Energy Policy 171 (2022) 113263

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Novel quota and tax regime design approach for green transition: A case study on Switzerland's aviation industry

Amir H. Keshavarzzadeh [a,b,*], Caspar Thut [c], Daniel Andersen [a], Levi Lingsch [d], Anthony G. Patt [c]

[a] Department of Information Technology and Electrical Engineering, ETH Zürich, Zurich, Switzerland
[b] Department of Mechanical and Process Engineering, ETH Zürich, Zurich, Switzerland
[c] Department of Environmental Systems Science, ETH Zürich, Zurich, Switzerland
[d] Department of Mathematics, ETH Zürich, Zurich, Switzerland

ARTICLE INFO

Keywords:
Sustainable aviation fuels
Metaheuristic optimization
Tax
Quota

ABSTRACT

In the present study, a novel approach for calculating optimal quota and tax regimes is investigated. A metaheuristic framework has been developed to find the optimal quota regime for the national or worldwide aviation industry. The minimization of ticket prices and CO_2 emissions are considered to be objective functions. The results of the current study indicate that implementing optimized quotas is more effective than intensive tax regimes. To elaborate, much more important than the value of the carbon price is the shape (convexity or concavity) of the tax regime. The optimal tax regime shape is also obtained. Based on the optimal quota and tax regime, the concept of golden time and value is introduced. In the golden time window, investing in Sustainable Aviation Fuels (SAFs) will be the most cost-effective. Furthermore, the results demonstrate that neither the sole introduction of quotas nor the imposition of high carbon taxes are beneficial from an economic and decarbonization standpoint. Thus, an optimized quota regime should be employed. These quotas should be introduced as soon as possible, and their implementation should be combined with political efforts to introduce a carbon tax and policies supporting the development of an alternative jet fuel industry.

1. Introduction

Air transportation is a powerful engine for social and regional cohesion, boosting tourism, stimulating the economy, and connecting people. A well-functioning and competitive international aviation market is essential for the mobility of citizens and the economy as a whole (Commision and Transport, 2021). Nevertheless, according to the greenhouse gas inventory, Switzerland's national and international air traffic causes about 13.5% of its total CO_2 emissions (Neu, 2021). Due to the expected growth in demand for air travel, CO_2 emissions will continue to rise if no efforts are made to reduce the environmental impact of aviation (Ecoplan and „ Road Map Sustainable Aviation ", 2021).

In general, there are three ways to decarbonize the aviation industry (Becattini et al., 2021). Electric planes are suitable for short-haul aircraft with relatively low passenger capacities (Hall et al., 2018; Vardon et al., 2022). Carbon offsetting is seen as a key mitigation measure of the International Civil Aviation Organization at achieving carbon-neutral growth after 2020 (ICAO, 2021). However, from a scientific point of view, carbon offsetting does not reduce the CO_2 concentration in the atmosphere (Becken and Mackey, 2017). Thus, it needs to be a secondary measure. Also, the immense amount of carbon that needs to be offset for a net-zero aviation industry makes this measure unrealistic in the near term. Although SAFs are still emerging technology, the potential for decarbonization is promising (Scheelhaase et al., 2019).

Decarbonizing the aviation sector is complex and will rely considerably on shifting towards SAFs (Chiaramonti, 2019). SAFs need to be transportable and storable, as well as fulfill high-energy density and safety requirements (Neuling and Kaltschmitt, 2018). Promising alternatives are synthetic hydrocarbons, biofuels, and hydrogen fuels. While hydrogen fuels are more efficient than synthetic hydrocarbons and biofuels, entirely new infrastructure must be established and thus are instead a long-term option (Hall et al., 2018). By contrast, blended with Jet A-1 kerosine, biofuels and synthetic fuels can be used as drop-in fuels without changes to aircraft and infrastructure (Scheelhaase et al., 2019). The ASTM certification (ASTM International, 2018) currently verified five different production pathways of SAFs for blending with up to 50% vol.

---

* Corresponding author. Department of Information Technology and Electrical Engineering, ETH Zürich, Zurich, Switzerland.
E-mail address: akeshavarzza@ethz.ch (A.H. Keshavarzzadeh).

https://doi.org/10.1016/j.enpol.2022.113263
Received 4 May 2022; Received in revised form 19 August 2022; Accepted 14 September 2022

Biofuels based on vegetable oils, waste lipids, and crops are mature fuel technologies used in ground transport (Commision and Transport, 2021). Hence, pricewise, these biofuels are the most competitive SAFs compared to conventional jet fuels. However, land-use changes and competition for scarce resources raise sustainability questions. In comparison, advanced biofuels based on lignocellulose, algae, and bio-waste feedstock have a higher emission reduction potential (Vardon et al., 2022). The reduction potential differs substantially between different fuel conversion processes and feedstocks. Life cycle emission values from the ICAO differ between 7.7 gCO_2eq/MJ for global agricultural residues with the Fischer-Tropsch (FT) process and 99.1 gCO_2eq/MJ the Hydroprocessed Esters and Fatty Acids (HEFA) fuel conversion with Indonesian palm oil. Meanwhile, conventional jet fuels values stand at 89 gCO_2eq/MJ (ICAO, 2021). Resource scarcity, different feedstocks, and land-use changes play a minor role in advanced biofuel production. Despite the promising outlook for advanced biofuels, production capacities are limited, and policy interventions are needed to ramp up fuel production (Panoutsou et al., 2021).

Synthetic hydrocarbons are synthesized from hydrogen generally produced by electrolyzed water and a carbon feedstock (Becattini et al., 2021). Such power to liquid (PtL) fuels have the potential to be carbon neutral if renewable energy is used for the production and CO_2 is used as feedstock either from direct air capture (DAC) or other organic sources (Detz et al., 2018). However, similar problems exist with advanced biofuels. Since PtL is a new technology, production is costly compared to conventional jet fuels, and no large-scale plants exist. Although scaling up production and technological learning curves will reduce the price of PtL fuels, fuel prices are expected to stay higher compared to conventional jet fuels (Schmidt et al., 2018). This is primarily due to the sophisticated conversion process with substantial energy input for synthesis and the required feedstocks. However, PtL and advanced biofuels will play an essential role in the aviation sector's decarbonization (Chiaramonti, 2019). Policy interventions are necessary to incentivize large-scale investment into SAFs technologies because of high upfront capital costs and the lack of price competitiveness (Scheelhaase et al., 2019; Panoutsou et al., 2021).

An effective policy instrument to implement SAFs is indispensable. Two conventional policy measures that are usually employed are imposing taxes or introducing quotas. One of the most important properties of SAFs is that they can be blended with kerosine and refuel airplanes without further modification of existing infrastructure and equipment. This is why SAFs are known as drop-in fuel. This is a substantial advantage of SAFs in comparison to other alternative energy resources such as electricity and hydrogen. Hence, SAFs are the main short-term alternative to reduce the aviation industry's carbon footprint. The drop-in property of the SAFs makes them suitable to be implemented with increasing supply on a timetable basis. This is what is referred to as drop-in quota. To elaborate, introducing a quota obligation for jet fuels is a practice that forces airlines to allocate a certain share of the total volume of conventional jet fuels to SAFs on an annual basis. On the other hand, imposing carbon tax is considered as a punitive economic measure that levied against CO_2 emissions. Although drop-in quota systems are one of the major policy instruments for green energy transition, there is a relatively small stream of literature investigating the effect of quota regimes on the economics of airlines and aviation industry CO_2 emissions. Jiang and Yang (2021) developed a model to study the impact of SAF quota on the CO_2 emissions and compare it with carbon tax policies. They found that SAF quotas are capable of outperforming carbon taxes when the CO_2 emission reduction target is ambitious and conventional jet fuel prices exceeded the lower bound of the expected values. However, they did not study the effect of combined quota and tax regimes or the optimal quota regime. Also, Norberg (2014) conducted research on the SAF quota policy. It has been found that for obtaining a desired reduction in the aviation industry emissions, SAF quota regimes must be introduced on a larger scale. The mentioned study, similar to other pieces of literature, does not provide a vivid picture of this SAF quota obligation. For instance, it is an open question what the optimal annual increment rate for SAF quota is.

There is a more developed stream of literature on carbon taxes (either on emission tax or fuel tax) for the aviation industry. The existing studies stress the fact that carbon taxes have an explicit effect on the CO_2 emissions of the aviation industry (Brueckner and Zhang, 2010; González and Hosoda, 2016). Also, there is another stream of literature that studies the indirect impact of the aviation tax on the emission reduction. For instance, a study by Mayor and Tol (2007) implied that the aviation tax in UK not only was not successful to cut the emissions but also increased the aviation CO_2 emissions as such taxes have made longer air travel more attractive due to reduction in the relative price difference between far and near holidays. The third mainstream literature is about the combination of a carbon tax and quota and its effect on the aviation industry and CO_2 emission. The main focus of these studies is to investigate the impacts of implementing carbon tax revenue to subsidize the development of SAFs. Scheelhaase (Scheelhaase et al., 2019) proposed three main policy instruments (taxes, compulsory blending quota and green certificates) for incentivizing the use of synthetic fuels. Increasing the costs of CO_2 emission by imposing taxes is not considered a widely accepted approach as it is directly related to the increase of the aviation industry costs which typically can increase the rate of unemployment. Proposing a quota regime for SAFs on the other hand can send signals to investors to invest in the SAFs industry which can result in cost-effective SAFs. The last policy measure can be the introduction of the green certificate. Although this policy instrument bound the aviation industry to consume a certain level of SAFs, it is not mandatory for the certificate holders to use SAFs in their own flights. Panoutsou et al. (2021) studied the possible market share of biofuels and relevant policies that can result in desired CO_2 mitigation. They investigated policy measures challenges and possible state interventions to reach desired decarbonization. They restated that the main aim of the policies should be in a direction that makes biofuels competitive with conventional fuels by increasing the conventional fuels price.

Although most of the literature has suggested carbon taxes or quotas for reaching the desired level of CO_2 emission, there is no in-depth study on the exact quota or tax regimes that can result in the cost-effective reduction of CO_2. Therefore, there is no established approach for designing and evaluating tax and quota regimes. As a result, it is of particular interest to many countries, including policy-makers in our case study of Switzerland, to know what tax and quota regime they should employ. To this end, the present study aims to provide information about the optimal tax and quota regimes and values for the Swiss aviation system with relevant information on a quantitative basis. In this analysis, only flights that are refueled in Switzerland, i.e., departing from Switzerland, are considered. This analysis investigates the impact of an optimal SAF quota in the air transport market on ticket prices and CO_2 emissions. Scenarios are developed using a systems dynamics model. Additionally, the parameters in our model are tested using a sensitivity analysis. To achieve an optimal balance between ticket prices and minimal CO_2 emissions, an evolutionary-based optimization algorithm is developed. Finally, recommendations for action are given based on the results. The present study proposes a novel approach to the design of a tax regime for conventional fuels and a quota regime for SAFs for the Switzerland aviation industry. The following highlight the novelty of this research and its importance:

- Proposing a novel framework/approach for designing tax or quota regimes based on metaheuristic techniques.
- Studying the effect of convexity or concavity of tax and quota regimes on decarbonization and costs
- Obtaining the robust optimal shape for the tax regime, which is the most optimum carbon price for all projected SAF prices.
- Obtaining the most optimum quota regime shape and figure for the Swiss aviation industry

- Introducing the concept of golden time and value that is a time window for SAF quotas; keeping the quotas at golden value can reduce the CO_2 emission considerably while ticket prices do not experience a considerable change, although the price of conventional fuel increases due to taxes.

The rest of the paper is organized as follows. Section 2 provides description about the system dynamics model and metaheuristic optimization algorithm and how these two modules integrated together. Section 3 evaluates the general behavior of the model and its accuracy. In Section 4, first the obtained Pareto optimal solutions of all scenarios for Swiss aviation industry are discussed and compared to each other; Next the two most important and insightful scenarios (LConv LSyn, LBio scenario and optimal tax scenario) among all other scenarios are picked and enhanced in detail. Section 5 presents further discussion and concluding remarks.

2. Methodology

In the present study, a combined metaheuristic-system dynamics model of the aviation industry is developed. The schematic of the framework is represented in Fig. 1.

The designed system dynamics model can be categorized into three main sections, unit costs, aviation emissions, and airline fares (Kieckhäfer et al., 2018). Between the aforementioned sections, there are interdependencies based on exogenous and endogenous factors. The model calculates annual airline fares per passenger kilometer and annual aviation emissions.

The unit costs depend on the fuel prices of conventional jet fuel, synthetic jet fuels, and biofuels. The drop-in quotas associated with synthetic fuels and biofuels set the fuel-mix composition of the model. The unit costs steer the modeled annual airline fares, as a change in the operating margin will be adjusted by altering airline fares. The annual aviation emissions depend on the fuel composition, fuel quantity, and the mitigation potential of alternative fuels. Different mitigation potentials for synthetic fuels and biofuels are used (Schmidt and Weindorf, 2016). To represent the Swiss aviation sector, input parameters are adopted for the Switzerland aviation industry. The key parameters of the model can be found in Appendix I.

2.1. Unit costs

One of the critical outputs of the proposed model is the unit costs per available seat kilometer $UC(t)$. Furthermore, all additional costs per available seat kilometers AC by airlines $FC(t)$. The ratio of additional costs to fuel costs in 2015 is set to 7/3 (Pierre-Selim, 2018); resulting in a value of 0.1236 CHF/seat kilometer, which is assumed to be constant over time. Hence, the change in unit costs is merely driven by changes in fuel prices.

$$UC(t) = FC(t) + AC \tag{1}$$

Total fuel costs per available seat kilometers $FC(t)$ can be defined as the sum of alternative fuel costs per available seat kilometers $FC^{AF}(t)$ and conventional fuels costs per available seat kilometers $FC^{CF}(t)$.

$$FC(t) = FC^{AF}(t) + FC^{CF}(t) \tag{2}$$

The available seat kilometers $ASK(t)$ are obtained by the multiplication of the aircraft in use $AU(t)$, average flight distance per seat $DPS(t)$, and the load factor $LF(t)$.

$$ASK(t) = AU(t)^{*}DPS(t)^{*}LF(t) \tag{3}$$

The costs of SAFs $FC^{AF}(t)$ are calculated by multiplying the fuel price of synthetic fuels $FP^{SYN}(t)$, and biofuels $FP^{Bio}(t)$ with their respective Quotas $Q^{SYN}(t)$, $Q^{Bio}(t)$. To receive the total costs, the fuel prices are multiplied by the annual fuel consumption $FU^{ANN}(t)$. The costs of conventional jet fuel $FC^{CF}(t)$ are given by the fuel price of conventional fuels $FP^{CF}(t)$ multiplied by the annual conventional fuel consumption $FUC^{ANN}(t)$.

$$FC^{AF}(t) = \left(FP^{SYN}(t) * Q^{SYN}(t) + FP^{Bio}(t) * Q^{Bio}(t)\right)^{*}FU^{ANN}(t) \tag{4}$$

$$FC^{CF}(t) = FP^{CF}(t)^{*}FUC^{ANN}(t) \tag{5}$$

The annual fuel consumption $FU^{ANN}(t)$ is obtained by the multiplication of available seat kilometers $ASK(t)$ with the fuel consumption per seat and kilometer $FU^{ASK}(t)$. Since policies on alternative fuel quotas drive our model, annual conventional jet fuel consumption $FUC^{ANN}(t)$ is given by total fuel consumption $FU^{ANN}(t)$ subtracted by the annual alternative fuel consumption $FUA^{ANN}(t)$.

$$FU^{ANN}(t) = ASK(t)^{*}FU^{ASK}(t) \tag{6}$$

$$FUC^{ANN}(t) = FU^{ANN}(t) - FUA^{ANN}(t) \tag{7}$$

Fuel consumption per available seat kilometer $FU^{ASK}(t)$ is the ratio of fuel consumption per kilometer FUL^{ANN} divided by aircraft in use $AU(t)$. FUL^{ANN} is the annual fuel consumption. Finally, the annual fuel consumption of alternative jet fuel $FUA^{ANN}(t)$ is set by the synthetic fuel quota $Q^{SYN}(t)$ added to the biofuel quota $Q^{Bio}(t)$ and multiplied by the

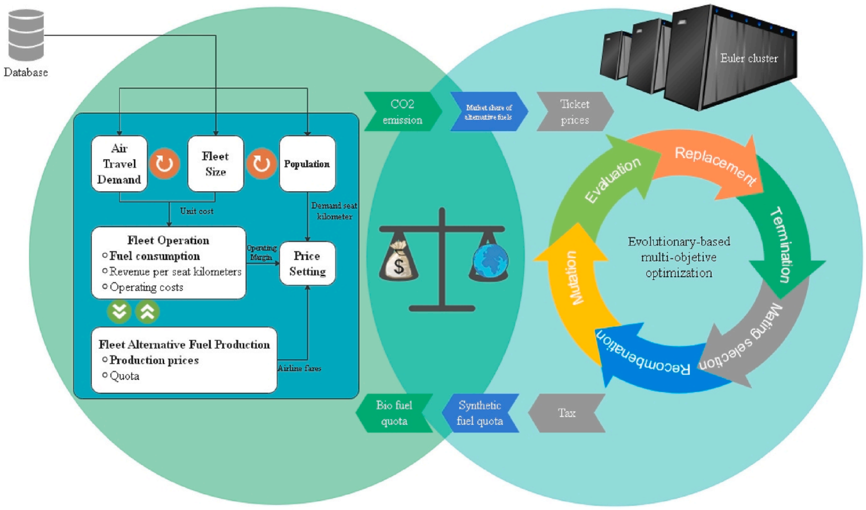


Fig. 1. The schematic of the proposed metaheuristic-system dynamics model for the Swiss aviation industry.

annual fuel consumption $FU^{ANN}(t)$.

$$FU^{ASK}(t) = \frac{FUL^{ANN}(t)}{AU(t)} \tag{8}$$

$$FUA^{ANN}(t) = \left(Q^{SYN}(t) + Q^{Bio}(t)\right) * FU^{ANN}(t) \tag{9}$$

2.2. Aviation emissions

The computation of annual aviation emissions is based on Kieckhäfer et al. (2018) formula 24 and adjusted to the purpose that two different types of SAFs are used with different mitigation potentials. Annual aviation emissions $E^{ANN}(t)$ are computed by calculating the total possible emissions by the annual fuel consumption FU^{ANN} multiplied by the conventional jet fuel emission index EI adopted from Kieckhäfer et al. (2018). Secondly, the synthetic fuel quota Q^{SYN} and biofuel quota Q^{Bio} are multiplied by their respective mitigation potentials MP^{SYN}, MP^{Bio}. Finally, the total possible emissions are multiplied by 1 minus the obtained fraction of emission-free fuels.

$$E^{ANN}(t) = FU^{ANN}(t) * EI * \left(1 - \left(MP^{SYN} * Q^{SYN}(t)\right) - \left(MP^{Bio} * Q^{Bio}(t)\right)\right) \tag{10}$$

2.3. Airline fares

The implemented airline pricing mechanisms are based on Pierson and Sterman's (Pierson and Sterman, 2013) work. The airline fares $AF(t)$ were determined by anchoring and adjusting heuristics (Sterman, 2002; Sterman et al., 2007). The previous airline fares $AF(t-1)$ function as an anchor, adding the fare change $FAC(t)$. Additionally, the term is divided by the available seat kilometers $ASK(t)$.

$$AF(t) = \frac{AF(t-1) + FAC(t)}{ASK(t)} \tag{11}$$

Adjustments to airline fares are driven by changing operating margins. Therefore, the fare change $FAC(t)$ is defined as the targeted operating margin $OM^{tar}(t)$ subtracted by the actual operating margin $OM(t)$.

$$FAC(t) = OM^{tar}(t) - OM(t) \tag{12}$$

The targeted operating margin $OM^{tar}(t)$ was set in relation to the available seat kilometers, thus expanded airline fleets are considered. The ratio of the targeted operating margin in 2015 $OM^{tar}(2015)$ and the available seat kilometers in the respective year $OM^{tar}(2015)$, is multiplied by the available seat kilometers $ASK(t)$. Moreover, the actual operating margin $OM(t)$ is given by the operating revenue $OR^{tot}(t)$ subtracted by the total operating costs $OC^{tot}(t)$.

$$OM^{tar}(t) = \left(\frac{OM^{tar}(2015)}{ASK(2015)}\right) * ASK\left(t\right) \tag{13}$$

$$OM(t) = OR^{tot}(t) - OC^{tot}(t) \tag{14}$$

The total operating revenue $OR^{tot}(t)$ is computed from the airline fares $AF(t)$ multiplied by the available seat kilometers $ASK(t)$. Total operating costs $OC^{tot}(t)$ are derived from the unit costs $UC(t)$ multiplied by the available seat kilometers $ASK(t)$.

$$OR^{tot}(t) = AF(t) * ASK(t) \tag{15}$$

$$OC^{tot}(t) = ASK(t) * UC(t) \tag{16}$$

2.4. Optimization

In the last decade, evolutionary algorithms (EAs) have been widely utilized for optimization. The true power of EAs especially apparent when several contrasting objectives must simultaneously be optimized. To elaborate, the main task of EAs is to find the best compromise between competing objectives. The set of optimal solutions resulting from implementing multi-objective optimization is known as a Pareto set. Not only is the Pareto set itself (the quota and tax regime in the current study) of great importance but its image on the objective space (CO_2 emission and airline fares in the current study) can provide a broad outlook for the evaluation of the objectives.

For this purpose, EAs perform a partial order for all feasible points in the objective space. Several ranking methods have been developed that can be classified into three main groups: dominance depth method, dominance count, and dominance rank (Carlos et al., 2007). The main idea of dominance count and dominance rank methods is to obtain the mutual dominance of feasible solutions. For this purpose, the EA counts how many individuals are dominating the feasible solution and how many individuals are dominated by the feasible solution. In contrast to other methods, the dominance depth method is capable of finding the exact front for each feasible solution. The Non-dominated Sorting Genetic II (NSGA-II) algorithm (Deb et al., 2002) is one the most popular algorithms which utilizes the dominance depth rationale. NSGA-II is an evolutionary optimization technique that is based on the natural selection theorem. NSGA-II addressed previous algorithms' drawbacks such as the computational complexity. The optimization setup for the current study can be discussed as follows.

2.4.1. Objective functions

The two objective functions for the current study are ticket price (CHF/seat*Km) and aviation CO_2 emission. The goal is to minimize both objectives at the same time; however, these two objectives are in contrast to each other. For minimizing CO_2 emissions, airplanes need to be refueled with SAFs that are more expensive than kerosine. This will lead to higher airline fares and as a result, higher ticket prices. On the other hand, for decreasing ticket price, airlines will have tendency to refuel with kerosine which lead to higher CO_2 emissions. Therefore, the main task of the EA is to find the optimal trade off between these two objectives.

2.4.2. Decision variables

The value of the two objectives is controlled by decision variables. At a high-level, NSGA-II generates different combinations of decision variables and calculates the values of the objective functions for each combination. In the next step, the respective values of objective functions are compared to each other.

In the current study there are three different set of decision variables namely: biofuel quota, synthetic fuel quota and carbon tax. This can be mathematically described as follow:

$$D_{biofuel} = \left\{d^1_{biofuel}, d^2_{biofuel}, \ldots, d^t_{biofuel}\right\} \tag{17}$$

$$D_{synthetic\ fuel} = \left\{d^1_{synthetic\ fuel}, d^2_{synthetic\ fuel}, \ldots, d^t_{synthetic\ fuel}\right\} \tag{18}$$

$$D_{carbon\ tax} = \left\{d^1_{carbon\ tax}, d^2_{carbon\ tax}, \ldots, d^t_{carbon\ tax}\right\} \tag{19}$$

Here $d^t_{biofuel}$, $d^t_{synthetic\ fuel}$ and $d^t_{carbon\ tax}$ represents biofuel quota, synthetic fuel quota and carbon tax in year t, respectively. Also, NSGA-II requires an upper and lower bound for each decision variable so it can choose decision variables from this spectrum. The upper and lower bound of each set of decision variables cab be defined as follows:

$$0 \le d_{biofuel} \le 1 \ \forall d_{biofuel} \in D_{biofuel} \tag{20}$$

$$0 \le d_{synthetic\ fuel} \le 1 \ \forall d_{synthetic\ fuel} \in D_{synthetic\ fuel} \tag{21}$$

Equations (20) and (21) guarantee that the amount of quota for each SAF and in each year is not a negative value and it is less than 1. Therefore, NSGA-II can choose any value between 0 and 1. For instance, if NSGA-II chooses 0.1 for $d^1_{biofuel}$, biofuel will make up 10% of the total fuel volume in the first year.

The upper and lower bound of the carbon tax can be described as follows:

$$L \le d_{carbon\ tax} \le U \quad \forall d_{carbon\ tax} \in D_{carbon\ tax} \tag{22}$$

$$L = \{ l^1 , l^2 , \ldots , l^t \} \tag{23}$$

$$U = \{ u^1 , u^2 , \ldots , u^t \} \tag{24}$$

Here the upper and lower bound of the carbon tax is different for each year. l^t and u^t illustrate the respective lower and upper bound of year *t*. The upper and lower bound of carbon tax can be adopted from the future projection of carbon taxes. Fig. 4-a represents the future projection of carbon taxes up to 2050 in the form of kerosine price.

2.4.3. Constraints

Constraints are vital part of each optimization problem. The constraint of the current optimization is defined as:

$$d_{biofuel} + d_{synthetic\ fuel} \le 1 \quad \forall d_{synthetic\ fuel} \in D_{synthetic\ fuel}\ and\ \forall d_{biofuel} \in D_{biofuel} \tag{25}$$

The above constraint guarantees that the summation of biofuel and synthetic fuel quota in each year is not more than 1 (100%). Other constraints can be defined as:

$$d^t_{biofuel} - d^{t-1}_{biofuel} < \left|0.06\right| \tag{26}$$

$$d^t_{synthetic\ fuel} - d^{t-1}_{synthetic\ fuel} < \left|0.06\right| \tag{27}$$

$$d^t_{synthetic\ fuel} - d^{t-1}_{synthetic\ fuel} < |0.3\ CHF / l| \tag{28}$$

Equations (26) and (28) give the algorithm the ability to smoothly increase or decrease the amount of quota, preventing sudden jumps and extreme oscillations between 0 and 1. The amount of this increase or decrease is set to be 6% in each year. This value is sufficient for the current study as the results show that most of the values chosen by the NSGA-II is around 3%. The same idea holds for Equation (28) as it allows the algorithm to increase or decrease the carbon tax of kerosine by 0.3 CHF/l. To encapsulate the optimization process, NSGA-II algorithm chooses different sets of decision variables from the defined lower and upper bound and under the defined constraints for each decision variable and feeds those sets to a system dynamics model to calculate the objective functions. The calculated objective function then is used by NSGA-II to find the most optimal combination of decision variables. The exact details of the NSGA-II algorithm for optimization procedures can be found in (Deb et al., 2002). In contrast to classic optimization approaches, by applying a metaheuristic optimization algorithm, the true behavior of each objective function and their influence on each other can be investigated (Hamdani et al., 2007). In metaheuristic algorithms all objective functions can be considered at the same time (Murugan et al., 2009). Therefore, the whole feasible space induced by objective functions can be investigated (Wang et al., 2019). Also, based on the Pareto optimal solution the impact of each objective function on other objectives and their trade-offs can be obtained. Furthermore, the decision variables corresponding to a solution space can be acquired (Martínez-Vargas et al., 2016). Hence, these decision variables can draw a vivid picture of the corresponding quota and tax regimes.

2.4.4. Scenario formation

Fig. 4 illustrates the projected upper and lower bound for each aviation fuel up to 2050. The lower projected price for synthetic fuel and biofuel in Fig. 4-b and Fig. 4-c, respectively, indicates the lowest possible SAF price if considerable investment is allocated to SAF technology to make them compatible to kerosine. On the other hand, the upper bound indicates the scenario where minimal investment is allocated to SAFs. Fig. 4-a demonstrates the projected kerosine price under the relaxed and harsh carbon tax. The lower bound of kerosine price is the scenario that no taxes impose on the kerosine while the upper bound is the kerosine price under extreme tax regimes. The upper and lower limits for these fuels are adopted from (Becattini et al., 2021). In order to study the effect of each fuel's price scenario on the output of aviation industry model (CO_2 emissions and ticket price) and its respective optimal quota and tax regime, different combinations of the fuels scenarios are studied. This can help to capture the true impact of each fuel price on the optimal quota regime as well as the CO_2 emissions and ticket price. At the end in the optimal tax scenario, a freedom is given to the metaheuristic algorithm to choose the value of the carbon tax in *the optimal tax scenario* from the upper and lower bound of projected kerosine price up to 2050. The optimal tax scenario is also performed for different combination of biofuel and synthetic fuel projected price. The interesting observed phenomenon for the optimal tax scenarios is that the obtained optimal tax regime for all scenarios have the same shape but with different values. To elaborate, this is the most optimal tax regime that can be adopted for the transition to SAFs. This phenomenon will be discussed in more details in subsection 4.3.

2.5. The baseline scenario

The effect of the proposed drop-in fuel of the ReFuelEU-Aviation initiative (Commision and Transport, 2021) on Switzerland, if identical policy implications are conducted, is reflected by the EU Scenario.

3. Sensitivity analysis of the model

A sensitivity analysis of baseline scenarios is conducted for the two outputs of the system dynamics model: airline fares and the greenhouse gas emissions in 2030 and 2050. The percentage change of fares as a result of ±50% change of the key input parameters is illustrated in Fig. 2. As is shown in Fig. 2 the fares in 2050 have the highest sensitivity to the aircraft in use, followed by the fuel consumption and by the price for synthetic fuels. From 2030 to 2050, the sensitivity to the prices of synthetic fuels and biofuels significantly increased. In contrast, the sensitivity to the prices of conventional fuel decreased to zero. These changing sensitivities over time result from the share of sustainable fuels (i.e. synthetic fuels and biofuels) increasing the costs of fossil fuels over time.

The sensitivity of the aviation emission in 2030 and 2050 are shown in Fig. 3. Changes in the mitigation potential of synthetic fuels impact aviation emissions in 2050 the most, followed by changes in the mitigation potential of biofuels, the emission index, the fuel consumption, and the load factor. Similar to the sensitivity of airline fares, the impact of the two mitigation potentials of sustainable aviation fuels increases significantly over time due to the increased share of sustainable fuels. Compared to the airline fares, the aviation emission is more sensitive to the input data. Therefore, the improvement of the SAFs technologies has the highest impact on CO_2 mitigation.

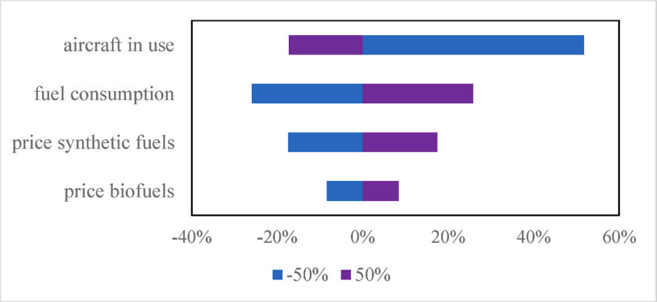


Fig. 2. Sensitivity of fares to key input data.

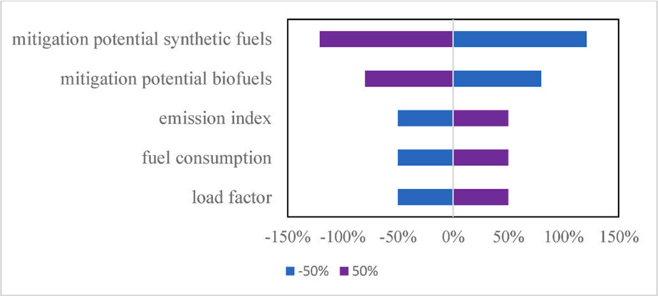


Fig. 3. Sensitivity of the CO_2 emission to key input data.

4. Results and discussion

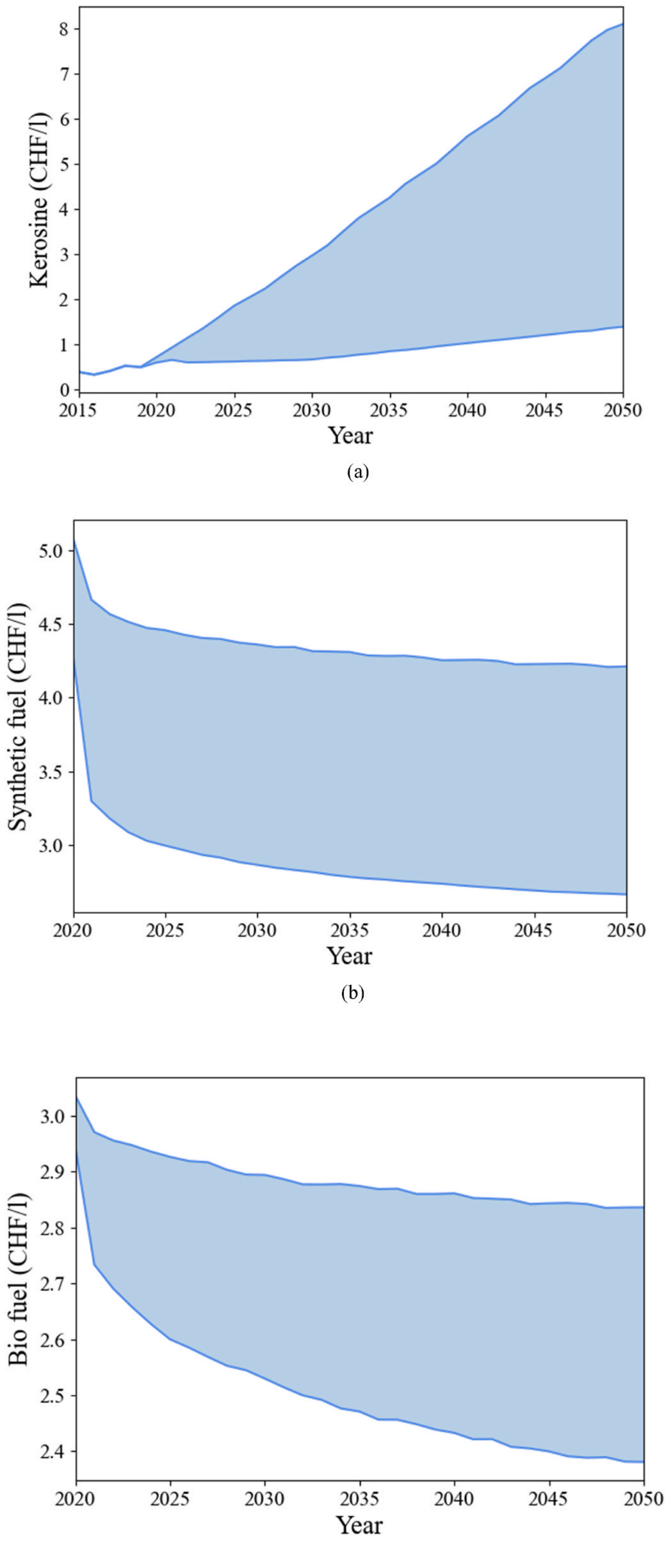
4.1. Optimization results

Decision variables in the current study are the synthetic fuel quota regime, biofuel quota regime, and tax on kerosine. The studied scenarios are developed around the upper limit and the lower limit of projected values for the price of biofuel, and synthetic fuel. The investigated scenarios are named based on the upper and lower limits (e.g., the lower limit of kerosine price-the lower limit of synthetic fuel-the lower limit of biofuel price [LConv LSyn LBio]). Different scenarios based on the upper and lower limits of SAFs are carried out to investigate the effect of convexity and concavity of quota regimes, separately. The goal of the meta-heuristic optimization is to find the optimum quota regimes for synthetic fuel and biofuel under different price scenarios. Another scenario is the optimal tax scenario in which the imposed tax on the kerosine is considered as another decision variable. In this scenario, both the optimal quota regime and the optimal tax regime are obtained. The results indicate that the calculated optimal tax regime shape is consistent for all possible SAFs prices in the future.

Furthermore, the sensitivity analysis of Pareto frontiers on the fuel prices is investigated. This can provide important information on the interdependencies of differing SAFs. In the present study, two different parameters are considered as objective functions, ticket price (CHF/seat*km) and CO_2 emission of the flights' departure from or entry to Switzerland.

It is worth mentioning that all the points on the Pareto frontier are optimal points. Hence, choosing different points from the Pareto frontier indicates different perspectives on the importance of objective functions. Therefore, choosing a point on the Pareto frontier is dependent on the decision-makers. A variety of Pareto optimal points provides the opportunity for decision-makers to strike balance between different objectives with different weighting systems. To elaborate, a decision-maker can decide to focus on the cost or environmental concerns or consider these two objectives at the same time with different weighting factors.

Fig. 5 indicates the obtained Pareto frontiers for Switzerland's aviation industry. As indicated the LConv LSyn LBio scenario has the closest Pareto front to the origin of the graph (utopia point). This demonstrates that with optimum quota regimes for synthetic fuel and biofuel (without having a significant tax regime) the CO_2 emission can be reduced by 20% to reach the value of 2.48 Mton. The comparison between the LConv LSyn LBio scenario and UConv LSyn LBio scenario reveals that with the most intense tax regime and optimal quota regimes the CO_2 emission is decreased to 2.13 Mton. This illustrates that the effect of optimum synthetic fuel and biofuel quota regime on the reduction of CO_2 is greater than the most intense taxes on the kerosine by a factor of 1.5. To elaborate the impact of imposing an optimal quota regime on CO_2 emission reduction is 1.5 times greater than any tax on the kerosine. On the other hand, the reduction in CO_2 emission by imposing an optimal quota regime without extreme taxes will lead to the increase of the ticket prices by 2% while the remaining 0.9 reduction due to the imposing of extreme taxation will increase the ticket prices by 7%. Also, the implementation of optimal quota regimes without extreme taxes increases the Pareto optimal front sensitivity to changes in ticket prices. As demonstrated in the LConv LSyn LBio scenario, the increase of the ticket price by one unit on the LConv LSyn LBio Pareto front leads to



(a)

(b)

(c)

Fig. 4. The upper and lower bond of kerosine, synthetic fuel, and biofuel prices up to 2050.

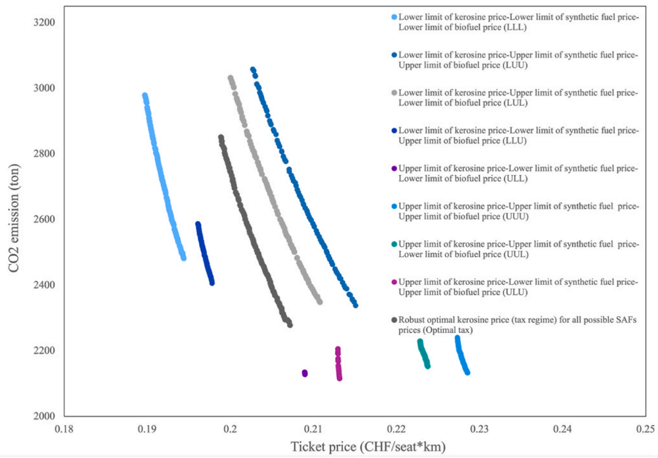


Fig. 5. Pareto optimal solutions for different scenarios. Each Pareto front is calculated based on the different projections of SAFs prices.[11]

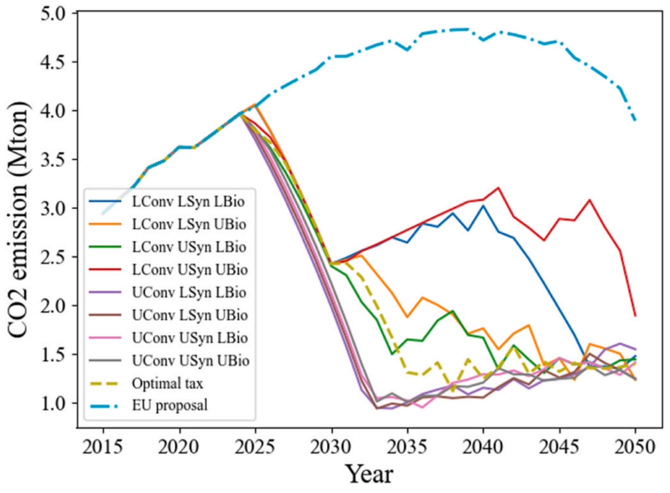


Fig. 6. Switzerland's aviation industry projected CO_2 emissions up to 2050 for different scenarios. Each CO2 emission projection is followed by a respective optimal quota and tax value and regimes.

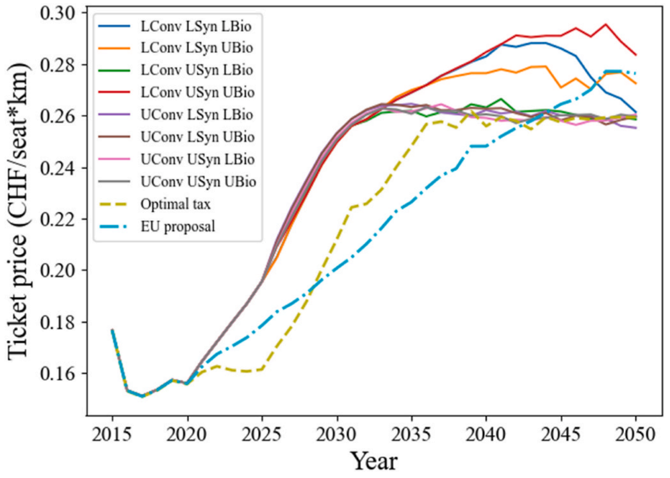


Fig. 7. Switzerland's aviation industry projected ticket prices up to 2050 for different scenarios. Each projected ticket price is derived from the respective optimal quota, the tax on kerosine, and the corresponding price regimes of the fuels.

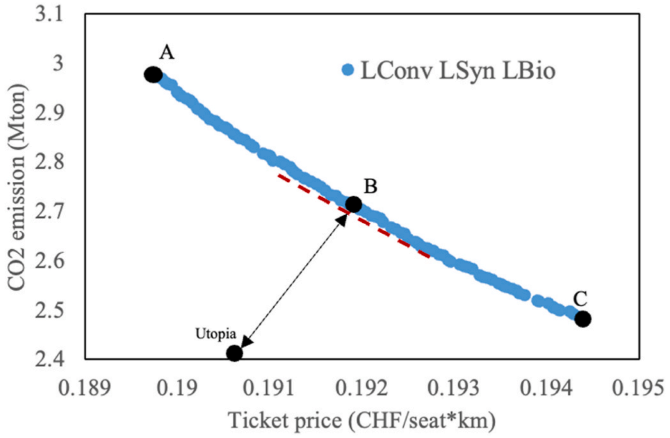


Fig. 8. The Pareto frontier of the LConv LSyn LBio scenario (alternative fuel-focused scenario)[21].

a much higher reduction in CO_2 emission in comparison with the UConv LSyn LBio scenario. The UConv USyn UBio scenario represents the scenario in which no investment is made in the alternative fuel, but the highest tax regime is imposed. This is the most expensive scenario as it is on the right of the graph while it has the same level of CO_2 emission as the UConv LSyn LBio scenario. The comparison between the UConv USyn UBio and UConv LSyn LBio scenarios reveals that in the case of the most intense taxes, investment in alternative fuels can reduce the price of tickets by 9%. Another important question is whether a priority should be given to investing in biofuels or synthetic fuels. The comparison between LConv USyn LBio and LConv LSyn UBio illustrates that with the same tax regime (weak taxes in the cases of LConv USyn LBio and LConv LSyn UBio), investment in biofuel should be prioritized as biofuel can decrease CO_2 emissions by 2.4%. In contrast, giving priority to investing in synthetic fuel can decrease the ticket price by 2%. With the same rationale, it can be seen that in the severe tax regime scenarios (UConv USyn LBio and UConv LSyn UBio), by giving priority to the synthetic fuel, both CO_2 emission and ticket price can be decreased by 1.7% and 4.4%, respectively. This reveals that investing in synthetic fuel is more beneficial than investing in biofuel under the intense tax regime. In the case of the relaxed tax regime, investing in synthetic fuel has a competitive advantage in terms of price reduction, while investing in biofuels can lead to higher CO_2 reduction. Of course, investing in just one of these alternative fuels is not the best option, and the important question is what combination of alternative fuels and what tax regime is the most optimum for the aviation industry. The optimal tax scenario proposes a tax regime as well as a biofuel and synthetic quota regime which lead to the most optimal CO_2 emission and ticket price. As is shown in Fig. 5 this scenario can reduce the CO_2 emission better than alternative fuel-focused scenarios (LConv LSyn LBio, LConv USyn UBio, LConv USyn LBio, LConv LSyn UBio), while also leading to cheaper ticket prices rather than tax-focused scenarios (UConv LSyn LBio, UConv USyn UBio, UConv USyn LBio, UConv LSyn UBio). Moreover, the Pareto front of the optimal tax scenario has an acceptable sensitivity to price, as a unit change in price leads to a substantial decrease in CO_2 emission. Although this sensitivity decreases in the higher ticket prices, it remains in an acceptable range. The CO_2 emission and ticket prices are projected up to 2050 in Fig. 6 and Fig. 7, respectively. As is shown in Figs. 6 and 7, although implementing intense tax regime scenarios (UConv LSyn LBio, UConv LSyn UBio, UConv USyn LBio, and UConv USyn UBio) can lead to drastic reductions in the first few years, the ticket prices will experience a rapid increase in these years. Furthermore, most of the other scenarios (including the optimal tax scenario) will reach the same amount of CO_2 emission in the later years. As is demonstrated in Fig. 6, all the proposed scenarios show a better reduction compared to the EU proposal. This clearly shows how an optimal quota regime for alternative fuels can improve CO_2 emission reduction. On the other hand, most of the proposed scenarios will reach the same amount of ticket price in the last years which is cheaper than the EU proposal. The optimal tax regime scenario shows an interesting behavior in both CO_2 emission and ticket prices. The CO_2 emission of the optimal tax scenario falls between that of the intense tax scenarios and alternative-fuel-focused scenarios. It also has a dramatically lower figure than the EU proposal. Although the ticket price will experience a higher increase rate from 2025 to 2035 in the optimal tax scenario, it reaches a stationary value in 2035 which is less than the final ticket price of the EU proposal. These two advantages of the optimal tax scenario make it much more suitable for the Swiss aviation industry in comparison to the EU proposal. The detailed alternative fuels quota, as well as the tax regime for the proposed scenario, will be discussed in the next subsections.

4.2. LConv LSyn LBio scenario

As is illustrated in Fig. 8, points A, B, and C represent three different perspectives for adopting a quota regime. Point A demonstrates a scenario that just focuses on the average ticket price. Although in this scenario (which can be considered as a single objective optimization) the increase of the ticket prices is at its lowest value, the average CO_2 emission is at its highest value. In contrast, to point A, point C represents a scenario in which the average CO_2 emission is at its lowest value and the increase of the ticket prices is at its highest value. As opposed to points A and C, point B represents a scenario in which both objectives are in equilibrium. Point B is the nearest point to the utopia point. The utopia point is an infeasible point that completely accomplishes both objectives. The slope of the Pareto frontier shows that the sensitivity of these two objectives is the same in the regions between A and B and between B and C. It can be inferred from this phenomenon that moving from point A to B requires the same effort as moving from point B to C. In other words, reaching the equilibrium from the least ticket price scenario is as difficult as reaching the least CO_2 emission. This illustrates a very stable behavior of the LConv LSyn LBio scenario. Decision variables (quota regimes for biofuels and synthetic fuels) for each perspective of the LConv LSyn LBio scenario are represented in Fig. 9.

Fig. 9 (a) and (b) show the optimal biofuel and synthetic fuel quota allocation from 2015 to 2050 under the least CO_2 emission perspective (point C). As is demonstrated for the least CO_2 emission perspective, the optimal biofuel quota regime shows a convex behavior with a slightly increasing slope after a fast pace linear increment from 2025 to 2030. On the other hand, synthetic fuel quotas show two concave parts. At the first concave part, the slope for the synthetic fuel quotas decreases at a constant pace up to 2038. In the second concave part, the slope decreases to rich zero and again increases. The value of quota in this part increases and then decreases. This is the part in which the alternative fuels quota gains equally 50% of the market share. The combination of these quotas is illustrated in Fig. 9 (c). Also, at this point, the prices of

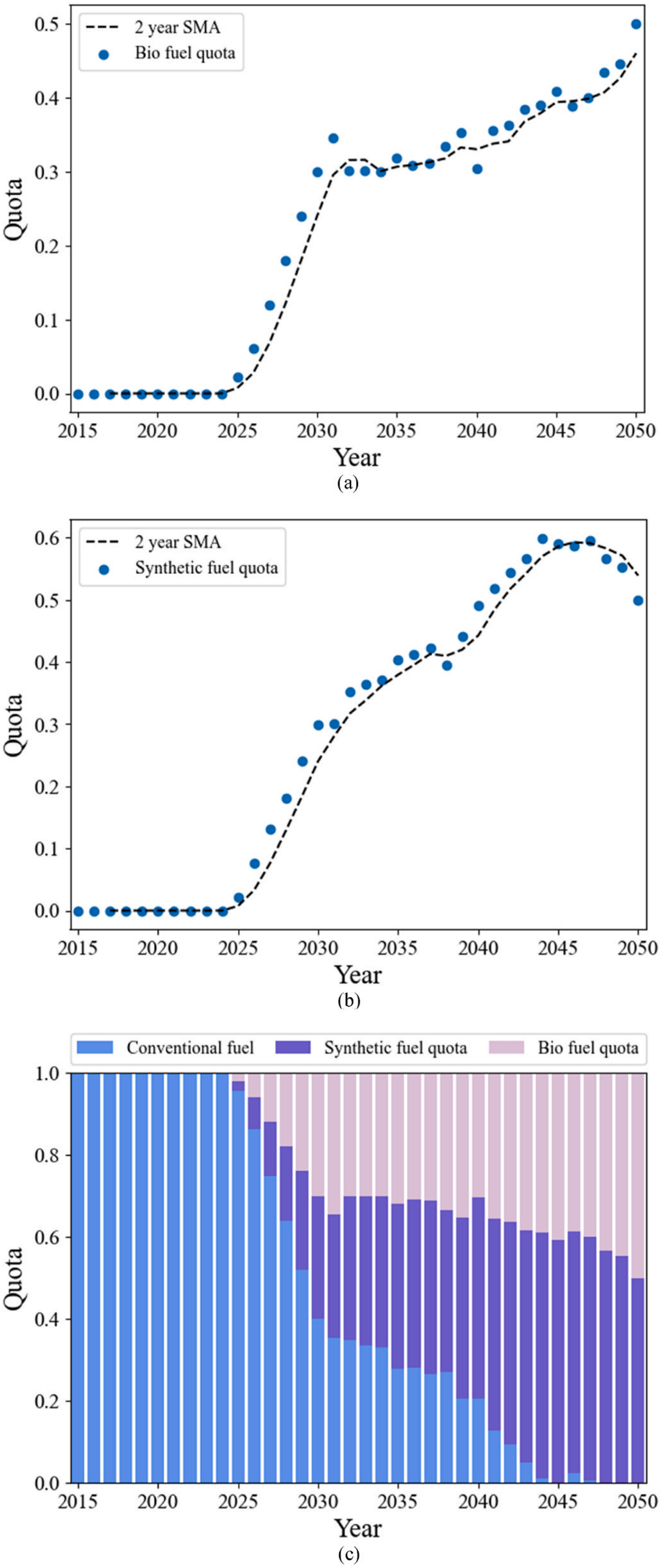
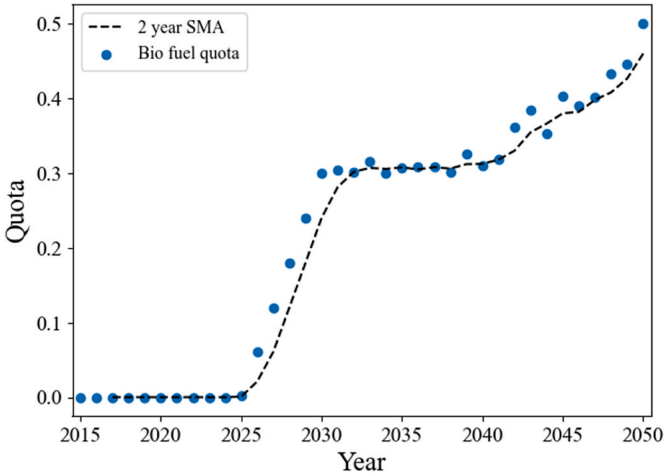


Fig. 9. The alternative quota regimes for the LConv LSyn LBio scenario (least CO_2 emission perspective).

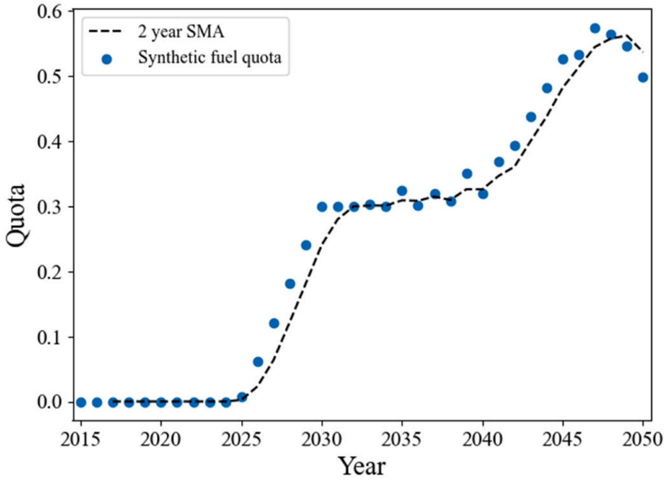
---

[2] As is discussed each point on the Pareto front is an optimal point and choosing one point from the Pareto front solely depends on decision-makers. Point A represents the least cost perspective of the LConv Lsyn Lbio scenario. At this point, however, CO2 emissions will also be greatest. Point C illustrates the perspective which leads to the lowest optimal value of CO2 emission. Point B, on the other hand, strikes balance between ticket prices and CO2 emissions. Choosing each point depends on the decision-makers if under the Lconv Lsyn Lbio scenario they want the lowest ticket price or the lowest CO2 emissions, or they want to take a strategy that considers both CO2 emission and ticket prices equally.

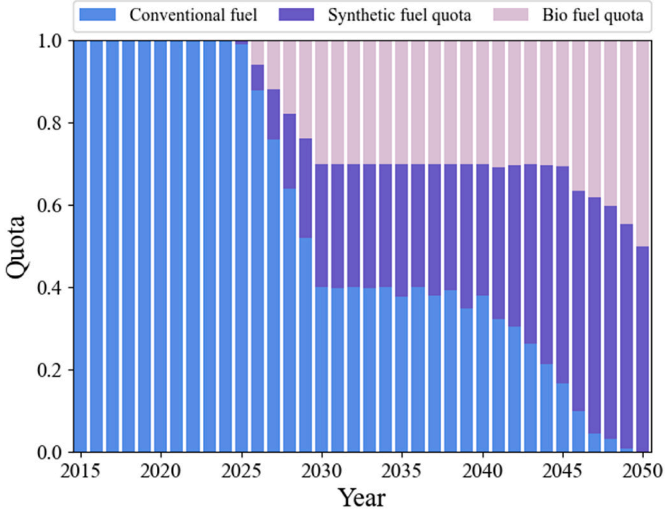
[2] As is discussed each point on the Pareto front is an optimal point and choosing one point from the Pareto front solely depends on decision-makers. Point A represents the least cost perspective of the LConv Lsyn Lbio scenario. At this point, however, CO2 emissions will also be greatest. Point C illustrates the perspective which leads to the lowest optimal value of CO2 emission. Point B, on the other hand, strikes balance between ticket prices and CO2 emissions. Choosing each point depends on the decision-makers if under the Lconv Lsyn Lbio scenario they want the lowest ticket price or the lowest CO2 emissions, or they want to take a strategy that considers both CO2 emission and ticket prices equally.



(a)

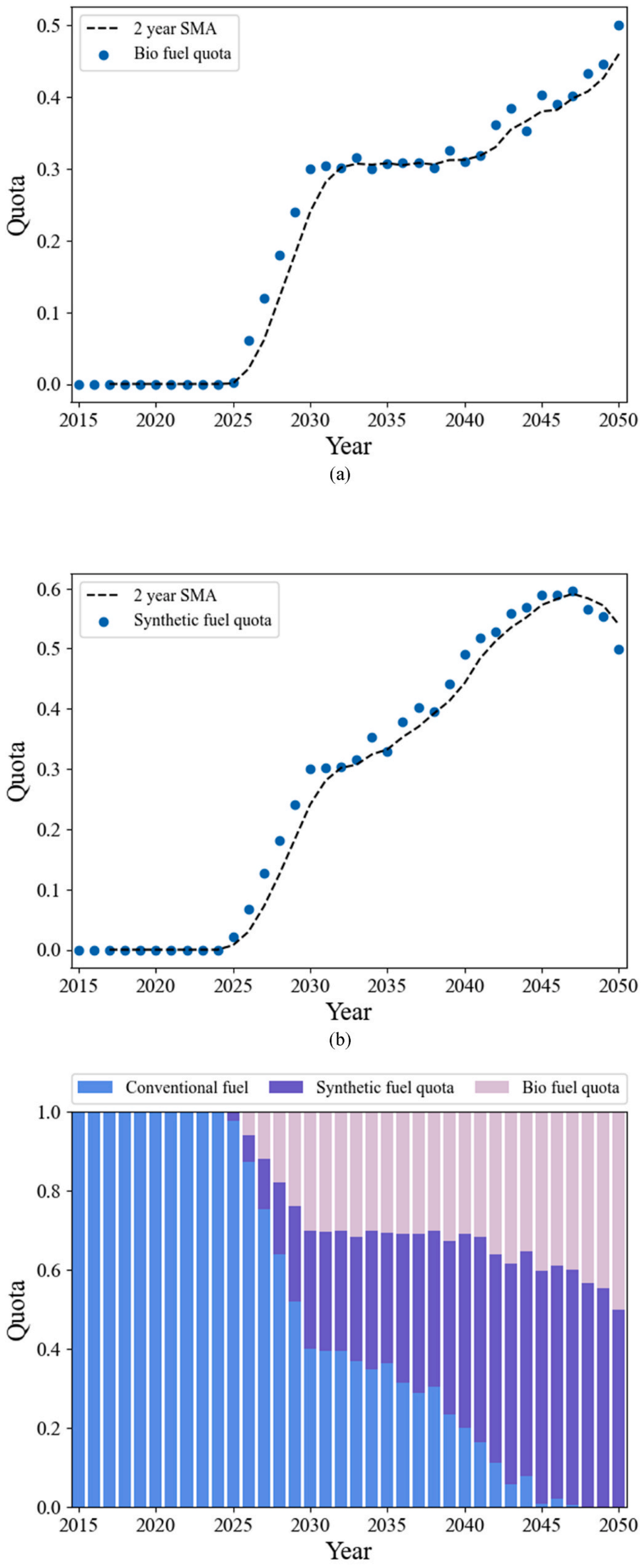


(b)



(c)

Fig. 10. The alternative quota regimes for the LConv LSyn LBio scenario (least cost perspective).



(a)

(b)

(c)

Fig. 11. The alternative quota regimes for the LConv LSyn LBio scenario (equilibrium perspective).

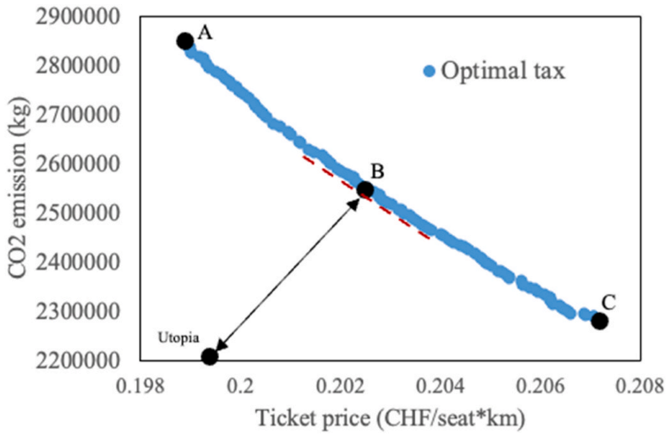
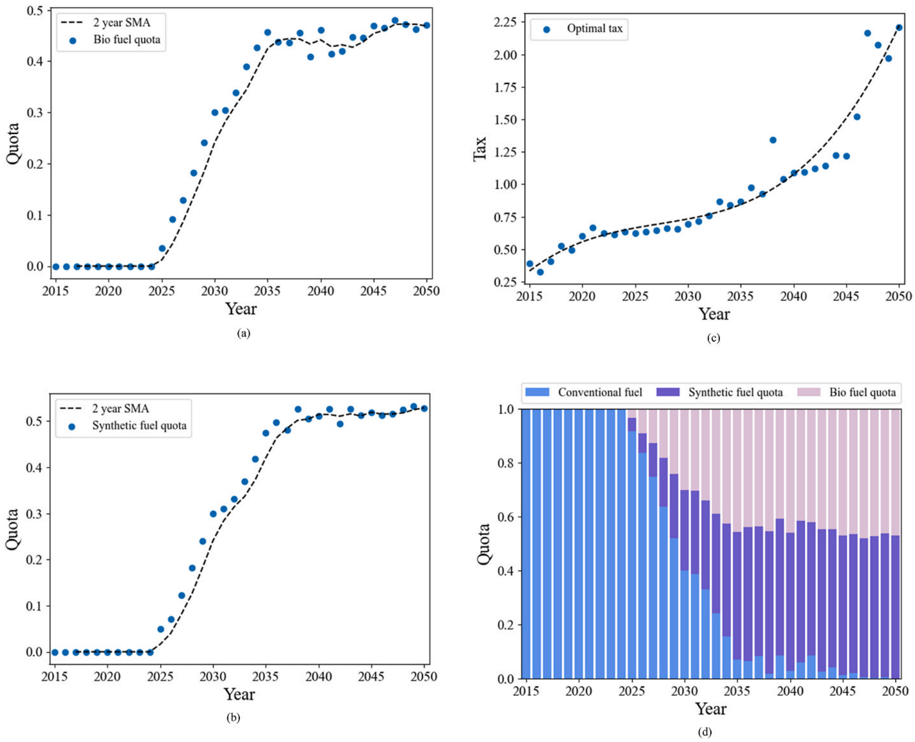


Fig. 12. The Pareto frontier of the optimal tax scenario.

synthetic fuels and biofuels reach a state where they can create a competitive market.

Fig. 10 shows optimal quota regimes under the least cost perspective (Pezalla, 2015). In this perspective, the biofuel optimal quota regime is consists three different parts. The first part illustrates a linear increase of the quota similar to the least CO_2 perspective. From 2030 to 2040 it remains roughly at the same value (0.3), and it starts to grow from 2040 by a convex (increasing slope) behavior. This time span in which the quota remains constant is hereafter referred to as *golden time*. The concept of golden time is always accompanied by a certain level of quota for alternative fuel which will be referred to as *golden value*. To elaborate, to have a considerable amount of CO_2 reduction, the quota regimes should reach a certain value. Keeping the quotas at this value can reduce the CO_2 emission considerably while the ticket prices do not experience a considerable change, even though the price of kerosine increases due to the taxes. Therefore, the Swiss aviation industry should endeavor to reach this value as soon as possible, as it is a milestone for CO_2 reduction. To summarize, when the intention is to minimize the ticket price as much possible in the case where considerable investment has been made in SAFs, the biofuel and synthetic fuel quota should consist of three parts: first, a concave part; second, a stationary part (golden time); and third, a convex part. This means that the aviation industry would meet the lowest possible ticket price if the implemented quota would be imposed fast with decreasing rate in the starting years (concave behavior) until it reaches a stationary point which quotas remain constant during the time for a specific time interval (golden time) and then quotas are imposed in a convex regime (increasing the rate of increment of SAFs quota) until the ending year. The ticket prices can be adjusted by the span of the golden time. Elongation or shortened golden time can be adjusted due to social and political responses to the proposed quota regimes as well as an airline's digestion rate. From the minimal CO_2 emission perspective, this golden time is zero. As a result, the social and political acceptance of such changes is high, and the airline industry digestion rate is fast enough to adopt the previous quota regime before 30% of drop in fuel quota. The shorter the golden time, the more intense the CO_2 emission reduction will be. Of course, the shape of the quota regime (concavity or convexity) after the golden value can show different perspectives and scenarios. The obtained optimal results show that the span of the golden time for the Swiss aviation industry cannot be more than 10 years. Fig. 9 (b) illustrates the synthetic fuels quota regime. After reaching the golden value (30%) for this perspective the quota regime emonstrates a convex behavior until it reaches its point and then decreases to approximately 50%. At the end of all the scenarios and perspectives, alternative fuels account the 100% of the market. The combination of these quotas is represented in Fig. 10 (c).

Fig. 11 illustrates the alternative fuels quota regimes for the equilibrium perspective (point B) of the LConv LSyn LBio scenario. As is



(a)

(c)

(b)

(d)

Fig. 13. The alternative quota and tax regimes for the optimal tax scenario (equilibrium perspective).

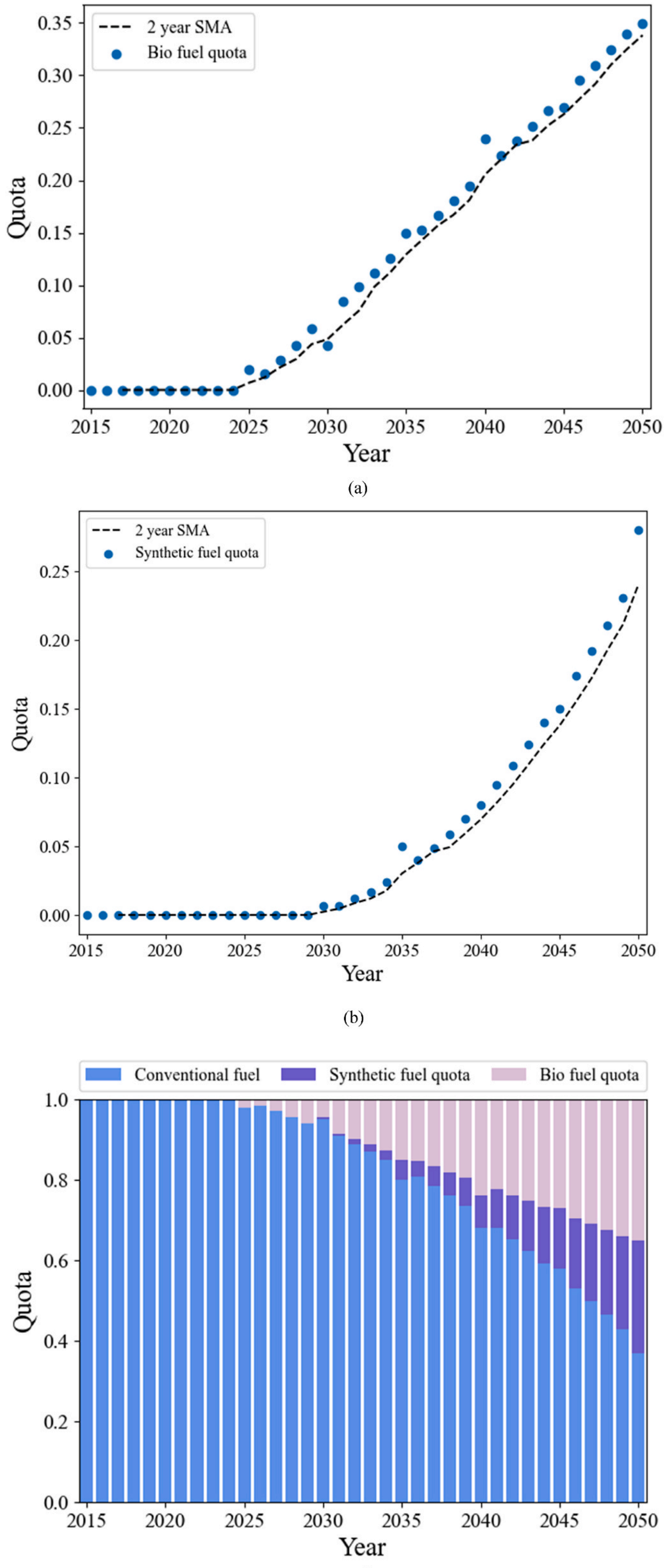
illustrated in Fig. 11 (a) and Fig. 11 (b) the equilibrium golden time for the Swiss aviation industry under the LConv LSyn LBio scenario is 7 years and 4 years for biofuels and synthetic fuels, respectively. The convexity of the synthetic fuels from this perspective is among the least cost and least CO_2 emission perspectives. Fig. 10 (c) shows the combination of the proposed quota for alternative fuels under the equilibrium perspective. A detailed description of the UConv USyn UBio scenario (Tax-focused scenario) can be found in Appendix II.

4.3. *Optimal tax scenario*

Fig. 12 demonstrates the Pareto frontier of the optimal tax scenario. The Pareto frontier of the optimal scenario shows a stable behavior for moving from A or C to B. This scenario is cheaper than all tax-focused scenarios while it can reach the lowest CO_2 emissions in comparison to alternative fuel-focused scenarios. Not only can the optimal tax scenario decrease the CO_2 emission dramatically in comparison to the EU proposal, it can also result in cheaper ticket prices. The alternative fuel quota and the optimal tax regime for the equilibrium perspective are illustrated in Fig. 13. It is worth mentioning that the obtained optimal tax regime (shape) for all perspectives are identical to each other. To elaborate, this is the most optimum tax regime that can be adopted for the transition to SAFs. Simultaneously, different alternative fuel quota regimes can be implemented for different CO_2 reduction and ticket prices scenarios. Additionally, the EU proposal for the SAFs quota is represented in Fig. 14. The golden time for this quota regime is from 2031 to 2037 (6 years) while the golden value is 0.44. The golden value of the optimal tax scenario is higher than the LConv LSyn LBio scenario (equilibrium perspective). This means for reaching the satisfactory level of CO_2 emissions and ticket prices for the optimal tax scenario, the level of 44% of the biofuel quota must be reached. Meanwhile, this value for the relaxed tax scenarios is only 30%. The increase of the biofuel quota, in contrast to the linear EU proposal, is concave and increases to a higher level. The higher share of the alternative fuels for Switzerland's aviation industry is a valid assumption as there is no limitation of production to cover the needs of Switzerland's aviation industry. Fig. 13 (b) demonstrates the synthetic fuel quota regime. The increase of the synthetic fuels quota regime is consisting of two concave parts. The increment rate of the share of synthetic fuels in the first part decreases between 2028 and 2031. The share of synthetic fuels then rises to 48% in 2036. This value then raises to roughly 50% in the following years. The golden time for this alternative jet fuel can be considered from 2036 to 2042 (6 years). The optimization results suggest that in contrast to the EU proposal (convex behavior), the synthetic fuels quota regime should instead follow a concave behavior for Switzerland. Fig. 13 (c) represents the optimal tax regime. As is shown, the optimal tax regime is consisting of a concave and convex part. In the first few years, it shows a concave behavior, and the rate of increase of the tax on the conventional fuel decreases. In the second part, the tax starts increasing under the convex behavior. As the SAFs obtain the majority of the market after 2047 in all scenarios, taxes will lose their influence on the ticket price and CO_2 emission. It is also worth mentioning that the highest kerosine price under the optimal tax price is about 2.25 CHF/l which is much less than the projected upper bond for the kerosine price (8 CHF/l). This shows the shape of the tax regime can leave a deeper impact rather than the values of the kerosine prices. Figs. 13 (d) and Fig. 14 (c) demonstrate the combinations of quota regimes for the optimal tax scenario and the EU proposal.

The results indicate that in the least CO_2 perspective, the share of the kerosine decreases faster. This decrease in the kerosine in the least cost scenario will be compensated by using biofuels which is a cheaper SAF.

The equilibrium perspective of the optimal tax scenario is more similar to the EU proposal in comparison to the least cost and the least CO_2 emission perspectives of the optimal tax scenario. However, optimization results suggest that the optimal increase of the biofuel (the cheaper SAFs) should be in concave form with a higher amount. On the other hand, the increase in synthetic fuels (the more expensive SAFs) should be concave with the lower rate of increment. It is worth mentioning that no restraints on capacity are present, which supports the enormous use of biofuels for the Swiss aviation industry. The ticket prices and CO_2 emission under each scenario for the equilibrium perspective for the flight from Zurich to Buenos Aires for one person



(a)

(b)

(c)

Fig. 14. The EU proposal for the alternative fuel quota regimes.

Table 1
The increment of ticket prices under different scenarios and equilibrium perspective for a flight from Zurich to Buenos Aires for one passenger (10% interest rate).

Scenario	Average increment of ticket price up to 2050 (CHF)	The increment of ticket price in 2050 in comparison to 2021 (CHF)
LConv LSyn LBio	17	32.5
UConv USyn UBio	25.5	30
Optimal tax	21	30
EU proposal	24	37

(~6500 km) are listed in Table 1.

5. Conclusion and policy implications

Airline fares differ significantly between scenarios. In some cases, prices may be nearly double that of other scenarios. When the fuel compositions of these scenarios are analyzed, a higher share of conventional fuel leads to higher airline fares. All optimization scenarios indicate lower airline fares than the EU and BAU scenarios in 2050. The results from the optimization emphasize the possible competition of SAFs with current aviation prices if production is upscaled. This is visible when airline fares of 2050 (0.27 CHF/seat*km) are compared with the fares of the optimized scenarios (0.24–0.25 CHF/seat*km). The implementation of the EU quota regime leads to a higher annual aviation emission in 2050, compared to optimized scenarios. Optimized scenarios show that net-zero pathways are possible and feasible with accurate policy intervention. The results illustrate that the most effective carbon tax regime consists of a concave and a convex region. Most of the scenarios have lower costs in the final years and all of them will lead to reduced emissions compared to the EU proposal. Therefore, it is suggested to neither implement no quota (BAU) nor the EU quotas. Instead, this study proposes several optimized quota regimes. Which one to use depends on policymakers' preferences (least costs, least CO_2 emissions, or equilibrium perspective). Also, the optimal tax scenario offers the most equitable quota and tax regimes for both customers and the aviation industry. The results indicate that the sooner the introduction of quotas, the better. Therefore, Switzerland can benefit from first-mover advantage by establishing a local SAF industry resulting in jobs, high profit through export opportunities for new technologies, and sustainable economic growth. Therefore, binding, long-term quotas are necessary regarding the risk for investors for these long-term investments in the production of SAF. In the present study, the concepts of *golden time* and *golden value* are proposed based on the optimized quota and tax regimes. Golden time is a time window in which keeping the quotas at the golden value can reduce CO_2 emissions considerably, while ticket prices do not experience a considerable change. The policy implication of the golden time and value implies that airlines can reach the lowest possible optimal price, in the case that notable investment has been made on SAFs, by imposing quota regimes under a concave, stationary, and convex setting, respectively. This means that quota increases with a decelerating pace in the first place, no quota change for a specific period, and finally quota increases with an accelerating pace would lead to the cheapest ticket price. Beside the demand pull through fuel quotas, the technology-push policies as R&D investments in the golden time period are highly recommended as they can decrease the CO_2 emission more effectively than intense taxes with lower prices. Investing in SAFs in this time window is the most cost-effective. This could additionally help create a local SAF industry, resulting in the economic benefits mentioned above. The prices for SAF, on the other hand, become cheaper than fossil fuels in 2050. In conclusion, a faster implementation of an optimized quota and tax regime based on the optimal tax scenario is strongly recommended for Switzerland. Additionally, policies should also focus on fostering the ramp-up of a local SAF production and introducing a carbon tax to benefit economically and financially from the implemented quota regime.

CRediT authorship contribution statement

Amir H. Keshavarzzadeh: Conceptualization, Optimization, Methodology, Visualization, Validation, Writing – original draft. **Caspar Thut:** Conceptualization, System dynamics, Data collection, Methodology, Visualization, Validation, Writing – original draft. **Daniel Andersen:** Conceptualization, Formal analysis, Data collection, Methodology, Visualization, Validation, Writing – original draft. **Levi Lingsch:** Writing – review & editing. **Anthony G. Patt:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgement

The authors acknowledge the use of the Euler Cluster and the advanced support from the High-Performance Computing group at ETH Zurich to carry out the research presented here.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2022.113263.

Nomenclature

AC	additional costs per available seat kilometers
AF	airline fares
ASK	available seat kilometers
AU	aircraft in use
AU	aircraft in use
DPS	average flight distance per seat
E^{ANN}	annual aviation emissions
FAC	fare change
FC	Total fuel costs per available seat kilometers
FC^{AF}	alternative fuel costs per available seat kilometers
FC^{CF}	conventional fuels costs per available seat kilometers
FC^{CF}	cost of conventional jet fuel
$FP^{Bio}(t)$	biofuel price
FP^{CF}	conventional fuels price
FP^{SYN}	synthetic fuel price
FU^{ANN}	annual fuel consumption
FU^{ANN}	annual fuel consumption
FU^{ASK}	fuel consumption per seat and kilometer
FUA^{ANN}	annual alternative fuel consumption
FUC^{ANN}	annual conventional fuel consumption
FUL^{ANN}	fuel consumption per kilometer
LF	load factor
MP^{Bio}	biofuel mitigation potential
MP^{SYN}	synthetic fuel mitigation potential
OM	actual operating margin
OC^{tot}	total operating costs
OM^{tar}	targeted operating margin
OR^{tot}	operating revenue
Q^{Bio}	biofuel quota
Q^{SYN}	synthetic fuel quota
UC	unit costs per available seat kilometer

Appendix I

Table. 1
The key input parameters for the Switzerland aviation industry

Name	Unit	Description and source
Aircraft in use	number of seats	The number of passengers in scheduled and charter air traffic in Switzerland (FSO. Zivilluftfahrt Übersicht, 2021) is divided by two to include only outgoing passengers. Additionally, this number was divided by the passenger load factor (see "Load Factor" below) to obtain the number of seats instead of passengers (Airlines for America, 2021).
Annual fuel consumption	liter/km	The annual fuel consumption of all Swiss airports in tons (FSO. Zivilluftfahrt Übersicht, 2021) is converted to liters. The total fuel consumption was divided by the average flight distance (see "Flight distance per seat" below).
Load factor		Load factor is defined as the used seat capacity or passenger load factor PLF. The worldwide factor from (Airlines for America, 2021) was used which we assumed to be similar to the Swiss factor because there were no data for Switzerland. In addition, the linear trend based on historical data would have overshot 100% before 2050 which is unrealistic. Therefore, we assumed that a PLF above 90% is not reached based on (Pezalla, 2015; Pande, 2021) and modified the prediction until 2050 accordingly.
Flight distance per seat	km/seat	The average flight distance per seat was obtained by multiplying the number of flights per region (i.e., Europe, Africa, Asia, Oceania, North America, Central America, South America) (FSO, 2019) by an average distance to this region (i.e., 700, 5700, 6500, 17,000, 8000, 9800, 10,200 km, respectively). This figure was divided by the number of flights to obtain the average kilometers per flight or seat.
Mitigation potential RFNBO		It is defined as the emission reduction of synthetic fuels compared to fossil fuels. According to Schmidt et al., (Schmidt and Weindorf, 2016) synthetic fuels produced with renewable electricity have a mitigation potential between 0.85 and 1 depending on the electricity mix. Assuming a rapidly increasing share of renewable electricity production and carbon capture for synthetic fuel production, the synthetic fuel mitigation factor of 1 was used.
Mitigation potential biofuels		It is defined as the emission reduction of biofuels compared to fossil fuels. According to Schmidt et al., (Schmidt and Weindorf, 2016), the mitigation potentials of biofuels range between [0.35–0.8]. For this study, the average potential (without land-use changes) derived from the study of Schmidt et al., (Schmidt and Weindorf, 2016) is used. Thus, a biofuel mitigation factor of 0.6184 is present.
Price conventional jet fuel	CHF/liter	The data for conventional fuel refers to the modeling results of Becattini (Becattini et al., 2021), which are given in Jet Fuel costs in €/liter. The prices were converted into CHF/liter with a factor of 1.11. There, a price range is defined for various scenarios (Becattini et al., 2021). In the present study, the upper and lower as well as optimal value is assumed. In addition to the base jet fuel price, a CO_2 tax (Becattini et al., 2021) is used from 2023. The tax has a value consistent with the price range required to meet the Paris Agreement temperature target (World Bank Group, 2019). The cost of the conventional fuel is considered one of the decision variables in the metaheuristic algorithm.
Price biofuel and synthetic fuel	CHF/liter	As a basis for the biofuel and synthetic fuel data, the modeling results of (Becattini et al., 2021) are used, which are given in Jet Fuel costs in €/liter. The prices were converted into CHF/liter with a factor of 1.11. In the present study, the upper and lower bound price is employed for different scenarios under a metaheuristic algorithm.

Appendix II

Fig. 1 demonstrates the Pareto frontier of the UConv USyn UBio scenario. The slope of the Pareto frontier shows that the sensitivity of the CO_2 emission and ticket price is higher among points A and B in comparison to optimal points between B and C. It can be inferred from this phenomenon that moving from point A to B under the intense tax regime is easier than from point B to C. In other words, under the intense tax regime reaching the equilibrium from the least ticket price scenario is easier than reaching the least CO_2 emission. Also, generally reaching a point with the least average ticket price and highest CO_2 emission is much easier than reaching a point with the least CO_2 emission and the highest ticket prices. This shows that the effect of taxes is not as influential as alternative quota regimes. Decision variables (quota regimes for biofuels and RFNBOs) for the equilibrium perspectives (point B) are represented in Fig. 2. As is discussed, this is the most expensive scenario, although the ability of the CO_2 reduction in this scenario is similar to other scenarios. As is shown in Fig. 2 (a) and (b), in this scenario the alternative fuel quotas will increase dramatically in the first years to the value of around 0.5; however, the synthetic fuel quota is decreasing, and the biofuel quota is increasing in the ending years. The quota regimes of alternative fuels illustrate that under this scenario and equilibrium perspective the golden time is reduced to zero. Alongside the fact that this is the most expensive scenario, the zero duration of golden time is one of the biggest drawbacks and the cause of why this scenario is the most expensive one. This means the research and development for alternative fuels cannot leave their impact properly on the lowering of ticket prices and the aviation industry does not have enough time to adapt to the changes. Furthermore, the rapid increase of the alternative fuel quotas in the first five years, from 2025 on, can impose a shock on the ticket prices and can be a source of social dissatisfaction.

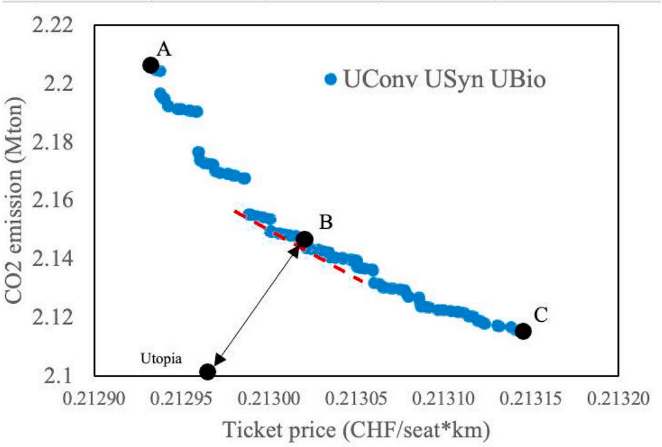
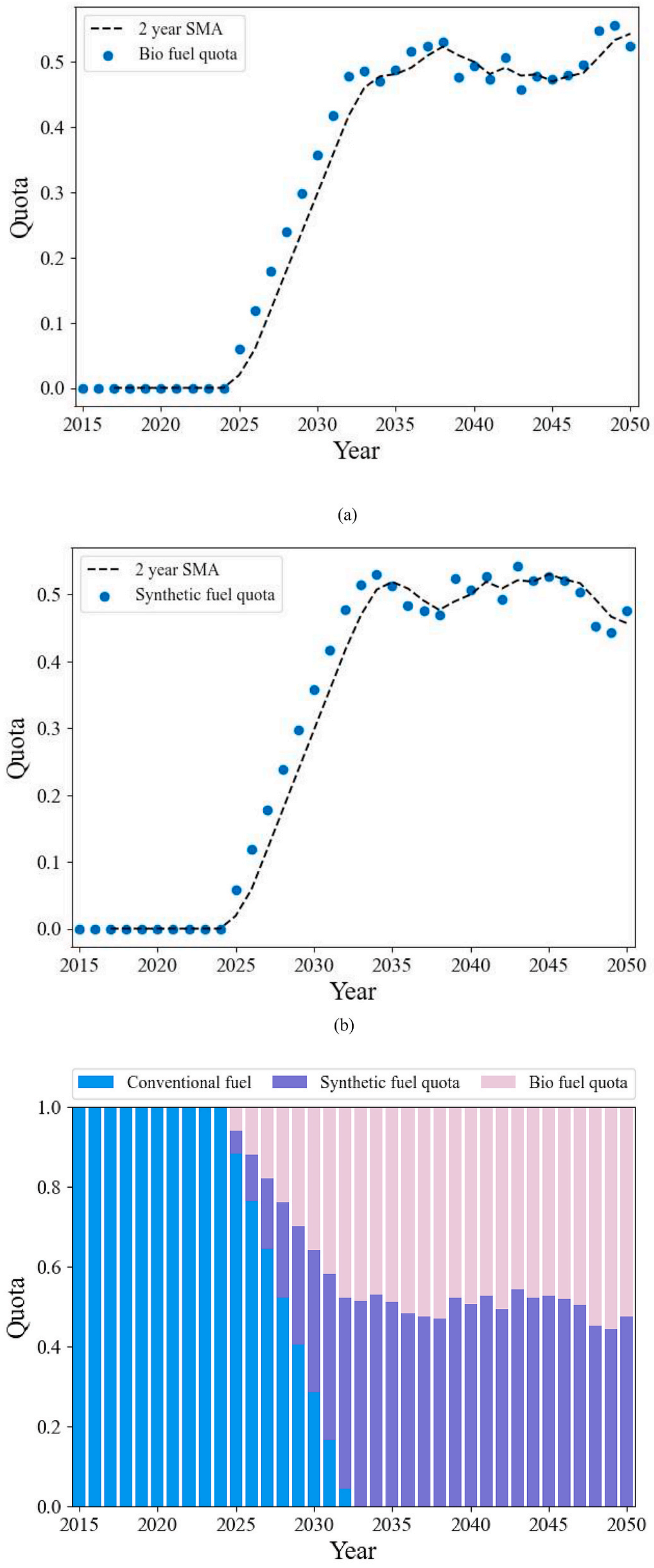


Fig. 1. The Pareto frontier of the UConv USyn UBio scenario (Tax-focused scenario)



(a)

(b)

(c)

Fig. 2. The alternative quota regimes for the UConv USyn UBio scenario (equilibrium perspective)

References

Airlines for America, 2021. World airlines traffic and capacity [cited 2021 11.28]; Available from: https://www.airlines.org/dataset/world-airlines-traffic-and-capacity-2/.

ASTM International, *ASTM D7566-18 Standard specification for aviation turbine fuels containing synthesized hydrocarbons.* 2018.

Becattini, V., Gabrielli, P., Mazzotti, M., 2021. Role of carbon capture, storage, and utilization to enable a net-zero-CO2-emissions aviation sector. Ind. Eng. Chem. Res. 60 (18), 6848–6862.

Becken, S., Mackey, B., 2017. What role for offsetting aviation greenhouse gas emissions in a deep-cut carbon world? J. Air Transport. Manag. 63, 71–83.

Brueckner, J.K., Zhang, A., 2010. Airline emission charges: effects on airfares, service quality, and aircraft design. Transp. Res. Part B Methodol. 44 (8), 960–971.

Carlos, A. Coello, Coello, G.B.L., Van Veldhuizen, David A., 2007. Evolutionary Algorithms for Solving Multi-Objective Problems. Springer, New York, NY.

Chiaramonti, D., 2019. Sustainable aviation fuels: the challenge of decarbonization. Energy Proc. 158, 1202–1207.

Commision, European, 2021. In: Transport, M.a. (Ed.), Proposal for a Regulation of the European Parliament and of the Council on Ensuring a Level Playing Field for Sustainable Air Transport. European Union, Brussels, p. 173.

Deb, K., et al., 2002. A fast and elitist multiobjective genetic algorithm: nsga-II. IEEE Trans. Evol. Comput. 6 (2), 182–197.

Detz, R., Reek, J., Van Der Zwaan, B., 2018. The future of solar fuels: when could they become competitive? Energy Environ. Sci. 11 (7), 1653–1669.

Ecoplan, Schweizer, *„Road Map Sustainable Aviation“*, 2021. Wege zu einer Dekarbonisierung des Flugverkehrs. Bern.

FSO, 2019. Passagiere im Luftverkehr - Linien- und Charterverkehr (Lokal- und Transferpassagiere) [cited 2021 11.28]; Available from: https://www.bfs.admin.ch/bfs/en/home/statistics/catalogues-databases/tables.assetdetail.8546344.html.

FSO. *Zivilluftfahrt Übersicht.* 2021 [cited 2021 11.28]; Available from: https://www.bfs.admin.ch/bfs/en/home/statistics/mobility-transport/cross-sectional-topics/civil-aviation.assetdetail.18564374.html.

González, R., Hosoda, E.B., 2016. Environmental impact of aircraft emissions and aviation fuel tax in Japan. J. Air Transport. Manag. 57, 234–240.

Hall, D., Pavlenko, N., Lutsey, N., 2018. Beyond Road Vehicles: Survey of Zero-Emission Technology Options across the Transport Sector. International Council on Clean Transportation Working Paper, p. 11.

Hamdani, T.M., et al., 2007. Multi-objective feature selection with NSGA II. In: Adaptive and Natural Computing Algorithms. Springer Berlin Heidelberg, Berlin, Heidelberg.

ICAO, 2021. CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels.

Jiang, C., Yang, H., 2021. Carbon tax or sustainable aviation fuel quota. Energy Econ. 103, 105570.

Kieckhäfer, K., et al., 2018. Simulation-based analysis of the potential of alternative fuels towards reducing CO2 emissions from aviation. Energies 11 (1), 186.

Martínez-Vargas, A., et al., 2016. Application of NSGA-II algorithm to the spectrum assignment problem in spectrum sharing networks. Appl. Soft Comput. 39, 188–198.

Mayor, K., Tol, R.S.J., 2007. The impact of the UK aviation tax on carbon dioxide emissions and visitor numbers. Transport Pol. 14 (6), 507–513.

Murugan, P., Kannan, S., Baskar, S., 2009. Application of NSGA-II algorithm to single-objective transmission constrained generation expansion planning. IEEE Trans. Power Syst. 24 (4), 1790–1797.

Neu, U., 2021. Die Auswirkungen der Flugverkehrsemissionen auf das Klima. Akademie der Naturwissenschaften Schweiz: Bern.

Neuling, U., Kaltschmitt, M., 2018. Techno-economic and environmental analysis of aviation biofuels. Fuel Process. Technol. 171, 54–69.

Norberg, P., 2014. Will a Quota Obligation Fly?.

Pande, P., 2021. What Is an Airlines Load Factor and Why Does it Matter? [cited 2021 12.2]; Available from: https://simpleflying.com/load-factor/.

Panoutsou, C., et al., 2021. Advanced biofuels to decarbonise European transport by 2030: markets, challenges, and policies that impact their successful market uptake. Energy Strategy Rev. 34, 100633.

Pezalla, C., 2015. 4 Reasons Airline Load Factors Will Never Reach 100 [cited 2021 12.2]; Available from: https://seekingalpha.com/article/3452476-4-reasons-airline-load-factors-will-never-reach-100-percent##comments.

Pierre-Selim, H., 2018. How Much Fuel Per Passenger an Aircraft Is Consuming? [cited 2021 12.2.]; Available from: https://blog.openairlines.com/how-much-fuel-per-passenger-an-aircraft-is-consuming.

Pierson, K., Sterman, J.D., 2013. Cyclical dynamics of airline industry earnings. Syst. Dynam. Rev. 29 (3), 129–156.

Scheelhaase, J., Maertens, S., Grimme, W., 2019. Synthetic fuels in aviation–Current barriers and potential political measures. Transport. Res. Procedia 43, 21–30.

Schmidt, P., Weindorf, W., 2016. Power-to-Liquids: Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel. German Environment Agency, Dessau-Roßlau.

Schmidt, P., et al., 2018. Power-to-Liquids as renewable fuel option for aviation: a review. Chem. Ing. Tech. 90 (1–2), 127–140.

Sterman, J., 2002. System Dynamics: Systems Thinking and Modeling for a Complex World.

Sterman, J.D., et al., 2007. Getting big too fast: strategic dynamics with increasing returns and bounded rationality. Manag. Sci. 53 (4), 683–696.

Vardon, D.R., et al., 2022. Realizing "Net-zero-carbon" Sustainable Aviation Fuel. Joule.

Wang, S., et al., 2019. Application of NSGA-II Algorithm for fault diagnosis in power system. Elec. Power Syst. Res. 175, 105893.

World Bank Group. *State and Trends of Carbon Pricing* 2019 [cited 2021 12.12]; Available from: https://openknowledge.worldbank.org/handle/10986/31755..