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Personal carbon trading applied to Swiss air travel

Guaranteeing a fair access to climate ambitious aviation

Master's Thesis

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Abstract

The climate crisis requires rapid and substantial emission reductions from all economic sectors, aviation included. Given the limited impact that existing policies in aviation will provide in the next decade, national policies might be required to rapidly start reducing the climate impact from international air travel. This study explores the feasibility of implementing a Personal Carbon Trading (PCT) scheme for air travel, focusing on Switzerland as a case study. By allocating emissions based on passengers' country of residence and employing downstream enforcement, the national policy can cover emissions from residents flying all over the globe.

To tackle the full climate impact from air travel, the policy incorporates both CO_2 and non-CO_2 emissions, with the help of the Average Temperature Response over 100 years (ATR100). With a 90% reduction target by 2050 compared to 1990 levels, the mitigation pathway is consistent with a definition of climate neutrality for aviation rather than sole warming neutrality. To address business travel, various approaches are considered, including auctioning quotas and granting exemptions for organizations, depending on their status. Children above two are included to the same level as adults in the allocation of free flight quotas. A quota exchange market is introduced, in which mechanisms like a price floor, banking, and borrowing can reduce price volatility. A solution to implement a price ceiling while keeping a hard cap on emissions is proposed, by the mean of a priority order for the purchase of additional quotas.

Results from an explorative scenario of individual quotas for Swiss residents indicate limited free quotas by 2050, only allowing for a single European flight per person in the absence of major technological breakthroughs like synfuels. A distributional impacts analysis highlights the progressive nature of the policy, which would mainly benefit lower-income brackets and penalize individuals with the highest incomes. However, legal and administrative challenges remain, requiring further examination. Despite these, urgent climate action is imperative, and introducing a flight quota scheme could ensure fair access to climate ambitious aviation for all members of society.

Keywords: climate policy, aviation, Personal Carbon Trading (PCT), Switzerland

Résumé

L'urgence climatique exige un réduction rapide et drastique des émissions dans tous les secteurs économiques, aviation comprise. Compte tenu de l'impact limité que les politiques existantes auront sur l'aviation au cours de la prochaine décennie, des politiques nationales pourraient s'avérer nécessaires pour commencer sans plus attendre à réduire l'impact sur le climat du transport aérien international. La présente étude examine la possibilité d'appliquer un système de budgets carbones individuels (de l'anglais Personal Carbon Trading) pour les voyages aériens, en utilisant la Suisse comme étude de cas. En allouant les émissions en fonction du pays de résidence des passagers et en applicant la loi en aval (downstream enforcement), la politique nationale peut couvrir les émissions des résidents voyageant en avion dans le monde entier. Pour s'attaquer à l'ensemble de l'impact du transport aérien sur le climat, la politique intègre à la fois les émissions CO_2 et non-CO_2 avec l'aide de la métrique climatique ATR100. Avec un objectif de réduction de 90% des émissions d'ici à 2050 par rapport à 1990, la trajectoire d'atténuation est compatible avec une définition de neutralité climatique pour l'aviation, plutôt qu'une simple neutralité de réchauffement (warming neutrality). Pour les voyages d'affaires, plusieurs approches sont envisagées, notamment la mise aux enchères de quotas ou l'octroi d'exemptions aux organisations, en fonction de leur statut. Les enfants de plus de deux ans sont inclus au même niveau que les adultes dans l'attribution des quotas de vols gratuits. Un marché d'échange de quotas est mis en place, dans lequel des mécanismes tels qu'un prix plancher, la mise en réserve et l'emprunt de quotas peuvent réduire la volatilité des prix. Une solution pour mettre en œuvre un plafond de prix tout en conservant un plafonnement absolu des émissions est proposée, au moyen d'un ordre de priorité pour l'achat de quotas supplémentaires.

Un scénario exploratoire pour les résidents suisses illustre la faible quantité de quotas gratuits alloués en 2050, n'autorisant qu'un seul vol aller en Europe par personne, en l'absence de percée technologique majeure comme les carburants synthétiques. Une analyse des impacts redistributifs démontre la nature progressive de la politique, qui profiterait avant tout aux tranches de revenus inférieures et pénaliserait les personnes les plus aisées. Toutefois, des questions juridiques et administratives subsistent et nécessitent un examen plus approfondi. Malgré cela, il est impératif de prendre des mesures urgentes en faveur du climat, et l'introduction d'un système de quotas de vol pourrait garantir à chaque membre de la société un accès équitable à une aviation ambitieuse sur le plan climatique.

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Many thanks to Dr. Romain Sacchi, Nicoletta Brazzola and Dr. Tim Tröndle for taking the time to answer my questions. I am also grateful to the entire LEURE lab for the numerous feedbacks they provided me and the pleasing lunch breaks we had during those six months.

I also acknowledge the use of ChatGPT[1] for refining the wording in sections of my report.

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[1] chat.openai.com

Contents

Chapter 1

Introduction

When I carried out my mandatory military service four years ago, I felt like I was living in a parallel reality. Today, after six months of academic research on climate policies for aviation, the impression is oddly similar. As Chamberlin et al. so eloquently put it, "there is a rift in realism" [1].

On one side, humankind must undertake radical emissions reductions in the next decades in order to avoid disastrous temperature increases [1]. On the other, neither national policies nor international agreements will effectively reduce aviation emissions in their current state [2].

On one side, when the full climate impact of aviation is considered, Swiss air travel ranks as the largest emitting sector in Switzerland [3]. On the other, even an unambitious tax on flight tickets was rejected by the Swiss population [4].

On one side, calls for a reduction in air traffic from civil society, industry actors and academic researchers keep piling up [5][6][7]. On the other, airlines proudly display endless growth forecasts and misleadingly formulated climate targets [8][9][2]. Between the two, governments try to make both ends meet, with scenarios based on questionable (if not fallacious) assumptions, and always, an unshakable confidence in life-saving technologies [10].

The present work is an attempt in reconciling both sides. It tries to imagine a national policy that could target emissions from international air travel, include both the possibilities of technological solutions and a reduction in air traffic, and achieve an ambitious mitigation goal while still ensuring fairness and public acceptability. To do so, a Personal Carbon Trading (PCT) scheme is applied to air travel. Switzerland is used as a practical case study to design the flight quota policy and anticipate some potential outcomes of the latter.

This report starts by contextualizing the climate impact, current policy landscape and debates in the field of aviation, and introduces the concept of Personal Carbon Trading (PCT) (Chapter 2). Then, the design of the flight quota policy is discussed in details, with a specific focus on Switzerland (Chapter 3). Finally, the future national emission budget and individual flight quotas are derived for Switzerland, and the fairness outcome of the policy analyzed with the help of a distributional impacts analysis (Chapter 4).

Chapter 2

Literature review

2.1 The aviation sector

2.1.1 History

On 23 May 1926, the first commercial airline passenger flight took off from Salt Lake City, in the United States [11]. In less than a hundred years, air travel has established itself as an integral component of the global economy and people's travel preferences. In 2016, 4.5 billion passengers flew by plane, marking a more than tenfold increase since the 1970s [12].

These global statistics need to be put into context, however, as "there is no such thing as an "average citizen" in aviation" [13]. In 2018, only 4% of the world's population was estimated to have participated in international air travel [14]. In fact, air travel mostly serves tourism and leisure trips purposes [15]. In western countries, the idea of traveling abroad for holidays - more and more often by plane - was transformed "from an aspiration to an expectation" [15]. But even in one of the wealthiest countries in the world, Switzerland, less than half of the population (41%) has been estimated to have flown in the year 2006-2007 [15].

2.1.2 Full climate impact

There's a common misconception about aviation that flights would only contribute to global warming through the emission of CO_2. In reality, however, flights also impact the climate via a variety of non-CO_2 forcers (see Figure 2.1). Their effects differ from those of CO_2 in mainly four ways.

First, their release at high altitudes interacts with the climate both directly and indirectly. The direct impacts result from the emissions of water vapor (H_2O), sulfur dioxide (SO_2) and soot particles, as all three have a direct radiative effect. Indirect contributions include the formation of contrail induced cirrus (CiC), as well as changes in the atmospheric concentration of O_3, CH_4, and stratospheric water vapor due to emissions of nitrogen oxides (NO_x).

Second, their effects can not only warm the climate, but also cool it. For exam-

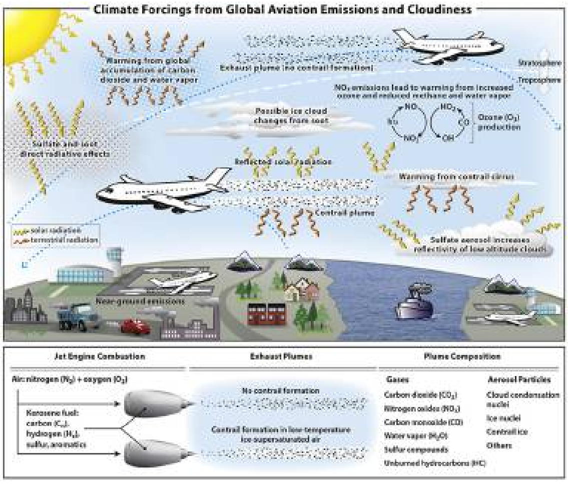

Figure 2.1: Graphical illustration of all climate effects caused by flights. Taken from Lee et al. 2021 [16]

ple, NO_x emissions will cause the accumulation of O_3 in the atmosphere, causing a warming effect, but also decrease the concentration of CH_4, creating a cooling effect. SO_2 has only a direct cooling effect. Overall, the net warming effect on climate of all non-CO_2 forcers, dominated by CiC and NO_x emissions, is strongly positive.

Furthermore, in contrast to CO_2, the impacts of non-CO_2 emissions depend not only on the emitted amounts, but also on the location, time of day, and weather conditions related to their release in the atmosphere [17].

Finally, non-CO_2 forcers tend to have shorter life spans. Where CO_2 is estimated to warm the climate for thousands of years [18], CiC will typically disappear within a few days [19]. For this reason, these non-CO_2 forcers are sometimes referred to as short-lived climate forcers (SLCF).

The shorter life spans of non-CO_2 forcers might not seem important at first glance, but it poses a great challenge for climate mitigation. If the level of CO_2 emitted each year was stabilized at a constant level, the climate would still continue to warm. To stop any further warming, CO_2 emissions must be reduced to net zero. This is not the case for SLCF. If their level of emissions was stabilized, their concentration in the atmosphere would reach an approximate constant level [16]. Also, if the emissions of short-lived substances are decreased at a sufficient rate, their effect on the climate could take the form of a relative cooling effect, compared to the warming caused when the level of emissions reached its peak [20].

In practice, how much do the non-CO_2 emissions of aviation warm the climate compared to CO_2? First, it should be pointed out that the complexity of the dynamics described above makes their evaluation more challenging. Recent assessments of the aviation net effective radiative forcing (ERF) show that non-CO_2 forcers contribute eight times more to uncertainty in calculations than CO_2 [16]. Despite these challenges, it is estimated that given decades of global aviation growth, emissions from aviation are warming the climate at three times the rate associated with aviation's CO_2 emissions alone. In other words, CO_2 emissions currently only account for a third of the full climate impact from aviation.

Put in a global perspective, aviation is responsible for approximately 4% of all human-induced warming to date [21]. This contribution to warming reaches 5.3% when looking at global emissions only since 1990. Again, these statistics do not properly reflect the fact that emissions from air travel are caused by a minority of people. In 2018, only 1% of the world population was estimated to have caused half of the emissions from commercial passenger travel [14]. Those high emitters represent only 10% of the most frequent flyers and are generally rich individuals from a few developed countries. Even within these wealthy countries, the disparities are high. In Switzerland, the top 5% of frequent flyers was estimated to cause a third of total CO_2 emissions from Swiss air travel [22]. Compared to other sectors, air travel is a predominant share of Switzerland's climate impact. When including the full climate impact of departing international flights in the national emission inventory, aviation becomes the first impacting sector on the climate [3]. With 27% of Switzerland's climate impact in 2019, it exceeds ground transport (23%), industry and energy transformation (20%), and housing (12%) (see Figure 2.2). In comparison, aviation was only the fourth contributing sector (15.6%) back in 1990.

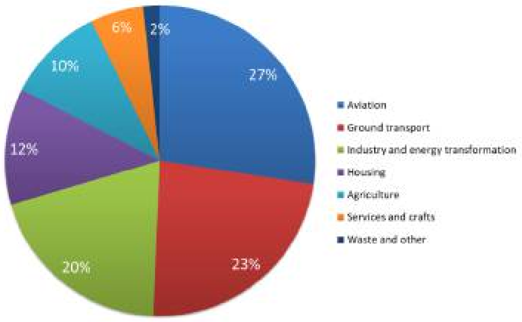

Figure 2.2: Total global warming impact of main source sectors in Switzerland in 2019, including international aviation. Taken from Thalmann et al. 2021 [3]

2.1.3 Demand forecasts

Barring exceptional circumstances, the growth of air traffic is not expected to stop anytime soon. Despite the shock of COVID-19, the demand for air travel has recovered rapidly, with 95% of pre-COVID levels reached in 2023 [9]. Once the effects of the COVID-19 pandemic absorbed, the aviation sector hopes to surpass its previous growth rate of 3% (1970-2019) [21]. With an expected growth of 4.2% per year, global passenger traffic would double from 2023 to 2040 [23]. In Switzerland, post-COVID forecasts suggest that European passenger traffic could grow at an annual rate of 2.3-3.1% [10].

2.2 Aviation policies

2.2.1 International aviation policies

The widely spread expectation of ever increasing air traffic poses serious concerns with regards to aviation's future impact on the climate. International aviation, responsible for around two third of air travel's emissions, is not covered by the Paris Agreement [24]. To bridge this gap, two international policies are already in place. But these are incomplete.

The International Civil Aviation Organization (ICAO) launched in 2016 the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). From the beginning, the original mitigation goal seriously lacked ambition, as the program aims to achieve “carbon neutral growth” from 2020. Put more simply, only CO_2 emissions above 2019 levels are planned to be offset, via mitigation projects outside the aviation sector. Given the voluntary first phase and the various exemptions granted, CORSIA is only expected to cover 12% of the CO_2 emissions from aviation in 2030 [2].

Before the CORSIA agreement, aviation was already partially included in the European Union Emissions Trading System (EU ETS). This Cap-and-Trade (CAT) scheme, covering over 12,000 energy and manufacturing facilities in the EU, uses tradable emission allowances to achieve overall emissions reductions [25]. Since 2012, airlines must cover CO_2 emissions from flights within the European Economic Area (EEA) with emission allowances [25][26]. International flights from and to the EEA were initially supposed to also be covered, but the "reduced scope" has been extended multiple times [26][27]. In addition, airlines will continue to receive some allowances free until 2026 [27]. As a result, only 1.2% of global passenger traffic related CO_2 emissions were estimated to have been mitigated by the EU ETS in 2017 [2].

In short, even if implemented successfully, both policies will only cover a negligible share of the CO_2 emissions caused by global passenger traffic. Put together, they're only expected to achieve CO_2 emissions reductions of about 0.8% per year. All this while neglecting two-thirds of aviation's climate impact. And because both schemes imply mitigation via other sectors, direct CO_2 emissions will most likely continue to increase, and so will non-CO_2 emissions, leaving up to 80-90% of the climate impact of aviation unmitigated [5][28].

In light of these rather mixed observations and given the urgency of addressing climate change, additional measures are needed. Because no stronger international policy will likely emerge in the short term, national policies might be required to finally initiate the reduction of aviation's impact on the climate [14][25][29].

2.2.2 Switzerland's strategy

In 2023, the Swiss population approved the climate law, setting the path for climate neutrality by 2050 [30]. For once, international aviation was not (entirely) left behind. In fact, CO_2 emissions from departing international flights must be fully mitigated by 2050, potentially via Carbon Dioxyde Removal (CDR) projects.

To achieve this goal, the Swiss Federal Council revealed its strategy in early 2024 [10]. According to their report, Swiss aviation can reach carbon neutrality by 2050. Mainly through the use of Sustainable Aviation Fuels (SAFs), which would make up for 55 to 78% of the mitigation effort, and Negative Emission Technologies (NET), expected to mitigate the remaining 10 to 23% of the emissions. Yet, this report is considerably flawed. First, SAFs are considered to be carbon neutral, which is simply impossible, even with the most optimistic life cycle assessments (LCA)[1] [31]. Second, non-CO_2 emissions, even if mentioned briefly at the bend of a chapter, are once again not included in the scenario, leaving the majority of the climate impact of aviation untouched. Finally, the volume of Swiss aviation is presumed to stay at its 2019 levels. This assumption does not reflect actual demand forecasts, since the authors themselves acknowledge that demand is expected to grow by 2.3-3.1% per year (p.15). Given those numbers, the demand would already be up by 14-20% in

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[1] The report does mention LCA and claims to include all climate impacts in each measure presented (p. 8). But when looking more closely to the mitigation achieved by SAFs (p.12), it is stated that a 70% blending of SAFs would achieve 70% of the remaining emission reduction (after efficiency gains), clearly showing that the authors considered SAFs to be emission-free in the scope of their scenario.

2030[2], as would emissions to some extent.

2.2.3 The imperative degrowth of air travel?

The strategy of the Swiss Federal Council is not an isolated case of flawed climate strategy within the field of aviation. More likely, it is an indicator of the growing gap between the aviation industry's aspiration for unlimited growth and its likely incompatibility with serious mitigation targets.

Given the context of emergency and the race for climate neutrality initiated by the Paris Agreement, the aviation industry had no choice but to follow suit and present its own mitigation pathway. To do so, aviation is, without surprise, willing to explore but also potentially sell to the public and politics any technological solution that would allow it to maintain its economic growth [32][33]. Unfortunately, technological solutions might not make it on their own this time. Efficiency gains in airplane design only show limited room for improvement and it is acknowledged within the aviation industry itself that hydrogen and electric planes won't play any significant role before 2050 [34][35]. Relying mostly on offsetting is clearly impossible in a growing aviation world as it would requires unreasonable amounts of CDR [28][5]. Two technological solutions remain to hope reach climate neutrality alongside an expanding air travel demand: biofuels and synthetic fuels [36].

Biofuels are still a largely advocated replacement to kerosene fuel within mitigation strategies from both the industries and governments [8][10], but such enthusiasm might be misleading. Even though airlines started setting ambitious SAF targets back in 2007, none of them was ever reached and thus quietly abandoned [32]. As of 2019, while 341 Mt of kerosene was consumed, only about 0.05 Mt biofuel was available [37]. Leaving aside the highly questionable impact of its current production on climate and biodiversity[3], their potential appears limited in all cases[37][5][25]. Even optimistic industry plans, with 30-195 Mt available SAFs for aviation by 2050, still fall short of replacing today's consumption of kerosene [37][38]. Regardless of bio-feedstocks availability, the idea itself of mitigating most of aviation's emissions through biofuels seems questionable. Even a full replacement of kerosene with biofuels in 2050 could result in increases in absolute emissions compared to 2005 levels, when considering the lifecycle emissions of biofuels [39].

In order to overcome the limited capacities of bio-feedstock, synthetic fuels (synfuel, for short) are becoming the new focus of attention [40][36]. Typically, synfuel

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[2] considering aviation fully recovers by 2024 and reaches 2019 levels.

[3] See Nick et al. 2022 for more details [37]

relies on the use of captured CO_2, renewable electricity and water [36]. Careful LCA are needed to fully appreciate the potential of this technology. However, as pointed out by Sacchi et al. 2023 [5], these synfuels will hardly allow the current growth of traffic to be sustained. In fact, to cover departing flights from Europe alone, more than the current annual electricity output of Europe would be needed each year after 2050. An estimated 200 to 250 million hectares-year of land would be necessary, surpassing the surface dedicated to European agriculture today. Similarly, freshwater use would be nearly equal to the annual consumption of the EU-28.

Alternative methods for the production of synfuel are being investigated to alleviate the dependence on significant levels of renewable energy and freshwater through thermochemical processes [41], but the fundamental question remains the same: considering the urgency of the climate crisis, relying exclusively on technology to mitigate aviation's climate impact "rests upon very ambitious and potentially unfeasible technological breakthroughs and optimistic assumptions on their ability to rapidly curb emissions" [28]. Likewise, there is little to no doubt that technological change will be needed to some extent, as climate neutrality appears equivalently unattainable with demand reduction measures alone [5].

In general, not only do both approaches seem necessary to fully mitigate the climate impact of aviation, but they might also help each other out. In the short term, a sustained decrease in air traffic would stop any further aviation-induced warming thanks to the short lifespan of non-CO_2 effects [21][5][28]. By doing so, SAFs technologies could gradually be implemented until they completely replace fossil fuel jets. In the long term, reduced demand for air travel could bring the overall resource used by these SAFs to reasonable levels [5].

2.2.4 The past and future failure of carbon taxes

Carbon pricing has long dominated academic and political discussions about appropriate climate policies, particularly in imagining ways to reduce air traffic demand [25][42]. In Switzerland, a revision of the CO_2 Act planned on introducing a tax on flight tickets for flights departing from Switzerland. The tax would have ranged from CHF 30 to CHF 120 per ticket, depending on the length of the flight and the seat class chosen. In 2021, the law was rejected by a close majority of Swiss voters, burying the hopes of seeing air traffic emissions taxed, at least in the short term [4]. It had been estimated that such a tax could have led to a 13-21% reduction on demand [3]. At first glance, it appears quite effective, but given that Swiss air traffic grew by 8.5% per year from 1990 to 2019, the tax would have been absorbed by the sector growth within a few years [10].

Anyhow, taxes would prove ineffective in significantly reducing aviation emissions. If the tax is set too low, it would have a limited impact on demand [43][3]. To be effective, the price of the tax would need to be set to levels that will likely show politically unacceptable [44]. In fact, a tax on air travel would probably be bound to reduce demand first and foremost through lower-income passengers, who would give up their trip due to higher ticket prices. Therefore, new approaches are needed to, if not directly affect demand, at least finally reduce aviation emissions.

2.3 Personal Carbon Trading

Personal Carbon Trading (PCT), first proposed in 1990s, aims to propose an alternative to carbon taxes by linking personal action with global carbon reduction goals [45]. PCT is an umbrella term used to describe a range of policy schemes[4], which all differ in their detailed design but share one core common concept: the implementation of a cap-and-trade (CAT) scheme to individuals [46].

Similarly to a CAT scheme, a finite emission budget is defined given the scope considered, and this so-called cap then reduced progressively. Emission rights are allocated to individuals by redistributing the budget equitably among the population to ensure fairness in carbon mitigation efforts [47].

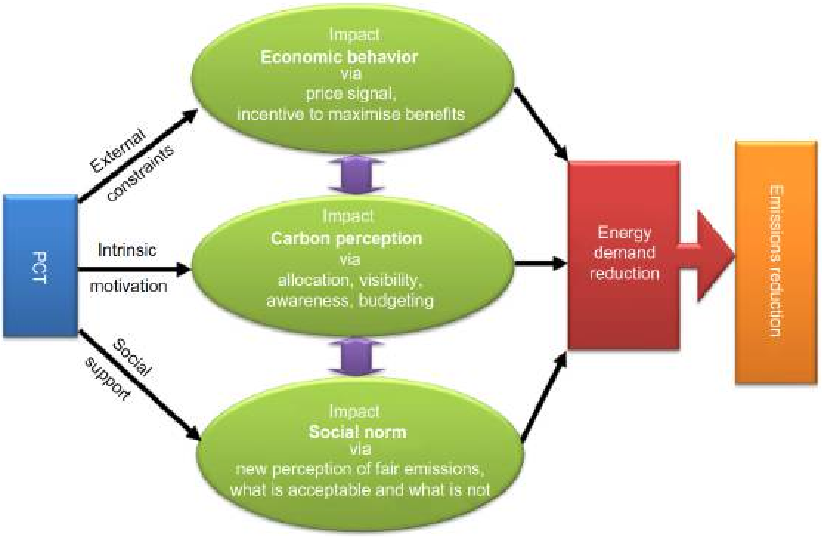

Figure 2.3: Underlying levies of PCT (taken from [47])

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[4] Among others: Personal Carbon Allowances (PCA), Personal Carbon Budgets (PCB) and Tradable Energy Quotas (TEQ).

PCT integrates three fundamental levers to achieve emission reductions at the individual level (see Figure 2.3)[47][48]. First, it creates an economic incentive for emission reductions by the mean of a price signal, as the decreasing cap is expected to be reflected in the price of emission rights. Next, individuals are made aware of the emissions resulting from their actions. This increases their carbon perceptions and thus offers an additional psychological lever for emission reductions. Finally, the split of the emission budget into individual quotas among the population proposes a shared definition as to what an acceptable and fair personal carbon footprint might look like in practice.

On paper, PCT presents several distinct advantages compared to carbon taxes. Let's start with the most obvious one: the certainty in emission reductions provided by the allocation of a finite amount of emission rights [47]. The guarantee of an effective mitigation effort not only provides environmental benefits, but could also enhance public acceptability. On that topic, surveys reported a theoretical preference of PCT over carbon taxation [47]. In addition, the personalized nature of PCT could encourage greater engagement and compliance from the population with emission reduction targets [46]. In terms of equity, PCT achieves a high level of fairness thanks to the equitable distribution of free emission rights, making it a progressive policy by nature.

The 2000s witnessed a surge of interest in PCT, with the UK government signaling its potential as a transformative climate policy tool [49]. Several years of enhanced research followed, but the idea was finally dropped by politics due to claimed risks of low social acceptability, technological barriers and high implementation costs [45][48][49].

Nevertheless, in recent years, Personal Carbon Trading (PCT) has experienced a comeback among research and civic society [46][48][50][51]. Amongst other reasons, the shifting policy landscape, characterized by increasing urgency to address climate change, seems to have propelled PCT back into the spotlight [48]. Advancements in technology have facilitated the theoretical feasibility of PCT implementation and lowered its expected administrative burden. Growing public awareness and engagement regarding climate change have reinforced the case for PCT. As individuals become more aware of their carbon footprint, there is a rising demand for participatory and radical solutions like PCT to translate individual actions into real collective impact.

The idea of applying PCT in Switzerland, or even more specifically to the aviation sector, is not totally new. In 2016, an in-depth review on PCT in the Swiss context was conducted on the behalf of the OcCC, an advisory body on climate change [52]. PCT was identified as a promising policy instrument, and the OcCC recommended the rapid implementation of pilot projects, but with no success. In 2019, a proposal for individual flight quotas was made during a conference by Roger Nordmann, member of the Swiss federal parliament [53]. While it garnered some attention in the media, the proposal never made it onto the political scene.

Despite these missed opportunities, as countries continue to grapple with the urgency of climate action, exploring new policy solutions like PCT appears imperative in the pursuit of fair and effective mitigation strategies.

Chapter 3

Policy scheme

3.1 Introduction

3.1.1 PCT for air travel

In light of the existing lack of robust aviation policies and in the context of climate urgency, is there a policy that could initiate the needed decrease in the climate impact of air travel, in a fair and acceptable manner? In the following chapter, a Personal Carbon Trading (PCT) scheme applied to air travel is proposed, in an attempt at imagining a national policy for international aviation. Switzerland will be used as a practical case study.

The detailed design of the policy will be discussed in more depth in the following parts, but the following lines present a brief overview of what it would consist of. As mentioned previously, PCT can be seen as a cap-and-trade (CAT) scheme applied to individuals. In the present case, a country would fix a cap on the emissions caused by air travel, given the specific scope considered (see 3.2). To do that, the definition of climate neutrality in the context of aviation first needs to be clarified and a consistent mitigation goal derived from the latter (see 3.2.4). After the cap is determined for the starting date of the policy (see 3.2.4), it is reduced progressively. Each year, the national aviation budget, i.e. the total emissions given by the cap, is allocated to the individuals participating in the policy (see 3.3). When a person wants to fly, they need to surrender flight quotas in parallel to paying the ticket with money (see 3.4.1). In order to do this, the airline selling these flight tickets must first determine the climate impact linked to each of the offered seats (see 3.4.3). On its side, the government must have a way to make sure airlines report their emissions correctly, in addition to enforcing the use of the flight quotas by the passengers (see 3.6). Finally, in case someone would not have enough flying quotas to purchase a flight ticket, they should have the possibility to buy extra quotas from other people (see 3.5).

3.1.2 Motivations

The use of flight quotas, moreover applied to individuals, might seem unnecessary for mitigating aviation's emissions or judged democratically unacceptable, or both. I believe the contrary to be true, and I will try to explain why in the following lines.

Let's assume that SAF are no false promise, and that they could indeed replace fossil kerosene quickly enough and at sufficient scale. Likewise, NET would be used to offset the remaining non-CO_2 effects. On paper, SAF and NET could allow aviation to sustain its growth in the future. Still, these technologies are and will likely stay too expensive to overtake kerosene fuel on their own [40][54]. Consequently, additional policies are needed to restrict the use of kerosene in parallel of incentivizing its alternatives.

One way this could be achieved would be to require from the aviation industry an increasing share of SAF in the jet fuel mix, combined to a gradual ramp up in offsetting programs, as to completely neutralize the climate impact from aviation by 2050 at the latest. However, to be able to meet such an ambitious target, these measures would need to be introduced in the next few years. The required technologies, whether it be synfuels for SAF or Direct Air Carbon Capture (DACC) for NET, will not scale up to the required capacity in just 5 years. Yet, this is what the Energy Perspectives 2050+, one of the key prospective model in Switzerland's climate strategy, appears to rely on [55]. In its ZERO scenario, despite no synfuel[1] used until as late as 2045, its volume suddenly increases by 11-13 PJ (3.1-3.6 TWh) every year, until fully replacing fossil kerosene in 2050 [56]. Establishing a reduction target exclusively for the year 2050 would not only pose significant risks for the achievement of such technological breakthroughs, but also allow emissions to continue rising in the next decades, potentially resulting in substantial temperature overshoots during this period[2].

Alternatively, governments could simply request the reduction of emissions to the aviation industry while letting it find the most effective way to do this, be it through synthetic fuels, carbon offsets, airplane efficiency, or, if necessary, a reduction in air traffic. This approach abstains from deciding between technological solutions and the degrowth of demand. It could be achieved either through a tax or a cap-and-trade (CAT) scheme. I have already argued why a carbon tax would not be suited for aviation (see 2.2.3). Because it is a quantity-based mechanism, a CAT scheme, unlike a carbon tax, can ensure that emissions are reduced as much and as fast as

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[1] referred to as power-to-liquid or power-to-kerosine in the report

[2] see Gold definition of climate neutrality in Brazzola et al. 2022 [28]

needed. In practice, CAT systems are generally implemented as supply-side policies. In other words, emission allowances are allocated to companies. This is the case with the EU ETS for example, in which European airlines are involved. Nonetheless, even if the full climate impact was taken into account (which the EU ETS does not) and the mitigation pathway ambitious enough, this approach would not be suitable in the context of aviation.

No matter how it is achieved, the fast (piloted) reduction of aviation's climate impact would increase the price of air tickets. If the required technologies came on stream quickly enough, they would still be more expensive than fossil kerosene, while a decrease in air traffic would most likely create scarcity, thus driving prices up [40]. This not only raises concerns about ensuring equitable access to air travel but also, more fundamentally, about the chances of success of such a policy in terms of democratic acceptability. A supply-side CAT scheme is likely unable to address these concerns adequately. However, a demand-side CAT scheme, wherein quotas are allocated to individuals, seems more promising. The PCT approach outlined here, because it proposes to allocate free flight quotas to each individual, could ensure an equitable access to sustainable aviation for all.

3.2 Policy scope

3.2.1 Residency-based allocation

A crucial first step in designing the proposed policy is to clearly define who it should apply to. Who are the above mentioned individuals, passengers, people, etc., who would fall under this policy, receive quotas and be required to use them in order to fly?

As shown in the previous chapter, the proposed policy should be put in place at a national scale, at least in its first phase. Switzerland is used within this work as a practical case study, but other countries could naturally introduce such scheme by adapting it to their national specificities.

In order to introduce an impactful policy, Switzerland could not restrict itself to aviation within its borders, as the latter only represented 0.11 Mt CO_2 in 2019, compared to the 5.69 Mt CO_2 emitted by international flights departing from the country [57]. With that said, the question of allocating the emissions from international aviation between countries is not so trivial. Fortunately, it is not new either. As pointed out by Larsson et al. 2018 [29], a total of eight possible allocation rules were already discussed in the 1990s, to which the authors added a ninth options. Based on five criteria[3], the allocation of emission from international aviation according to the country of residency of the passenger was argued to be the most suitable accounting method.

This allocation method will be used here, for the following reason. The idea of introducing a quota system for individuals was briefly described as putting in place a demand-side policy. To do this, emissions must be linked to the consumer. This is quite straightforward for air travel, as one flight ticket can easily be linked to a single passenger and equivalently a single resident of a country, like proposed above. Also, it would properly reflect the responsibility of the emissions from the aviation sector, as air travel is mostly a transport mean used for leisure and is closely correlated to wealth levels. This it true between and within countries, as both the wealthiest countries and the wealthiest individuals within countries travel - and thus emit - the most by air. Moreover, such an approach would accurately acknowledge the individual responsibility of the emissions resulting from air travel[4], classified as a luxury good and described as a "non-essential, highly conspicuous consumption" [15].

If Switzerland was to come up with a national aviation policy based on a quota system for individuals, the latter would therefore involve Swiss residents. It is important to make the distinction between Swiss residents, which describes people with a permanent residency in Switzerland, from Swiss citizen, i.e. people who own a Swiss citizenship. In Switzerland, around a quarter of the permanent residents do not have the Swiss nationality [58]. Given the high share of non-Swiss citizen permanently established in Switzerland, the proposed policy should be applied to Swiss residents.

An ideal version of the policy should cover flights taken by Swiss residents all over the globe, no matter the country of departure or arrival. In practice, however, if the Swiss government wanted to gain knowledge of its own residents taking a flight from Dubai to Tokyo and ensure compliance with the quota scheme, it would require a careful consideration of the technical and ethical issues such enforcement level would raise (see 3.6). Consequently, only international flights departing and arriving within Swiss jurisdiction could for sure be targeted, at least in a first phase. The term Swiss jurisdiction is used here in place of Swiss territory because although the Basel airport lies on French territory, it does partially fall under Swiss jurisdiction, in particular

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[3] sensitivity, additivity, non-leakage, validity and reliability.

[4] When PCT is studied for other sectors, like residential heating or mobility, it becomes much more challenging to allocate emissions to individual actions rather than structural contexts.

regarding customs services. As a result, it will be regarded as an airport where the Swiss government could acquire enough information on passengers to ensure compliance to the quota scheme.

At the start, despite the residency-based approach putting the focus on Swiss residents, the policy should probably also deal with the passengers from Swiss airports who do not live in Switzerland, such as tourists and residents of neighboring countries. If Swiss residents have to comply with a quota scheme, it might prove politically unacceptable to not affect non-Swiss passengers in any way. In a system with downstream enforcement, one solution could be to introduce a tax on flight tickets that would only apply to non-Swiss residents[5]. For consistency, the price of the tax could be set at the same level or just above the price paid by Swiss residents on the exchange market (see 3.5). In case another country joined the quota scheme, information on passengers residing in one country but flying from or to the other could be exchanged, and their passengers exempted from the tax.

3.2.2 Climate forcers

As pointed out before, in order to address the full climate impact of aviation, the non-CO_2 effects caused by different SLCF must be taken into account (see 2.1.2). Although strictly speaking, the Paris Agreement only frames mitigation goals by means of a "greenhouse gas balance", the shared practice within the scientific community is to interpret such concept of "balance" as a net-zero CO_2-equivalent emission target.

In addition to CO_2, three additional climate forcers are to considered in the policy:

- **NO_x**: Nitrogen oxides have both a cooling (destroying CH4) and a warming effect (increasing O_3 in tropospheric ozone), thus their net warming effect should be considered.
- **Contrail induced Cirrus (CiC)**: those ice crystal clouds formed around the emitted soot particles (aerosol) and water vapor (H_2O) have both a short-wave cooling effect and a long-wave warming effect. Therefore, they should also be included by means of their net warming effect.
- **H_2O**: The emissions of water vapor, classified as a greenhouse gas, usually do not pose concerns for climate warming. But when emitted by airplanes, that is at potentially high altitudes and therefore in dry atmosphere, H_2O can have a warming

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[5] This is the case for a system with downstream enforcement, which, as will be shown, is probably more consistent with a residency-based approach (see 3.6). In a system with upstream enforcement, airlines could be given the responsibility to acquire the quotas for non-Swiss residents.

effect. As of today, it does not have as much of an impact as the former two climate forcers (and CO_2), but a potential transition to hydrogen planes could increase its impact.

On the other hand, the effect of SO_2 should not be considered. Because of its net cooling effect, its inclusion could promote the adoption of solar radiation modification (SRM) techniques, a geoengineering method which is not supported in the Paris Agreement and raises many issues [24][59][60]. How these climate forcers can be expressed alongside CO_2 emissions to form a single indicator suitable for a CAT scheme will be described later (see 3.4.2).

3.2.3 Flight types

On a global scale, commercial passenger flights accounted for about 71% of aviation emissions in 2020 [14]. Freight was the next largest emitter (17%), followed by military flights (8%) and private jets (4%). In Switzerland however, military aviation appears to have a smaller share of national emissions, as it only consumes about 2% of the kerosene used in Switzerland [10].

The following policy proposal primarily focuses on commercial passengers flights, while entirely putting aside military flights and freight aviation. Private jets can be classified as a type of passenger flights and should therefore be included in the policy, if feasible. Even though it is not entirely clear if they could be targeted as well by a quota scheme, I believe they might represent the Achilles heel of this policy, in terms of public acceptance.

To make it clear, tackling private jet emissions is not a question of scale. In 2022, private jets departing from Switzerland only emitted about 166 kt CO_2, just about 4% of the CO_2 emissions from commercial passenger flights [61][62]. On the other hand, it is a fundamental issue of fairness. In the context of a policy aimed at radically cutting down emissions from air travel, with a potential limitation on demand, it is hardly imaginable that people would accept this collective effort if the biggest emitters were perceived as left untouched. Put differently, the perspective of asking Swiss residents to lower their emissions from air travel cannot be justified if a small share of the population can continue to fly without limit, especially considering that a single Geneva-Paris flight by private jet emits more than 3x the flight quotas a Swiss resident would receive in 2025[6].

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[6] A swiss resident would receive quotas worth around 2 t CO_2-eq in 2025, or 0.67 t CO_2 if taking back the multiplier for climate impact used in the original budget calculations (see 4.3). A total of 2745 private flights for the route Geneva-Paris were estimated to have emitted 6916 t CO_2 in 2022, or 2.5 t CO_2 per flight (p.76 from [61]).

3.2.4 Mitigation pathway

The core idea of a CAT scheme is to indirectly pilot mitigation with the help of a decreasing cap on emissions. Typically, the cap is set to equal or lie just below the level of emissions recorded the year before the start of scheme.

To illustrate the mitigation pathway described here, amongst others, a hypothetical starting date of the proposed policy will be set for 2025[7]. In case of a real introduction of such cap, the government should carefully assess the emissions within the defined scope one or multiple years before its introduction.

Once the initial cap on emissions is determined, it is reduced continuously until reaching the desired residual level of emissions, defined by a mitigation goal. Typically, this process involves referencing the Paris Agreement. While the Paris Agreement only formulates mitigation goals in terms of temperature increase[8], it does provide a shared global target that can be used as a basis for deriving mitigation plans. For instance, the Intergovernmental Panel on Climate Change (IPCC) has identified that achieving the most ambitious temperature goal of the Paris Agreement, i.e. limiting warming to 1.5°C, necessitates reaching net zero CO_2 emissions by approximately mid-century, followed by transitioning to net negative CO_2 emissions thereafter[9].

While the Paris Agreement serves as the primary framework for deriving mitigation pathways, its application to international aviation presents challenges due to the unique nature of this sector [24]. First of all, the international scope of aviation complicates its integration in Nationally Determined Contributions (NDCs), the climate actions plans each country needs to submit as part of the Paris Agreement. There exist approaches to allocate the emissions from international aviation between countries, but as of today, these emissions are not taken into account in NDCs [29].

In addition, the non-CO_2 effects of aviation complicate the interpretation of the articles of the Paris Agreement, as shown previously (see 3.2.2). Moreover, because of the potential short term cooling effect[10] from reducing the non-CO_2 effects of

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[7] It is highly unlikely, if not impossible, that such a policy, if it even earned itself a spot in the political debates, would be introduced just one year from now. But keeping it as close in the future reduces the uncertainty of hypotheses that are made, like for example the future air traffic demand.

[8] more specifically global average temperature increase relative to pre-industrial levels.

[9] It is common albeit technically incorrect to directly attribute the goal of achieving net zero CO_2 emissions or climate neutrality by 2050 to the Paris Agreement.

[10] To be more specific, what would be named a cooling effect only really expresses the reversibility of the rise in temperature caused by sustained and increasing emissions of short-lived climate forcers (SLCFs). Thus the cooling effect that could be expected from reducing non-CO_2 effects (in parallel of CO_2) of aviation to net-zero should only be understood with regards to the peak temperature

aviation (see 2.1.2), the definition itself of climate neutrality for aviation can be ambiguous.

The most important clarification to make is distinguishing between warming neutrality and climate neutrality [5][28]. Warming neutrality refers to reaching net-zero CO_2 emissions but only stabilizing non-CO_2 emissions. This would stop any further warming of the climate and is thus equivalent to the outcome of reaching climate neutrality for CO_2 only (which I will refer to as standard climate neutrality from now on). On the other hand, bringing both CO_2 and non-CO_2 emissions to net zero could retroactively neutralize part of the past induced warming. With CO_2, this could only be achieved by removing CO_2 from the atmosphere via Carbon Direct Removal (CDR). This somehow reversible nature of the non-CO_2 effects of aviation can be used as an argument to limit mitigation efforts to warming neutrality. Alternatively, it can be seen as an opportunity for aviation to contribute further to mitigation than what other sectors can, if aiming for climate neutrality.

In the context of a CAT, however, the implementation of a warming neutrality goal is hardly achievable. In fact, it would involve following a "multi-basket" mitigation pathway, by reducing CO_2 emissions to zero on the one hand, and stabilizing non-CO_2 emissions on the other. Such approach would not only complexify the implementation of the national budget, but also affect the use of flight quotas as well as the public understanding of the policy. Consequently, a "single-basket" approach is preferred here, by combining all the CO_2 and non-CO_2 effects of aviation in a single metric (see 3.4.2) and bringing them jointly to zero. As a result, a definition of climate neutrality is applied here.

Now that the mitigation goal is more precisely framed, the mitigation pathway required to reach climate neutrality by 2050 can be defined. To stay in tune with the most recent climate law passed in Switzerland [30], the policy could aim for a 90% reduction of the emissions by 2050 compared to 1990s levels, with the remaining 10% intended for offsetting. However, unlike the Swiss Climate law, the emissions covered by the policy should also cover the non-CO_2 effects of aviation, which means that the emissions to be reduced by 90% are not solely CO_2 emissions but all considered emissions species, expressed in CO_2-eq (see 3.4.2). In addition, the mitigation pathway cannot settle for a sole reduction target in 2050. The Swiss Climate law, despite setting both global and sectoral intermediate reduction targets, did not include international flights departing from Switzerland in any of them [30][10]. As explained previously (3.1.2), doing so would both undermine the chances of suc-

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that would have been reached before the reduction was initialized, not compared to the temperature level of a world without aviation.

cessfully scaling up the required technologies, all while allowing significant emission levels to persist in the next decades.

To get an idea of the latter point, let us compare a mitigation pathway without intermediate target with the present policy. In the ZERO scenario from the Swiss Energy Perspectives 2050+, the delayed mitigation of aviation - mostly between 2045 and 2050 thanks to a rapid shift from kerosene to synfuels, causes about 380 Mt CO_2-eq emissions between 2025 and 2050[11]. In comparison, with continuously decreasing cap, the present policy would limit emissions to only 142 Mt CO_2-eq, or about 62% less emissions on the same period[12]. Consequently, delayed mitigation efforts like the one found in the Energy Perspectives 2050+ would have caused substantially more warming by 2050 than the present quota policy. For this reason, contrary to the Swiss climate law, the quota policy should contain intermediate mitigation targets. These could for example resemble those assigned by the Swiss climate law to the mobility sector, with a 57% reduction target by 2040. In fact, in the hypothetical mitigation pathway constructed in 4.2, with a start in 2025 and a cap reduced at constant rate, this target is reached in 2037, or 3 years before the due date.

3.3 Quotas allocation

3.3.1 From a national budget to individual quotas

Once the national emission budget for a given year is determined, the latter needs to be allocated to the Swiss residents as what I will call flight quotas. The allocation of quotas to the individuals is a critical step of any PCT scheme, as it will impact the perceived fairness and the social outcomes of the policy[63][64].

Even though passengers could be exclusively considered as individuals taking a flight on their own will, it should be pointed out that some of them are flying on behalf of an organization or company. With this consideration in mind, the

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[11] The emissions found in Table 6 of the available data [56] are summed for the period 2025-2050 and multiplied by a factor 3 to estimate the full climate impact of aviation [20]. The simplified use of a fixed RFI factor is justified here as it is solely used for comparison with the national budget, which was also computed with the same constant factor. In fact, it is a rather conservative approach, as the RFI factor increases (respectively decreases) with growing (respectively decreasing) air traffic, which would widen the gap between the two present emission sums [5].

[12] First the national emission budget from 4.2 is summed for the period 2025-2050, equaling 165 Mt CO_2-eq. Then, to cover the same scope as in the Swiss Energy Perspectives 2050+, the following correction factors are taken back: 1. the inclusion of Basel airport 2. the inclusion of arriving flights 3. the removal of non-Swiss residents. Which gives: $165/1.09/2 * 1.87 = 142$ Mt CO_2-eq.

possibility emerges of incorporating not only individuals but also various groups and institutions into the allocation process.

3.3.2 The inclusion of groups

In order to try answering that question, let us first consider a distinction that is often made within commercial passenger air travel. In fact, passengers can be separated in two categories, based on the motive of their trip: private travel, which includes leisure trips, visits to family and friends, etc.; and business travel, that is trips taken as part of someone's job. Business travelers can fly on behalf of private companies, but let's not forget government employees (e.g. diplomats), members of non-governmental organizations (NGOs) and international organizations (IOs), academic researchers, or even people following a career for which they need to travel regularly (like athletes, singers, etc.).

Should some or all of these groups be protected from potential restrictions on air travel access imposed by the quota system? While most people would probably agree that humanitarian workers should not see the achievement of their missions constrained by flight quotas, the debate complicates when trying to give an answer for the case private companies. This complex issue has many dimensions, which I will try to summarize here, though the considerations listed here cannot be regarded as exhaustive.

First, the perceived societal contributions of the groups listed above will affect the collective willingness to grant them special considerations in the quota system. Humanitarian organizations, to stick with this example, are often viewed as essential contributors to society due to their altruistic missions. Granting them unrestricted air travel access might align with a shared moral imperative in supporting their recognized efforts. Similarly, other groups could be perceived as making significant positive impacts on society and ensured that their work is not hindered by potential travel restrictions.

Moreover, business travel plays a crucial role in the operations of private companies and the broader economy. In the context of a globalized economy, private enterprises, especially in industrial sectors like pharmaceutics, have shown increasing need for business travel [65]. Restricting air travel access with quotas could impact international trade relations and affect their relative competitiveness.

Similarly, the imposition of air travel restrictions at a national scale could lead to undesired side-effects on the labor market, particularly in regions with many NGOs and IOs. For instance, in a city like Geneva, where these entities constitute substantial employers, limited air travel access for employees with Swiss residency could create competitive disadvantages with non-Swiss workers. Such a situation could make organizations hire more non-Swiss residents to circumvent these limitations.

In reality, the distinction made before between private travel and business travel is more blurred than initially expected [65], due to the intertwined nature of these categories [66]. This interplay further complicates the delineation between different types of travel and questions the idea itself of separating both categories when allocating flight quotas.

Potential approaches

As the few non-exhaustive issues underlined here show, the decision on whether certain groups should be safeguarded from restricted air travel access under a quota system comes with a range of ethical, political, economic, and practical considerations. Ultimately, the approach chosen for allocating the flight quotas will impact both the effectiveness and the perceived fairness of the CAT scheme. It requires to find a balance between potential privileges on air travel for certain groups and the collective commitment to reduce emissions from aviation, all while preventing any risk of perceived unfairness because of such differentiated treatment between all actors of society.

In light of the above considerations, three approaches are proposed to apprehend the (non-)inclusion of groups in the allocation scheme. Again, those options shall not be considered as an exhaustive listing of all the possible ways to tackle this problem, but reflect what I would consider as the main structures that could be used to obtain a coherent allocation scheme, with each approach acknowledging the inclusion of groups at a varying degree.

1. Fixed budget share

The first allocation approach takes inspiration from the concept of Tradable Energy Quotas (TEQ), a type of PCT which proposes to cover all sectors of the economy.[47][1]. To do so, the national budget is split in two, with households on one side and organizations like companies and the government on the other. Typically, 40% of the budget would be allocated for free to individuals, as to reflect their current share in national emissions. The other 60% would be intended for entities like private companies or the government, but the latter would have to purchase the quotas through auctions.

Coming back to the case of air travel, in a similar manner, the national emissions budget could be split in two, with a first share allocated for free to the Swiss residents and the second part auctioned to any organization (government, company, NGO, etc.) in need of quotas for their business travel. The share of quotas put in auction could be set at around 10-20% of the national budget, in order to reflect the current share of business travel[13].

The first benefit of such mechanism is the income generated by the auctions, which could for example be used to finance the policy itself, but also investments in NET, for example. Furthermore, selling the public auctions could provide transparency with regards to the allocation to organizations, if judged necessary. However, it is questionable if all organizations cited previously should be put in the same basket and have to pay for extra quotas.

2. Exemptions

Another way of providing a differentiated treatment to organizations would be to grant special exemptions to some of them. These exemptions would be awarded via an application process in which organizations would have to justify either a status (e.g. diplomats) or a specific mission (e.g. a mission from an NGO). Compared to the previous option, an exemption mechanism would benefit fewer organizations, mainly for two reasons.

First, some exemptions could allow for a complete bypassing of the quota scheme, rather than using a fixed share of the national budget. The emissions resulting from the trips taken by exempted organizations would de facto not be accounted for in the system, leading to emission leakage within the policy. This leakage should be kept as small as possible and not sum up to anything near the emissions of the current 14% business flights, thus limiting the amount of eligible exemptions.

Moreover, the concept of exemptions would most likely not be applicable to private companies. The application process would rely on criteria related to common interest, like humanitarian aid and diplomacy, thus excluding profit-driven actors. If industries were also eligible to free-of-charge exemptions from the quota system, the public perception of the policy might be affected [67]. Nonetheless, private companies and other groups which would not have been granted exemptions could still finance business travel directly through their members.

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[13] According to the MTMC 2015, business travel represented 14% of all flights taken by Swiss residents in 2015 [57]

3. Focus on individuals only

Quotas could be allocated to individuals only, without this necessarily meaning the denial of business travel. Say only individuals would receive free flight quotas, and be able to buy and sell quotas on the exchange market. Yet, for business trips, nothing would keep organizations from financing extra flight quotas directly to their members.

Such a system would simplify the entire system, as it would solely need to be tailored for individual use. There would be no necessity to facilitate access for organizations or implement auction processes. This approach also circumvents the ambiguity of distinguishing between business and leisure travel, as the only distinction here would be the source of funds used to purchase additional quotas, if necessary. Finally, as already mentioned, this process could operate in combination of the second option and provide an alternative solution for private companies or any other organizations not eligible for exemptions.

However, depending on the rules put in place for the exchange of quotas, especially in the case of a combined hard cap and price ceiling, the access to extra quotas might not be guaranteed at all times (see 3.5). Relying solely on this allocation approach may thus lead to travel restrictions for organizations. That being said, a shortage of flight quotas could happen with the first option too. But again, the risk of restricted access to air travel might be considered unacceptable for some identified groups, such as humanitarian and diplomatic missions. For this reason, granting exemptions to a restricted group of organizations seems unavoidable.

Emerging trends

By unfolding those thoughts and lines, the temptation to mix all three options gets bigger, rendering numerous in-between approaches to handle the business travel dynamics of organizations. Rather than doing so and ending up with countless design options, let me highlight here the main options that seem to stand out:

Critical organizations: a special treatment seems necessary for some publicly recognized organizations. The case of humanitarian aid is not isolated but remains an iconic illustration of the need to protect certain groups from not only travel restrictions, but also potentially expensive flight quotas. I described before how they could be granted full exemptions, but a fixed amount of free flight quotas could also be granted to them via a similar application process.

Private companies: contrary to non-profit and public organizations, it is harder to justify the allocation of free flight quotas to private companies. Those should either take part in auctions or finance the purchase of quotas for business trips through their employees.

In all cases, the allocation of flight quotas cannot be designed without considerations for the rules that would dictate their exchange (see 3.5). Key design aspects like a hard cap, a price ceiling or an annually limited purchase of quotas will influence the respective advantages and limitations of each the allocation approaches just discussed.

3.3.3 Allocation to individuals

In addition to deciding how groups should be treated in the policy, the rules dictating the allocation of quotas to individuals need to be settled as well. Two recurrent questions found in research on PCT research need further clarifications: if and how children are being included in the quota system, as well as on which basis the national budget is split between the population.

Children

In general, discussions about whether children should also receive quotas arise in the context of PCT schemes framed around households and applied to residential heating and mobility [64][68][49]. In these contexts, there exist uncertainties about knowing who within a household, between adults and children, does indeed cause emissions and in what proportions.

In contrast, when it comes to air travel, it is rather trivial to determine the difference between the emissions caused by adults and children, simply because there is none. In fact, if neglecting the weight of people when allocating the emissions of a flight between the passengers, the only determining factor is whether or not a child on board is using its own seat. Typically, airlines only allow children to travel without a separate seat reservation (i.e. on an adult's lap) until they reach 2 years old [69][70].

Consequently, the flight quota policy should apply to Swiss residents aged two and above, both for the allocation of free flight quotas and the surrendering of these in order to fly.

Per-capita vs. age group allocation

If asked how much of the global emissions budget each individual should be entitled to, the majority of us would most likely jump to the same answer: everyone should receive the same amount of quota. The equal per-capita allocation (EPCA) not only appears to be the simplest approach, it also feels like the fairest, at first glance. However, this claim requires careful examination.

First, at a conceptual level, there is a notable absence of sound arguments in support of EPCA within academic philosophy [71]. In more concrete terms, surveyed people do not tend to perceive EPCA as the fairest allocation [63]. Furthermore, when estimating the outcomes of PCT schemes by the mean of distributional impacts analysis, doubts have been raised regarding potential low-income "losers"[14], an undesirable outcome both for social justice and public acceptability [64][72]. These findings led to propositions for alternative allocation types that could solve such issues [68][63]. While their proponents tend to keep the EPCA as a starting point, they try to target groups that are identified as in need. The allocation procedure is then refined to improve either the perceived fairness or the social outcomes of the policy. Among others, the question of giving extra quotas to people with disability or with children is discussed [68][49]. Similarly, additional quotas could be given to groups pinpointed as potential low-income losers, like families from rural areas for example. [73][74].

Such citizen-specific allocation options are motivated by the pursuit of the so-called "equity by capability", in contrast to the "equity by equality" principle used for EPCA [63]. Although it does seem relevant to consider the different principles of equity when defining the rules for allocating flight quotas, it is unclear how to properly integrate them in the case of air travel. While heating and mobility can be identified as fundamental needs to which climate policies should try to guarantee a minimum access, air travel cannot be categorized as such, as pinpointed before (see 2.1). Consequently, identifying specific social groups for which extra flight quotas would be justified reveals more ambiguous. Nonetheless, it is worth an attempt.

The starting point of the following considerations lies in the Swiss Microcensus [57]. The frequency of air travel across different social groups reveals some strong disparities among different age groups (Figure 3.1). Young adults (aged 18-44) fly the most frequently, closely followed by older active persons (45-64). The first group (18-44) takes about twice as many flight trips than under-aged individuals (6-17) and the first bracket of retired people (65-79), with this gap reaching tenfold when compared to the oldest age group (>80). Given this observation, the following question arises: should age influence the number of flight quotas allocated to each individual? For example, is there any valid rationale for which a young adult would

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[14] A loser being defined as the people which would not receive enough quotas to cover their emission level prior to the introduction of the PCT scheme.

be entitled to more free quotas than a retired person?

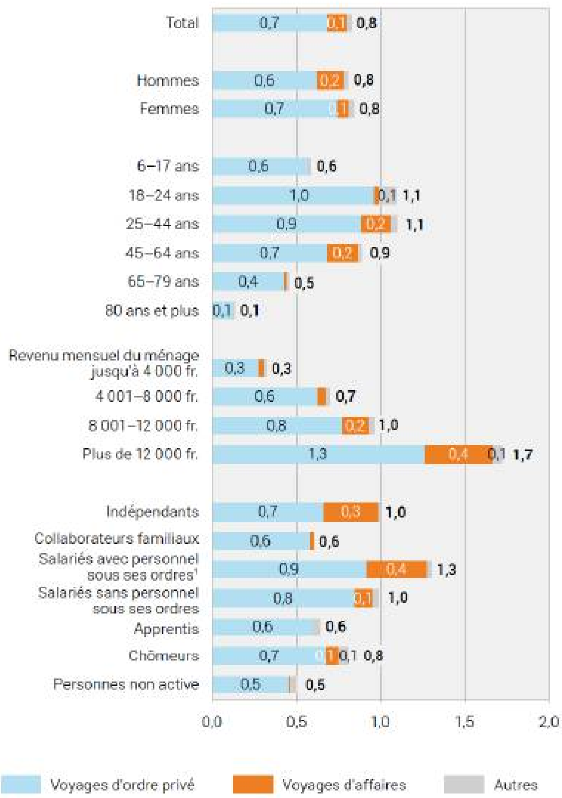

Figure 3.1: Number of trips by plane per person per year by population group and reason, in 2015. Source: Swiss Microcensus 2015, figure G.3.7.3.1 [57]

The sole differences found in air travel consumption between age groups cannot justify on their own allocating more quotas to some of them. If that was the case, higher income groups would also be entitled to more quotas. Yet, it can be argued that these two socio-demographic factors should be treated differently. As mentioned before, proposals for alternatives to EPCA focused on individual needs [63]. So the challenge posed here is to settle if younger adults would have some sort of mobility need justifying a wider access to air travel. Again, this "need" does not have to be argued in absolute terms. It should reflect the collective understanding of mobility needs, with the ultimate goal of improving the perceived fairness of the allocation scheme by the public.

In that sense, higher income groups can probably not justify a "need" for extended mobility. For younger adults, the need for increased access to air travel could be argued in terms of experiences like studying abroad or the broadening of horizons at a crucial stage in life. In a more practical sense, allocating more quotas to younger individuals would give them more flexibility, as they could choose to use these quotas immediately or save them for later use[15].

Still, the allocation of more free quotas to young adults seems to be lacking strong arguments. The needs identified above are quite thin compared to the original proposals for alternatives to EPCA, where need was articulated around the question of daily mobility or residential heating for example. Moreover, even if society agreed that young people were entitled to more quotas, this could be achieved in other ways than via the allocation process. If the free exchange of quotas between relatives was made possible (see 3.5.4), the elderly could for example transfer their quotas to their grand-children to allow them to study abroad. Similarly, introducing a borrowing mechanism (see 3.5.4) would allow a young person to use parts of their future quotas in advance.

Alternatively, this question can also be analyzed from the standpoint of its impact on various income groups. To do so, a comparison of the distributional impacts between a EPCA and an age group allocation is conducted in a later stage of this report (see 4.4). Overall, even if the case of young adults does not seem to fully justify additional quotas, this example serves as a reminder that EPCA is not the only way quotas can be allocated and that additional allocation rules can be imagined to further increase the public acceptability of the policy.

3.4 Flight quotas

3.4.1 The nature of flight quotas

Once the Swiss residents receive their flight quotas, accordingly to the allocation rules I just discussed, what do those even represent? Kilometers or emissions[16]?

When choosing between kilometers or emissions as the unit for flight quotas, the kilometer-based method may initially seem appealing for its simplicity. However, this approach fails to accurately capture the essence of what truly matters here: the emissions that a passenger is responsible for when taking a flight.

As shown earlier (2.1.2), the assessment of the full climate impact of aviation depends on a complex entanglement of climate forcers. The focus on single flights does not simplify this task. Their impact on the climate varies greatly depending on the flight route, the airplane type, the fuel mix, etc. [17][75][76][77]. Relying

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[15] The banking of quotas is discussed in more details in 3.5.4.

[16] It could even be imagined to have flight quotas in terms of number of flights. As it would represent a further simplification from the kilometers approach, the arguments presented to discard using kilometers as a unit can also be applied for flight numbers.

solely on kilometers would not give any incentive to reduce the climate impacts at the level of single flights, only at a larger scale (airplane efficiency, SAF, etc.). In fact, it could even give the wrong signal in some cases, as the route with minimum distance for a given flight does not guarantee achieving the lowest climate impact [78][17]. However, by adopting an emissions-based approach for flight quotas, several advantages emerge for passengers, airlines, and even the government.

For passengers, this method provides a clear "climate impact signal", similar to the concept of carbon price signal used in the context of a carbon tax [47]. That is, it would give them an accurate estimate of the climate intensity of each flight ticket, allowing them to make informed travel choices. This could for example involve selecting between two flights of similar distances but different climate impacts[17], or between different seat classes on the same flight.

From an airline's perspective, emissions-based quotas provide an overarching climate impact signal that would neutrally incentivize all kind of emission reductions strategies, from increased load factors to route optimization and investments in SAFs. By doing so, not only are airlines given the flexibility of choosing between all those mitigation strategies, but they are also given a chance to maintain their activity by counterbalancing the decreasing cap of flight quotas with effective climate impact reductions.

The government also benefits from determining emission-based quotas, as those can be derived more easily from the national emissions budget than kilometers. By focusing solely on emissions, it also shows an agnostic position with regard to the future air traffic volume. Where the government finally makes sure that the climate impact of air travel decreases to an acceptable level, which share of such mitigation effort is fulfilled by technological improvements, demand reduction or other means is both the responsibility and the freedom of the aviation sector.

With that being said, implementing an emissions-based quota system poses multiple challenges. First, people purchasing a flight ticket need to be provided with a clear and understandable value reflecting the climate impact of their potential trip. In practice, this would require expressing the CO_2 and non-CO_2 effects with a single CO_2-equivalent metric. Second, airlines need a method to not only estimate and report the emissions of their planned flights, but then also to split those between the individual seats they put in sale.

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[17] see 4 for an example of the added climate impact of tropical flights

3.4.2 Picking the right climate metric

As just briefly mentioned, flights should be represented by a single indicator which would merge the CO_2 and non-CO_2 effects of aviation together. This "single-basket" approach is not only necessary to be understood by the public and people purchasing flight tickets, it also allows the overarching CAT scheme to be monitored using one single cap.

Bringing different climate forcers together is precisely what CO_2-equivalent (CO_2-eq) emissions are used for. There exist many CO_2-eq metrics in the scientific literature, but they all try to achieve the same goal: to quantify the contribution to climate change of various climate forcers (or more generally greenhouse gases (GHGs)), by expressing those in terms of a reference gas, CO_2.

The most prominent climate metric of all is the Global Warming Potential (GWP), widely recognized as the standard measure for converting emissions from various gases into a common scale. The GWP, specifically for a 100-year time horizon as defined by the IPCC (hence GWP100), has been utilized as a metric to facilitate the multi-gas mitigation strategy integrated within the UNFCCC and concretized through the Kyoto Protocol.

Yet, a single-basket approach is not all trivial. Because the definition of "climate effect" is ambiguous, climate metrics use different indicators to describe it (temperature increase, warming potential, radiative forcing,...). On top of that, climate forcers have varying lifespan, which inevitably leads to compromises when merging them into a single metric. GWP100 for example has been widely debated for its difficulties in differentiating long- and short-lived climate forcers (SLCFs) [79][80][81].

At present, the scientific debate to find the best overall climate metric is still ongoing [82][83][84][85]. Thankfully enough, in the case of aviation, research seems to be converging towards one of them. As a matter of fact, recent studies focusing on varying aspects related to aviation, from aircraft design to aviation policy and individual flights, have favored the same climate metric: the Average Temperature Response (ATR) [86][17][87].

The ATR metric stands out because of its ability to consider the lifetime variations of different species, diverse climate sensitivities, and the thermal inertia of the atmosphere-ocean system. Moreover, it offers advantages such as reduced dependency on time horizons, qualitative consistency in results between pulse and constant emissions, low reliance on historical emissions, and alignment with the GWP100 for historical emissions, facilitating its integration into existing policy frameworks.

I must briefly comment on another climate metric which has also gained popularity in the past years, the Global Warming Potential star (GWP*) [88][84][20]. Though argued by some as an appropriate solution for considering short-lived substances, it has been clearly disqualified for usage in the domains we're interested in here. Because GWP* can show reducing or even negative CO_2-eq emissions on a year-to-year basis, in the context of reducing SLCFs emissions, it was described as "ill-equipped" to be used as a control feedback [85].

Nonetheless, I will still use the GWP* factor to derive the initial CO_2eq cap of the national emissions budget (see 4.2). This is primarily due to the lack of any similar factor found for ATR100, but judged acceptable by the fact that it will l not be used for a annual accounting of the cap, but rather as an estimate of the starting cap. In fact, GWP* is described as "appropriate to calculate remaining emissions budgets" [20].

3.4.3 Single-flight emissions accounting

Under the proposed policy proposed, airlines departing from and arriving to Switzerland would have to calculate and report the emissions from their flights, for multiple reasons.

First, a Swiss resident planning to take a flight would not only have to be informed about the price of the flight ticket when purchasing it, but also the flight quotas they will have to spend in parallel. Just as anybody taking a flight has the guarantee that they will only pay the price that was indicated at purchase, the same should apply for the flight quotas. This means that in practice, airlines would need to determine the emissions of a planned flight in advance, before they even start selling flight tickets for the latter.

Then, once the flight has occurred, the airline reports the effective emissions of the flight to the government (or another agency in charge). Depending on the specific scheme chosen in practice (see 3.6), the airline would also be asked to submit flight quotas for the operation of the flight. In all cases, the government then proceeds to check the consistency between the emissions estimates prior to the flight and the actual recorded data.

Calculations methods

In practice, calculating the emissions of a single flight is a balancing act between reaching a high precision and ensuring operational simplicity. Determining CO_2

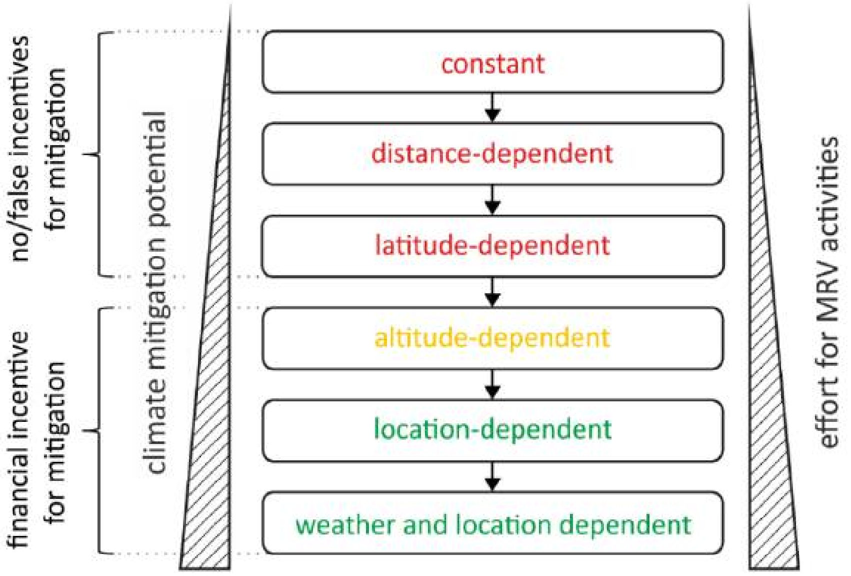

Figure 3.2: Multiple single-flight emissions calculations methods, with increased accuracy requiring more data effort. Taken from Dahlmann et al. 2022 [89]

emissions is a relatively trivial process, as they can directly be derived from the fuel consumption and their impact on climate does not depend on where they occurred. However, accurately reporting non-CO_2 emissions would require having detailed information on factors such as aircraft trajectory, engine emissions, and ambient atmospheric conditions. Most of the times, such data is not available or would require too much effort. Consequently, some degree of simplification with reality is needed.

But how simple can it reasonably get? As mentioned before, the method chosen should be easy to compute without significant administrative burdens, capable of being calculated before flights (for ticket sales purposes), and transparent enough for the controls by the government. This being said, it should still be accurate enough to encourage efforts towards mitigating non-CO_2 effects (via SAFs or climate-optimized routing for example).

This is the tricky part of including non-CO_2 effects in the scheme, as the full climate impact of a flight can be reduced despite increased emissions. Some simple calculation methods (see Figure 3.2) can be utilized, including constant values or those dependent on distance or latitude. These are not able to correctly reflect the impact of mitigation strategies targeting non-CO_2 climate forcers. If implemented, they could create false incentive by focusing more on CO_2 reduction.

Adding some more parameters to those simpler calculations can however fix such issue. First, by taking into account the altitude of the flight, the real climate impact of H_2O, O_3 and CiC is better reflected, as their effects all have a strong altitude dependency [86][90]. Similarly, including the longitude of the flight enables the full 3D location of the flight (altitude, latitude and longitude) to be considered, creating an incentive for climate-optimized routings.

Ideally, the precise weather situation during the flight should be analyzed in order to determine more precisely the effective impact of non-CO_2 forcers that occurred. But integrating such factor would not only increase the administrative effort even more. Weather data can only be fully trusted about a day prior to the flight. Hence in all cases, it could not be used for the emissions estimates shown on the flight tickets, as those are sold weeks or months in advance.

On the other hand, the weather dependency of non-CO_2 climate effects can partially be reflected via their climatological mean over a year. This might produce false incentive several days a year, for example if a route is increased to avoid contrail formation on a day where the weather is such that no contrail formation would happen anyway. Nonetheless, mean annual weather situation in each region would still accurately be reflected, ensuring an effective incentive for climate-optimized routes.

Climate impacts calculations post-flight

For the sake of simplicity, let's first analyze how the climate impact of flight which has already occurred can be calculated. During each flight, the airline needs to record the following data:
- 4D position (time, lat, long, alt)
- fuel flow
- aircraft mass
- ambient temperature

After the flight, the emissions indices for all relevant species (CO_2, H_2O, NO_x) need to be calculated along the flown flight profile. CO_2 and H_2O emissions are independent of the engine type and the operating conditions of the flight and can be easily be derived from the fuel consumption. In contrast, calculating the NO_x indices requires the aircraft type, engine type, combustor variant, and the fuel flow recorder during the flight. Still, such calculation can be automated by already existing Fuel Flow Methods [89].

Once the emission inventory is complete, the CO_2-eq emissions can be calculated within a minute with the help of a simplified response model (typically AirClim), which uses climatological mean data and therefore serves the calculations method discussed before appropriately. Then, both the flight data and the CO_2-eq emissions are reported to the authorities for verification.

Climate impacts calculations prior to a flight

In order to estimate the CO_2-eq emissions of a planned flight, airline have to make a few adjustments to the procedure just described. In fact, the exact 4D position, fuel flow and ambient temperature have to be estimated. This could be done with monitoring data from similar flights operated in the past, and improvements could even be achieved by optimizing for future weather forecasts, for example. In practice though, no matter the level of precision airlines aim for, there will always remain a gap between the emissions estimated before the flight and the exact emissions that occur when flying.

Still, some incentive for precision in the emissions estimates is needed. Even more importantly, airlines must be dissuaded from any ill-intentioned underestimations, a potentially tempting way to sell flight tickets "costing" less flight quotas. To do so, airlines could be charged proportionally to any difference found between the pre-flight estimates and the post-flight calculations of the climate impacts. Some exceptions could be imagined for reroutings caused by bad weather conditions or any other exceptional circumstances.

Lookup tables

In some cases, the administrative burden caused by the estimation and reporting of each flight's emissions could be reduced with a simplified procedure (similar to the Eurocontrol Small Emitters Tool (SET) [86]). Utilizing a public look up table, CO_2-eq estimates for different aircraft types, flights paths, climate conditions,... could be determined without calculations. It could serve as a fallback option when detailed data is unavailable, for verification purposes and most importantly for small operators for whom the full calculation process could reveal too costly.

Nevertheless, to prevent airlines from intentionally withholding data, such system should be assumed conservatively. That is, airlines using those should not be better off with estimates than specific calculations, i.e. the resulting CO_2-eq emissions found in the look up table should be slightly higher than the calculations.

3.4.4 From single-flight to single-seat emissions

Before putting flight tickets to sale, airlines need to allocate the emissions they've just estimated for the given flight to each seat. This process involves more than simply dividing total emissions by the number of offered seats, as it requires considerations regarding the inclusion of freight transport, load factors, and seat classes.

For the sake of simplicity, I focused from the start on passenger air travel. But in most cases, airplanes combine passenger and freight transport in a same flight. The inclusion of freight transport in the allocation of the flight emissions highly depends on the approach chosen for the reporting of quotas (see 3.6). In case of a downstream enforcement, passengers would report their flights directly to the government. On their side, airlines would most probably only have to communicate passengers information for the flights they operate. In that sense, freight transport could easily be disregarded in the quota scheme.

On the other hand, with upstream enforcement, passengers surrender their flight quotas to the airline when purchasing a ticket, and the latter then surrenders enough flight quotas to the government as to operate the flight. In such system, it could be imagined that parts of the flight quotas used to operate a flight could come from the freight transport. To do so, the airline could pay some kind of CO_2-eq tax allowing them to purchase the flight quotas related to the weight of freight transported.

Similarly, the difference between the expected and effective load factors of a flight must be considered. Again, with an upstream approach, the airline could easily be allowed to buy flight quotas for the empty seats. In a downstream system, the logic applied would resemble more to the one used for the differences in the forecasted vs. effective single-flight emissions discussed above. In a first phase, the flight emissions could be divided between seats expected to be filled (given load factors from previous flights). After the flight, the airline would need to pay in case the effective airplane occupancy happened to be lower than expected. Still, to avoid any frauds, the expected load factor used would require a standardized method allowing controls by the government.

The consideration of travel classes is another key aspect in the allocation of seat emissions [91]. Seats in premium class occupy more space in an aircraft compared to the ones in economy class. Similarly, first class takes up more space than business class. This difference results in a reduction in the total number of passengers that can be accommodated on a flight, consequently leading to an increase in the average CO_2 emissions per passenger.

Airlines determine freely the relative allocation of economy and business seats, based on profit maximization strategies. In a quota system, such optimization would probably adapt to not only include the class-specific seat price, but also the quota factor of the multiple class-specific seats. In other words, airlines would now need to not only find a profit-maximizing seat classes arrangement, but a combination of the latter with the minimization of the average per-seat emissions. In case flight quotas became scarce, business-class passengers might start to fly more in economy-class to spend less flight quotas.

In practice, incorporating a factor for the average space per class-specific seat is hence necessary. While passenger weight could also be taken into account in seat allocation, its impact on a flight emissions is relatively minor compared to the spatial considerations of different seat classes. Therefore, focusing on the space utilization of each class-specific seat provides a more accurate representation of emissions per passenger. The average load factor for each travel class can even be combined as to reflect the tendency for higher travel class to show lower load factors. Following this method, a seat in business class typically emits 2.5 to 3 times more than an economy class seat [91]. More surprisingly, the gap between seats in first and economy class can reach up to a factor nine.

3.5 Quota exchange market

3.5.1 Goals

Although each Swiss resident would receive a fair share of free quotas each year, given the high disparities of air travel consumption among the population, most of the people would either find themselves with too much or not enough quotas to meet their travel desires. It would therefore be necessary to introduce a platform on which individuals could exchange flight quotas with others, given some monetary counterpart.

Such system, that I will call flight quota exchange market (or exchange market for short), would greatly increases the flexibility of the flight quota scheme. Individuals which normally fly little, or do not fly at all, would still benefit from the policy by selling their quotas and thus receiving monetary compensation. Similarly, the more frequent flyers, which might find the free flight quotas they initially received to be insufficient, could purchase additional ones. In the following lines, I will try to express what shape such exchange market could take. Starting from the functioning of a more classic (some would say unregulated) market, mechanisms to alleviate potential issues will gradually be introduced and discussed.

It should be reminded here that such market would be intended for trade between individuals, not private companies. In such context, efficiency cannot be the sole compass used for designing it. As elegantly pointed out in 2006, "the perfect system may be exist in theory, but is of little benefit if it cannot be implemented in practice" [92]. The rules defining how individuals might trade quotas with each others will undoubtedly impact the perceived fairness and therefore the public acceptability of the entire quota scheme. With that in mind, the rules of this market should thrive to find a balance between economic efficiency and expected fairness.

3.5.2 Basic structure

Under a "pure" form of CAT system, the emissions quotas traded on the market follow a standard supply-demand dynamic: the quantity of exchanged quotas and their price are found at the market equilibrium between the supply and demand. Put simply, the market equilibrium lies where the number of people willing to sell their quotas (the supply) at a given price matches the number of people accepting to buy those quotas at this price (the demand). In practice, this system can lead to two extremes.

In case the demand is too low compared to the offer, prices might sink. In our case, this could happen if the original cap on emissions was too high for example. Consequently, individuals would receive more flight quotas than needed at a national scale, and so extra flight quotas would be relatively inexpensive. I will develop in a moment if such situation should be regarded as undesirable, and the case being, how to avoid it.

3.5.3 Who has access to limited flight quotas?

Let us first focus on the other end of such market, which turns out to be more concerning. If the demand increased more than the offer, the price of the flight quotas would rise accordingly. In concrete terms, the decreasing cap of emissions could reach a point where the overall amount of flight quotas in circulation would be significantly lower[18] than the people's desire to fly. The case being, more individuals would be looking to buy extra quotas than ready to sell some. A quota would therefore become a rare commodity, and its price on the market would increase.

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[18] This could either be the case if the starting cap was set too low compared to the air traveling habits prior to the introduction of the scheme, and more likely in the years closer to 2050, with the emissions budget getting close to the 10% level of 1990's emissions.

High prices for flight quotas are to be expected if a CAT scheme was applied to the aviation sector. Because it is regarded as a hard-to-abate sector, a rapidly decreasing cap on emissions could require the reduction of the traffic. In concrete terms, with individuals receiving less free quotas with time, if these quotas did not allow them to fly as much as before, they might increase the price they would be ready to pay for extra quotas.

This situation could be considered as unfair, as only the richer individuals would be able to afford extra flight quotas, the case being. Thus is especially concerning for the later years of the scheme, when the amount of flight quotas allocated for free might be too small to fly without purchasing extra quotas. Even before its introduction, the expectation of such outcome could hinder the perceived fairness of the policy. With that in mind, a way to ensure affordable flight quotas to everyone should be examined.

Price ceiling

The upper limit that can be set to the price of a commodity on a given market is known as a price ceiling. The idea itself is quite straightforward: the commodity cannot be bought or sold above a certain price (the price ceiling). In practice, however, it poses multiple challenges. Going back to the market equilibrium described above, what happens if the point were the demand and the supply curves would normally cross lays at a price above the price ceiling? Again, this could be the case if at the price ceiling, more people were willing to buy extra quotas than people ready to sell theirs. With a price ceiling, the price cannot increase to reach the balance between the number of sellers and buyers, leaving a gap in the number of quotas available for purchase.

To cover this gap, a central reserve is typically imagined. This entity would fall under the control of the regulator, like the government or an independent institution created for this purpose. If the price ceiling is reached, the central reserve emits extra quotas on the market so that all buyers have the possibility to purchase quotas. Price ceiling has not only been advocated for its ability to address fairness concerns. It could also reduce price volatility by protecting the market from price shocks [93][94].

However, introducing a price ceiling in that manner comes with two major drawbacks. First, because of the extra quotas emitted by the central reserve, the CAT scheme is transformed into a "soft" cap, where the level of emissions is not capped in absolute terms anymore[19]. Allowing such uncertainty about emissions might pose

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[19] A soft price ceiling can also be implemented, with only a limited amount of extra quotas

a greater risk to society than leaving the emissions level uncertain [98]. For this reason, priority should be given to the certainty in emission reductions rather than in emissions prices [92]. More essentially, the use of a soft cap comes down to turning the policy into a revisited carbon pricing mechanism, not a quantity cap mechanism [1]. As one of the primary motivation of the present work is to explore an alternative to price-based schemes, the idea of designing a hybrid (or flexible) carbon tax is consequently incompatible.

Given these considerations, a hard cap should most likely be maintained. On the other hand, ensuring a fair price of quotas to everyone might be considered necessary and should therefore be explored. This leaves us with two options. First, a more classic hard cap without price ceiling can still be defended. Alternatively, given the specific context of the policy, there exists a way the exchange market could be designed to combine both a hard cap and a price ceiling.

1. Hard cap without price ceiling

One could argue that the price of flight quotas on the exchange market should simply be left untouched, mainly for two reasons. For one thing, it can be reminded that all individuals do receive free flight quotas in the first place. With that, a high degree of fairness is already achieved. More than that, setting an upper limit to the price of quotas exchanged might even negatively impact the lowest income brackets of the population. As a matter of fact, people could sell their quotas at a higher price if there was no price ceiling, thus experiencing some profit losses if the latter was introduced. Considering that it is more likely that people selling quotas would be the ones with lower income (see 4.4), a price ceiling could be argued to cause unexpected negative distributional effects. Allowing individuals to earn more money on unused quotas might therefore be considered more desirable than guaranteeing affordable extra quotas to everyone.

2. Hard cap with priority order

At first glance, maintaining a hard cap on emissions appears incompatible with the introduction of a price ceiling. In reality, there is a third key element in the design of a market that makes these two mechanisms incompatible, if left untouched. As a matter of fact, with a price ceiling, the soft cap is only necessary if the market

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emitted at the ceiling price. Once such cost containment reserve (CCR) is emptied, the prices can potentially rise again. This hybrid ceiling price hence allows for an absolute cap on emissions. On the other hand, it does not guarantee a maximum price at all time [95][96][97].

guarantees the purchase of quotas at anytime, even when the price ceiling is reached. Such situation is no fatality, but a deliberate choice of design, similar to opting for a hard cap rather than for a soft one.

In discussions on the introduction of a price ceiling in already functioning CAT systems, like the EU ETS, the guarantee of purchasable quotas at all times is well justified. First, those CAT systems apply to companies, not individuals. In such context, the fairness concerns are much smaller, and the market is primarily designed and discussed to achieve efficiency rather than equity principles. But above all, the guarantee of quota availability is bound to the way these are operated. Typically, the CAT scheme is administered like a tax system, with emissions quotas surrendered at the end of the regulated period. Put more simply, a company can buy missing quotas after having caused the emissions these will cover. In such context, it would be harder to not guarantee that extra quotas could not be purchased at any time, as it could lead to the impossibility to cover past emissions.

Coming back to the context of flight quotas, I would argue that such issues could be overcome when designing the exchange market, and that the latter could work properly even without ensuring the availability of extra quotas at all times. The main challenge being that if there is no central reserve to fill the gap between the supply and demand when the price ceiling is reached, how to choose who gets to buy the limited flight quotas first? The idea would be to construct a priority order between all potential buyers, in an ascending order of purchased quotas in the past X years. In other words, in case of quotas shortage (i.e. the price ceiling reached), purchase priority would be given to the individuals which would have flown the least in the past recent years.

To give a concrete example, with such mechanism, a person who has only flown once in the past two years would be given priority for the purchase of extra flight quotas (again, only in case the price ceiling is reached) on an individual which has flown five times during the same period. This example is only given to illustrate the idea behind this proposal. In practice, the priority order would be defined based on emissions and not flight numbers. The exact period in the past considered is open to debate but could range between one and three years.

As described before for the typical CAT systems, such mechanism would be easier to implement in an upstream enforcement (see 3.6), where individuals surrender their flight quotas directly to airlines. With this approach, a person would need to have enough flight quotas before flying. If that person did not have enough quotas to book a flight, it would first need to purchase some on the market. In case the latter has reached the price ceiling and the person does not have priority to purchase the limited amount of quota available, it could simply not purchase their flight ticket. In an upstream quota scheme, however, this mechanism would only work if the fine for not surrendering quotas at the end of the year was set high enough as to dissuade anyone from flying while knowing that they won't be able to buy extra quotas before the end of the year.

I would argue that a price ceiling with priority order would work quite well in the context of air travel. As a reminder, even in developed countries, a very small share of flyers - the so-called frequent flyers - are responsible for a large share of the emissions caused by passenger air travel [13][14]. On top of that, frequent flyers are commonly found within the highest income brackets of society [14][15][66]. With that in mind, an exchange market without price ceiling, in case of quota scarcity, could limit the availability of extra quotas mainly to the wealthier segments of the population. Conversely, a hard cap with priority order might benefit more to the lower income brackets first, by guaranteeing both an affordable price and the priority of purchase to casual flyers.

Looking at the bigger picture, the priority order could settle a collective agreement between infrequent- and frequent-flyers. The latter would implicitly be allowed to fly as much as they want, as long as the people which had not flown as much yet would be given a chance to do it first. In a world where scarce flight quotas might translate into reduced air travel access as to ensure a sustainable aviation sector, the access to quotas would not necessarily have to be settled with the standard, rather unfair and most often invisible rule of "The one who can afford", but with a new rule: "The one who emitted the least yet".

3.5.4 Other mechanisms

Price floor

In a similar fashion to the price ceiling, a price floor can be added to the exchange market. This mirror instrument sets a limit to the minimum price, under which no quota can be bought or sold. In general, the purpose of a price floor is to encourage pollution reduction even in times when the price of quotas would otherwise be too low to achieve this end [92][99]. Strictly speaking, the price of a quota would never be "too low" to achieve pollution reduction in the long term, as the always decreasing cap of quotas would ensure the reduction of emissions as desired. In the short term, though, a price floor could achieve a more ambitious mitigation than the original planned cap. Furthermore, with a price floor both the price uncertainty and volatility are reduced, which would most likely improve the public acceptability of the system [99][93].

In a similar fashion to a price ceiling, if the price was to hit the set floor, an imbalance could emerge, this time between a higher supply (people willing to sell their quotas) than demand (people wanting to buy). There are three main known ways such gap can be bridged. First, the regulator or government can simply confiscate some of the quotas [100]. I would consider such approach unacceptable, for equity reasons mainly (which quotas are confiscated?), and will discard it right away.

A second option would be for the government to buy back the surplus of quotas, at the price floor [100][99]. By doing so, the total amount of quotas in the system can be reduced, thus readjusting the cap and improving the mitigation effort. However, it requires the government to set some monetary reserve in place. Because the fund needed to buy the quotas back would not be fixed, such unpredictable budgetary cost could severely undermine the credibility of the policy [99]. On the other hand, the purchase of flight quotas and their elimination from the system when the price floor is reached could be open to NGOs willing to fund mitigation programs.

Alternatively, to reduce the number of quotas in the system and consequently increase their scarcity and price, the number of quotas allocated in the next year can be reduced. This approach eliminates the need for a fund.

Banking and borrowing

Put simply, banking would allow individuals to maintain quotas for more than a year. It makes the accumulation of free quotas possible for later use, in case of a bigger travel planned for example. Similarly, its mirror version, the borrowing mechanism, would allow people to access quotas they were only supposed to receive in the following year.

Both mechanisms add flexibility to the quota scheme, and by doing so, price volatility can be greatly reduced [101][102][103]. One reason for this effect is that, in the absence of such mechanisms, the market could experience stresses at the beginning and the end of each allocation period. In our case, however, this could already be partially avoided by allocating the quotas at the birth date of individuals rather than all at once at the beginning of each year.

There are still some conditions that must be met for effective banking and borrowing. In fact, the efficacy of banking was argued to depend strongly on the liquidity of the market [101]. Typically, free allocation of quotas tends to reduce the need for trading, so the market is generally thinner. Consequently, the added value of the flexibility offered by banking is less pronounced. To ensure a decent level of liquidity on the market, a depreciation rate could be applied to banked quotas, which would give an incentive to people to sell unused quotas rather than keeping them conservatively for many years.

The introduction of borrowing alongside with banking has often been controversial. It did show promising results, especially as a way to correct start-up problems such as an under-allocation of quotas [101]. All things being equal, it is as legitimate as introducing banking, as the end goal of the CAT system is to maintain a cumulative cap over a long period of time, not to meet specific emissions over a single year.

But still, the idea of allowing people to use quotas they don't own yet is harder to defend than for quotas they received in the past. Also, introducing a borrowing option would add one layer of complexity to the entire system. This would not only complicate the public understanding of the policy, but might also lead to even more annual emissions differences. Such fluctuation might be detrimental to airlines, as it would add uncertainty to their demand forecasts.

Free exchange between relatives

In parallel with putting in place an exchange market, free exchange between relatives could also be authorized. It would facilitate the accounting of quotas within households and families, and even allow for people to gift their flight quotas to friends and beloved ones. The most direct way to achieve this would be to allow people to link their personal quota account to their phone number.

This mechanism is tempting on paper, as it could improve the perceived level of freedom given to individuals within the quota scheme. It does however suffer from relatively high risks of misuse. In fact, if put in place in combination with some of the mechanisms exposed above, the latter could be bypassed.

To demonstrate those concerns, consider the example where both a price ceiling with priority order and the free exchange with relatives were put in place. As a reminder, the priority order could, in some cases, prevent parts of the individuals to purchase extra quotas. This would more likely be the case for frequent-flyers, which tend to have higher incomes (see 2.1). Some of these people might be tempted to try finding extra quotas elsewhere. To do so, they might even offer a higher price than the limit (the price ceiling) set on the exchange market. Similarly, some individuals might be drawn by such an offer and end up selling their quotas outside of the exchange market. A black market could emerge online, with the monetary transaction taking place out of the exchange market, and the flight quotas then exchanged for free via the phone numbers.

3.6 Quotas usage & reporting

After individuals received their share of flight quotas, how do they use them to travel by plane? Who do they surrender these quotas to? And consequently, from which actor does the government receive quotas back?

3.6.1 Upstream enforcement

In an upstream system, individuals would surrender their quotas directly to airlines when purchasing flight tickets. Airlines would then be responsible for transferring these quotas to the government, typically on an annual basis, when reporting their emissions for each flight.

Such approach is usually preferred for multiple reasons [104]. Firstly, it avoids the need for individuals to interact directly with the government, potentially enhancing public acceptance. Secondly, it reduces administrative costs for the government, compared to a centralized enforcement system. Finally, upstream enforcement could enable a more exhaustive policy by covering non-Swiss residents and freight transport emissions[20] (see 3.4.4), which could minimize the risks of emission leakages.

Despite all the above observations, implementing an upstream approach probably does not align with a residency-based quota policy, which aims to cover all emissions from Swiss residents flying globally. Initially, with only one country involved, the government could only require airlines to surrender quotas for flights departing from its territory. This would not only leave international flights fully outside the country's jurisdiction untouched, but also arriving international flights. Notably, the rejected Swiss CO_2 law intended to tax flight tickets for departing flights from Switzerland only, not arrivals.

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[20] Airlines could be asked to surrender flight quotas to cover their entire flight emissions. To do so, in addition to the flight quotas from Swiss residents, they would be allowed to purchase the remaining quotas for freight and non-Swiss residents. This would create some sort of carbon pricing for these two categories. In practice though, airlines might be tempted to bypass the limited quotas scheme applied to Swiss residents and purchase flight quotas for these passengers too. Also, the fact that airlines would have to apply a differentiated treatment between Swiss and non-Swiss residents might render unfeasible, as they could probably not know the country of residence of passengers, contrary to governments.

3.6.2 Downstream enforcement

In contrast, a downstream PCT system would have Swiss residents surrender their flight quotas directly to the government. Downstream enforcement was often rejected by research in the past because it was seen as impractical and too costly if applied to the whole economy [104][105]. However, such conclusions do not seem to hold given the present time and context studied. Most of these critiques were formulated in the 2000s when quota schemes were imagined in terms of bank accounts and carbon cards. Sixteen iPhone releases later, the technological solutions needed to implement a downstream enforcement policy could show both technically and financially feasible [48].

In practice, the system could resemble a tax declaration system. Individuals would be required to disclose all flights taken throughout the year and demonstrate possession of adequate flight quotas, which would subsequently be deducted from their personal account. This process could be facilitated through a website and mobile application[21], where individuals would have access to a personal account. Flights could easily be reported by uploading flight tickets or entering a related reference number. After that, the quotas required for the flight could be deducted, either based on the emissions directly indicated by the airline at purchase, or based on a central lookup table (see 3.4.3). In Switzerland, the cost of establishing a digital account for Swiss residents could be greatly reduced with the introduction of the new electronic identity that should be issued by the government in 2026 [106].

This approach, based on the self-declaration of flights by individuals, would require the government to put in place measures to combat fraud. At national level, the government could probably require airlines to transmit passenger data for both departing and arriving flights. For international flights outside Switzerland, the challenge lies in effectively detecting fraud without appearing overly intrusive to the population. In absolute terms, the technical means to check whether a person has taken a flight seem to exist [107], but the data protection and ethical issues involved need to be analyzed in more detail. In this regard, there are valuable lessons to be learned from the COVID-19 pandemic [48].

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[21] This application could also directly integrate the exchange market of flight quotas.

Chapter 4

Impacts and scenarios

4.1 Motivations

To better understand what was discussed in the former chapter, it might be worthwhile to illustrate what shape such policy could take if implemented in the near future. To grasp the orders of magnitude that are involved, I will construct several straightforward yet illustrative scenarios and calculations. First, I will derive the best estimate for the starting cap of the policy, given the scope defined in 3.2. In addition, and given the mitigation goal discussed in 3.2.4, the evolution of the emission budget until 2050 will be presented. The latter will allow a more tangible understanding of the evolution of allocated flight quotas to be derived. Finally, a distributional analysis is built to illustrate the substantial strength of the policy in terms of climate justice, but also to compare different allocation rules and their social outcome.

4.2 National emission budget

4.2.1 Initial emission cap

If a flight quota scheme was put in place in Switzerland tomorrow, how big would the initial emission budget be? To derive the starting cap of the proposed policy, the scope of the policy (described in 3.2) needs to be carefully considered.

The starting point of this estimate will be the emissions from bunker fuels for all flights departing from Switzerland, published every year by the Swiss Federal Statistical Office (FSO) [62]. The policy will be assumed to start in 2025 and consequently the cap derived from the emissions of the previous year, 2024. Because of the COVID-19 pandemic, it is assumed that the aviation sector fully recovers with its 2019 levels in 2024. Consequently, the initial cap is fixed to equal 2019 emissions from bunker fuels.

From this baseline, a few corrections factors are added to adapt the data to the scope of the policy. First, the Basel airport is not included when reporting the bunker fuels emissions [108], but it is taken into account for national statistics on passenger kilometers numbers [109]. Given that this airport was included in the scope of the quota scheme (see 3.2.1), Basel airport is re-integrated in the bunker fuel emissions, by the mean of reported offered seat kilometers (SKM). In 2019 for example, Basel airport accounted for 8.7% of all SKMs for flights departing from Swiss airports (including Basel) [109], so the bunker fuel emissions are multiplied by the correction factor $\mathrm{C}_{\mathrm{Basel}}$, which equals to 1.095 in 2019[1]. Next, because the emissions reported from bunker fuels data only represent departing flights, the total is doubled ($\mathrm{C}_{\mathrm{arrivals}} = 2$) in order to also include arriving flights.

Once the emissions from all flights from and to Switzerland are estimated, only the emissions caused by Swiss residents must be kept. To do so, the ratio of inbound to outbound travelers can be used [110]. This indicator measures the ratio of foreign visitors (inbound) traveling to a country to the locals (outbound) traveling abroad:

$$\text{ratio} = \frac{\mathrm{N}_{\mathrm{inbound}}}{\mathrm{N}_{\mathrm{outbound}}} \tag{4.1}$$

In 2019, Switzerland had a ratio of 0.879, meaning that the country had more outgoing locals than incoming tourists [111]. From equation 4.1, the share of Swiss residents among all travelers can be derived:

$$\text{share locals} = \frac{\mathrm{N}_{\mathrm{outbound}}}{\mathrm{N}_{\mathrm{inbound}} + \mathrm{N}_{\mathrm{outbound}}} = \frac{1}{1 + \text{ratio}} \tag{4.2}$$

From that we can estimate that in 2019, Swiss residents represented around 53% of all passengers.

Once the CO_2 emissions are derived, they are multiplied by a factor in order to reflect the current full climate impact of aviation [20]. We get the following equation:

$$\mathrm{Budget}_{\mathrm{CH}} = \mathrm{CO}_2 * \mathrm{C}_{\mathrm{Basel}} * \mathrm{C}_{\mathrm{arrivals}} * \mathrm{Share}_{\mathrm{Swiss\ passengers}} * \mathrm{F}_{\mathrm{climate\ impact}} \tag{4.3}$$

Given the 2019 data, the initial cap on emissions lies just below 20 Mt CO_2-eq (19,85 Mt CO_2-eq) before the start of the policy, in 2024.

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[1] By assuming that the share of emissions from Basel airport in the Swiss total are proportional to share of SKMs from Basel airport in the Swiss total (i.e. $\frac{\mathrm{E}_{\mathrm{basel}}}{\mathrm{E}_{\mathrm{total}}} = \frac{\mathrm{SKM}_{\mathrm{basel}}}{\mathrm{SKM}_{\mathrm{total}}}$), we can find derive the correction factor: $\mathrm{C}_{\mathrm{basel}} = \frac{\mathrm{E}_{\mathrm{total}}}{\mathrm{E}_{\mathrm{total}} - \mathrm{E}_{\mathrm{basel}}} = \frac{1}{1 - \frac{\mathrm{SKM}_{\mathrm{basel}}}{\mathrm{SKM}_{\mathrm{total}}}}$

4.2.2 Budget evolution

From 2025, the cap is decreased each year such that in 2050, a reduction of 90% compared to 1990 levels is reached (see 3.2.4). Consequently, in addition to creating a scenario for the future evolution of the budget, from 2025 to 2050, the emission level in 1990 is also needed.

For completeness, the full emission pathway since 1990 is derived. To do so, data from bunker fuel sales for the period 1990-2022 are retrieved [62][112]. Annual PKMs from Basel Airport and for whole Switzerland were only found for the period 2006-2022. The 2006 value is therefore used when calculating the correction factor C_{Basel} for the years 1990-2005. The ratio of inbound and outbound tourism is available from 1995 to 2003 and for 2008 to 2021. Again, the 1995 value is used for the previous years. For the 2004-2007 period, the average between the 2003 and 2008 ratios is computed. Finally, because the emissions for 2023 had not yet been released, those were extrapolated as an average between 2022 and 2024 (i.e. 2019) emissions.

Starting from 2025, the budget follows a constant reduction rate of 10.15%[2] to pass from 19.85 Mt CO_2 in 2024 to 1.23 Mt CO_2 in 2050, or 10% of the 12.3 Mt CO_2 estimated for the given scope in 1990.

The emission pathway is shown in Figure 4.1. In addition to past emissions for 1990-2024, followed by the national budget for 2025-2050, a ramp up of negative emissions via CDR is showcased. CDR is assumed to be implemented starting 2030, with 0.1 Mt CO_2-eq removed that year. After that, it grows at a constant rate (13.4%) until it fills the gap of the remaining 10% emissions in 2050, to achieve climate neutrality.

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[2] The reduction rate is given by: $1 - \frac{\text{Emissions}_{2050}}{\text{Emissions}_{2024}}^{(1/(2050-2025+1))} = 10.15\%$

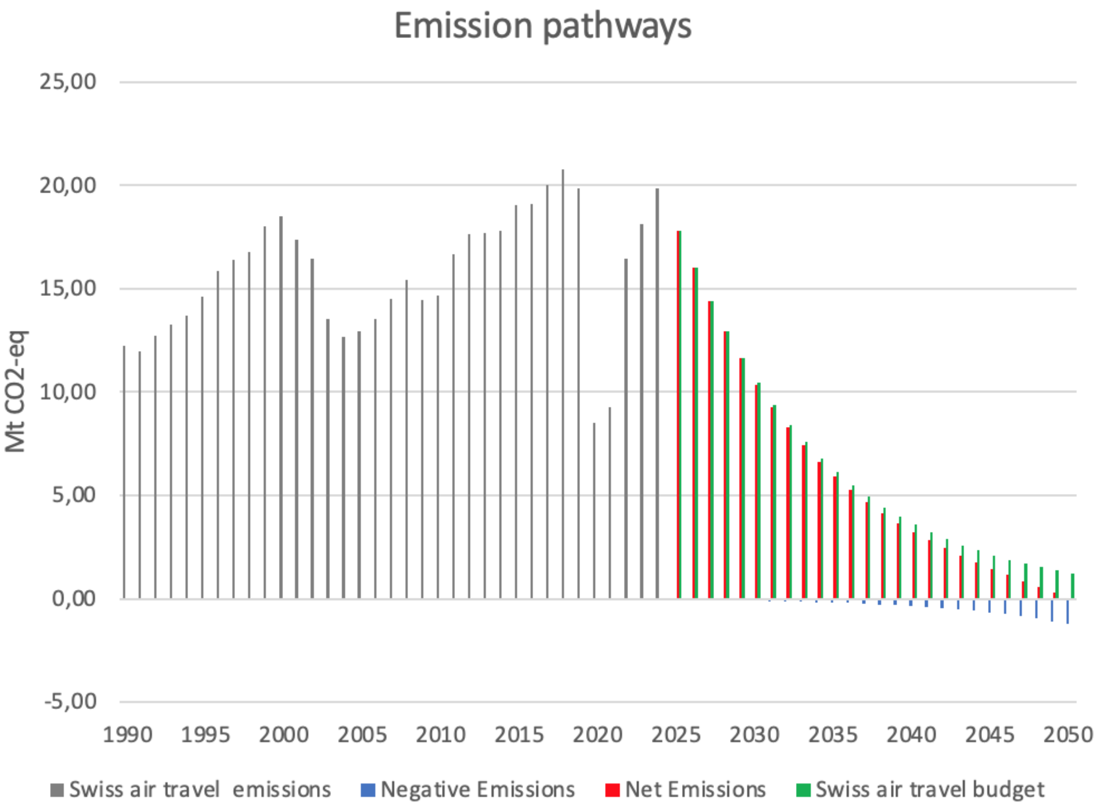

Figure 4.1: Evolution of the national emissions budget. In grey, the past emissions from Swiss air travel. In green, the emissions from Swiss air travel, decreasing due to the introduced cap. In blue, the negative emissions achieved through NET, with a start in 2030. In red, the net emissions, given as the difference between the Swiss air travel budget and the negative emissions, are brought to zero by 2050.

4.3 Individual flight quotas

Now that the emission budget is known at national scale, it would be interesting to get an idea of how many flight quotas each Swiss resident would receive. This would not only allow a better appreciation of the evolution of the quota scheme up to 2050, but also to illustrate the outcome from allocating quotas with an equal per-capita allocation (EPCA) or with a differentiated age group allocation.

4.3.1 Methods

In order to partition the national budget into individual quotas, the future size of the Swiss population needs to be forecasted. To do so, population scenarios from the Swiss Federal Statistical Office (FSO) are retrieved [113]. While with an EPCA only the total population size at a given year is needed, for the age group allocation each group size is required. From the base case scenario, the population is split in four age groups: 2-17, 18-24, 25-64 and >65 years old.

Once that done, the national emission budget is split between the four age groups[3]. Each group is given a weight wi. In ECPA all groups have a weight of 1. In the age group allocation, young adults (18-24) will be allocated 25% more quotas than the rest of the population ($w_i = 1.25$). To derive the individual quotas for each age group given their respective weight, the weighted average quotas are first calculated:

$$q^\star = \frac{Q}{\sum_{i=1}^{n} w_i p_i} \tag{4.4}$$

Next, the quotas allocated to each individual within a specific age group i is given by:

$$q_i = q^\star w_i \tag{4.5}$$

A simplified single-flight emissions calculator is used to illustrate the quotas allocated between 2025 and 2050 [114][4]. The calculator takes an airplane category, a pair of airports, a target year and annual gains in fuel consumption and NO_x emissions as inputs. It then calculates the single-flight CO_2-eq emissions with the ATR100 metric. To derive single-seat emissions from the latter, today's average number of seats (165 and 303) and load factor (0.796 and 0.82) for short-haul and long-haul flights are taken from the online carbon footprint calculator myclimate [115]. From the latter, the average share (26%) of single-flight emissions allocated to freight transport is also retrieved. Estimates of annual improvements between 2023 and 2050 in fuel efficiency (0.6%), reduction of NO_x emissions (0.6%), seating capacity (0.3%) and load factor (0.3%) are taken from the industry report Destination 2050 [5][8]. The numbers used for deriving single-seat emissions from the single-flights emissions given by the calculator are summarized in Figure 6.2. Based on these

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[3] It is assumed here that the whole national emission budget is allocated to individuals, and consequently that no quotas are being auctioned to organizations (see 3.3.2 for a discussion on business travel and organizations).

[4] The paper from which the calculator was retrieved was only published as a preprint version, and the per-review processed abandoned midway, after its main author left academic research. The comments made during the review process were analyzed and did not show any disqualifying element, but the results from the calculator should still be used with precaution. Still, this calculator was judged the most suited to illustrate the present policy, as it uses ATR100 to express CO_2-eq emissions and calculates route specific non-CO_2 effects, which is much more appropriate for single-flights emissions than using a constant factor of 3 like the calculator from myclimate does.

assumptions, the results provide an estimate of the anticipated flying capacity of Swiss residents in a future of kerosene-powered aviation, without accounting for the potential impact of Sustainable Aviation Fuels (SAF) or optimised flight routes. The single-seat emissions reflect the impact from individuals flying in economy class.

4.3.2 Results

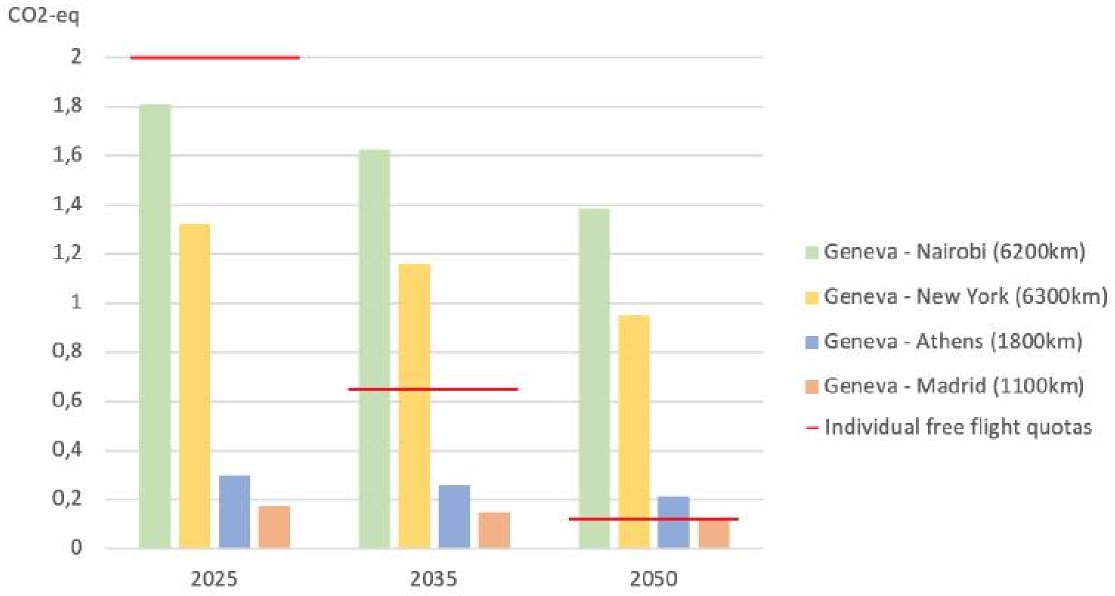

Figure 4.2: Singe-seat emissions from different flight routes and years, as well as the amount of free quotas allocated at the given year.

At the hypothetical start of the policy, in 2025, the national budget reaches 17.8 Mt CO_2-eq. With an EPCA, Swiss residents all receive the same amount of quotas each year. In 2025, with 2 t CO_2-eq worth of quotas, a Swiss resident could easily afford a round trip to Greece as well as an on-way flight to New York. A trip to Nairobi, on the other hand, despite involving a similar flight distance than New York, would require almost 40% more allowances, due to the greater non-CO_2 effects caused by flights passing over tropical latitudes.

In 2035, with a national budget down to 6.11 Mt CO_2-eq, Swiss residents receive quotas worth about 0.64 t CO_2-eq. Even within a kerosene-powered aviation, they could still travel to Greece with only the quotas received the same year.

In 2050, at the due date for climate neutrality of Swiss air travel, the national budget has shrunken down to 1.23 Mt CO_2-eq. Consequently, allocated individual quotas have fallen down to 0.12 t CO_2-eq. With these, a person can take a flight to

Madrid. In order travel back by plane, however, they need to either have banked quotas in the previous years, or purchase extra quotas.

The age group allocation is self explanatory, with young adults receiving reach year 25% more quotas than the rest of the population. One thing to remember is that given the absolute cap on emissions, the other age groups consequently receive less quotas (about 2%) at a given year than in the EPCA.

While the national budget sees a 14.5 fold decrease between 2025 and 2050, individuals receive almost 17 times less quotas by this time, as the Swiss population increases by 16% between 2025 and 2050. Table 6.4 summarizes the flight quotas received by Swiss residents from 2025 to 2050, given an ECPA or an age group allocation.

4.4 Distributional impacts

In order to understand the potential social impact of a flight quota policy, as well as to verify the claimed progressive nature of PCT, an analysis of distributional impacts among the Swiss population is conducted.

4.4.1 Methods

Data

The Swiss Mobility and Transport Microcensus (MTMC), already used in the introduction of the following analysis, is a national statistical survey, published every five years and analyzing the mobility behaviors of the Swiss population [57]. With a sample of over 55000 residents and a special section dedicated to air travel patterns, it clearly stands out as the most robust and comprehensive data available for analyzing air travel behaviors of the Swiss population. The last version published before the COVID-19 pandemic (2015) was preferred to the last available version (2021) for the obvious effects the pandemic had on air travel.

The specific numbers from the survey used hereafter can be found in the Chapter 3.7.3 of the MTMC 2015, where distances covered by airplane, around the world and as part of multi-day trips taken by Swiss residents, are shown for different household income groups. After contacting the authors of the survey, the Swiss Federal Office for Spatial Development (ARE) and the Swiss Federal Statistical Office (FSO), more detailed data was made available for the following analysis, with air travel distances not only distributed for income groups, but also for the different age groups considered in the survey. The income groups considered in the survey are expressed in terms of monthly income of the household and are categorized as follow: <4000 CHF, 4001-8000 CHF, 8001-12000 CHF, >12000 CHF per month. The age groups are given as: 6-17 years old, 18-24 years old, 25-44 years old, 45-64 years old, 65-79 years old, 80 years and more.

It is to be noted that within this part of the survey, air travel is not being counted on the basis of flights, but rather by aggregating overnight trips - and their estimated overall distance - where the plane is used as the main means of transport. This leads to a certain overestimation of the effective flown kilometers, while no robust way to correct for this bias was found. In addition, the distances covered by plane considered here only account for about two thirds of the estimated total average annual distance traveled by airplane [T3.8.1]. This remaining one third of distances travelled by airplane, around 3000 km on average in 2015, are calculated on the basis of daily mobility. After discussion with the authors of the survey, such numbers were argued to be inappropriate for this analysis. In fact, because the part of the survey analyzing daily mobility is based on a single reference day, there were too few reported flights to be able to make a reliable estimate of daily air mobility for each of the income and age categories considered. More anecdotally, the distances covered by airplane within the single-day trip category were also discarded, but those only summed up to an average of 44 flown kilometers per person in 2015.

Approach

With regards to the available data that will be used to conduct the distributional impact analysis, the exact question the latter will answer could be phrased as such: ”If the studied policy scheme, a quota system for passenger air travel, had been introduced in 2015, at a global scale for Swiss residents, with an initial cap set 10% below the distances covered by Swiss residents flying around the globe, what percentage of the people within each age- and income- group would have received enough or more free quotas than needed (winners)?”

In order to estimate the impact that a PCT scheme would have on the Swiss air travel, a simulated population sample is being created in the fashion of a Monte Carlo experiment [116]. Such method enables the generation of numerous draws given a probability distribution. In the statistical data retrieved from the MTMC survey, the mean kilometers flown within each subgroup are given, as well as the 90% confidence interval of such a sample mean, from which the standard deviation can be derived.

Statistical Distribution

In order to generate the 10000 random samples for each subgroup, an assumption regarding what distribution the flown kilometers follow still needs to be made. While the statistical data for the MTMC survey would be most correctly used by the mean of a normal distribution, such approach would answer the wrong question, that is: "What is the probability that the average kilometers flown by this subgroup is less than the whole population sample average?". Whereas the question to be answered here resembles more: "What is the probability for a person of this given subgroup to fly less than the whole population sample average?".

To that end, a log-normal distribution for flown kilometers is assumed, as it is found to be consistent with regards to observed patterns in mobility [117]. Nevertheless, such distribution makes the use of the standard deviation derived from the confidence interval of the data less coherent, as the latter expresses the standard deviation of the sample mean, not the distribution of the flown kilometers of the sample. The results using the standard deviation from the MTMC will therefore be compared with taking a bigger standard deviation, in our case by multiplying it by a factor two.

The reason for taking a bigger standard deviation is motivated by looking at the maximum value found in the 10000 random samples drawn for a given subgroup. For example, in the subgroup of people aged between 25 and 44 and part of a household with income between 8001 CHF and 12000 CHF, the maximum distance flown generated by the Monte Carlo simulation is 10800 kilometers. This gives an indication that using the standard deviation from the MTMC survey might underestimate the spread of the distributed flown distances within a subgroup[5]. This is especially the case for air travel, where few individuals are found to accumulate large flown kilometers over a year and end up accounting for a large share of the total flown distances by the population [14].

Some subgroups from the MTMC survey were discarded for having a sample size too small, which would not make the derived mean and standard deviation robust enough. Two subgroups with less than 100 interviewed persons were discarded: 80+ years old with household income between 8001CHF and 12000 CHF, as well as 80+ years old with household income above 12000 CHF. Moreover, as part of the survey, interviewed people in the age group 6-17 years old were not asked about the income

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[5] Again, the standard deviation retrieved from the MTMC is linked to the sample mean, not the sample distribution itself. While it seems reasonable to use the sample mean as the mean of the sample distribution, the same does not seem to hold for the standard deviation, hence the attempt to increase it by a factor two to increase the spread of the distribution.

of their households. For that reason, within this age group, only the distribution for income category ”Doesn’t know/No indication” is simulated, thus representing the entire age group distribution.

Output table

After drawing the 10000 samples for each retained subgroup, the percentage of samples with kilometers falling below the 90% threshold of average kilometers of the entire experiment samples is calculated and used as the indicator for the share of winners within a subgroup.

Allocation schemes comparison

In order to compare the EPCA of quotas with the allocation differentiated by age groups, the output table is calculated with an additional step. First the ratio λ between the weighted average quota and the classic per-capita quota is calculated. From the equation of weighted average quota (see 4.4), and the simplified formula for EPCA quotas:

$$q = \frac{Q}{P} \tag{4.6}$$

The ratio λ is then:

$$\lambda = \frac{q^\star}{q} = \frac{P}{\sum_{i=1}^{n} w_i p_i} \tag{4.7}$$

Next, the correction factor f_i for each age group is given as

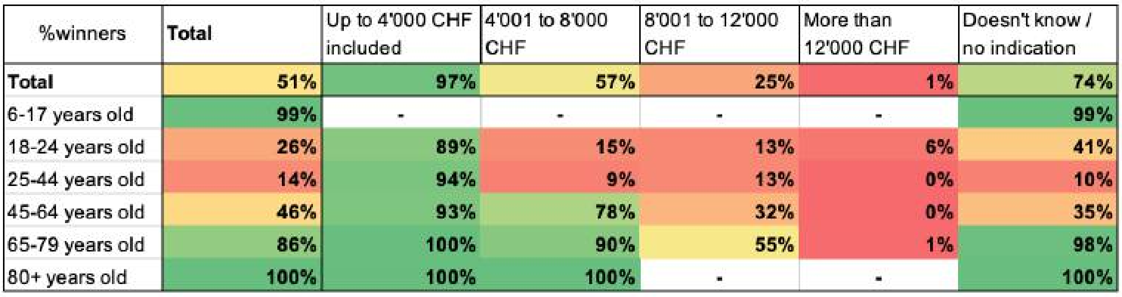
$$f_i = \lambda * w_i \tag{4.8}$$

The output table can then be calculated as the percentage of samples within each subgroup with kilometers falling under 90% of the average kilometers of the entire experiment samples times the correction factor of the specific subgroup. In a second phase, a differentiated age group allocation rule, as discussed in 3.3, will be analyzed. In this example, young adults (age group 18-24) are allocated 25% more quotas than the rest of the population.

4.4.2 Results

The results are first analyzed for the per-capita allocation before a comparison is conducted to reveal the different outcomes resulting from the second allocation approach, the differentiated allocation per age group.

As shown in Figure 4.3, there are strong disparities in flown kilometers amongst the multiple income and age groups. Within the simulation, the majority of individuals would benefit from the quota scheme, as 51% of all generated samples cover fewer distances by air than the set cap, at 90% of the average kilometers.



%winners	**Total**	Up to 4'000 CHF included	4'001 to 8'000 CHF	8'001 to 12'000 CHF	More than 12'000 CHF	Doesn't know / no indication
Total	**51%**	**97%**	**57%**	**25%**	**1%**	**74%**
6-17 years old	**99%**	-	-	-	-	**99%**
18-24 years old	**26%**	**89%**	**15%**	**13%**	**6%**	**41%**
25-44 years old	**14%**	**94%**	**9%**	**13%**	**0%**	**10%**
45-64 years old	**46%**	**93%**	**78%**	**32%**	**0%**	**35%**
65-79 years old	**86%**	**100%**	**90%**	**55%**	**1%**	**98%**
80+ years old	**100%**	**100%**	**100%**	-	-	**100%**

Figure 4.3: distributional impact analysis. Percentage of winners under the simulation, for different income and age groups and given equal per-capita allocation (EPCA).

Distributional impacts on income levels

The simulation shows that over all age groups, the vast majority of individuals within the two lowest household income brackets would receive more free quotas than initially needed (winners), while people in the two highest income brackets would mostly require to purchase extra quotas. All age groups in the lowest income bracket reach +89% of winners with an average over all age groups within this income bracket of 97% winners. The opposite also holds for households with the highest income (>12000 CHF). Only 1% of the generated sample within this income bracket receives more free initial quotas than their recorded air travel consumption. Between the two, the second income bracket (4001-8000 CHF), despite having an overall majority of winners (57%), contains a majority of losers within the two first adult age groups (18-24 and 25-44), with only 15% and 9% winners. The third income bracket (8001-12000 CHF) shows results similar to the highest income bracket, with all subgroups containing a majority of losers, no matter the age considered.

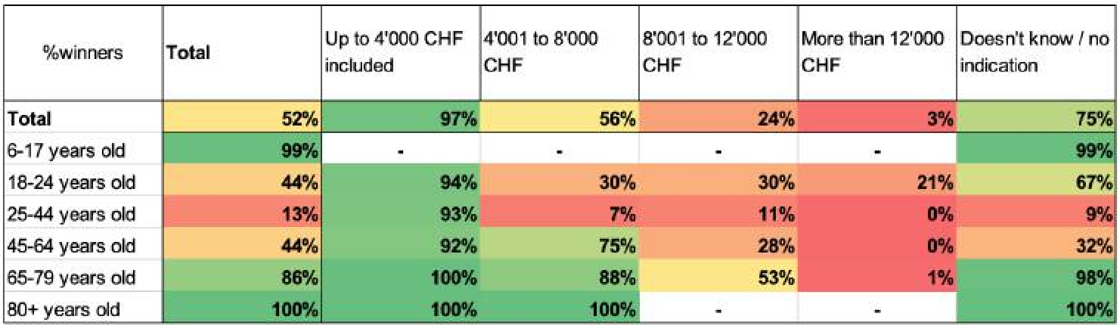
Distributional impacts on age groups

The total outcome by age groups reveals that all underage persons within the simulation would get allocated enough free quotas, just as for the elderly (80+ years old). The rest of retired people (65-79) mostly end up as winners (86%), while the

45-64 group has a slight minority of people getting enough or extra quotas, with 46% winners. The two remaining age groups, 18-24 years and 25-44 years old, are losing age bracket, with only 26%, respectively 14% of generated samples with air travel consumption falling below the set cap. Nonetheless, as mentioned above, the lowest income individuals within those two age groups are still almost entirely winners. On the other hand, still looking at those two age groups, a minority of winners are found in the next income bracket (4001-8000 CHF). These two later subgroups (aged 18-24 and 25-45, with household income of 4001-8000 CHF) could be regarded as an area of potentially undesirable losers, as they represent the losing subgroups with the lowest income. In fact, this income bracket could be argued to represent lower-middle class groups, as the income is expressed as the household income and not individual income. Thus, these two subgroups, people with an household income between 4001CHF and 8000 CHF and aged 18 to 24 and 25 to 44, will be carefully considered when comparing the EPCA with the allocation per age group.

Impact of the allocation per age group

If younger adults (18-24) were allocated 25% more quotas than the rest of the population (Figure 4.4), according to the simulation, this age group would contain 18% more winners (44% versus 26% in the per capita allocation scheme), maintaining it an overall losing age bracket. Within this age group, individuals in the lowest income households only benefit marginally from the quotas increase (+5% winners), but this can be explained by the already very high share of winners (89%) within this subgroup with the EPCA. The other three income brackets within this age group benefit almost equally from the quota increase, with 15-17% more winners.



%winners	Total	Up to 4'000 CHF included	4'001 to 8'000 CHF	8'001 to 12'000 CHF	More than 12'000 CHF	Doesn't know / no indication
Total	52%	97%	56%	24%	3%	75%
6-17 years old	99%	-	-	-	-	99%
18-24 years old	44%	94%	30%	30%	21%	67%
25-44 years old	13%	93%	7%	11%	0%	9%
45-64 years old	44%	92%	75%	28%	0%	32%
65-79 years old	86%	100%	88%	53%	1%	98%
80+ years old	100%	100%	100%	-	-	100%

Figure 4.4: Percentage of winners under the simulation, for different income and age groups and given an age group allocation of quotas in which individuals aged 18-24 would receive +25% quotas than the rest of the population.

Overall, the extra allocation for young adults (18-24) has a similar outcome on the total number of winners (+1%). As for the other age groups, results show a marginal negative effects on their shares of winners. The two other active adult brackets (25-44 and 45-64) contain 1-2% more losers, while the underage and retired people are not affected by the extra allocation for young adults. The most impact subgroup are individuals aged 45-64 and part of a household with monthly income between 8001 and 12000 CHF, where 4% more losers are found.

Chapter 5

Discussion

The objective of this study is to explore the feasibility of implementing a Personal Carbon Trading (PCT) scheme to air travel. By conducting a case study focused on Switzerland, the present report identifies the practical implications of such a policy, examines different design alternatives, and investigates the potential outcomes associated with its implementation.

5.1 Key findings

Emissions from international aviation can be allocated between countries by the mean of the country of residence of passengers. This approach is well-suited for a PCT scheme and enables countries to implement national aviation policies for their residents traveling abroad. This can be achieved through downstream enforcement, where individuals report their flights and surrender the required quotas directly to the government.

Compared to previous research on PCT [104][118][72], the focus on aviation necessitates quotas reflecting not only CO_2 emissions but also additional non-CO_2 forcers such as NO_x emissions, contrail-induced cirrus (CiC), and water vapor (H_2O). It is important to recognize the considerable uncertainty associated with quantifying the Radiative Forcing (RF) potential of non-CO_2 effects [16][119]. Despite this uncertainty, the significance of these effects justifies their inclusion when developing strategies to mitigate aviation's contribution to climate change [5]. The Average Temperature Response over 100 years (ATR100) is best suited to aggregate CO_2 and non-CO_2 emissions into a single CO_2-eq metric compatible with an emission cap and the reporting of single-flight emissions.

Aligned with Switzerland's recent climate legislation, the policy aims for a 90% reduction of the climate impact from Swiss air travel by 2050 compared to 1990 levels, with the remaining 10% of emissions to be removed with NET. Additionally, an intermediate mitigation target, such as a 57% reduction by 2040, is required to increase the chances of scaling up technologies like synfuels and SAF, while simultaneously preventing temperature overshoots in the coming decades. This mitigation pathway is consistent with the definition of climate neutrality of aviation, rather than sole warming neutrality. However, even with an early start, emissions would need to be reduced by more than 10% every year to meet this mitigation target. This illustrates the need for urgent action to bring aviation to acceptable levels. A more delayed mitigation, which is likely to occur as the pathway imagined here assumed a start as early as 2025, would require a even more rapidly decreasing cap, which could negatively impact the aviation sector's ability to adapt and transition.

Various approaches can be adopted to address business travel within the quota scheme. First, a fixed share of the national emission budget (e.g., 10-20%) can be auctioned to organizations, generating revenue for the policy. Second, organizations that are recognized to serve the public interest and that are not driven by profit could be granted exemptions from the quota scheme. Finally, organizations could still finance the purchase of flight quotas to their members. Excluding private flights from the policy scope could prove detrimental to its public acceptability.

To maintain consistency with a single-seat emission accounting of aviation, children above two should also participate to the policy and receive the same amount of free flight quotas than adults. While alternative approaches to equal per-capita allocation (EPCA) exist, in the practical example studied, the allocation of more quotas to young adults does not find support when trying to identify specific needs related to this age group. Results from the distributional impacts analysis lead to the same conclusion. Allocating 25% more quotas to young adults (18-24) would not benefit the lowest income bracket of this age group furthermore, as they are already clear winners of the policy, even in the EPCA. It does however increase the share of winners within the next income bracket (4001-8000 CHF monthly household income, aged 18-24), but at the cost of benefiting young adults with higher income in the same order.

The distributional impact analysis also indicates that the vast majority of Swiss residents in the lowest income brackets would receive more flight quotas than necessary at the policy start, while individuals with the highest incomes would be clear losers. Such results emphasize the high disparities in air travel consumption between the least fortunate and the wealthiest parts of society, even in Switzerland.

Results from the scenario for individual flight quotas suggest that at the start of the policy, transcontinental air travel (which requires round trip flights) would already require the purchase of additional quotas or the use of banking. Without any scale-up in low-carbon technologies like synfuels, Swiss residents may only afford one European round-trip flight every two years with free flight quotas in 2050. This highlights both the necessity for alternative solutions like sustainable aviation fuels (SAF) and the challenge posed to the aviation industry in order to maintain air travel capabilities under ambitious mitigation pathways. Also, it stresses the importance of including flexibility mechanisms in the quota scheme, like an exchange market and banking options.

5.2 Implications

This study directly addresses the "need to map out a plausible route [. . .] to full implementation" of PCT [49]. In this context, aviation stands out as a promising sector. The high level of emissions caused by individual air travel consumption makes it an ideal candidate for consumer-oriented policies like PCT. As a luxury, non-essential good, air travel does not raise concerns about the low carbon capability of individuals, as heating, food or daily mobility do [47]. On top of that, the lack of ambitious aviation policies in times of climate urgency might represent an opportunity to bring PCT back on the policy agenda [49]. The strong progressive outcome of a flight quota scheme, as suggested by the distributional impact analysis, directly addresses one of the major concerns that were raised back in 2008 and led the UK government to abandon PCT [120].

Switzerland, as one of the biggest per-capita emitter in global passenger air travel [121], could set the example with the implementation of an aviation policy at national scale. In practice, the unique political structure of Switzerland might enable PCT to bypass the political barriers identified in the past. In fact, the same elements perceived within the research field as in favor of PCT could well constitute barriers to its adoption by the standard political sphere: where the radical mitigation approach would challenge politicians due to the political risk it would represent, the strong fairness outcome might well upset the wealthiest parts of the population, who also happen to be the most influential in the political system [48][122][49]. Switzerland's partly direct-democratic political system could well be the fertile ground for both the propulsion on the political agenda and the acceptance of a radical and fair climate policy. The Swiss Climate law is a prime example of this, having originated from a popular initiative [123].

The proposed policy corrects the numerous shortcomings identified in the strategy presented by the Swiss Federal Council to mitigate aviation's emissions (see 2.2.2). The residency-based approach aims to encompass all flights taken by Swiss residents abroad, whose emissions should not be imputed to any other country. In addition, it proposes to include non-CO_2 emissions from flights, without which any policy is bound to overlook the majority of aviation's current impact on the climate [28][5]. Ultimately, this approach does not hinge solely on technological breakthroughs but ensures a gradual reduction of emissions, remaining agnostic regarding the choice between technological solutions and the degrowth of aviation.

5.3 Limitations

While the residency-based approach appears suitable for addressing emissions from international aviation within the context of a PCT scheme, the implementation of national aviation policy with international scope presents multiple challenges which could not all be addressed in this report. First, the compatibility of a quota scheme with international agreements on aviation like the Chicago convention was only briefly analyzed. Legal expertise would be required to ensure the validity of such a policy, especially when choosing between an upstream and downstream system. In addition, the potential for an international broadening of the policy was not discussed in detail and could improve both the effectiveness of the policy at national scale and the pursuit of successfully mitigating international aviation. The study did not venture into considerations regarding the personal data that would be required for the functioning of a quota policy, but acknowledges the latter as a critical point for legal feasibility and public acceptability.

This study did not examine the cost of implementing and operating the proposed policy. Given the lack of real case PCT policies, the precise administrative cost appears in any case challenging to measure. Nonetheless, contrary to the conclusions drawn from the UK 2008 experience, it is likely that, given the recent developments in information and communication technologies, this cost might not represent a significant barrier to the development of a quota system anymore [48]. Moreover, for aviation, proposed mechanisms such as the auctioning of quotas to organizations could enable the system to self-finance, the case needed.

The distributional impact analysis is subject to several limitations. The standard deviation retrieved from the MTMC survey was already considered inappropriate, but this issue was only addressed by multiplying it with a factor of two to increase to spread of the distribution. While this modification was based on reasoned assumptions and ultimately improved the simulation, a more robust quantification based on real evidence would have been preferable, if time constraints had permitted. In addition, replacing the log-normal distribution with other statistical methods could better reflect the large spread found in individual air travel distances, between non-flyers and frequent flyers [15][124]. Finally, because the analysis relies on reported annual kilometers, it does not accurately reflect the emissions from specific flights or seat-classes, like the proposed policy would.

5.4 Recommendations

Future research should delve into the current legal framework to identify potential barriers for implementing PCT schemes to international air travel. A thorough examination of the usage, reporting and enforcement of flight quotas is necessary to evaluate the advantages and disadvantages of choosing between an upstream and a downstream system. The feasibility of expanding a national flight quota policy to other cooperating countries requires further investigation. Surveys could contribute by assessing the public acceptability of a flight quota scheme among the population, as well as preferences between the multiple design options. Further modelings of exchange markets within a PCT scheme would provide insights into the practical implications of combining a hard cap with a price ceiling through some priority order.

While further research is welcome to gain a better understanding on both aviation policies and PCT schemes, the present policy and climate action in general cannot wait for academic research to resolve all uncertainties before starting to implement the radical changes called for without delay by the Paris Agreement. If an effective aviation policy is to be introduced, civil society must engage with these issues across private, associative, and political domains. In a world where feasibility of solely relying on technological advancements to effectively mitigate the climate impact of aviation is being questioned not only by the scientific community but also by actors from the industry [21][5][28][7][6], it is becoming necessary for policy proposals to incorporate the possibility of traffic reduction, achieved in a fair and equitable way, the case being. In this regard, it is important to remind to anyone concerned with climate mitigation that the absence of proposals for a reduction of air traffic from the aviation industry is not the result of a meticulous study of the costs and benefits of such an option. It is inherent to any capitalistic economic sector, which will never give credence to the possibility of a reduction in its activity, even if the latter was necessary to achieve credible climate objectives.

Chapter 6

Conclusion

This study assesses the possibility of introducing a Personal Carbon Trading (PCT) scheme for air travel, with the help of a case study centered on Switzerland. A consistent method for allocating emissions from international aviation between countries is identified, based on the country of residence of passengers. With the help of downstream enforcement, the national policy can cover emissions from residents flying abroad.

The policy addresses the full climate impact of air travel by incorporating non-CO_2 forcers, which currently warm the climate at twice the rate of CO_2 emissions. The Average Temperature Response over 100 years (ATR100) emerges as the most suitable CO_2-eq metric, ensuring compatibility with the emission cap and the reporting of single-flight emissions. The latter can be determined by airlines and governments using a variety of methods, which ultimately depend on the chosen balance between accuracy and administrative effort. Similarly, seat emissions can be derived to accurately reflect travel classes.

The mitigation pathway is framed around the definition of climate neutrality for aviation, rather than warming neutrality. In Switzerland, a 90% reduction of the emissions by 2050 compared to 1990 levels is proposed, with the remaining 10% to be mitigated through carbon direct removal (CDR). In addition, an intermediate reduction target is required to scale up low-emissions technologies early enough and avoid dangerous temperature overshoots before 2050.

The allocation of flight quotas can address business travel through various approaches, such as by auctioning a fixed amount of quotas or granting exemptions for publicly recognized organizations, all while allowing quotas to be financed through members and employees. Individuals are allocated free flight quotas each year, children above two included. Both a qualitative and quantitative analysis led to the conclusion that the allocation of more quotas to young adults might not be justified, suggesting that overall, the equal per-capita allocation (EPCA) might be the most suited allocation approach in the context of air travel.

An exchange market is established to bring flexibility in the quota scheme. To keep the policy as a quantity-based mechanism with certainty in emission reductions, a hard cap must be maintained. A novel approach to combine a price ceiling with a hard cap is introduced by means of a priority order for the purchase of additional flight quotas, in ascending order of recent air travel consumption. Additional mechanisms such as a price floor, banking and borrowing can help reduce price volatility in the market. Finally, allowing free quota exchange between relatives is advised for more flexibility, if feasible.

Results from the hypothetical policy scheme in Switzerland from 2025 show that each Swiss resident would receive free flight quotas equivalent to 2 t CO_2-eq in 2025 and just 0.12 t CO_2-eq in 2050. In absence of technological breakthroughs such a synfuels, free allocated quotas would only permit a single European flight per year per Swiss resident in 2050, compared to a long-haul tropical flight in 2025.

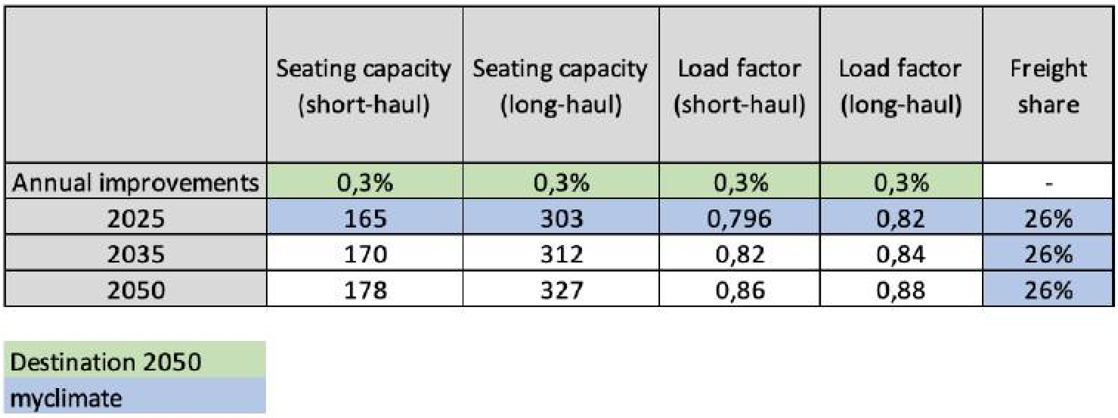
Through a simple yet illustrative distributional impacts analysis utilizing Monte Carlo simulations with available data on air travel from the Swiss population, the progressive nature of the policy is showcased. At the policy start, the vast majority of Swiss residents in the two lowest income brackets would receive more flight quotas than necessary, while individuals within the two highest income groups would either have to purchase additional quotas or fly less.

While this study provides valuable practical considerations, legal and administrative challenges related to the introduction of a national quota policy with international scope require further examination. Surveys on the public acceptability of a flight quota scheme could give more credit to such a radical proposal. Despite these challenges, urgent climate action is needed. In a global race towards climate neutrality where technological solutions alone may not suffice, policies incorporating the possibility for a reduction of air traffic are essential. Given the unequal nature of air travel consumption across income groups, introducing a flight quota scheme should not be perceived as a restrictive policy, but as a guarantee of fair access for all individuals of society to climate ambitious aviation.

Appendix

Year	Swiss air travel emissions [Mt CO2-eq]	National emission budget [Mt CO2-eq]	Negative Emissions [Mt CO2-eq]	Net Emissions [Mt CO2-eq]	Annual growth rate	Cumulative growth rate since 1990
2019	19,85					
2020	8,49					
2021	9,27					
2022	16,45					
2023	*18,15*					
2024	19,85					
2025		17,83	0,00	17,83	-10,15%	45,38%
2026		16,02	0,00	16,02	-10,15%	30,61%
2027		14,39	0,00	14,39	-10,15%	17,35%
2028		12,93	0,00	12,93	-10,15%	5,44%
2029		11,62	0,00	11,62	-10,15%	-5,27%
2030		10,44	-0,10	10,34	-10,15%	-14,89%
2031		9,38	-0,11	9,27	-10,15%	-23,53%
2032		8,43	-0,13	8,30	-10,15%	-31,29%
2033		7,57	-0,15	7,43	-10,15%	-38,27%
2034		6,80	-0,17	6,64	-10,15%	-44,54%
2035		6,11	-0,19	5,93	-10,15%	-50,17%
2036		5,49	-0,21	5,28	-10,15%	-55,23%
2037		4,93	-0,24	4,69	-10,15%	-59,78%
2038		4,43	-0,27	4,16	-10,15%	-63,86%
2039		3,98	-0,31	3,67	-10,15%	-67,53%
2040		3,58	-0,35	3,23	-10,15%	-70,83%
2041		3,22	-0,40	2,82	-10,15%	-73,79%
2042		2,89	-0,45	2,44	-10,15%	-76,45%
2043		2,60	-0,51	2,09	-10,15%	-78,84%
2044		2,33	-0,58	1,75	-10,15%	-80,99%
2045		2,10	-0,66	1,44	-10,15%	-82,92%
2046		1,88	-0,74	1,14	-10,15%	-84,65%
2047		1,69	-0,84	0,85	-10,15%	-86,21%
2048		1,52	-0,95	0,56	-10,15%	-87,61%
2049		1,37	-1,08	0,28	-10,15%	-88,87%
2050	0,00	1,23	-1,23	0,00	-10,15%	-90,00%

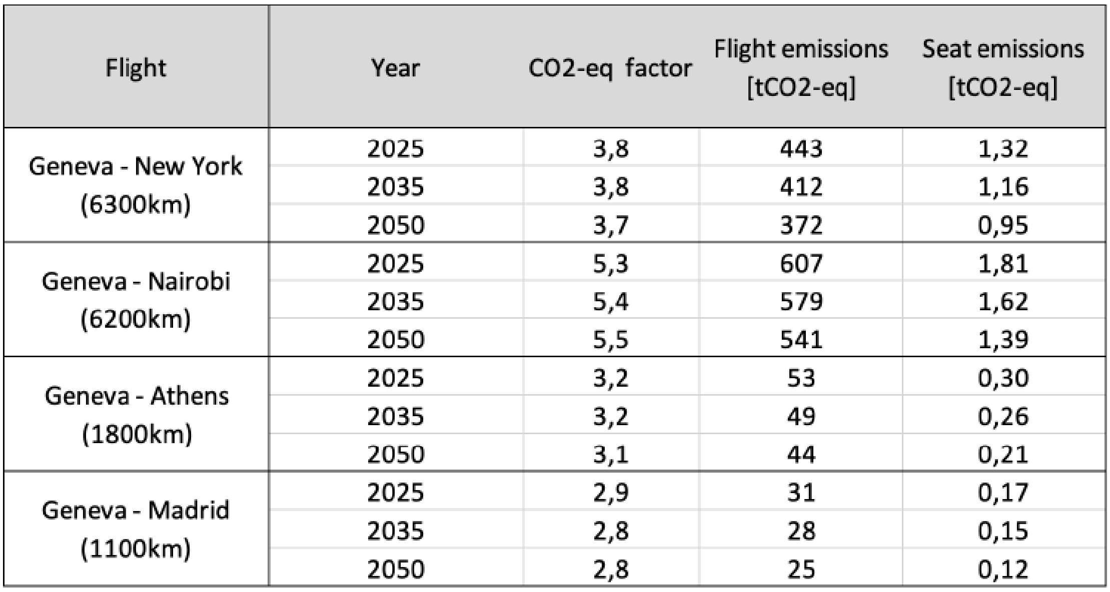
Figure 6.1: Emissions from Swiss air travel, national emission budget & negative emissions, as computed in 4.2.



	Seating capacity (short-haul)	Seating capacity (long-haul)	Load factor (short-haul)	Load factor (long-haul)	Freight share
Annual improvements	0,3%	0,3%	0,3%	0,3%	-
2025	165	303	0,796	0,82	26%
2035	170	312	0,82	0,84	26%
2050	178	327	0,86	0,88	26%

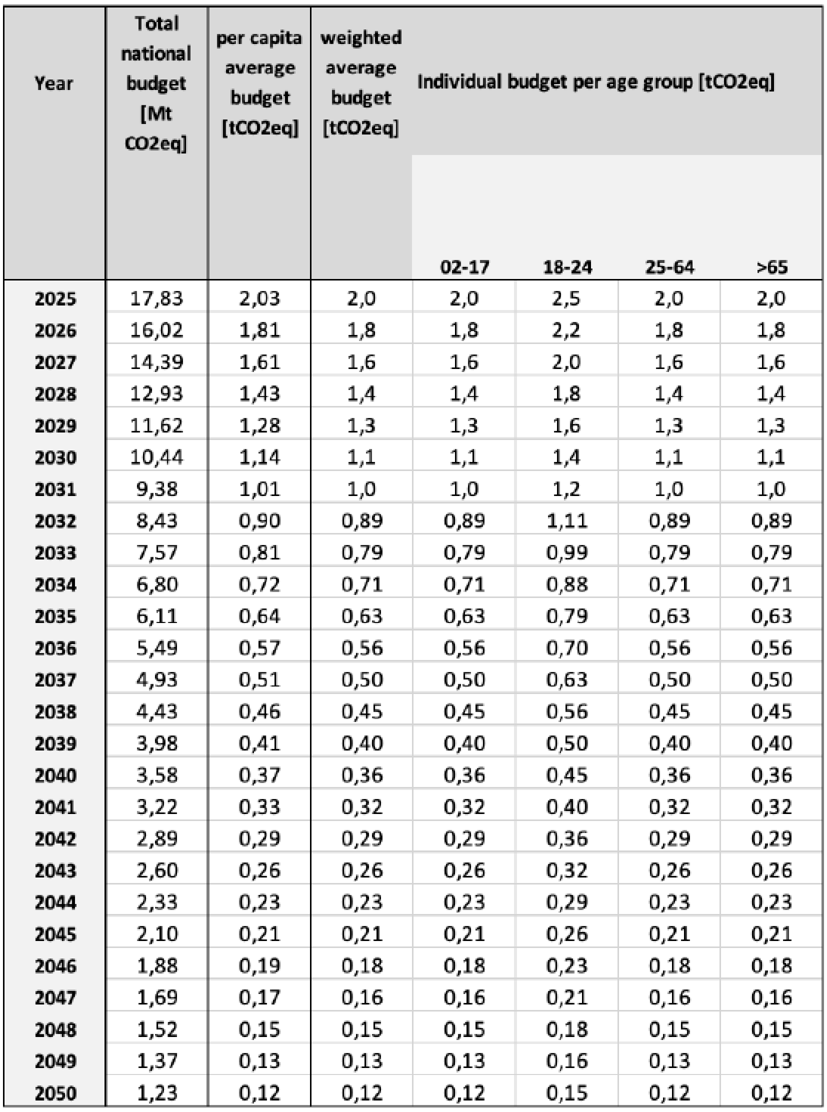
🟩 Destination 2050
🟦 myclimate

Figure 6.2: Assumptions on future improvements in seating capacity and load factors.



Flight	Year	CO2-eq factor	Flight emissions [tCO2-eq]	Seat emissions [tCO2-eq]
Geneva - New York (6300km)	2025	3,8	443	1,32
	2035	3,8	412	1,16
	2050	3,7	372	0,95
Geneva - Nairobi (6200km)	2025	5,3	607	1,81
	2035	5,4	579	1,62
	2050	5,5	541	1,39
Geneva - Athens (1800km)	2025	3,2	53	0,30
	2035	3,2	49	0,26
	2050	3,1	44	0,21
Geneva - Madrid (1100km)	2025	2,9	31	0,17
	2035	2,8	28	0,15
	2050	2,8	25	0,12

Figure 6.3: Single-flight & single-seat emissions for different flights. The CO2-eq factor indicates the CO2-eq/CO2 ratio given each flight's specific route and emissions levels.



Year	Total national budget [Mt CO2eq]	per capita average budget [tCO2eq]	weighted average budget [tCO2eq]	Individual budget per age group [tCO2eq]			
				02-17	18-24	25-64	>65
2025	17,83	2,03	2,0	2,0	2,5	2,0	2,0
2026	16,02	1,81	1,8	1,8	2,2	1,8	1,8
2027	14,39	1,61	1,6	1,6	2,0	1,6	1,6
2028	12,93	1,43	1,4	1,4	1,8	1,4	1,4
2029	11,62	1,28	1,3	1,3	1,6	1,3	1,3
2030	10,44	1,14	1,1	1,1	1,4	1,1	1,1
2031	9,38	1,01	1,0	1,0	1,2	1,0	1,0
2032	8,43	0,90	0,89	0,89	1,11	0,89	0,89
2033	7,57	0,81	0,79	0,79	0,99	0,79	0,79
2034	6,80	0,72	0,71	0,71	0,88	0,71	0,71
2035	6,11	0,64	0,63	0,63	0,79	0,63	0,63
2036	5,49	0,57	0,56	0,56	0,70	0,56	0,56
2037	4,93	0,51	0,50	0,50	0,63	0,50	0,50
2038	4,43	0,46	0,45	0,45	0,56	0,45	0,45
2039	3,98	0,41	0,40	0,40	0,50	0,40	0,40
2040	3,58	0,37	0,36	0,36	0,45	0,36	0,36
2041	3,22	0,33	0,32	0,32	0,40	0,32	0,32
2042	2,89	0,29	0,29	0,29	0,36	0,29	0,29
2043	2,60	0,26	0,26	0,26	0,32	0,26	0,26
2044	2,33	0,23	0,23	0,23	0,29	0,23	0,23
2045	2,10	0,21	0,21	0,21	0,26	0,21	0,21
2046	1,88	0,19	0,18	0,18	0,23	0,18	0,18
2047	1,69	0,17	0,16	0,16	0,21	0,16	0,16
2048	1,52	0,15	0,15	0,15	0,18	0,15	0,15
2049	1,37	0,13	0,13	0,13	0,16	0,13	0,13
2050	1,23	0,12	0,12	0,12	0,15	0,12	0,12

Figure 6.4: Flight quota allocated to Swiss residents from 2025 to 2050, given an equal per-capita allocation (EPCA) and an age group allocation in which individuals aged 18-24 receive +25% more quotas than the rest of the population.

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