The CORSIA climate agreement on international air transport as a game

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Abstract

The CORSIA climate agreement requires the signatories to cap their bilateral international aviation carbon emissions to 85% of the level of 2019. Signatories can satisfy the cap by using offsets and sustainable aviation (SAF) fuels.This international agreement faces three handicaps: the agreement must be self-enforcing, very cheap offsets and SAF's with a high indirect emission are not credible and offsets and SAF's do not guarantee climate neutrality. We study the participation decision of a country to join or not CORSIA in a Nash context. It is shown that there are pairs of countries for whom it is beneficial to join CORSIA if their climate benefit is higher than half the cost of offsets or SAF fuels. The numerical model illustration for the 10 most important countries shows that only a few countries are likely to effectively participate and will do this via offsets rather than via SAF blends.

Keywords

Aviation, climate, international climate agreement, fuel efficiency aviation, offsets, biofuels

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1. Introduction

The CORSIA agreement is an agreement by countries reached within the ICAO (International Civil Aviation Authority) and foresees that the growth in emissions for international flights between two CORSIA signatories need to be compensated by offsets or sustainable aviation fuels. Offsets are additional abatement efforts in other sectors of the economy and sustainable aviation fuels stand for eligible biofuels and e-fuels. In this paper we study the strategies of the signatories of the agreement as well as the decisions to participate in the agreement.

The intra EU emissions are covered by the EU-ETS that caps emissions of industry, power generation and domestic aviation. Table 1 shows that the domestic air transport emissions are regulated by the Paris agreement. The international emissions of the EU count for approx. 22% of world emissions and are more important than the domestic emissions (only 14%). In the Rest of the World (ROW) international emissions are also important. This makes CORSIA, covering 60 to 65% of world GHG emissions, an important agreement for climate policy.

The cap on the growth of international emissions can be realized via different policy instruments that can differ from those used for domestic climate policy. As an example, for the offsetting of the domestic emissions, the EU has opted for the use of the EU-ETS permits, while for the (outbound and inbound) international emissions that are regulated by the CORSIA agreement, other, cheaper, credits could be used. The cost of these CORSIA credits could be only 20% of the cost of ETS permits (EC, 2021). Also the use of SAF (Sustainable Aviation Fuels) is allowed to compensate the growth in international aviation emissions.

Flights	Within EU	EU to ROW	ROW country to ROW country	Within ROW country
% world emissions in 2019	14%	22%	39%	?25%
Internat. Agreement	PARIS	CORSIA	CORSIA	PARIS
Policies	EU-ETS SAF fuels	Offsets (SAF)	Offsets (SAF)	…
Issues		Offset price? What SAF's? Participation?	Offset price? What SAF's? Participation?	…

Table 1 Coverage of aviation emissions by the Paris and the CORSIA agreement (source: IATA and ICAO),

In this paper we study the economic aspects of the implementation of the CORSIA agreement. What is the rationale for the EU opting for a cheaper version of offsets than the EU-ETS permit system? How does this affect the CORSIA participation decision of other countries and does this change the role of the two complementary instruments, SAF and more efficient aircrafts?

Several papers study the effects of policy instruments on aviation activity, fuel efficiency and emissions. One of the first is the paper by Brueckner and Zhang (2010) who consider the effect of an effective price of kerosine in a model with competing duopoly airlines. They find higher fares, reduced flight frequency, increased load factors and increased aircraft fuel efficiency but no effect on aircraft size. Brueckner and Abreu (2017, 2020) and Fukui and Miyoshi (2017), show that airline fuel usage falls as the fuel price rises. Brueckner et al (2023) detail how airlines adjust their operations and how their aircraft stock responds to fuel price increases. They show the trade-off between speed and fuel efficiency. Less fuel-efficient aircrafts reduce speed and utilization time and are replaced more quickly by more fuel-efficient aircrafts.

The EU integrated the intra-EU aviation into the European tradable emission permit system (EU-ETS) together with the electricity and industry sector. Fageda and Teixido (2022) analyze empirically the effects of the EU-ETS on aviation emissions. Comparing the emissions of flights that are comparable in terms of size and distance but are within the ETS and outside the ETS system; they show that the emission permits are effective, even when they are grandfathered. The permit system has a more pronounced effect for routes where an alternative (rail) exists and find them also to be more effective for the low-cost airlines. In a more recent paper (2023) they decompose the fuel efficiency reactions into aircraft choice, retrofitting and volume of flights, confirming the improvement of the fuel efficiency of aviation within the EU.

Andreana, Adler and de Jong (2023) are the only paper to consider explicitly climate policy for a continental and intercontinental network (US and EU) , where two competing regulators can use carbon taxes to address carbon emissions. They use a simulation model representing a complex network and find that the two regulators set a carbon tax that is lower than their own climate damage. The main reason for the very low carbon tax is the inefficiently high initial price driven by the Cournot duopoly assumption. In this context setting an externality tax below the damage may be justified if the price elasticity is high enough (Barnett, 1980). Ovaere and Proost (2024) still take a different approach and look into the option that the duopoly of the main aircraft producers (Airbus and Boeing) is incentivized by the EU and the US to improve the efficiency of aircrafts in the world. This has an important potential but requires full cooperation between the two producing countries.

In this paper the focus is not on the reaction of airlines on climate policy but on the behavior of countries in relation to the implementation of the CORSIA agreement: will they participate and what policy instruments do they prefer to realize the commitments. The paper is organized as follows. Section 2 explains the CORSIA agreement in more detail. Section 3 briefly discusses the economics of international climate agreements. Section 4 sets up a small model to study the game between two countries that join the CORSIA agreement. Section 5 discusses the forces at work when a carbon tax can be used, section 6 discusses the use of offsets and its effect on the CORSIA participation decision. Section 7 does the same for SAF's. Section 8 compares offsets and SAF's. Section 9 analyzes the potential role of fuel efficiency improvements of aircrafts. As countries differ in their growth rates and in their sensitivity to climate damage, only a numerical assessment in section 10 can generate insights on the possible degree of participation. Section 11 concludes.

2. Corsia agreement

2.1 The international agreement

In 2016, the ICAO (International Civil Aviation Organisation) Assembly adopted Resolution A39-3 'Consolidated statement of continuing ICAO policies and practices related to environmental protection – Global

Market-based Measure (MBM) Scheme'. This Resolution established the basic features of the 'Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)'.

The main aim is to achieve carbon neutral growth of aviation starting from the level of 2019. Most recently, at its 41st Assembly, ICAO set 85% of 2019 emissions as CORSIA's baseline from 2024 until the end of the scheme in 2035: a significantly more ambitious target than originally planned. CORSIA applies to inbound and outbound flights between two countries that are signatories but does not apply to flights with non-signatories. For flights with non-signatories there are no commitments.

The scheme has three phases: a voluntary pilot phase is scheduled to run from 2021-2023, followed by phase 1 (2024-2026) where States can also volunteer to participate, followed by a phase 2 (2027-2035), which covers all States that had a share above 0.5% of total Revenue Tonnes Kilometres (RTKs) in 2018 or whose cumulative share in the list of States from the highest to the lowest amount of RTKs reaches 90% of total RTKs. States can withdraw from the agreement each year.

The CORSIA agreement is still an open agreement. Although 126[2] countries have signed it, some of the most important blocks and destinations (China, India, Brazil, Russia, ..) did not yet sign it. The US intends to sign if there is sufficient participation. The EU Member States (plus Iceland, Norway, UK and Switzerland) have notified ICAO of their voluntary participation in CORSIA from 1 January 2021 onwards, subject to differences filed under Article 38 of the Chicago Convention.

As there is no real enforcement of the CORSIA agreement[3], a country that signed can always leave the agreement and cannot be punished for that. The share of international climate emissions from aviation that would be covered by the agreement could well be less than 60% (EC, 2022). Interesting to note is also that the Assembly:… "affirms the preference for the use of aircraft technologies, operational improvements and sustainable alternative fuels that provide the environmental benefits within the aviation sector"[4] . This quote shows that some signatories prefer actions in the air transport sector rather than to rely on other sectors for emission abatement.

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[2] Corsia (2023) https://www.icao.int/environmental-protection/CORSIA/Pages/state-pairs.aspx

[3] CORSIA foresees explicitly that the enforcement cannot be delegated to the ICAO nor can any participating country enforce another signatory to comply with the agreement.

[4] (CORSIA agreement art a39_3 " (https://www.icao.int/environmental-protection/documents/resolution_a39_3.pdf)).

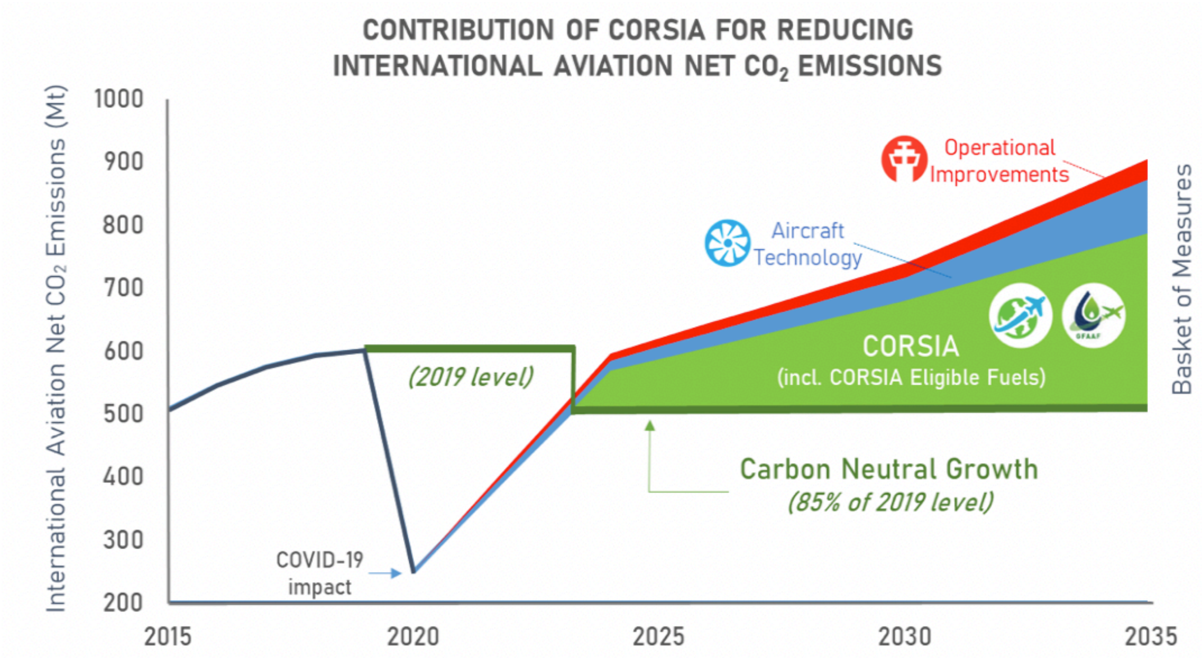

Figure 1 CORSIA's aspirations for net CO2 emissions [5]

Figure 1 shows how CORSIA reckons to stabilize CO2 emissions of the bilateral flights at a level 15% below the level of 2019. As other expected technological developments at the level of aircraft and operations are insufficient to limit the expected growth of aviation emissions, additional reductions of emissions in other sectors are needed via offsets as well as via the use of SAF's.

The emissions of other GHG gasses than CO2 are not included in the CORSIA agreement.

2.2 The implementation

Currently (i.e. 2023), we are still in a monitoring and voluntary phase. During this phase, the signatories are required to monitor total emissions by airline . The actual implementation from 2024 – 2026 remains voluntary. Two decisions need to be taken during this process. The first decision pertains to the allocation of compensation obligations by airline while the second pertains to the compensation methods that airlines can use. The implementation of the carbon neutrality between two countries must be translated into obligations for airlines, taking into consideration that they can face different growth rates of emissions. The easiest implementation is by grandfathering carbon emission rights to airlines for part (85%) of their international emissions in 2019. One could also auction part of these rights, but international carriers may object and consider this as a taxation of fuel by one of the participating countries. To protect the "younger" airlines from strongly growing nations, CORSIA imposes that the offset requirement must be met in proportion to the total emissions of that airline. This comes down to grandfathering a larger share of the permits to the strongly growing airlines.

When it comes to compensation methods, airlines have the option to use offsets and SAF's to limit the net growth of aviation emissions. However, both strategies have their own problems. As we will see later in the paper, there is a strong variation in price and quality of offsets, so the type of acceptable offsets will be part of the future CORSIA negotiations. Airlines have also the option to use SAF's. CORSIA does consider the use of SAF's as

[5] source: https://www.icao.int/environmental-protection/CORSIA/Pages/CORSIA-FAQs.aspx

carbon neutral. However, eligibility criteria of SAFs are of importance. The ICAO Council approved three criteria: (1) fuels must result in at least a 10% reduction in lifecycle GHG emissions, compared to standard aviation fuel; (2) fuels must not be made from biomass obtained from land converted after 2008 with a high carbon stock; and (3) in the event of land use conversion after 1 January 2008 the dLUC (direct land use change) value shall replace the ILUC(induced land use change) value. There is a large variety of SAF that could be eligible and their cost and CO2 emissions are complex (Mayeres,et al. 2023 and ICAO, 2023). According to EC 2021, these criteria do not guarantee that the production of alternative fuels will avoid negative consequences for e.g. food security, land rights and biodiversity. So also, this type of compensation will require further negotiations.

Furthermore, both offset and SAF use is affected by specific national policies that can be very different. The EU has a well-functioning carbon credit market and has set a blending mandate for aviation fuels with a minimum of 2% in 2025 and 70% in 2050 with minimum blending rates for e-fuels[6]. The US uses subsidies for SAF's in function of their lifecycle emissions and so do many other countries (OECD/ITF, 2023).

In order to focus on our research question, this paper simplifies the implementation questions by using a set of strong assumptions on airlines, fuels and offsets. These are detailed in section 4.

3. The participation decision

The CORSIA agreement covers the major part of the emissions of the air transport sector and even if more than 100 countries have signed the agreement, this is not a guarantee for an effective action by the signatories. The problems are the lack of enforcement and the volatile character of national politics.

Climate Change is a typical prisoner's dilemma where non-cooperative solutions tend to be the standard outcome. As there is no enforcement of International Agreements (IA), for an IA to work, it must be "self-enforcing", a simple but important insight (Barrett, 1994). Countries will only participate in the agreement when they are at least as well off signing the agreement as not signing the agreement and this is a very strong requirement. To know how many countries might join (and comply with the agreement), Barrett offers a clearcut result. He shows that, in the case of identical countries, when the cost of compliance is quadratic and the marginal benefit of reducing emissions per country is constant, there will be maximum 3 countries (out of N>3) signing the agreement. These 3 countries will agree to minimize their joint damage. This requirement implies that the number of signatories and the efforts that can be expected will be low. Consider 10 identical countries and a marginal damage per country equal to 1 and a quadratic abatement function with a marginal abatement cost of 0 for reducing 0 emissions and 1 for reducing one unit of emissions. The cooperative equilibrium will imply a total abatement effort of 100 (10 counties that reduce each the total marginal damage so the MC=MD and this implies10 times 10 units of emissions), the non-cooperative equilibrium will involve a total effort of 10 units abated (each country compares its marginal abatement cost with its own marginal damage). The self-enforcing agreement will have 3 countries reducing each 3 units (the total climate damage for the 3) and 7 countries not joining the agreement and reducing

[6] E—fuels are made by combining hydrogen and carbon and have lower carbon footprint (Mayeres et al, 2023).

one unit of emissions each. So a total effort of 16 units abated (9+7) and this is only 16% of what a full cooperation agreement would produce.

Of course, the world and the climate issue is more complex than this simple numerical example. Kornek and Marschinski (2018), generalize the Barrett model for abatement uncertainty and analyze the choice between international quantity and price agreements. They show that a coalition of cooperating countries is more likely to choose a quantity regulation than non-cooperating countries but the uncertainty in the abatement costs may aggravate the free riding which would mean a smaller coalition size.

The agreements are long term and countries may learn and adapt their international commitments. Harstad (2022) compares the structure of the Paris (2015) agreement and the structure of the Kyoto (1997) agreement. The Kyoto agreement is considered as a top-down agreement where the consortium of the signatories decided on the emission reduction effort to be reached by 2012. This resulted in low participation with primarily high-income countries accepting a reduction of around 7%. In contrast, the Paris agreement adopts a more bottom-up approach where each country makes a pledge and this is reviewed every 5 years. In this case, almost all countries made a pledge, and the commitents made were very different. According to Harstad, the pledge and review process gives fewer deep promises but a higher participation rate and on balance a larger total effort.

More recently 126 countries agreed to join the CORSIA – agreement that promises to stabilize aviation emissions from international aviation by using offsets. As the objective imposed to all signatories is the same, this agreement is more of the Kyoto type than of the Paris type and we can expect a rather low level of compliance.

Despite the skepticism in the Barrett result, we see climate agreements, that include deep reduction commitments and here the national politics come into play. Battaglini and Harstad (2020) develop a theory why politicians, in the presence of re-election concerns, negotiate agreements with weak or no sanctions but leave the ultimate decision on compliance to the politicians who win the next elections. They consider a bi-partisan model. An international agreement is negotiated by one political party, but in the following election, the voters may be "green" or "brown". In function of the vote, the elected party decides to comply or not with the treaty. This implies that the party negotiating the agreement, anticipates that, after the election, it may have to comply if the vote is green but will not comply if the vote is not green. This explains why, in equilibrium, the green party designs an international agreement that can be enforced if it is re-elected and similarly the brown party negotiates an international agreement that allows them to escape enforcement if it is re-elected.

Crucial in the results is the rent of staying in office after the elections. The larger is this rent, the more the parties will try to differentiate themselves for the voters by complying when the election chooses a green party and not complying when the election chooses a brown party. As both the depth of the agreement and the sanction determine the voting outcome, this can lead to strong agreements (all parties comply), weak agreements (where only the green party complies), ineffective agreements (nobody complies) and even overambitious agreements. The weak IA problem is more likely to occur in a democratic regime where the office rent is high and there are polarized parties.

Following the criteria developed by Battaglini and Harstad, we can qualify **CORSIA as a weak agreement with no effective sanctions. As a result there may be many signatories but some of the signatories may not comply if their local political majority turns brown rather than green.**

It is interesting to check what countries did not join and why they did not join. Several countries made the reason why they did not sign very explicit. For instance, China and India stated that the growth cap for international aviation is unfair for their country that is still growing very strongly – the cap is indeed the same for all the signatories and this was not the case for the Paris agreement where differentiated efforts (individual pledges) were provided. The US, on the other hand, indicated that it will only sign if enough participants who are important in terms of flight volume, agree. This is strategic behavior which our model cannot represent as we take the behavior of the other countries as given.

4. The model

In this paper we study the CORSIA agreement as a game between different countries. We examine a non-cooperative equilibrium where each country takes the decisions of the others as given. Countries benefit from flights that connect two countries, but the flights generate climate damage that will hurt both countries as well as the entire world.

4.1 Distinction between carbon neutral and climate neutral aviation growth

It is important to distinguish *carbon* neutral growth of international aviation and *climate* neutral growth of international aviation. A ton of carbon emitted by international aviation using kerosene produced, in the period 2000-2018, had on average approx.. $\varphi \approx 1{,}7$ times more radiative forcing than an emission of a ton of carbon emitted at ground level (Lee et al.2021, Table 5). This multiplier is the result of complex processes, involving aviation emissions of carbon dioxide (CO2), nitrogen oxides (NOx), water vapor, soot and sulfate aerosols, and increased cloudiness due to contrail formation. There is an important uncertainty margin but there is no simple remedy to decrease this multiplication factor. One of the problems is that this multiplier depends on the future profile of the aviation emissions. The non-CO2 GHG are in general short-lived while CO2 is long lived. If kerosene use would stabilize, the effect of the non-CO2 emissions would have an approximately constant additional warming effect and as they do not cumulate, they would have a smaller effect than the pure CO2 effects and the multiplier would return to 1. The multiplier is therefore not necessarily constant and could decrease over time. In any case, the existence of a multiplier larger than 1 has large implications for the use of offsets that compensate carbon emissions in aviation by additional carbon emission reductions in other sectors.

For SAF's , the climate forcing multiplier ($\chi \leq \varphi$) may be smaller than for kerosene [7] in the case of engineered fuels (e-fuels). This leads to two definitions we use in this paper:

Carbon neutral growth compensates the carbon emissions of a flight via flight volume reduction, more energy efficient flights, via blending with SAF's or via additional reduction of carbon emissions in other sector (offsets).

Climate neutral growth realizes an effective reduction of total radiative forcing via flight volume reduction, more energy efficient flights, via the use of more SAF's or via $\varphi \approx 1{,}7$ times more offsets.

[7] Recent evidence by DLR (2023) indicates that SAF fuels of the HEFA family would have an advantage in terms of other GHG emissions that would point to a lower multiplicator for particular SAF fuels, but this is only one experiment..

4.2 Model assumptions

Consider three countries A, B and C.

ASS1: the marginal production cost of international flights is constant and there is perfect competition on the international flight market. [8]

The marginal cost and price p_{AB} for a return flight A to B with a distance z_{AB} is then

- the non-fuel cost c per unit of distance which is the same for all flights
- plus the cost of fuel before taxes or offsets $f \cdot p_E$, where f stands for the fuel consumption per unit of distance and p_E stands for the constant price of kerosene
- plus the tax t_A or offset cost for the fuel loaded at A plus the tax or offset cost t_B for the fuel loaded at B for the return flight:

$$p_{AB} = (c + f(p_E + 0{,}5t_A + 0{,}5t_B))2z_{AB} \qquad (1)$$

ASS2: We have one representative individual in each country. His utility of flights is quasi-linear and separable for the different destinations and international aviation is unrelated to domestic aviation.

We assume that domestic aviation is unrelated to international aviation, so we neglect local connecting flights. Assume first that the consumption of these three international aviation volumes (y_{AB}, y_{AC}, y_{BC},) is separable in the utility function of each of these three countries. The utility of country A is then (where m represents the consumption of other goods than aviation):

$$U(y_{AB}, y_{AC}) = m + 0{,}5(\sum_{i,j=AB,AC}(a_{ij}y_{ij} - 0{,}5b_{ij}y_{ij}^2 - p_{ij}y_{ij}) \qquad (2)$$

We follow Mandell & Proost (2016) and consider flights between two countries as benefiting equally the two countries even when they have a different size, this means that the utility of a return flight is half of the net utility. This can be justified either as half of the passengers being from the other country or by considering a flight as a trade deal (tourism, business) where the benefits are shared.

ASS3 The aircraft stock is homogeneous, and its fuel efficiency is exogenous for the airlines

Aircrafts can become more efficient over time through technical progress but as we do not have an explicit supply model of aircrafts and no dynamic model that tracks the use of the stock, aviation fuel demand for a given stock in a given year can only decrease by decreasing speed, by changing the load factor and by lowering the number of flights[9].

ASS 4 Producers of aircrafts can offer a more efficient aircraft stock when effective fuel prices are higher or when producers are subsidized to produce more efficient aircrafts.

[8] Andreana et al 2023 use the carbon tax to indirectly correct the oligopoly pricing. We neglect this element. Possible justifications are first, the Bertrand equilibrium rather than the Cournot equilibrium. Second, that there is already a powerful competition authority at work that limits the monopoly margins. Finally, the governments have, up to now, not tried to correct the monopoly margins by subsidies for aviation fuel.

[9] De Jong (2023) uses a model with several vintages of aricrafts and shows how higher fuel prices in one region (EU) can lead to a shift of the less efficient aircrafts to other regions.

Aircrafts have become more efficient over time and there is still potential to improve their fuel performance. ICCT (2016) estimated that fuel efficiency of new aircrafts improved by 1% per year between 1980 and 2016. In an aggressive energy efficiency scenario for the US, ICCT sees an efficiency improvement of 24% in 2024 and of 40% in 2034 for new aircrafts.
Producers of aircraft will be incentivized to work more on fuel efficiency when effective fuel prices are higher or when they receive specific subsidies to reach efficiency objectives.

ASS5 The marginal climate damage of small variations in emissions is constant for one country.
This assumption can be justified by the small share of aviation emissions of one country in total emissions. Alternatively, one could start from the quantitative emission targets that a country sets for the country as a whole and compute the shadow value or permit price needed in the economy to reach that target. But the climate ambitions of a country are difficult to gauge from its official declarations, the use of a constant unit damage is then the simplest way to integrate climate ambitions.

Let the (discounted) marginal climate damage of the emission of one unit of fossil energy on land for country i be d_i. The damage from aviation equals φ times the discounted damage of one ton of fossil energy at ground level. The world climate damage per unit of fossil energy used in aviation equals $\varphi(d_A+d_B+d_C)$.

The welfare of country A without any climate measures for aviation is then:

$$W_A = U(y_{AB}, y_{AC}) - d_A\varphi\,(2f(z_{AB}y_{AB} + z_{AC}y_{AC} + z_{CB}y_{CB})) \qquad (3)$$

Note that country A suffers climate damage from all the trips: from the return trips their citizens make (responsible for factor 2 for y_{AB} and y_{AC}) as well as from the trips between other countries (y_{cb}). This is the result of the global nature of the climate damage.

ASS 6 The price of offsets *op* and the price of SAF's p^{SAF} is constant and exogenous.

Offsets and SAF's are scarce, have an increasing marginal production cost and can be supplied by many countries. This has two implications for our modelling process. First, they generate producer surplus for the suppliers. Second, the cost of climate policy depends on the demand for offsets and SAF's of the other countries and thus the participation in climate agreements becomes interdependent. The constant price assumption avoids both complexities on which we return in our discussion section.

Notation

As there is a fixed proportion between fossil energy use in aviation and CO2 emissions and as the energy efficiency *f* is assumed to be the same for all flights, there is a one-to-one correspondence between demand for flights and demand for energy. To save on notation we express utility and welfare in terms of fossil energy consumption.

Let x_{ij} be the fossil energy consumption of a number of return flights y_{ij} between countries *i* and *j*. Using Ass 2 (separable and quasi-linear utility function) we will use $U(y_{ij}) = U(x_{ij}) = CS(x_{ij})$ to derive most of the results. Where, using (1) and (2), we have

$$x_{ij} = 2fz_{ij}y_{ij}$$

5. Why carbon taxes were not accepted by CORSIA

We derive first a Nash equilibrium in carbon taxes rather than offsets or permits as this clarifies the most important forces at work. Using a Nash equilibrium, we assume implicitly that there are many countries involved and that there is no strategic behavior between the bigger players.

Focus first on the link between A and B which are both signatories. The tax set by country A on the flights between A and B maximizes the sum of half the consumer surplus plus the tax revenue for country A minus the climate damage. ASS 1 makes that all the elements of the generalized price of a return trip (1) are constant except for the fossil fuel price including tax. The only element of the generalized price that country A controls is the tax on fossil fuel (or emissions) t_A^{AB} .

Max 0,5 $CS(x_{AB}) + (t_A^{AB} - \varphi d_A)x_{AB}$ (4)

Optimizing wrt t_A^{AB} gives:

$$-0.5x_{AB} + (t_A^{AB} - \varphi d_A)\left(\frac{\partial x_{AB}}{\partial t_A}\right) + x_{AB} = 0 \quad (5)$$

Country B follows a similar non-cooperative behaviour and this leads to their Nash equilibrium in taxes[10]:

$$t_A^{AB} - \varphi d_A = t_B^{AB} - \varphi d_B = -(0{,}5\, x_{AB}) \,/\, (\partial x_{AB}/\partial t_A) > 0 \quad (6)$$

PROP 1 ***carbon taxes on international flights***

Every country prefers to tax fossil fuel for international flights at more than its own climate damage and the mark-up is half of the revenue maximizing tax.

The intuition is that only part of the tax on international flights is paid by locals so there is room for tax exporting. Benoot et al (2015) look at the game between regulators of airports serving intercontinental flights and find the same tendency to charge airport operations more than the marginal social costs. An additional problem is that the assessment of climate damage is uncertain so that the external damage claims of a country cannot be verified by the international community. One solution is to force the country to use the revenues for additional climate measures[11]

The air transport community is very much aware of this tendency: in the Chicago convention[12], that can be considered as the "constitution" of international air travel, one does not allow to tax kerosene that has been taken

[10] A sufficient condition for a Nash equilibrium to exist in pure strategies is that demand function is linear and the demand is positive for $t_A = \varphi d_A + \varphi d_B$,, see Mandell & Proost, 2016.

[11] There is a parallel with the transport tax export literature where a region can add a tax margin to a congestion tax but where the federation can add a regulation to invest the tax revenues in capacity extension (Brueckner, 2015 and De Borger & Proost, 2016)

[12] https://en.wikipedia.org/wiki/Chicago_Convention_on_International_Civil_Aviation

on board in a foreign airport. The main idea is to avoid double taxation. Although the ICAO does not like fuel taxes, taxes on the fuel taken in one country are not explicitly forbidden by this convention.

6. The choice of offsets as a carbon-neutral growth instrument

6.1 Issues with offsets

According to CORSIA, the stabilization of emissions, when it cannot be reached by SAF's or by efficiency improvements, must take the form of an offset provided by an accepted offset scheme. Offsets are different from permit systems because they lack the monitoring and enforcement institutions to check the use and sales of permits. In aviation, voluntary offsets have been a popular feature offered by airlines at the demand of climate conscient passengers. This option is used by only a minority of passengers (Peixoto de Melo, (2024)). The CORSIA offsets are not voluntary but are an obligation for airlines to compensate the growth of emissions for bilateral flights.
In offset markets, asymmetric information creates several incentive problems, including adverse selection and moral hazard (Bushnell, 2012). The primary goal and benefit of offset programs is to provide a cheap solution for stringent emission caps. The main concern with offset programs is that they do not really deliver emission reductions. In the case of an international agreement like CORSIA, the international institution (ICAO) relies on individual countries to monitor an effective and additional emission reduction that compensates the growth in airline emissions. In some countries, institutions are incapable to do this. An example is the monitoring of deforestation in large countries like Brazil, where third party satellite observation has shown that the deforestation was much larger than claimed by government sources. The same problem is present in the Clean Development Mechanism created by the Paris agreement where 73% of the analyzed projects were unlikely to deliver the claimed additional emission reductions (Oko-Instituut (2016)). California uses offsets under the form of additional forest investments but Badgley et al (2020) found an overestimation of 30% between the credits sold and the realization.
An effective offset program requires two elements: an emission baseline and an additional emission reduction program. The emission baseline describes the future emission path in the absence of projects, which requires an extensive set of assumptions on future energy prices, technological developments, and existing climate policy commitments. The offset must be an additional effort on top of the baseline. Those selling the offsets have an incentive to overstate the baseline emissions. The additionality requirement wants to avoid that projects that are considered to meet the "National Determined Contributions", promised for domestic emission reductions (Paris 2015 agreement), are also used for CORSIA.
Warnecke et al (2019) investigated the potential demand and supply of offsets for aviation. They recommend that policy makers, when establishing new sources of demand for offset credits, restrict the eligibility to new "offset" projects that are developed in direct response to the new demand and/or to existing projects that are vulnerable to discontinuing GHG abatement. So, the eligible offsets should be based on new additional projects, specifically developed to meet the demand by CORSIA.

As already mentioned, there is another more fundamental concern with the offset approach in CORSIA. Offsetting a growth of 1 ton of CO_2 in aviation by an emission reduction of 1 ton of CO_2 in other sectors is carbon neutral but not climate neutral.

Note 1 Offsetting the growth of 1 ton of CO2 emission in aviation by 1 ton of CO2 emission reduction in other sectors is carbon neutral but not climate neutral: radiative forcing increases by $(\varphi - 1)$ ton of CO2 equivalent when an offset is used.

It is not yet clear how the Corsia offsets will function. First, offsets only require carbon neutrality not climate neutrality. Second, there are large differences in what countries consider as acceptable offset regimes: can internationally certified offsets be used when they have a very low price and are probably unreliable?
A low priced and unreliable offset has two disadvantages. First it is unreliable to carbon compensate international aviation emissions and second it will generate a smaller increase in the consumer price of aviation. A smaller increase in the consumer price of aviation means that there will be a smaller reduction in flight activity and a relatively larger increase in net radiative forcing and net climate effects.

For the analysis of the working of CORSIA one needs to specify a limit offset price op_i .This limit offset price specifies what every country *i* considers as acceptable. Acceptable offset prices will be defined in the next section.

6.2 The participation decision of one country in the case of offsets

We first analyze the participation decision for a given international offset price *op**. Countries A and B will join CORSIA and stabilize the emissions associated to their bilateral flights x_{AB} via offsets if it increases their welfare:

$$W_A(join, op^*) > W_A(not\ join, op^*)$$
$$W_B(join, op^*) > W_B(not\ join, op^*)$$

To operationalize the change in welfare, we use the following definitions: x_{AB}^0represents the fossil energy use in the base year, $(1+g)x_{AB}^0$ represents the volume of fossil energy use in the target year, given a growth rate of aviation activity g and (1+g) $x_{AB}(op^*)$ represents the use of fossil energy associated to a volume of aviation activity in the target year, that is reduced because the participation in CORSIA requires to acquire offsets at a price *op**. The additional climate damage for country A due to the growth of emissions of aviation activity (without offsets) is $d_A\varphi\ g\ x_{AB}^0$.

Consider now the effect of participation of country A on its welfare. It consists of 5 elements:

1. The loss of CS of aviation between A and B due to the price increase caused by the offsets:
$$-0{,}5(CS((1+g)x_{AB}^0 - CS(\ (1+g)x_{AB}(op^*))$$
The CS loss is due to the increase of the marginal cost by *op**, the factor 0,5 stands for the sharing the CS with the destination country (cfr. (3)).
2. The gain in producer surplus for airlines (PS) created by the increase of the marginal cost due to the offset obligation (under perfect competition, the initial PS was zero, and countries split the total PS of the two-way journey):

$$+0{,}5\ op^{*}.\,(1+g)\ x_{AB}(op^{*})$$

3. The costs of the offsets bought by the airlines (the cost of the two-way journey is split between the two countries), ζ represents the decrease in the baseline emissions that is agreed in CORSIA for 2035, this factor is 0.85:

$$-0{,}5\ op^{*}.\,[(1+g)x_{AB}(op^{*}) - \zeta.\,x_{AB}^{0}]$$

4. The reduction of climate damage by the decrease of aviation activity (here the two journeys count):

$$d_A\varphi\ [(1+g)x_{AB}^{0} - (1+g)x_{AB}(op^{*})]$$

5. The reduction of climate damage associated to the use of offsets – as offsets compensate emissions by a reduced emission in other sectors - the effective reduction of climate damage is lower than by a reduction of emissions on land ($d_A$instead of $d_A\varphi$) – again the two journeys count:

$$+d_A.\,[(1+g)x_{AB}(op^{*}) - \zeta x_{AB}^{0}]$$

To simplify the expressions, we can make use of the linearity of the demand function so that the shift (1+g) of the demand function is a parallel shift and this gives the two following expressions:

$$\begin{aligned}&-\frac{1}{4}\ op^{*}.\,(1+g)\big(\,x_{AB}^{0} - x_{AB}(op^{*})\big)\\&+(d_A - \frac{1}{2}.\,op^{*})[(1+g)x_{AB}(op^{*}) - \zeta x_{AB}^{0}]\\&+d_A\varphi\ (1+g)[x_{AB}^{0} - x_{AB}(op^{*})]\end{aligned} \qquad (7)$$

$$\begin{aligned}&(d_A\varphi - \frac{1}{4}\ op^{*}).\,(1+g)\big(\,x_{AB}^{0} - x_{AB}(op^{*})\big)\\&+(d_A - \frac{1}{2}.\,op^{*})[(1+g)x_{AB}(op^{*}) - \zeta x_{AB}^{0}]\end{aligned} \qquad (8)$$

This can be graphically illustrated. Figure 2 represents the intercontinental aviation market between A and B. The quantity represents the number of flights both ways (x= 1 stands for one flight A to B plus a return flight). The Y-axes represents the price of aviation fuel. There is a demand function for aviation fuel in a base year (2019) and a demand for aviation fuel in a future year (2035) that is shifted with a growth factor (1+g). The price level of 2019 has no climate policy included and is assumed constant until 2035. When country A joins country B for CORSIA, it accepts to compensate the growth in emissions by buying offsets for an equivalent quantity.

The loss of consumer surplus and producer surplus is given by half of the area ABCD. The reduction in climate damage is given by the area ABED (if the price of offsets is equal to the climate damage on land) plus the area FGCE as the latter area corresponds to a genuine reduction of fossil fuel consumption in aviation.

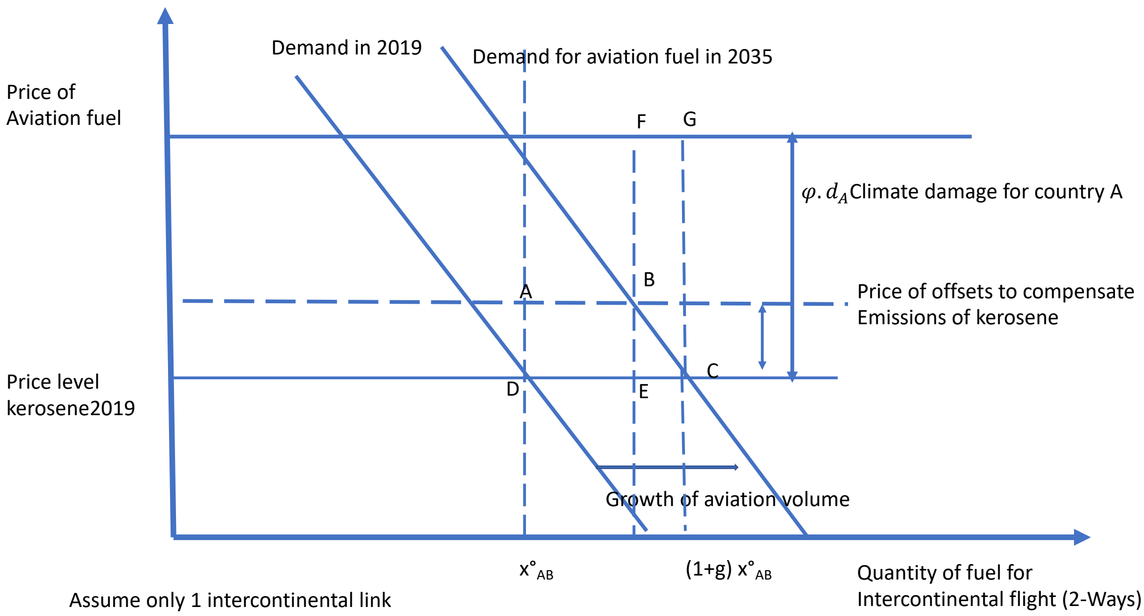

Figure 2 The Costs and Benefits of CORSIA participation for country A

Expression (8) shows the two main drivers for the participation of a country in CORSIA. The benefit is of course the reduction of climate damage, full benefit ($d_A\varphi$) for the reduction in flight activity and partial (only $\varphi - 1$)) for the volume that is offset. The reciprocity of the effort (the effort done for A to B is repeated by country B for the trip B to A) makes that the cost in terms of lost consumer surplus and in terms of offset costs is only half of what it would be for a local externality.

Expression (8) can be used for comparative statics. First note that if the marginal damage d_A is larger or equal to half of the offset price (($0,5\ op *$), it is always beneficial for country A to participate: the second term is zero or positive and the first term is then always positive. Second, if countries are confronted with a higher growth rate, if d_A is larger than half of the offset price , the benefits of participation increase but if d_A is smaller than half of the offset price, a higher growth rate decreases the benefits of participation. The benefits of participation increase in the multiplicator φ for air transport emissions and decrease in the cost of offsets op^*.

We summarize in the following proposition:

PROP 2 ***Participation decision in the case of offsets***

Country A will always join country B in the CORSIA agreement if its marginal climate damage d_A is larger than or equal to half of the price of the offset op*. The benefits of participation are increasing in the growth rate of air transport activity if the marginal damage d_A is larger or equal than half of the price of the offset.

One of the major issues with offsets is unreliability of the cheap offsets: to what extent do they effectively reduce the emissions in other sectors. We can consider the reduction of offsets as an uncertain variable and op* as the price of an offset with expected zero emissions. Then the participation decision is a decision with expected constant marginal benefits and the participation decision is not affected by the uncertainty as such.

7 The use of SAF's as carbon neutral instrument

7.1 Issues with SAF's and the required blending rate

There are two issues with SAF's: what SAF's are eligible and what is the net climate effect of substituting kerosene by SAF's.The eligibility discussion is closely connected to the issue of land use where opinions have converged between the EU and the other countries.

The net climate effect depends on two elements. First making SAF's, whether they are biofuels or e-fuels, always requires energy to produce them. When this energy is not carbon free (is not renewable), one needs to account for the indirect carbon emissions associated to their production. Let the relative carbon emission of SAF's be equal to β. In the ideal case this parameter equals 0 (e-fuels using hydrogen and carbon produced using renewable energy have the lowest relative carbon emission factor but this is still 0.15 (Mayeres et al, 2023)), but for some biofuels this indirect emission can even become larger than 1. Ballal et al. (2023) expect this relative emission level decrease over time. CORSIA limits the eligible SAF's to those with a lifecycle emission savings of at least 10%, so $\beta \leq 0.9$. Second, SAF's used in aviation have also a climate forcing effect $\chi \leq \varphi = 1{,}7$ that is larger than fossil fuels used at land level (equal to 1) but may be smaller than the climate forcing factor assumed for kerosene.

We can derive the necessary blending rate for carbon neutral and for climate neutral aviation: using p^{SAF} for the unit price of SAF's:

$$p^b = \alpha p^{SAF} + (1-\alpha)p^0 \qquad (9)$$

To realize climate neutral growth, the emissions in the base period (fossil fuel use x°) need to be compensated by using a blend with share α of blended fuels:

$$\zeta\varphi x^0 = [\chi\beta\alpha + \varphi(1-\alpha)]\,(1+g)x(p^b) \qquad (10)$$

As SAF's are more expensive than kerosene, emissions will be limited by blending with cleaner fuels but also by the demand effect of a more expensive blended fuel.

$$\frac{x(p^b)}{x^0(p^0)} = 1 - \epsilon\alpha\left[\frac{p^{SAF}}{p^0} - 1\right] \qquad (11)$$

Where -ϵ is the demand elasticity w.r.t. the fuel price. Using (11) in (10), we obtain an (implicit) expression for α (assuming $\left(1-\frac{\chi\beta}{\varphi}\right) \neq 0$

$$\alpha^{climate} = \frac{1}{\left(1-\frac{\chi\beta}{\varphi}\right)}\left[1 - \frac{\zeta}{1+g}\frac{1}{\left\{1-\epsilon\alpha\left[\frac{p^{SAF}}{p^0}-1\right]\right\}}\right] \qquad (12)$$

Consider first the simplest case where $\chi = \varphi$ and $\epsilon \approx 0$, then

$$\alpha^{climate} = \frac{1}{(1-\beta)}\left[1 - \frac{\zeta}{1+g}\right]$$

The blending is in this case an increasing function of (1+g) and of β .

Adding the demand effect of more expensive fuel allows to decrease the required blending rate because the blending rate in (12) is decreasing in the price elasticity and in the extra cost $\frac{p^{SAF}}{p^0}$of SAF fuels.

In this paper we use three definitions of climate and carbon neutral. CORSIA accepts a SAF as carbon neutral as long as the indirect emission rate β<0.9. The indirect emissions are then for CORSIA irrelevant but not necessarily for the signatories themselves that are concerned about the real climate effect.

Note 2 Offsetting the growth of 1 ton of CO2 kerosine emission in aviation by using SAF's requires a blend for "CORSIA carbon neutrality" (with β<0.9)

$$\alpha^{CORSIA} = \left[1 - \frac{\zeta}{1+g} \frac{1}{\left\{1 - \epsilon\alpha\left[\frac{p^{SAF}}{p^0} - 1\right]\right\}}\right] \quad (13)$$

For "carbon neutrality", one requires a higher blending rate to take into account the indirect emissions $\beta$of SAF's

$$\alpha^{carbon} = \frac{1}{1-\beta}\left[1 - \frac{\zeta}{1+g} \frac{1}{\left\{1 - \epsilon\alpha\left[\frac{p^{SAF}}{p^0} - 1\right]\right\}}\right] \quad (14)$$

For "climate neutrality", one needs to take into account the possibly lower climate multiplicator $\chi \leq \varphi$ for SAF fuels (12) that requires a smaller blending rate than for carbon neutrality (14).

Of course, when the SAF's have still a high indirect carbon emission $\beta = 0.7$ and no lower climate forcing factor $\chi = \varphi$, it may be impossible to compensate the climate effects of the growth in aviation via SAF's. When the aviation volume growth is higher than 30%, even substituting all kerosene by SAF's is insufficient.

7.2 The participation decision of one country when emission growth is compensated by SAF's

For the use of SAF's to compensate the growth of kerosene emissions, we follow a similar procedure as in the case of offsets. First define a common price and quality of SAF's to be used by 2 countries and next compute the welfare effect of signing the CORSIA agreement for the country studied. We define the participation decision as a function of the full climate impact of the use of SAF, even if the official CORSIA criteria are much weaker (they allow $\beta < 9$ and they assume $\chi = 1$).

We assume that SAF's are supplied in a competitive market and that the price of SAF is constant. As the supply of cheap SAF's is limited, there is a producer surplus for the inframarginal supplier that we neglect in the country A's decision.

Using a common price for SAF's, p^{SAF*} , a common indirect emission rate β^* and a resulting blending rate $\alpha^{*climate}$ (defined by (12)) for the link AB, and the resulting price of the blend p^{b*} (defined by (9)), country A's participation depends on the welfare effect that consists of:

1. The loss of CS of aviation between A and B due to the price increase caused by the blending mandate:

$$-0{,}5(CS((1+g)x_{AB}^{0} - CS(\,(1+g)x_{AB}(p^{b*}))$$

The CS loss is due to the increase of the fuel cost from p° to p^{b*}.

2. There is no gain in producer surplus (PS) because the blended fuel is used for all flight activity between A and B.
3. The reduction of climate damage compared to no policy is .

$$\varphi\, d_A\, x_{AB}^{0}[(1+g)\ -\zeta]$$

Regrouping all the terms, making use of the linearity of the demand function, the welfare benefit of CORSIA participation for country A, using SAF's is:

$$-(1+g)(p^{b*} - p°)\big[0{,}5^2\big(x_{AB}^{0} - \ x_{AB}(p^{b*})\big) + 0{,}5\, x_{AB}(p^{b*})\big]$$
$$+d_A\varphi\, x_{AB}^{0}[(1+g)\ -\zeta]$$

(13)

Which can be simplified into:

$$-\frac{1}{4}(p^{b*} - p°)(1+g)[\,x_{AB}(p^{b*}) + x_{AB}^{0}]$$
$$+d_A\varphi\, x_{AB}^{0}[(1+g)\ -\zeta]$$

(14)

For price elasticities tending to 0 and using $\chi = \varphi$, expressions (9) and (12) we obtain the following cost and benefit:

$$\frac{1}{2}[(1+g)-\zeta\ ]\left\{2d_A\varphi - \frac{1}{(1-\beta)}(p^{SAF} - p^{0})\right\}x_{AB}^{0}$$

Where we note the importance of the indirect emissions (β) of the SAF's. The reciprocity of the effort by country B makes that the CORSIA agreement can be a useful agreement as it decreases the cost of climate policy by a factor 2.

PROP 3 ***Participation decision in the case of SAF's***

For very low price elasticities, participation in CORSIA via SAF's is beneficial for couuntry A if the additional cost of SAF's, multiplied by the indirect emission rate $\frac{1}{1-\beta}$, is smaller than twice the saved climate damage per ton of kerosene.

Prop 3 assumes no price elasticity, and this makes it difficult to compare SAF's with offsets as the latter only work with a price elasticity

Countries have very different climate damage assessments and expected growth rates so determining the number of participants requires a numerical assessment in section 9.

8 Comparing offsets and SAF’s

Both offsets and SAF’s involve many parameters to express their climate efficiency and their costs. Both policies are difficult to compare but have very distinctive characteristics that are worthwhile mentioning. Table 2 compares some of their features:

	OFFSETS	SAF BLENDING
Incentive	Marginal cost increase	Average cost increase
Airline volume	Stronger decrease	
Producer surplus	More beneficial for airline if grandfathered	
Implementation issues	Additionality of emission reduction	Indirect emissions at production SAF Lower climate forcing of SAF’s?

Table 2 comparing features of Offsets and SAF blending mandate

When perfectly competitive airlines have to compensate emission reductions via offsets, they increase the marginal cost of flying (like in the case of a permit), while in the case of blending mandates, the average price of flying increases. For a comparable cost, one can expect that the use of offsets decreases more strongly the aviation volume.

When airlines receive grandfathered emission rights for the initial volume, offsets can generate a larger producer surplus.

9. The participation decision and the role of technology policy

Up to now, we considered a static game in emission reduction, where each country decides to participate once and for all in the international agreement. The CORSIA agreement is a long-term agreement: it extends to at least 2035 but could be continued. In the recent environmental literature, attention is paid to the effect of technology investment as complement to emission reductions. By lowering the relative cost of more environmentally sound technologies, technology policy can increase incentives for countries to comply with international climate obligations (IPCC (2014).

Barrett (2006) looked into international agreements where the signatories agree to contribute to the development of a clean technology that solves the problem. He found that simply focusing on technology is not very useful because the technology development comes down to a round of contributions for a pure public good. We know that, in that context, the free riding problem cannot be neglected. Harstad, Lancia, Russo (2019) consider a repeated game and reach a more positive conclusion. They distinguish the participation decision (signing the agreement) and the compliance decision (to reduce emissions every period). The promises of countries that benefit less from the agreement, become more credible to comply when they invest in green technology. The most interesting result of Harstad et al (2019) deals with technology spillovers. When countries are identical and spillover rates of technology are high, it will be more difficult to design self-enforcing treaties via technology investment requirements. On the other hand, when countries are very heterogeneous and with high technology investment spillovers, the more motivated countries can invest in new technologies and help the less motivated countries to comply.

This will be our take on technology development investments by a limited number of richer and more climate conscious countries. The two main technology levers for aviation are more fuel-efficient aircrafts and a cost decrease in SAF's.

9.1 Efficiency standards for aircrafts

The EU and the US pushing their aircraft industry to develop more fuel-efficient aircrafts is a promising option (Ovaere & Proost, 2024). In their paper they consider Airbus and Boeing as duopolists who are stimulated by subsidies from EU and US government that cooperate to develop more efficient aircrafts. But the other countries may react by capturing part of the duopoly rents via higher fuel taxes. The higher fuel taxes decrease the willingness to pay of the other countries to buy aircrafts at high prices. Our setting does not allow this complex interaction, but we can illustrate a simplified case.

In this simplified case the EU and or the US subsidize the development of a more efficient aircraft, but it is offered to the airlines at slightly lower full cost: the sum of the rental cost, other operation costs and fuel costs is infinitesimally smaller than in the reference: $p_{AB}^0 - \epsilon$. The higher fuel efficiency and lower fuel cost is compensated by a higher rental cost. In this case, the EU and/or US carry all the R&D costs and have as benefits, the increased reduction of emissions by the aviation sector. The emission reduction applies to all countries whether they participate or not in the CORSIA agreement.

Additional R&D efforts by the manufacturers (Airbus and Boeing) allow to reduce fossil fuel use per mile from f° to f^t so that total fuel use and emissions decrease by $(1+g)(f^\circ - f^t)2z_{AB}y_{AB}^0$.

To see the benefits and costs we need to consider the three types of countries affected by this technological improvement: the non-signatories, the signatories other than the EU and US, and finally the EU and the US.

The non-signatories do not change their flight volume as the total operation cost per mile is hardly affected, but the damage of their own emissions will decrease as the flight volume of 2019 would be produced in 2035using more fuel efficient aircrafts. This is illustrated in Figure 3 where the climate benefit of better technology now equals the area HBB'I. As before, the non-signatories will benefit from all reductions of emissions in other countries.

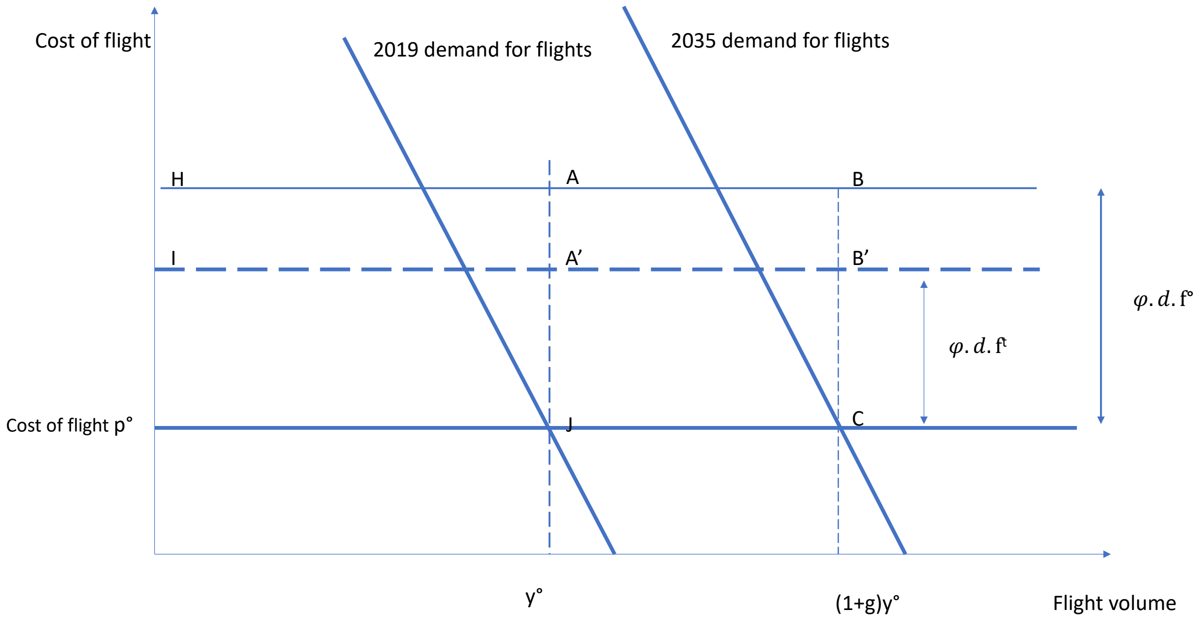

Figure 3 Effect of a strong technological improvement on a non-signatory country

For the signatories, the effects are more complex as the volume of flights will change. A lower emission rate means a lower offsetting cost $f^t.op*$and therefore a higher flight volume compared to the case without technological progress.

For the signatories, the cost of participation in the agreement changes:

a) Lower CS loss

$$-0{,}5[(CS\ (1+g)y^0_{AB}(f^0) - CS(1+g)\ y^0_{AB}(f^t.op*)]$$

b) lower gain in PS (if flight price elasticity is limited)

$$+0{,}5(f^t op*)\ \ y^0_{AB}(f^t.op*)$$

c) lower cost of offsets (if flight price elasticity is limited)

$$op*f^t 2.z_{AB}[y^0_{AB}(f^t.op*) - \zeta y^0_{AB}(f^0)]$$

d) lower climate damage for their flights

$$+\varphi.d_A\ (1+g)2\ z_{AB}[f^0 y^0_{AB}(f^0) - f^t y^0_{AB}(f^t.op*)]$$

e) smaller decrease of climate damage through offsets:

$$f^t 2.z_{AB}[y^0_{AB}(f^t.op*) - \zeta y^0_{AB}(f^0)]$$

The benefit of participation of one country has become lower as there is an exogenous decrease of emissions, but also the cost of participation has decreased. The equilibrium number of signatories can therefore increase or decrease.

The final category of countries to consider are the aircraft producing countries (EU and US) that produce the more efficient aircrafts. It is difficult to know the costs of R&D and the additional production costs of a more fuel-efficient aircraft. If one assumes that the duopoly profits do not change but that the additional R&D costs are paid

by the EU and/or the US governments, one can compute the total climate benefits (valued at d_{EU} and /or + d_{USA}) and other benefits for the EU and US for a given decrease in fuel use per mile (f^t-f^o) .
This needs a numerical computation as the decrease in climate emissions will depend on the number of signatories, that is itself a function of the emission rate.

9.2 Sustainable aviation fuels?

Carbon-free fuels will probably be more costly than offsets (Mayeres et al, 2023), so it will be hard to impose their use on international aviation. At least if one considers the full climate impact of SAF's that include the indirect emissions (β). But one could hope that the additional fuel cost of offsets, gives an extra stimulus for R&D that makes SAF cheaper and reduces their indirect emissions. This is what several countries like the EU and the US hope for (OECD/ITF, 2023) by imposing a growing blending obligation for domestic flights, ranging from 2% in 2025 to 70% in 2050 including a minimum share of e-fuels. IATA (2023) reckons that SAF's will be able to reduce carbon emissions by 63% in 2050 and achieve net zero emissions for aviation in 2050.
Of course, SAF's that have low indirect emissions (β) and cost less than kerosene and have a radiative forcing factor $\chi < 1{,}7$ would be a game changer as this allows to reduce all aviation emissions and reduce the impact of the growth in aviation. But there remains an important gap between expected performance (prices and indirect emissions) and the official IATA expectations.

10 Model illustrations

The model findings are illustrated with a simplified model of world aviation. We focus on an illustration for 2040 rather than 2035 as, given the difficult start in the COVID period (2021-2023), the CORSIA agreement is likely to be extended and would be in full force after 15 to 20 years.

10.1 Data for reference case

For the numerical illustration we consider flights between ten countries, namely the EU28, US, Canada, China (including Hong Kong), India, Australia, United Arab Emirates, Brazil, Russia and Japan. The choice of these countries was to ensure a diverse group of countries but was also dictated by the availability of data. To calibrate the demand functions for fuel in 2019 and 2040 we used flight data and annual growth rates provided by IATA (see Appendix for more details). Other aviation parameters used are assumed equal for all flights and summarised in Table 3:

Parameter	Value	dimension
load factor	233	pass/flight
fuel consumption	0.036511	liter/pkm
jet fuel emissions	2.465	kg CO2/liter fuel
fuel cost in 2019	0.44	euro/liter
elasticity fuel demand	-0.42	
fuel cost ratio 2040/2019	1.13	

Table 3 basic flight data used. (sources: Mayeres et al (2023), Eurostat

The fuel demand elasticity is taken from Mayeres et al (2023) and combines all fuel efficiency reactions and reactions to ticket prices.

The valuation of climate damage is a key parameter. As we assume that the CORSIA agreement is not enforceable (see section 3), the signing of the CORSIA agreement is as such not an indication of the climate valuation. We have chosen to rely on revealed climate policy of the different countries. We use OECD – data, more precisely the extent to which countries have priced all carbon emissions at 60 € per tonne CO_2, the so called "carbon pricing scores" (OECD, 2021). This carbon pricing includes all types of excises, carbon taxes as well as permits. This is probably an underestimate of the national climate damage valuation as the cost of fuel efficiency regulations is not included. Some countries like the EU, have in their discussions also manifested a higher willingness to pay for international aviation (their permit price ranged between 50 and 100 €/ ton of CO_2). The damage parameter d parameter gives then the climate damage per ton of CO_2 emitted at land level.

	%CPS60
EU	0.47
US	0.22
CHINA	0.09
INDIA	0.13
AUSTRALIA	0.2
UAE	0.005
RUSSIA	0.07
Canada	0.34
Brazil	0.01
Japan	0.24

Table 4: Valuation of emission reductions by different countries: % of the 60 €/ton of CO2 gap charged on average by a country

For example: the EU charges on average 28,2 €/ ton of CO_2 (0.47 x 60 €) as carbon levy via taxes or permits. The other countries charge much less.

Other climate related parameters are the multiplicators for kerosene used by aviation φ, the possible lower multiplicator for SAF χ, the indirect emission of SAF's β and the baseline emission ζ factor that needs to be achieved.

φ	1.7
χ	1.2
β	0.5
ζ	0.85

Table 5: parameters values used

10.2 Results for reference scenario

OFFSETS

Results for EU and US

We first focus on the EU and the US, the two countries with the highest climate valuation. As the EU has a $d_A = 0.06951$ (CPS60 = 47%) while the USA has a much lower evaluation of the environmental damage $d_A = 0.03254$ (CPS60 = 22%), the USA will be the determining country to find the highest acceptable offset price and SAF fuel price at which the two countries are ready to participate effectively in the CORSIA agreement .

In this particular case an offset price of 31.7 euro/ton CO2, will lead to a break even welfare for the USA. An offset price of 31.7 euro/ton CO2, amounts to an increase of the fuel cost from 0.497 €/l to 0.575 €/l which will lead to a reduction of 6.6% in flights in 2040. As the EU has a higher climate damage valuation, the EU will have a positive welfare effect of 420 Mill € per year. This welfare benefit consists of a climate benefit of 788 Mill € due to reduced amount of emissions of which nearly 20% is due to the reduction in flight activity and nearly 80% comes from offsetting emissions elsewhere. As the USA has a lower evaluation of the climate damage, the environmental benefits will be lower (370 Mill euro). The consumer surplus due to the decrease in flights for both countries is (0,5) 1810 Mill € and the costs of the offsets is (0,5)676 Mill €, this is compensated by an increase in producer surplus of (0,5) 1748 Mill €, summing all effects, we have a neutral welfare outcome for the US.

We can also check Proposition 2 which states that the offset price needs to be at least smaller than twice the marginal environmental damage: $op^* < 2\,d_A$ for country A to participate. In this case $2\,d_A = 0.6508$ which corresponds to an offset price of 26.4 euro/ton CO2. We see that indeed the highest acceptable offset price lies above this threshold.

The level of offset prices and the net welfare gains or losses depend on the basic parameters of the model. In Table , we summarize the results for different sets of parameters. In the columns we give, respectively, the highest offset price [euro/ton CO2] for which the EU and the USA will participate in a bilateral CORSIA agreement and the associated fuel price [euro/litre], the environmental benefits and the net welfare impact associated to the offset price in [Mill euro/year].

Changes	Offset price €/ton	Fuel price €/l	Env ben offset Mill €/y	Net welfare mill €/y
REFERENCE	31.7	0.575	788	419.5
	31.7	0.575	370	0
Annual growth 3.5% instead of 1,9%	30	0.571	1457	774
	30	0.571	682	0
Low demand elasticity (0.001)	26.4	0.562	712	379
	26.4	0.562	333	0
Higher climate multiplicator φ=3	41	0.598	996	530
	41	0.598	466	0

Table 6: results for offsets for different parameter values

With a higher growth rate for aviation, the environmental benefits increase as the committed reduction in flights will be much higher. But the welfare cost increases even more as there will be a higher loss in consumer surplus and a higher cost of offsets. At an offset price of 31.7 euro/ton CO2, the net welfare gain for the USA would be -34.65 Mill euro and for the EU 743 Mill euros.

Low demand elasticities will make it more difficult to obtain an agreement. The reduction in emissions are now only obtained through offsetting emissions on land which have less impact on the climate damage than a reduction of flight activity and the environmental benefits are reduced. As the number of flights is almost not affected the total costs of the offsets will also be higher and the loss of consumer plus producer surplus are higher. This all leads to lower welfare gains for the same offset price in the case of low demand elasticities.

For higher climate damage multiplicator for kerosine φ, the environmental benefits of avoiding kerosine use will be higher and countries will be willing to pay 20% higher offset prices (41 instead of 31,7 €/ton).

Results for 10 selected countries

For the EU and the USA to participate in a bilateral agreement, the offset price needs to be lower than 31.7 euro/ton CO2. In Table 10, we show the welfare results for all the 10 countries if CORSIA would require them to use an offset price of 31 euro/ton CO2.

		Country B									
		Australia	**Brazil**	**Canada**	**China**	**EU28**	**India**	**Japan**	**Russia**	**USA**	**UAE**
Country A	**Australia**			-0.20	-12.74	-0.44	-0.51	-1.11		-1.49	-6.05
	Brazil			-1.94		-35.06				-53.02	-8.87
	Canada	3.19	1.00		35.62	38.34	3.60	3.56		112.12	2.80
	China	-56.04		-46.34		-123.83	-26.30	-135.49	-47.15	-60.07	-38.05
	EU28	3.68	44.27	79.88	215.53		77.18	84.57	99.92	419.47	165.96
	India	-1.53		-2.70	-19.17	-32.68		-3.39	-12.71	-10.33	-91.00
	Japan	0.82		0.58	8.51	3.97	0.20		0.58	9.34	0.34
	Russia			0.00	-53.73	-59.23	-19.96	-5.83		-4.24	-16.62
	USA	1.07	-2.23	-4.53	4.14	0.00	-1.14	84.97	0.03		-2.60
	UAE	-42.52	-9.07	-5.82	-60.18	-157.12	-196.76	-8.63	-23.24	-52.86	

Table 7: Net gain or loss for a country in Mill €/ year in 2040 from participating in CORSIA, given an offset price of 31 euro/ton CO2

CORSIA requires a signatory A to stabilize emissions (at 85% of 2019 emissions) of its bilateral flights with country B. In table 7 we check for each pair of countries whether they benefit from this stabilization if the acceptable offset costs 31 €/ton. A negative figure in the table for country pair C,D means that for these countries, they run a welfare loss if they participate in the agreement. The country pairs with a welfare benefit are shown in yellow.

In this case, only the EU, USA, Japan and Canada would be willing to enter in bilateral Corsia agreements with each other as both countries would gain of doing so. For India and China to join, the offset price needs to decrease strongly.

So although the CORSIA agreement is interesting for some pairs of countries as it allows to join efforts in reducing emissions, only a small share of the countries would enter the agreement at offset prices of 31 €/ton of CO2. This offset price can be compared with the EU's permit price for domestic flights that are in the range of 50 to 100 €/ton of CO2. At these offset prices, no country would participate in the CORSIA agreement.

SAFs

For a given price of SAF fuels, the countries need to choose a blending rate that neutralises the increase in emissions. As SAF's are more expensive, the higher cost of blended fuels will decrease the consumer surplus. There will be a maximum SAF fuel price for which a blend exists that allows a country to compensate emissions and not lose in terms of welfare.. In the case of the USA, the maximum acceptable SAF price is 0.574 €/l in 2040. At this price it will use 62% of SAF in it's blend resulting in a blended fuel price of 0.545 /l in 2040. The welfare gains for the EU will be higher than in the case of offsets: 645 Mill euro because the SAF fuels are by assumption less damaging for climate than kerosene (multiplicator of 1,2 instead of 1,7).

In Table 8, we summarize the results for different sets of parameters. In the columns we see: the highest SAF price [€/l)] for which the countries will agree to a SAF mandate, the net blended fuel price in case of SAF mandate, the environmental benefits for SAFs for each country and the net welfare gains for the countries.

	SAF price €/l	Blend Price €/l	Env ben SAF Mill €/y	Net welfare effect SAF Mill €/y
	0.508	0.483	1210	645
	0.508	0.483	570	0
Annual growth 3.5%	0.508	0.499	2310	1226
	0.508	0.499	1050	0
Low elasticity (0,001)	0.504	0.482	1210	643.5
	0.504	0.482	570	0
Lower price elast and	0.492	0.483	1210	643.5
$\varphi = \chi$=1.7	0.492	0.483	570	0
Higher climate multiplicator φ=3	0.6	0.517	2140	1136
	0.6	0.517	1000	0

Table 8: Results for SAFs for different parameter values

For higher growth rates the price of SAF remains the same but blending rate will be higher (87% in stead of 62%). Despite the fact that the environmental benefits are higher with larger growth rates, the losses in consumer surplus also grow.

Propostion 4 tells us that for low elasticities and when $\phi = \chi$, participation in CORSIA via SAF's is beneficial for country A if the additional cost of SAF's, multiplied by the indrect emission rate $\frac{1}{1-\beta}$, is smaller than twice the saved climate damage per ton of kerosene. Note that for the USA: $2\ d_A\ \phi = \frac{1}{1-\beta}(p^{SAF} - p^0) = 0.1106$, where $p^0 = 0.497€/l$ and $p^{SAF} = 0.552 = 0.47 * 1.13$ is the price of SAFs in 2040.

For higher ϕ and thus higher climate damage for kerosine, the environmental benefits of avoiding kerosine will be higher. As SAFs will have an even lower impact on climate damage, the benefits using SAFs are larger and higher prices become acceptable.

Table 9 shows that for a SAF price of 0,509 €/l, more or less the same countries (EU, USA, Canada) would join CORSIA as in the case of offsets

Comparing offsets and SAF's

As policy instrument, SAF's are less efficient than offsets because they rely on average pricing (a greener blend is imposed for all flights) rather than through a marginal cost incentive (the cost of the offset).

The SAF prices that are necessary to have the EU and the US participating via SAF blends are very low. This is itself an important message as the expected prices of SAF's are much higher than 0,575 €/l. One expects prices of SAF's to be much higher (200 to 500%) than the price of kerosene (Mayeres et al, 2023). This means that SAF blends are unlikely to be used if one targets effective climate damage reduction.

Fuel efficiency

The fuel efficiency of the aircraft stock was taken as given in the future year (here 2040). One of the possible climate policies is to subsidize the producers of aircrafts to make an extra R&D effort that results in an exogeneous reduction in emissions per passengermile of 25% (instead of having a jet fuel emission rate of 2.465 kg CO_2/l, we assumed a jet fuel emission rate of 1.849 kg CO_2/l). Fuel efficiency improvements have several effects. First, all flights in 2040 become less polluting and this holds as well for countries that participate in CORSIA as for countries that do not participate. This benefit amounts to 2380 million €/year in the absence of CORSIA. The breakdown per country is given in **Error! Reference source not found.**:

		Country B										
		Australia	Brazil	Canada	China	EU28	India	Japan	Russia	USA	United Arab	Total
Country A	Australia			2.19	29.92	1.29	1.03	4.75		16.06	14.22	69.47
	Brazil			0.04		1.05				1.01	0.14	2.24
	Canada	4.53	1.33		43.70	57.33	4.18	5.29		156.01	3.43	275.79
	China	13.46		11.57		34.10	5.10	34.10	11.01	27.91	7.84	145.09
	EU28	3.04	49.25	79.25	178.07		59.93	69.87	101.23	416.17	128.88	1085.71
	India	0.67		1.37	7.37	16.58		1.54	5.44	5.24	34.98	73.19
	Japan	5.70		3.73	90.92	35.68	2.85		4.27	49.56	3.61	196.34
	Russia			0.00	8.56	15.08	2.93	1.25		1.08	2.65	31.54
	USA	17.67	22.23	100.95	68.24	194.81	8.87	45.43	3.39		34.50	496.08
	United A	0.36	0.07	0.05	0.44	1.37	1.35	0.08	0.19	0.46		4.35
												2379.81

Table 1: Environmental benefits of an improved fuel efficiency of 25% per country

From the point of view of the US and the EU, the countries subsidizing their aircraft manufacturers, the emission reductions count for a much larger benefit as these countries use a higher valuation for climate damage. The total benefit becomes then 4823 mill € for the EU and 2258 mill € for the US. This benefit depends on the assumption that the price of a flight does not decrease, so that there is no rebound effect in the rest of the world.

The question is whether this technological improvement increases the participation in CORSIA. Both the environmental benefit and the cost of participation decrease with better technology. In net welfare terms, it becomes less interesting for countries to participate in CORSIA. Table 10 is equivalent to Table 7 and gives the maximum offset prices at which any pair of countries would participate. We see that the maximum offset prices the US and EU would be ready to pay are now only 30,1 €/ton instead of 31,7 €/ton.

This smaller incentive to join the agreement is however much less important than the environmental benefit of the strong efficiency gain.

		Country B									
		Australia	Brazil	Canada	China	EU28	India	Japan	Russia	USA	UAE
Country A	Australia			27.8	11.2	26.3	16.3	26.7		27.8	0.6
	Brazil			1.2		1.2				1.2	0.6
	Canada	27.8	1.2		11.2	50.8	16.4	33.2		29.6	0.6
	China	11.2		11.2		11.2	11.1	11.2	8.6	11.5	0.6
	EU28	26.3	1.2	50.8	11.2		16.4	32.1	8.7	30.1	0.6
	India	16.3		16.4	11.1	16.4		16.4	8.6	16.4	0.6
	Japan	26.7		33.2	11.2	32.1	16.4		8.7	31.1	0.6
	Russia			0.0	8.6	8.7	8.6	8.7		8.7	0.6
	USA	27.8	1.2	29.6	11.5	30.1	16.4	31.1	8.7		0.6
	UAE	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	

Table 10: Offset prices in euro/tonCO2 in 2040 for which country A and B will both accept a bilateral CORSIA agreement with fuel efficiency improvements

11 Discussion

In this paper we analyzed the participation of countries in the CORSIA agreement, taking the design of the agreement as given. The agreement expects each pair of signatories to stabilize their bilateral aviation emissions to 85% of the emission level of 2019 and this up to 2035. The agreement covers some 60 % of world aviation emissions.

The emissions can be stabilized by reducing aviation activity but also by using offsets and SAF's. The international aviation community (IATA) counts mainly on SAF's to stabilize emissions.

As the agreement must be self-enforcing, countries would only participate if joining the agreement leads to a reduction of climate damage. This requires considering the multiplicator of aviation fossil fuel use (factor 1,7) as well as the indirect emissions of SAF (ranging from 0,15 for e-fuels to 0,9).

Using revealed preference for climate policy efforts (based on the OECD (2021) carbon tax gap), we offer the following insights. First pairs of countries who have a valuation for CO2 reduction that is half of the price of offsets or SAF's will benefit from joining the agreement. The main reason for this cooperation is that the reciprocity of the effort (the effort done for flight A to B is repeated by country B for the trip B to A) makes that the cost in terms of lost consumer surplus and in terms of offset costs is only half of what it would be for a local externality.

Second, an implementation of this agreement is much less costly via offsets. Offsets with prices of the order of 20 to 30 €/ton CO2 avoided, are credible and would allow countries like the EU, US, Japan Canada to join CORSIA. For these countries to join CORSIA via SAF blending would require SAF prices of 0,6 €/l to be compared with kerosine prices of 0,5 €/l. These SAF's do not exist (yet) as expected SAF prices cost 100 to 500% more than kerosene.

Third, technological progress in fuel efficiency for aviation reduces both the benefit and the cost of emission stabilization and will not increase participation in CORSIA.

Fourth, the CORSIA agreement imposes the same stabilization of emissions for all bilateral flights. As the cost of participation is increasing in the growth rate of aviation activity, this is likely to discourage the participation of strong growing economies as there are India, China and Brazil. An international agreement of the pledge type like the one in Paris would help to increase the number of countries participating.

This paper used a simple approach focusing on the participation decisions of individual countries that take the CORSIA setting as given and behave in a Nash sense. Follow-up research can improve the approach in three directions.

First, one can extend the non-cooperative setting by adding options for countries to make additional efforts that are motivated by the climate benefits of larger coalitions than two countries. A coalition of three countries will take into account the climate benefits for the three countries and this could lead to effective reductions of emissions beyond the 85% of 2019 emissions. But coalition building without enforcement is difficult.

Second, one can improve the modelling of the offset and SAF fuel markets. As the marginal costs of offsets and SAF fuels are increasing, there are producer surpluses involved that can increase the benefits of countries supplying them and improve participation rates. As all countries are interested in cheap offsets and SAF's this would however require analyzing all participation decisions simultaneously.

Third, our international aviation market is strongly simplified. There is no substitution between destinations and flights are offered by airlines in perfect competition. Consider now a duopoly. If one has a Bertrand competition or a strong competition policy, the participation results would not be very different. If one has Cournot competition, the participation results may be affected. In this case the initial price is larger than the marginal cost. Participation in CORSIA would require to increase the price of flights. Part of the increase is absorbed by the duopolists but the new price is an additional distortion that may not be justified in efficiency terms. Introducing imperfect competition may therefore reduce the benefits of CORSIA participation but this requires further research.

Appendix Data

Number of Flights per country pair:

Origin/ destination	USA	United Arab Emirates	Japan	Australia	Canada	India	Russia	Brazil	China	EU28
USA		11312	49203	12818	4E+05	4579	3741	23172	64416	3E+05
United Arab Emirate	11312		2894	10164	1402	100357	14079	1534	19451	80782
Japan	49203	2894		7012	4068	2663	4677	0	2E+05	25731
Australia	12818	10164	7012		1878	834	0	0	29177	730
Canada	391921	1402	4068	1878		1418	0	748	20873	52614
India	4579	100357	2663	834	1418		11662	0	18484	26677
Russia	3741	14079	4677	0	0	11662		0	26339	2E+05
Brazil	23172	1534	0	0	748	0	0		0	28901
China	64416	19451	2E+05	29177	20873	18484	26339	0		80512
EU28	305802	80782	25731	730	52614	26677	2E+05	28901	80512	

Table A1: number of flights between countries

Sources: IATA https://applications.icao.int/dataservices/default.aspx

Distances per connection:

average km	USA	United Arab Emirates	Japan	Australia	Canada	India	Russia	Brazil	China	EU28
USA		12589	10173	15187	2262	13595	9000	7301	11671	6200
United Arab	12589		8034	10159	10994	2609	3750	12000	5009	5240
Japan	10173	8034		6821	8103	5968	7355	17371	3054	9874
Australia	15187	10159	6821		14144	7802	0	0	7448	15157
Canada	2262	10994	8103	14144		11488	0	9287	9410	6862
India	13595	2609	5968	7802	11488		4345	0	2984	7379
Russia	9000	3750	7355	0	0	4345		0	6481	2494
Brazil	7301	12000	17371	0	9287	0	0		0	8609
China	11671	5009	3054	7448	9410	2984	6481	0		8042
EU28	6200	5240	9874	15157	6862	7379	2494	8609	8042	

Table A.2: Average distances between origin and destinations

Sources: https://distancecalculator.globefeed.com/

Annual growth rates per connection (average of annual growth rates of the two countries excpt for USA and EU28 where other sources where available):

For EU we use data provided by Euorcontrol giving the predicted annual growth rate between EU28 and other regions of the world.

EU28	USA	1.9
EU28	United Arab Emirates	3.5
EU28	Japan	3
EU28	Australia	3
EU28	Canada	1.9
EU28	India	3.5
EU28	Russia	1.8
EU28	Brazil	1.4
EU28	China	3

Table A.3: Annual growth rate for flights between the EU and other countries

While for the US, we use a combination of data provided by US Customs & Border Protection (except for connection with ARE, RUS and IND where we assume same growth rate as the EU):

USA	United Arab Emirates	3.5
USA	Japan	1.3
USA	Australia	1.3
USA	Canada	2.4
USA	India	3.5
USA	Russia	1.8
USA	Brazil	3.1
USA	China	1.3
USA	EU28	1.9

Table A.4: Annual growth rate for flights between the USA and other countries

For the other connections we used the growth information per country provided by IATA reports on value of aviation per country and took the average of the two connecting countries. The following table summarises the annual growth rates used:

annual growth rate	USA	United Arab Emirates	Japan	Australia	Canada	India	Russia	Brazil	China	EU28
USA		3.5	1.3	1.3	2.4	3.5	1.8	3.1	1.3	1.9
United Arab Emirate	3.5		3.5	3.8	3.55	5.8	4	4.35	5.1	3.5
Japan	1.3	3.5		2.2	1.95	4.2	2.4	2.75	3.5	3
Australia	1.3	3.8	2.2		1.3	4.5	2.7	3.05	3.8	3
Canada	2.4	3.55	1.95	2.25		4.25	2.45	2.8	3.55	1.9
India	3.1	4.35	2.75	3.05	2.8	5.05	3.25		4.35	1.4
Russia	3.5	5.8	4.2	4.5	3.5		4.7	5.05	5.8	3.5
Brazil	1.8	4	2.4	2.7	1.8	4.7		3.25	4	1.8
China	1.3	5.1	3.5	3.8	3.55	5.8	4	4.35		3
EU28	1.9	3.5	3	3	1.9	3.5	1.8	1.4	3	

Table A.5: Annual growth rate for flights per connection

Sources: Eurocontrol for EU28 growth rates, FAA 2022 for USA growth rates and IATA value of aviation for united Arab Emirates, Japan, Australia, Canada, India, Russia, Brazil and China.

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