outlines the proposed benchmark CO_2 intensity system. The final section concludes.

2. The CORSIA and Incentives for Aircraft Operators to Abate CO_2 Emissions

The regulations for the CORSIA are set out in ICAO (2016a, pp. I80-I86). The scheme will cover international flights on routes in which both the origin state/country and the destination state are participating in the scheme (with exemptions for some flights). A pilot phase will operate from 2021 to 2023 and the first phase will run from 2024 to 2026. Participation in both the pilot phase and the first phase is voluntary.[1]

The second phase will operate from 2027 to 2035 with mandatory participation by all states and airlines that do

1 Although both the pilot phase and the first phase are voluntary, they differ with respect to how emissions from aircraft operators in each state are determined in offset obligation calculations. In the pilot phase, states may either apply an aircraft operator's emissions in a given year during that phase (i.e., 2021; 2022 and 2023), or the aircraft operator's emissions in 2020. In the first phase, an aircraft operator's offsetting requirement for a given year is based on its emissions in that year.

not meet the exemption criteria of the CORSIA. States exempt from the second phase include countries that have an individual share of international aviation activities (measured in RTKs) in 2018 less than 0.5% of industry RTKs, or whose cumulative share in the list of states from the highest to the lowest amount of RTKs is less than 90% of total industry RTKs. Least developed countries, small island developing states and landlocked developing countries are also exempt. Aviation activities in participating countries are exempt for (1) aircraft operators that emit less than 10,000 metric tons of CO_2 from international aviation per year, (2) aircraft with less than 5,700 kilograms (kg) of maximum take-off mass, and (3) humanitarian, medical and firefighting operations.

Emissions from aviation activities that are not covered by the scheme, due to voluntary participation or exemptions, are not required to be offset by airlines participating in the agreement. Each new entrant is exempt from the scheme for three years after it commences operations, or until the year that its annual emissions exceed 0.1% of total industry emissions in 2020, whichever occurs earlier. Offset credits for use in the CORSIA can, with some restrictions (see ICAO, 2016a, p. I-85, para. 21), be sourced from mechanisms established under the United Nations Framework Convention on Climate Change and the Paris Agreement.

ICAO will review the CORSIA every three years from 2022 to evaluate the scheme's role in the sustainable development of the international aviation sector. Among other functions, this process will '…update the scheme's design elements to improve implementation, increase effectiveness, and minimize market distortion' (ICAO, 2016a, p. I84). A special review of the CORSIA on the termination of the scheme, its extension or other improvements beyond 2035 will take place by the end of 2032.

2.1 Offset Requirements for Aircraft Operators

As defined in ICAO (2016a, p. I-83), the quantity of CO_2 emissions that each airline operator i must offset in year t (f_{it}) is:

$$f_{it} = \lambda_t G_t e_{it} + (1 - \lambda_t) g_{it} e_{it} \quad (1)$$

where e_{it} is emissions from aircraft operator i covered by CORSIA in year t, G_t is the emissions growth factor for the sector, g_{it} is the emissions growth factor for aircraft operator i, λ_t is the weight on the sectoral emissions growth factor ($0 \leq \lambda_t \leq 1$). G_t and g_{it} are defined as:

$$G_t = \frac{E_t - E_0}{E_t} \quad (2)$$

$$g_{it} = \frac{e_{it} - e_{i0}}{e_{it}} \quad (3)$$

Table 1. Weight on the sectoral emissions growth factor in offset obligation calculations.

Period	λ_t
2021 to 2029	$\lambda_t = 1$
2030 to 2032	$\lambda_t \leq 0.8$
2033 to 2035	$\lambda_t \leq 0.3$

where $E_t = \sum_i e_{it}$ is total emissions covered by the CORSIA in year t, E is average annual total emissions covered by CORSIA between 2019 and 2020, and e_i is the annual average of aircraft operator's i emissions covered by CORSIA between 2019 and 2020. For the purpose of calculating marginal offset obligations (see Section 2.2), it is useful to note that if emissions increase relative to those in 2020 ($E_t > E$), the industry growth factor is between zero and one ($0 < G_t < 1$). Similarly, if $e_{it} > e_i$, $0 < g_{it} < 1$.

The weights on the sectoral and individual airlines' emissions growth rates vary over time according to the schedule for λ_t displayed in **Table 1**. From 2021 to 2029, offset obligations depend only on airline emissions and the sectoral growth factor ($\lambda_t = 1$). For other years, exact values of λ_t are yet to be determined but upper limits have been set for this parameter. From 2030 to 2032, the weight on the sectoral emissions growth factor must be less than 0.8 (and the weight on each airline's emission growth factor greater than 0.2), and there is a significant reduction in the upper limit on λ_t from 2033 onward. As detailed below, when $\lambda_t > 0$, aircraft operators face distorted incentives to abate emissions as the reduction in an airline's emissions by one ton reduces that airline's emissions offset requirement by less than one ton.

2.2 Marginal Offset Obligations Under the CORSIA

The change in an airline's CORSIA offset obligation from emitting an additional ton of emissions (its marginal offset obligation) can be determined by differentiating equation (1) with respect to e_{it}.[2] After some manipulation, this yields:

$$\frac{\partial f_{it}}{\partial e_{it}} = \lambda_t[\alpha_{it} + G_t(1 - \alpha_{it})] + (1 - \lambda_t) \quad (4)$$

where $\alpha_{it} = \frac{e_{it}}{E_t}$ is the share of airline's i emissions in industry emissions in year t ($0 < \alpha_{it} \leq 1$).

2 Our analysis assumes that a change in an airline's emissions does not change emissions from other airlines due to strategic competition or other effects.

Noting that $\alpha_{it} + G_t(1 - \alpha_{it}) < 1$, equation (4) shows that $\frac{\partial f_{it}}{\partial e_{it}} < 1$ when $\lambda_t > 0$. That is, when the weight on the industry growth factor is greater than zero, the quantity of emissions an airline must offset per ton of additional emissions is less than one. Consequently, emissions from each airline impose external costs on other airlines in the form of additional offset requirements to achieve carbon neutral growth. Ultimately (when $\lambda_t > 0$) this means that airlines will not have an inventive to implement all abatement options that cost less that the price of offsets.

Equation (4) also reveals that each airline's marginal offset obligation will increase over time due to two factors. First, as $\frac{\partial f_{it}}{\partial e_{it}}$ approaches one as G_t approaches one, growth in annual industry emissions will increase marginal offset obligations. Second, as $\partial \frac{\partial f_{it}}{\partial e_{it}} / \partial \lambda_t < 1$, reductions in λ_t in later phases of the CORSIA (see Table 1) will increase marginal offset obligations.

To further illustrate incentives for airlines to abate emissions under the CORSIA, **Figure 1** plots marginal offset obligations for an airline for alternative (constant) values of the share of an airline's emission in industry emissions (α_{it}). These calculations assume that both airline and industry-wide emissions grow by 4% per year. In years for which exact values for λ_t have not been determined, we set λ_t equal to the maximum thresholds permitted in the scheme (e.g., λ_t = 0.8 for 2030, 2031 and 2032).

The figure illustrates that, in the early years of the CORSIA, the marginal offset obligations are significantly less than one and that the share of an airline's emissions in total emissions has a moderate impact on that airline's marginal offset obligation. Through time, growth in industry emissions and decreases in λ_t: (1) increase marginal offset obligations, and (2) reduce the impact of each airline's emissions share on marginal offset requirements.

2.3 Incentives for Airline Operators to Abate Emissions

As the marginal offset obligation for an airline is less than one (in most cases), the CORSIA will incent less in-sector emissions abatement than is efficient from an industry perspective. This is because some of the cost of each airline's emissions is borne by other aircraft operators, so airlines will not implement all emissions abatement options that cost less than the offset price. Ultimately, the aviation industry will purchase more offsets than it would under a regulation that is efficient from an industry perspective. The industry could address this issue by basing airlines offset obligations solely on each airline's emissions-growth factor in the calculation of offset obli-

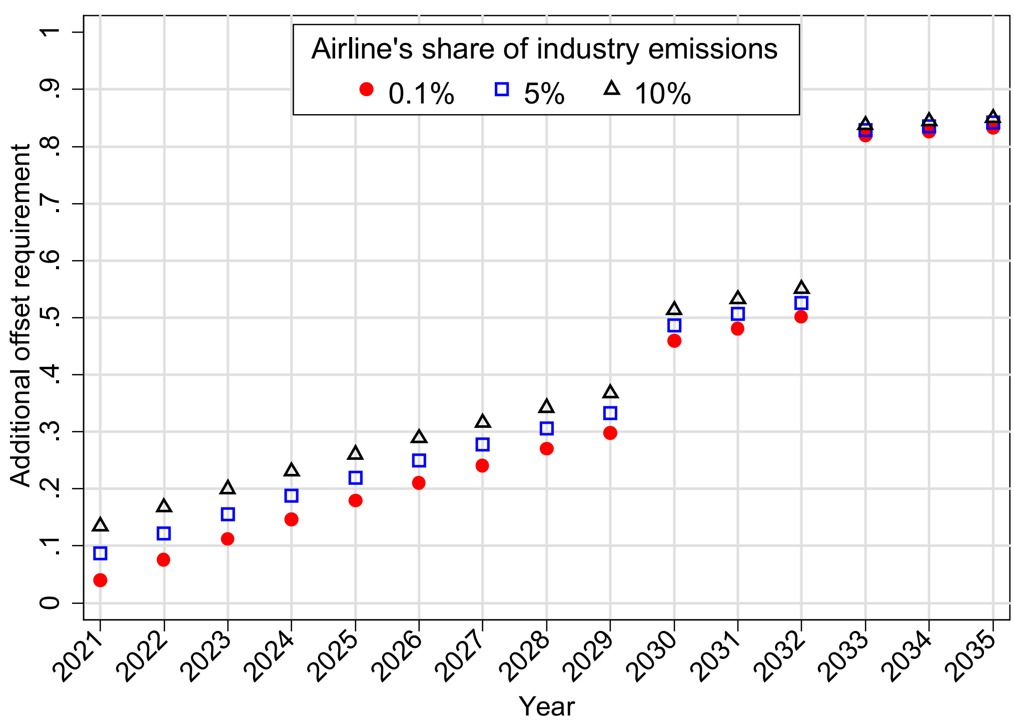

Figure 1. Additional airline offset requirements due to a one-unit increase in CO_2 emissions for alternative airline emissions shares (α_{it}).

Note: Airline CO_2 emissions and industry CO_2 emissions are assumed to grow by 4% per year.

gations (i.e., set $\lambda_t = 0$), but this is only likely to happen in the later years of the scheme (if at all).

From a societal point of view, the CORSIA is unlikely to result in an efficient level of abetment even if $\lambda_t = 1$. This is because current estimates for the SCC are around \$56/tCO_2 (Smith and Braathen, 2015; Evans *et al.*, 2017) and the price of Certified Emission Reductions—which are eligible for compliance with the CORSIA—was less than \$0.45/tCO_2 in May 2017.

3. Motivation for an Aviation Carbon Price Equal to the Social Cost of Carbon

Relative to the CORSIA when $\lambda_t > 0$ (and the price of offsets is less than the SCC), a policy that incents all abatement options that costs less than the SCC may increase or decrease costs for the aviation industry, as illustrated in **Figure 2**.[3] On one hand, the industry would gain by implementing additional abatement options that cost less than the price of offsets. On the other hand, executing abatement options that are more costly than the offset price (but less than the SCC) will impose additional costs on the industry. However, even if there are additional costs in some years, the aviation industry may experience dynamic gains from pricing emissions at the SCC by providing momentum for similar emission prices in other sectors.

Avoiding undesirable levels of global warming by 2100 requires meeting a 'carbon budget' for cumulative global GHG emissions out to the end of the century. As aviation emission abatement options are expensive relative to those for other sectors, the aviation industry has an incentive to preserve a share of the 'carbon budget' for its own use. The aviation industry can achieve this objective by implementing a cost-effective system that incents abatement options that cost less than the SCC. In addition to incenting more emissions abatement than under current measures, such a system can provide a blueprint for other industries to impose a socially efficient carbon price. In this connection, an important feature of the benchmark CO_2 intensity system outlined in Section 4 is that it only imposes the SCC on a fraction of each airline's emissions and is therefore likely to be more palatable than other measures for pricing emissions at the SCC, such as a carbon tax. A benchmark CO_2 intensity system may also prevent governments from imposing policies that impose a greater cost on the aviation industry in the future.

3 As the cost of an additional ton of CO_2 emissions varies across airlines under the CORSIA, Figure 2 represents the additional cost for an 'average' airline.

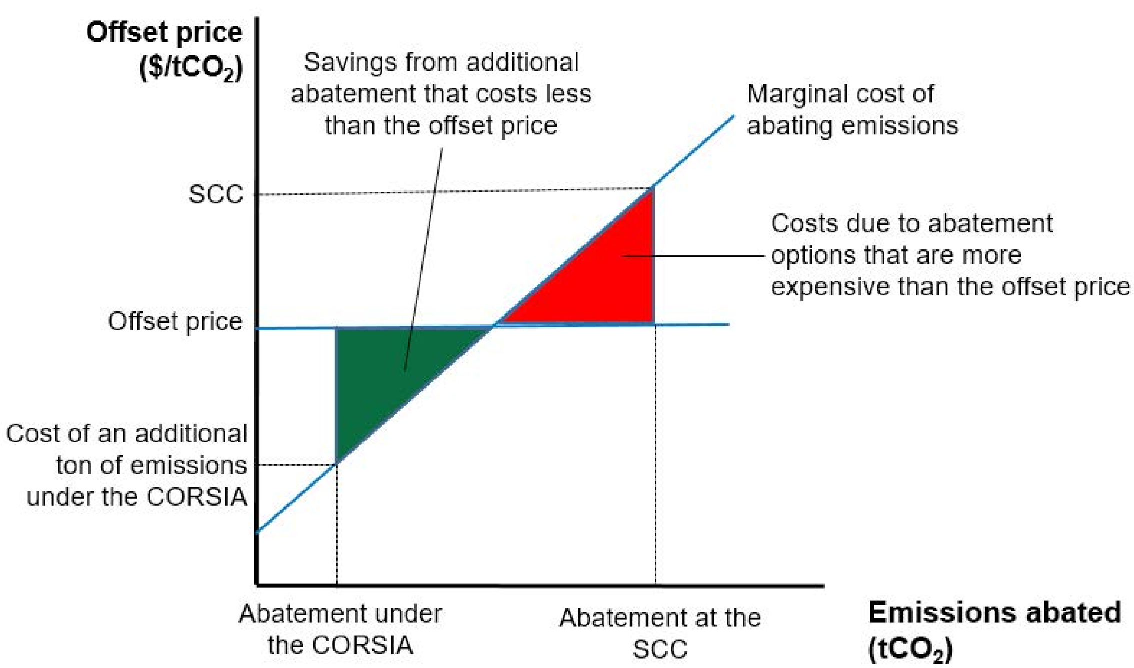

Figure 2. Costs and benefits to the aviation industry from implementing all abatement options that cost less than the SCC relative to costs and benefits from the CORSIA when $\lambda_t > 0$.

Note: The figure represents the cost of an additional ton of emissions for an average airline under this CIORSIA.

A carbon price equal to the SCC on marginal aviation emissions may also spur deployment of climate regulations by addressing 'tragedy of the commons' (Hardin, 1968) issues related to the carbon budget. First, results from the experimental economics literature show that first-mover choice is an important in influencing cooperation to obtain socially desirable outcomes (Clark and Sefton, 2001), and that reputation maintains contributions to the public good at an unexpectedly high level (Milinski *et al.*, 2002). Second, Weitzman (2014) shows that that a single internationally binding minimum carbon price is able to resolve the global warming free-rider externality problem.

The aviation industry also has an incentive to stimulate implementation of an efficient CO_2 price sooner rather than later. The current absence of appropriate mitigation incentives means that many low-cost abatement options are not implemented each year. As a result, larger (and more costly) emission reductions will be required in later years to stay within the carbon budget.

4. A Benchmark CO_2 Intensity System for International Aviation

In this section, we outline a benchmark CO_2 intensity system with tradeable permits as a cost-effective way for the aviation industry to price marginal emissions at the SCC. We also show that this system can operate concurrently with existing measures to abate aviation CO_2 emissions and has several other desirable attributes.

Output-based CO_2 benchmarks are common in emissions trading schemes (ETSs) to allocate free emission rights. For example, manufacturing firms in the EU ETS receive emissions rights based on, among other factors, their historical output and product-level CO_2 benchmarks (EC, 2017). In the New Zealand ETS, emission rights are allocated to trade-exposed, emission intensive firms based on CO_2 benchmarks and current output (Smith, 2009).

The benchmark CO_2 intensity system we propose for international aviation operates as an implicit ETS with (1) free allocation of emissions rights based on CO_2 benchmarks and current firm output, and (2) an endogenous emissions cap so that the price of emissions rights equals the SCC. Allocating emissions rights based on current output and CO_2 benchmarks generates an implicit output subsidy that, at the industry level, mitigates output price effects due to the emissions price. As such, emission reductions eventuate only by inducing changes in production techniques and not by reducing demand. Nevertheless, Mannix (2015) argues that such systems have substantial advantages as they are resistant to rent seeking and minimize the damage to the competitiveness of jurisdictions using them.

4.1 The Mechanics of a Benchmark CO_2 Intensity System for International Aviation

The key elements of a CO_2 benchmark intensity system with tradable permits, explained in detail below, include:

1. ICAO's sets benchmark CO_2 intensities (CO_2 emissions per RTK) for each route group.
2. Airlines that operate more efficiently than the benchmarks are able to sell permits and airlines with CO_2 intensities higher than the benchmarks are required to purchase permits.
3. The stringency of the CO_2 benchmarks is set so that the market price of permits is equal to the SCC.

The CO_2 benchmark system relies on setting benchmark levels of CO_2 emissions per RTK for each route group. To reflect differences in route characteristics (e.g., distance and cargo type) different benchmarks could be set for each route group, where a route-group consists of combinations of different characteristics selected by the industry. For example, a route group could be defined as passenger flights traveling fewer than 800 kilometers between origins and destinations in developed nations.

Under a benchmark CO_2 intensity system, the fleet-wide benchmark CO_2 intensity for each airline is a RTK-weighted average of the route-groups that it serves. Airlines with fleet-wide CO_2 emissions per RTK lower than their benchmarks are awarded permits, and airlines that operate at a felt-wide CO_2 intensity above their benchmark are required to purchase permits. Trade in CO_2 benchmark permits among airlines will lead to a market price for CO_2 benchmark permits.[4] This price will incent airlines to implement all efficiency improvements that cost less than the price of permits. Airlines with CO_2 emissions per RTK lower than their fleet-wide benchmark intensity will be able to sell more permits by improving efficiency. At the same time, airlines with CO_2 intensities that are higher than their fleet-wide benchmark will need to buy fewer permits by improving efficiency.

An economic efficient outcome under the system relies on a market price of permits equal to the SCC, achieved by judiciously setting the route-group benchmarks. Specifically, more stringent CO_2 benchmarks (lower benchmark emission intensities) will result in a higher permit price, while less stringent benchmarks (higher benchmark emission intensities) will lead to a lower permit price. To minimize the risks of imposing large costs

4 If the industry-wide, RTK-weighted average of the benchmark CO_2 intensities is lower than the industry-wide CO_2 intensity in 'business as usual', the market price will be positive. If the opposite is true, the permit price will be zero.

Table 2. A numerical example of a benchmark CO_2 intensity system.

	No CO_2 benchmark			CO_2 benchmark – 88 $kgCO_2$ / RTK		
	Airline A	Airline B	Industry	Airline A	Airline B	Industry
RTK (Revenue Ton Kilometers) *per year*	1 million	1 million	2 million	1 million	1 million	2 million
CO_2 emissions *kg per year*	95 million	85 million	180 million	93 million	83 million	176 million
CO_2 intensity *$kgCO_2$ / RTK*	95	85	90	93	83	88
Net permit purchases *kg per year*				5 million	-5 million	–

on the aviation industry, initial benchmark intensities could be set at a low level in an information-gathering/pilot phase. In practice, the CO_2 benchmarks would be lowered over time as new, more fuel-efficient aircraft enter service.

In addition to providing a catalyst for preserving the carbon budget, a benchmark CO_2 intensity system has at least three features that the aviation industry may find appealing. First, as permits purchased by airlines that operate above their CO_2 benchmarks are sourced from other airlines, the system is revenue neutral at the industry level. Second, the assignment of benchmark intensity allows free CO_2 emissions for each airline equal to the amount given by each airline's industry-wide benchmark multiplied by its industry-wide RTKs (i.e., it does not apply the SCC to all emissions). Third, by increasing in-sector emissions abatement, the system will decrease the number of offsets that the industry must purchase to achieve carbon neutral growth.

To illustrate the operation of a benchmark CO_2 intensity system, we consider an illustrative numerical example, summarized in **Table 2**. Suppose there is a single route group and the aviation industry consists of two operators, Airline A and Airline B.[5] In the absence of a CO_2 benchmark system, each airline flies 1 million RTKs per year and the CO_2 intensity for Airline A is 95 $kgCO_2$/RTK while that for Airline B is 85 $kgCO_2$/RTK, which results in an industry-wide CO_2 intensity of 90 $kgCO_2$/RTK.

Suppose that ICAO sets a benchmark CO_2 intensity of 88 $kgCO_2$/RTK—moderately more stringent than the industry intensity. Both airlines have an incentive to abate emissions by improving efficiency under this regulation. Airline A will improve efficiency to reduce the number of permits that it needs to buy, and Airline B will improve efficiency so that it can sell more permits. The second panel of Table 2 lists a potential equilibrium under a CO_2 benchmark of 88 $kgCO_2$ per RTK. Airline A emits 5 $kgCO_2$ per RTK more than allowed by the benchmark, so it has to purchase permits for 5 million $kgCO_2$ from Airline B, which has an emissions intensity of 5 $kgCO_2$ per RTK below the benchmark. The market price of CO_2 permits would depend on each airline's abatement costs relative to the benchmark CO_2 intensity and, as noted above, the benchmark intensity should be set so that the CO_2 price equals the SCC.

The example also highlights that the industry will need to purchase fewer permits to achieve carbon neutral growth (industry-wide CO_2 emissions fall from 180 million kg to 176 million kg), and that airlines will only face the SCC on a fraction of their emissions (Airline A emits 93 million $kgCO_2$ but only has to purchase permits for 5 million $kgCO_2$). Airlines only pay the SCC on a fraction of emissions because, as noted above, the CO_2 benchmark system is analogous to an ETS with 100% free allocation of emissions rights based on the benchmark CO_2 intensity and current output (and an endogenous emissions cap). That is, the same outcome would eventuate if each airline was allocated emissions rights for 88 million kg of CO_2 and Airline A purchased emissions rights for 5 million $kgCO_2$ from Airline B.

4.2 Interactions Between a Benchmark CO_2 Intensity System and Other Abatement Measures

A CO_2 benchmark system could operate concurrently with the CORSIA, as illustrated in **Figure 3**. Under the CORSIA, ICAO sets regulations for offset purchases to achieve carbon neutral growth and airlines purchase emission reduction credits from the offset market (solid lines). Adding a CO_2 benchmark system requires ICAO to set route-group benchmark CO_2 intensities and airlines to buy and sell permits from each other (dashed lines). Offsets and CO_2 benchmark permits are not tradable, so the rules for the CORSIA are independent of those for the CO_2 benchmark system. That is, introducing a CO_2 benchmark system does not require modifying

5 An example with multiple route groups is presented in Section 4.3.

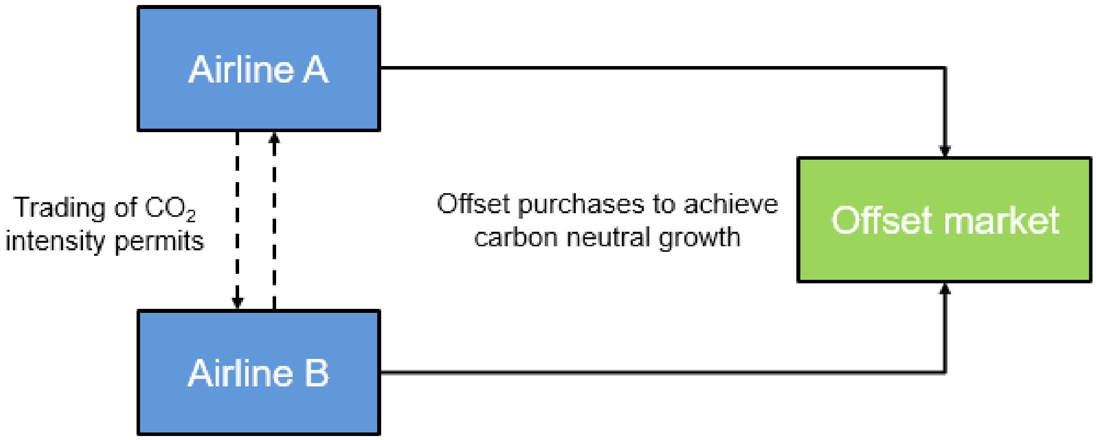

Figure 3. The CORSIA and a benchmark CO_2 intensity system with tradable permits.

Note: CO_2 intensity permits and offset credits are not tradable.

the regulations for CORSIA. Due to increased in-sector abatement, the CO_2 intensity benchmark system will reduce the number of offsets that the aviation industry needs to purchase to achieve carbon neutral growth.

A CO_2 benchmark system could also operate simultaneously with the CO_2 standard adopted by the ICAO Council in early 2017 (ICAO, 2016b). From 2020, the standard sets minimum performance thresholds for new aircraft using a metric related to fuel efficiency as a function of aircraft shape and mass. A benchmark CO_2 intensity system would provide additional incentives for manufactures to improve the efficiency of new aircraft—perhaps beyond that mandated by the standard—and would allow airlines to execute other options to reduce emissions (e.g., accelerating the introduction of new aircraft or changing the operation of existing aircraft).

4.3 Fairness Concerns

A benchmark CO_2 intensity system also provides the aviation industry with an optional lever to address 'fairness' concerns—influenced by, for example, differences in route characteristics, common but differentiated responsibilities, or differences in existing fleets across airlines—in the assignment of emission abatement obligations. Under the system, ICAO could reduce the cost to an airline by assigning less stringent benchmark CO_2 intensities to route groups accounting for a relatively large share of operations for that airline.

Table 3 illustrates the use of a benchmark CO_2 intensity system to address fairness issues. In the example, three airlines (C, D and E) each fly one million RTKs per year across up to three route groups. Suppose the benchmark CO_2 intensity on route 1 is 80 $kgCO_2$/RTK and those on routes 2 and 3 are, respectively, 90 $kgCO_2$/RTK and 80 $kgCO_2$/RTK. As Airline E services routes assigned higher intensity benchmarks, it has to meet a less stringent fleet-wide CO_2 benchmark intensity (95 $kgCO_2$/RTK) than the other airlines (90 $kgCO_2$/RTK). Assuming that operations for Airline C result in 85 kg/CO_2 and those for Airlines D and E each generate 95 kg/CO_2, Airline C will sell permits for five million tons of emissions to Airline D. Despite Airline E operating at the same CO_2 intensity as Airline D, it does not have to purchase permits (due to the assignment of benchmark intensities). Nevertheless, as it could sell permits by operating below its benchmark intensity, Airline E faces a marginal incentive to reduce emissions equal to the price of permits. As rules for the CORSIA are independent of those for a benchmark CO_2 intensity system, fairness concerns could also be addressed (entirely) by the assignment of CORSIA offsetting obligations if desired by ICAO.

5. Conclusions

Avoiding undesirable climate impacts requires limiting future global emissions of GHGs. As emission abatement options for airlines are relatively expensive, the aviation industry has an incentive to preserve the Earth's capacity to absorb GHG emissions for its own use. The aviation industry can achieve this objective by implementing regulations that result in an efficient level of in-sector emissions abatement that can also serve as a blueprint for mitigation of GHGs in other sectors. The CORSIA is a step in the right direction but it does not achieve these goals because the current price of offsets is much lower than the SCC and, for an individual airline, reducing emissions by one ton reduces that airline's offset obligation by less than one ton (in most circumstances).

This paper proposed a benchmark CO_2 intensity system with tradable permits that will price marginal emissions at the SCC, can operate alongside the CORSIA and the

Table 3. Using a benchmark CO_2 intensity system to address fairness concerns.

	Airline C	Airline D	Airline E
Airline operations *RTKs per year*			
Route 1 – 80 $kgCO_2$/RTK	–	⅓ million	–
Route 2 – 90 $kgCO_2$/RTK	1 million	⅓ million	½ million
Route 3 – 100 $kgCO_2$/RTK	–	⅓ million	½ million
Fleet-wide benchmark and actual CO_2 intensities *$kgCO_2$ / RTK*			
Average benchmark CO_2 intensity	90	90	95
Actual CO_2 intensity	85	95	95
Permitted and actual CO_2 emissions and net permit purchases *$kgCO_2$ per year*			
Emissions permitted	90 million	90 million	95 million
Actual emissions	85 million	95 million	95 million
Net permits purchased	-5 million	5 million	0

industry's CO_2 standard, and could provide several benefits for the aviation industry (and other industries that adopt similar measures). A key potential benefit of a CO_2 benchmark system is that it incents all in-sector emissions abatement options that cost less than the SCC while only applying the SCC to a small fraction of emissions. Consequently, an industry-initiated CO_2 benchmark system (that results in a socially desirable level of in-sector abatement) may prevent future government regulations that impose higher costs on the industry. In short, a benchmark CO_2 intensity system is an attractive, or at least a palatable, measure for industries to abate a socially desirable level of in-sector emissions. The benchmark CO_2 intensity system outlined in this paper also provides another (optional) channel for ICAO to address fairness concerns in the assignment of emissions abatement obligations.

The negotiating platform built for the CORSIA provides an opportunity to introduce a benchmark CO_2 intensity system for international aviation. In particular, the triennial review of the scheme by ICAO provides scope for the phase-in of a CO_2 benchmark system. As a CO_2 benchmark system would result in a socially efficient level of aviation emissions abetment, this system could eventually replace the CORSIA.

There is also scope to introduce a benchmark CO_2 intensity system for international shipping as, like the aviation industry, it has the necessary governance infrastructure to initiate a global sectoral measure. The International Maritime Organization (IMO) has declared itself as the 'appropriate international body to… address GHG emissions from ships engaged in international trade' (IMO, 2016). However, this organization has been criticized for its slow progress on climate issues (Darby, 2016) and several commentators have called for the implementation of a market-based measure (e.g., Rahim *et al.*, 2016). As the global carbon budget shrinks and inexpensive abatement options are left on the table each year, there is an urgent need for a socially efficient carbon price on emissions from aviation, shipping, and other industries.

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