A cost-benefit analysis of all-electric flight
How to do a CBA for a non-existing technology?

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Abstract

Increasing climate ambitions mean that emissions of greenhouse gases, even from the aviation sector, must fall. The purpose of this study has been to contribute to this development by doing a benefit-cost analysis of all-electric aviation (AEA). We define AEA as battery-driven aviation without a combustion engine or fuel cell on board. Since the technology only exists in very small scale today, much of the work has been to find guestimates of the costs. However, we have been able to build on very good data on all take-offs and landings in Sweden year 2019. On the other hand, the data we have had on ticket prices is very poor. Based on the available data, we have estimated supply and demand functions for conventional flight in 2019. These estimates have been used to calculate the producer and consumer surpluses from flight, both in 2019, in the business-as-usual using sustainable aviation fuels (SAFs), and for AEAs, the latter two in 2030, 2040, and 2050, respectively. The results indicate that at least from 2040 onwards, with the introduction of larger aircraft with the capacity of up to 100 passengers and a range of 650 km, AEAs will be commercially viable on many, if not all routes studied. AEAs seem to have a higher producer surplus than conventional, SAF-driven aircraft. Since AEAs, at least in 2030 and 2040 are slower than conventional aircraft, the consumer surplus falls given fixed ticket prices. We also calculate the benefits from reduced high-altitude effects, which gives a measure of the societal benefits from AEA and thus an indication of how much public funds that could be invested in airport infrastructure for AEAs. We recommend that investments for AEA infrastructure start from a few airports and are expanded over time. The only further policy we recommend is R&D subsidies for AEA and battery technology development. No other policy instruments seem to be necessary to get AEAs to fly.

Keywords

All-electric aviation; benefit-cost analysis; regional flight; Sweden

JEL Codes

D61; D62; R41

Kort sammanfattning

Ökade klimatambitioner leder till att utsläppen av klimatgaser från flygsektorn på sikt måste minska. Syftet med denna studie har varit att göra en kostnads-nyttoanalys för helelektriskt flyg, som vi definierar som helt batteridrivet flyg utan någon förbränningsmotor eller bränslecell ombord. Eftersom teknologin ännu inte existerar annat än i mycket liten skala har en stor del av arbetet gått åt att uppskatta olika kostnader. Vi har kunnat utgå från data om alla starter och landningar till eller från Sverige under 2019, medan vi däremot har mycket bristfälliga data om biljettpriser. Baserat på de insamlade data har vi skattat en utbuds- och efterfrågefunktion för konventionellt flyg år 2019. Denna skattning har sedan använts för att räkna fram producent- och konsumentöverskott, både för konventionellt flyg som blandar in ökande andelar av biojet över tiden, och för elflyg. Producent- och konsumentöverskotten har räknats för åren 2030, 2040 och 2050. Resultaten tyder på att, åtminstone fr.o.m. 2040, när vi uppskattar att större flygplan med möjlighet att ta upp till 100 passagerare och som kan flyga 650 km, kommer elflyg att vara kommersiellt lönsamt på många, om än inte alla de studerade rutterna. Dessutom verkar elflyg bli mer lönsamt än konventionellt flyg som blandar in biojet. Eftersom elflygplanen tenderar att flyga långsammare än konventionella flygplan minskar dock konsumentöverskottet, givet fasta biljettpriser. Vi räknar även på samhällsnyttan från minskade höghöjdseffekter, vilka ger en uppfattning om möjligheter till att använda offentliga medel för att investera i den infrastruktur som behövs på flygplatserna. Vi rekommenderar att investeringarna börjar vid ett fåtal flygplatser för att sedan utökas allteftersom möjligheterna för elflyg realiseras i större utsträckning. För övrigt rekommenderar vi enbart FoU stöd till utvecklingen av elflyg och den batteriteknik som dessa är beroende av, då inga andra styrmedel verkar behövas för att få elflyg att flyga.

Nyckelord

Helelektriskt flyg, kostnads-nyttoanalys, regionalt flyg, Sverige.

Abstract

Increasing climate ambitions mean that emissions of greenhouse gases, even from the aviation sector, must fall. The purpose of this study has been to contribute to this development by doing a benefit-cost analysis of all-electric aviation (AEA). We define AEA as battery-driven aviation without a combustion engine or fuel cell on board. Since the technology only exists in very small scale today, much of the work has been to find guestimates of the costs. However, we have been able to build on very good data on all take-offs and landings in Sweden year 2019. On the other hand, the data we have had on ticket prices is very poor. Based on the available data, we have estimated supply and demand functions for conventional flight in 2019. These estimates have been used to calculate the producer and consumer surpluses from flight, both in 2019, in the business-as-usual using sustainable aviation fuels (SAFs), and for AEAs, the latter two in 2030, 2040, and 2050, respectively. The results indicate that at least from 2040 onwards, with the introduction of larger aircraft with the capacity of up to 100 passengers and a range of 650 km, AEAs will be commercially viable on many, if not all routes studied. AEAs seem to have a higher producer surplus than conventional, SAF-driven aircraft. Since AEAs, at least in 2030 and 2040 are slower than conventional aircraft, the consumer surplus falls given fixed ticket prices. We also calculate the benefits from reduced high-altitude effects, which gives a measure of the societal benefits from AEA and thus an indication of how much public funds that could be invested in airport infrastructure for AEAs. We recommend that investments for AEA infrastructure start from a few airports and are expanded over time. The only further policy we recommend is R&D subsidies for AEA and battery technology development. No other policy instruments seem to be necessary to get AEAs to fly.

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Förord

Denna rapport sammanfattar resultaten från projektet ” Regionalt elflyg – lönar det sig för samhället, och i så fall hur?” Projektet, som finansierats av Trafikverkets luftfartsportfölj, genomfördes mellan februari 2021 och februari 2023. Utvecklingen av helelektrifierat flyg är snabb, och förändringar i olika företags planer har förekommit under perioden som arbetet har pågått. Vi har trots detta försökt hålla analysen relevant, framför allt genom att luta oss mot existerande litteratur.

Vi tackar alla som bidragit till arbetet på ett eller annat sätt: projektets referensgrupp bestående av Gunnel Bångman, Trafikverket, Fredrik Kämpfe, Transportföretagen, Lennart Thörn, Transportanalys, Rémi Vesvre, Transportstyrelsen och Lars Westin, Umeå universitet har bidragit med värdefulla diskussioner och bakgrundsinformation. Lisa Björk hjälpte till i projektets början och Angelica Andersson har bidragit med diskussioner om matematik. Avslutningsvis tackar vi rapportens granskare Ida Kristoffersson samt forskningschef Jan-Erik Swärdh för värdefulla synpunkter och förslag. Alla kvarvarande fel är våra egna.

Stockholm, mars 2023

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Projektledare

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Ida Kristoffersson, VTI. De slutsatser och rekommendationer som uttrycks är författarens/författarnas egna och speglar inte nödvändigtvis myndigheten VTI:s uppfattning./The conclusions and recommendations in the report are those of the author(s) and do not necessarily reflect the views of VTI as a government agency.

Innehållsförteckning

1. Introduction

The European Union (EU) currently works on revising its goal for reducing the emissions of greenhouse gases, proposing a goal of a 55 percent reduction by 2030, compared to emissions in 2005 (European Commission, 2021). As a part of the package of reforms, the ReFuelEU Aviation-proposal stipulates shares of sustainable aviation fuels (SAFs) that have to be used. These targets have been set at five-year intervals from 2025 to 2050 (European Council, 2023). Moreover, the creation of new emission allowances within the EU's emission trading system (EU ETS) will be reduced faster than until now, increasing from a reduction of 2.2 percent yearly until 2024 to 4.2 percent per year from 2024 onwards. This has the consequence of reducing the number of emission allowances that will be created from 82 million ton CO_2-equivalents (mton CO_2-eq) to 43 million ton CO_2-eq. Besides, the emissions ceiling will be subject to a once-off reduction (National Institute of Economic Research, 2022). According to calculations by the National Institute of Economic Research (2022), this means that no new emission allowances will be created after 2040.

The aviation industry, which is included in the EU ETS, thus faces a tough future in Europe. SAFs are expensive, the synthetic aviation fuels (renewable fuels of non-biological origin, RFNBOs, in EU-parlance) being even more uncertain. An alternative, at least on short routes, could then be to electrify aviation.

The purpose of this study is to contribute towards the electrification of aviation by doing a cost-benefit analysis (CBA) of all-electric aviation (AEA), and to highlight the difficulties in doing a CBA for a technology that, at present, barely exists. By AEA we mean battery-driven aircraft. Generally, electrifying aviation may mean at least three different things: more electric aircraft, i.e., electrifying some presently mechanical functions in an airplane, hybrid electric aviation, or AEA, i.e., where stored electricity is used to drive an electric motor (Schefer, et al., 2020; Thapa, et al., 2021). For example, in Norway the definition of electric aviation is based on the type of engine: electric engines, and includes both batteries, fuel cells, and hybrid technology as means of generating propulsion energy. In hybrid electric planes, mechanical energy is transformed to electricity to drive the electric engine, which in turn converts the electricity again to mechanical energy, entailing considerable losses of energy at every transformation step. Nevertheless, they can contribute to a general effectivization of aviation (Rutherford, 2011). In this report we do not consider hybrids, the focus is solely on AEA: flights powered with a rechargeable or non-rechargeable battery. The approach that we choose excludes some innovative projects, e.g. Airbus ZEROe, which intends to burn hydrogen as aviation fuel (Airbus, 2020). Table 1 shows some on-going or previous (since 2021) AEA projects. The table excludes previous projects that were discontinued before 2021.

Table 1. Some on-going or known previous all-electric aviation projects.

NAME	YEAR OF INTRO-DUC-TION	PASSE-NGERS	RANGE, KM	CRUISE SPEED, KM/H	SPECI-FIC ENER-GY WH/KG	SOURCE(S)
Heart Aerospace ES-19	2026 (discontinued in Sept-22)	19	400	300	250	Johan Erlandsson, 26/04/2021, SvD 04/05/2021, Levandowski (2021)
Heart Aerospace ES-30 (Hybrid)	2028	30				Heart Aerospace (2023)

Bye Aerospace eFlyer 800	2026	7	926	519		Bye Aerospace (2021)
Wright Spirit	2026	100	605		750	Wright Electric (2021)
Zeroavia	2024	19	320			Zeroavia (2021)
Zeroavia	2026	76	900			Zeroavia (2021)
AEA-400		180	370		400	Gnadt et al (2019)
AEA-800	2050	180	926	915	800	Gnadt et al (2019)
AEA-1200		180	1482		1200	Gnadt et al (2019)
AEA-1600		180	2222		1600	Gnadt et al (2019)
AEA-2000		180	2778		2000	Gnadt et al (2019)

We study the possible benefits and costs of electrifying regional aviation within, and to and from Sweden, and not only include private costs and benefits to passengers and airlines, but also study the societal costs and benefits. To our knowledge, this is the first cost-benefit analysis done of AEAs, with the exception of a pre-study conducted by RISE (Apanasevic, et al., 2021). Traffic Analysis (2020) also conducted a partial analysis, identifying status quo for electric flight, and making some scenarios of possibilities for electrified routes. They also proposed some policy instruments that could speed up the development and ended their report with a conceptual analysis of the societal and other impacts of electrified flight.

Literature on electric and hybrid aviation mainly consists of market analyses and contains analyses both of AEA and hybrid aircraft. Prapotnik Brdnik et al., (2019) calculate, based on the connection between the aircraft mass and energy consumption, basic technical characteristics and limitations of hybrid and all-electric aircraft. Thereafter they discuss market demand for regional aircraft, aiming to recognize the possibilities for replacing conventional aircraft with AEAs and hybrid aircraft. In the final step, they quantify the emissions of hydrocarbons (HC), carbon monoxide (CO) and carbon dioxide (CO_2), and nitrous oxides (NO_X) from regional aircraft in Europe. Based on this calculation they assess the possible reduction in emissions to air from hybrid aircraft and AEAs. Baumeister et al., (2020) study the possibilities for first generation electric aircraft in Finland, and especially the emissions reduction potentials these would have. They compare the CO_2-eq emissions and real travel times from door-to-door on 47 routes with existing aircraft, train, and car transport modes as well as with proposed high-speed rail and electric vehicles. They find, among other, that existing cars should only be replaced by electric aircraft on routes beyond 170 km, and that existing trains under the current energy mix should not be replaced at all. Grimme et al., (2020) study the possibilities for revitalizing regional air services in Germany using a 19-seat hybrid aircraft. They find that regional air services operating from small airfields could create travel time benefits over car or train in several region-pairs. The problem is the high cost per available seat kilometer for small aircraft. They thus conclude that electrification alone, even with substantial future carbon prices and increasing jet fuel prices will most likely not lead to a large-scale re-vitalization of regional aviation unless future technologies cut costs. At present, crew costs raise the operating costs per available seat kilometer to a level that does not allow profitable operations.

Roy et al., (2021) compare airlines, automobiles and air taxis for regional mobility. They conclude that the level of autonomy of the vehicle and the ability to facilitate ridesharing are the two most important factors that affect the market attractiveness of regional air mobility. These findings are in line with those in Grimme et al., (2020), who also note that automation might be able to lower the costs enough for regional aviation to become profitable. Justin and Mavris (2022) investigate whether new technologies and concepts of operations would be sufficient to restart regional air mobility operations in the United States (US). They describe how underutilized regional airports might offer regional air services abroad state-of-the-art small size regional aircraft and quantify the demand for regional air mobility services in the entire US on a region-by-region basis. Given a 19-seat aircraft, they found 980 markets that could be served. As a control, they also introduced additional aircraft, a 9-seat AEA and a 30-seat hybrid-electric aircraft. Given the availability of these two aircraft, the market for the 19-seat aircraft was reduced considerably, and on most routes that could be flown by both the 9-seat and the 19-seat aircraft, the 9-seat aircraft often displaced the larger aircraft.

The analysis in this study is based on many assumptions that can be questioned: in order to analyse a technology that, at present, only exists in very small scale – the only type certified AEA is Pipistrel's Velis Electro, a two-seat school airplane (EASA, 2020) – we have had to make assumptions about the future technological development of AEAs with very scant information. A large part of the study has been gathering data: we have appreciated the capital costs of both AEAs and conventional aircraft, have found information about fuel and electricity prices and their expected development in the future, have assessed future possibilities to develop more energy dense batteries etc. Based on our assumptions about technical possibilities and existing airports and routes, we have picked out routes where it would be possible to substitute an AEA for a conventional airplane, in 2030, 2040, and 2050, respectively. We have even made a tentative appreciation of new routes and calculate the climate benefits from moving passengers from private cars to electric aircraft on these routes. Based on the overall picture, we then conduct a CBA, and conclude with some suggestions about possible policy instruments that could be used to bring forward the technology.

To reduce the greenhouse gas emissions from the aviation sector, many different technologies will likely be needed. Assessments made by Rolls-Royce and Avinor of Norway indicate that for short-haul (urban) transportation, AEAs are sufficient. They may also be sufficient for the short(est) regional routes. For longer regional routes, hybrid electric and/or fuel cells will be needed. For even longer regional, and long-haul routes, there may still be a need for hydrocarbons, however. Alternatively, sustainable aviation fuels (SAFs), such as jet biofuel and e-fuels (renewable fuels of non-biological origin, RFNOBs) can be used, or hydrogen as envisaged by Airbus (Airbus, 2020). Avinor's assessment is that hybrid electric/fuel cell aircraft will be on the market from 2030 onwards, or possibly even a bit earlier.

Since the present report concentrates on AEAs, it excludes long regional and long-haul flights. The longest route length considered is about 900 km and is estimated to be feasible first from 2050 onwards. To compare the costs and benefits arising from AEAs against an alternative, we use the EU's proposal for a SAF/e-fuel mandate from the ReFuelEU Aviation as the business-as-usual (BAU) base case, assuming that conventional aircraft will be flown with a mixture of fossil jet fuel on one hand and SAFs and RFNBOs on the other.

The report is organized as follows: In the next section, we will shortly discuss cost-benefit analysis methodology and the policy landscape in which decisions will be made. In section 3, we present the assumptions underlying the calculations, enumerating costs and benefits arising from AEAs and conventional aviation, and summarize our data. The results are presented in section 3.7, starting with a presentation of the regression results about the supply and demand of aviation, and then with calculations of producer- and consumer surplus, and the total surplus from AEAs and conventional aviation. The section ends with some sensitivity analyses. In section 5 we discuss external effects, above all the high-altitude effect, and have a short description of possible new routes. Section 6 summarizes the results, discusses the challenges encountered in doing a CBA for a technology that does not exist, and concludes the report.

2. Methodology

2.1. Cost-benefit analysis methodology

The cost-benefit methodology used in this study is based on the so called ASEK 7.0-report (Swedish Transport Administration, 2020). The ASEK-series of reports describes the underlying assumptions and models used for analyses conducted by the Swedish Transport Administration ahead of national transport infrastructure planning. That is, the report describes harmonized values and methodology to be used to assess the profitability, or lack thereof, of transport infrastructure investments.

The base year for prices in ASEK 7.0 is 2017. We will calculate these prices up to 2021 terms using the producer price index (PPI) obtained from Statistics Sweden. Prices obtained from other sources in US dollar terms will be counted up to 2021 terms using the PPI from the United States Department of Labor. Prices in ASEK 7.0 are expressed in Swedish krona (SEK), which will be converted to euros using the average exchange rate in 2021, namely 10.1449 SEK per EUR (Sveriges Riksbank). US dollars will be converted to euros using the average exchange rate in 2021, 1.1835 USD per EUR (European Central Bank).

In a cost-benefit analysis (CBA), benefits and costs of an action are weighed against each other and compared to some business-as-usual (BAU) or baseline option to determine whether it is worth the society's while to undertake an action. In this report, we do this by estimating a simultaneous equations model for supply and demand of airline seats and number of passengers, respectively. We estimate translog supply and demand functions of the form:

(1)
$$\begin{aligned}\ln(seats_{ij}) = {} & \alpha_s + \beta_1 \ln(r(ticket)_i) + \beta_2 \ln(r(ticket)_i)^2 + \beta_3 \ln(fees_{ij}) + \beta_4 \ln(fees_{ij})^2 \\ & + \beta_5 \ln\left(p(fuel_{ij})\right) + \beta_6 \ln\left(p(fuel_{ij})\right)^2 + \beta_7 \ln\left(w(pilot_{ij})\right) \\ & + \beta_8 \ln\left(w(pilot_{ij})\right)^2 + \beta_9 \ln(CAPEX) + \beta_{10} \ln(CAPEX)^2 \\ & + \beta_{11} \ln(r(ticket_i)) \ln(fees_{ij}) + \cdots + \epsilon_{ij}^d\end{aligned}$$

(2)
$$\begin{aligned}\ln(pax_{ij}) = {} & \alpha_d + \gamma_1 \ln(p(ticket)_i) + \gamma_2 \ln(p(ticket)_i)^2 + \gamma_3 \ln(ttime_{ij}) + \gamma_4 charter_{ij} \\ & + \gamma_5 \ln(catchment_{ij}) + \epsilon_{ij}^d.\end{aligned}$$

i denotes a route, i.e., an origin-destination pair, and j denotes the type of airplane used to run a specific route. A route i can be served by several different types of airplanes, j, or just one. The supply function, equation (1), contains interactions between all the included variables, of which the first one has been written out explicitly. Summary statistics for the variables is shown in **Fel! Hittar inte referenskälla.**. The sources of the different variables are explained in detail in Section 3, here we give short definitions.

Seats is the proxy for supply and denotes the total seats supplied per route and type of airplane in 2019 in one direction. *Pax* is its demand-side equivalent, the total number of passengers per route and type of airplane. We take natural logarithms of both.

Ticket prices per route were obtained from searches on Skyscanner on four different occasions: on November 19, 2021 for March 1, 2022, on November 26, 2021 for February 8, 2022, on December 13, 2021 for March 10, 2022, and finally, on May 30, 2022 for August 31, 2022. We picked at most the three cheapest fares per route on each occasion, depending on the number of airlines serving a route. The reason for only keeping the three cheapest airfares was the assumption that they reflect the marginal cost of providing the service. Higher prices charged, e.g., of business travelers contribute to the airlines' profits. The ticket prices are used to construct two variables: the average ticket price per route as such, $p(ticket)$, and revenue per seat $r(ticket) = p(ticket) \times pax/seats$.

Operating expenditure consists of four types: airport charges as exemplified in Table 11, $fees = airport\ fees \times number\ of\ flights/pax$, the fuel cost, $p(fuel) = 0.62 \times fuel\ use/(seats \times distance\ km)$, ETS allowance cost, which is included in the fuel cost, and pilot cost, $w(pilot) = pilot\ wage\ per\ flight \times number\ of\ flights/seats$, where the pilot wage per flight is constructed from the flying time as defined in section 3.3.2 times a fixed salary cost of 0.8 EUR per minute (Statista.com, 2022) times the number of pilots required. We do not include the cost of cabin crew in the calculations; this variable is highly correlated with the pilot cost since both are based on flying time. Finally, we do not have airport charge information for non-Swedish ("foreign") airports. For this reason, we include a dummy variable *foreign* that takes the value of one for non-Swedish airports and zero otherwise. *foreign* is interacted with *fees* to control for the missing data.

CAPEX is a composite of two (three for AEAs) types of capital expenditure: engine maintenance cost and the capital cost per annum, (the annualized battery replacement cost for AEAs, at three specific points: 2030, 2040, and 2050). The natural logarithms of capital expenditure and engine maintenance are highly correlated with one another, in excess of 0.9. The variables are described in Section 3.6. CAPEX is calculated as the sum of engine maintenance and capital cost divided by the number of seats. The natural logarithm of CAPEX is used in the regression analysis.

Travel time measures the flight time and is calculated from the distance as described in Section 3.3.2, the time ascending and descending, and the cruise speed of the aircraft, normalized for the number of passengers and the distance in km: $ttime = mean\ flytime/(pax \times distance\ km)$. *Charter* is an indicator variable taking the value of one if the flight is a chartered one or a taxi flight, and zero for scheduled flights. Finally, catchment area is the total number of passengers leaving from the origin airport in 2019 (Eurostat, 2022; Swedish Transport Agency, 2022), and is used to capture the different sizes of the different airports catchment area and consequently, different expected demand for flights: $catchment = total\ pax\ at\ an\ airport/pax$.

The results from estimating equations (1) and (2) are used to calculate the producer- and the consumer surplus (PS and CS, respectively). Usually, these are depicted as the triangle above a supply curve, $S(q)$, and under the equilibrium price, and below a demand curve, $D(q)$, and above the equilibrium price. However, we have estimated supply and demand as functions of the equilibrium price instead. For this reason, we integrate under the estimated supply, $S(r)$, and demand functions, $D(p)$, on the interval between the minimum and maximum revenue per seat and ticket price, respectively. This is illustrated by the shaded areas in Figure 1.

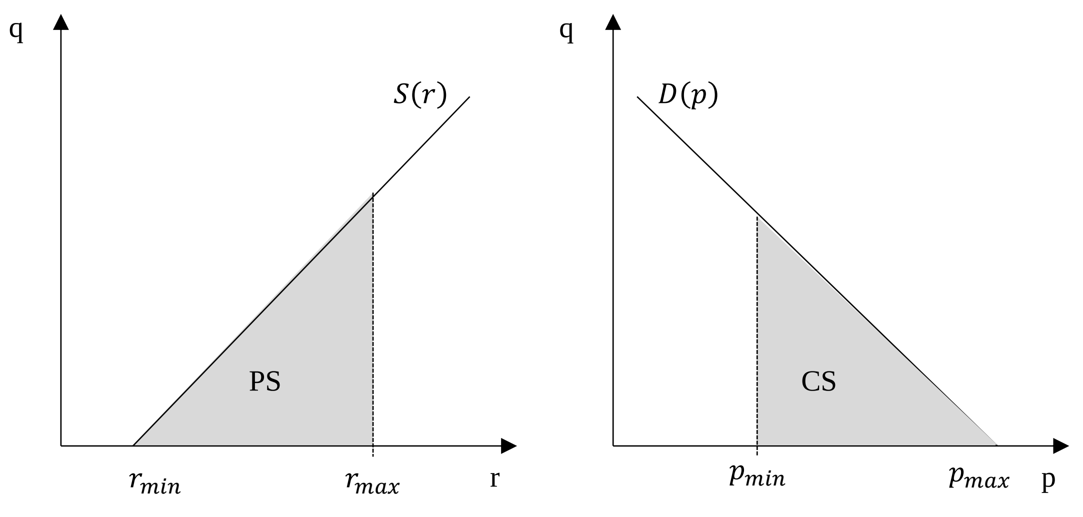


Figure 1. Producer surplus (PS) and consumer surplus (CS).

The final step of the analysis is to compare changes in PS and CS and the total surplus, which is the sum of PS and CS. We start by calculating PS and CS for 2019, the year from which the data used to estimate the supply and demand functions come from. In the next step we calculate the BAU PS and CS for conventional aircraft by using fuel price assumptions shown in Table 9, for the three years studied, 2030, 2040, and 2050, respectively. Thus, in the calculations of PS and CS for the baseline, the only thing that changes between 2019 and the three years is the fuel price. In the last stage of the analysis, we input values for AEAs into the formulae for PS and CS, and then compare these measures against their BAU values.

Where possible, we will use values from ASEK 7.0 (Swedish Transport Administration, 2020) to value effects. ASEK 7.0 does not contain information about AEAs, or, indeed, conventional airplanes, routes, expected fuel costs etc., however. These are covered in the next section, section 3. Before turning to the question of the costs, we will briefly describe the policy landscape in which the AEAs are introduced.

2.2. The policy landscape

The development of AEA until 2050 will be affected by various policies, already in place or presently under consideration. For the development of European aviation, the European Union emissions trading system (EU ETS) is important. As the European Commission (2021b) notes, the EU ETS covers 45 percent of EU greenhouse gas emissions, including those from aviation. The EU ETS for aviation is, at the time of writing (November 2021) subject to a new review in the light of the international developments related to the operationalization of the International Civil Aviation Organization’s (ICAO) framework for reducing greenhouse gas emissions from aviation, CORSIA. Would the EU ETS not be amended, aviation will fall out of EU ETS from 2024. For the purposes of this study, we assume that European aviation will be subject to the EU ETS even after 2024, and therefore, that the greenhouse gas emissions arising from the burning of aviation fuel face a carbon price equal to the EU ETS price for intra-European Economic Area (EEA) flights.

Another factor affecting the introduction of AEAs is the proposed SAF mandate for air transport (European Commission, 2021d). We assume that the proposed legislation is implemented as it is described by the Commission and calculate future emissions from conventional flight using the required levels of sustainable aviation fuels (SAFs), and also assuming the presence of EU ETS for the remaining fossil emissions.

Finally, there are some domestic (Swedish) taxes and fees on flight. We include the airport fees, including a fee on the emissions of NO_X, noise, and on the number of passengers in our calculations. However, we do not consider the carbon dioxide fee imposed on the state-owned Swedavia airports. There are three reasons for this omission: First, the fee is in fact a feebate system, which is revenue neutral to Swedavia. We have not been able to calculate the bonus and the malus parts of the fee at any level of accuracy, however. Secondly the fee only applies at two Swedish airports, Arlanda in Stockholm and Landvetter in Gothenburg. It is therefore of minor importance, at least in an international perspective. Thirdly, the climate externality arising from aviation is already internalized due to the inclusion of intra-EU flight in the EU ETS. Other omitted fees include fees such as parking fees for aircraft, since we are not able to assess the parking time for any aircraft, glycol handling charge, and fuel handling infrastructure charge. Again, the reason for the omission is a lack of information to include the fees.

We will not calculate the costs to the airport owners of, e.g., installing charging equipment for AEAs but assume that this cost is covered by the ordinary airport fees. Finally, we have no information of airport fees on foreign airports and consequently, these are omitted from the analysis.

3. Costs and benefits

3.1. All-electric airplanes, batteries and range

All-electric aviation (AEA) is in its infancy, and, at the time of writing (February 2023), the only type certified all-electric airplane (according to EASA.A.573 TCDS) is the Pipistrel Velis Electro, a plane optimized for pilot training and up to 50 minutes training missions. It has a maximum payload weight of 172 kg (Pipistrel, 2021). Instead of investing in AEAs, the large aircraft manufacturers, Airbus and Boeing, along with the largest engine-maker, Rolls-Royce, all intend to invest in hybrid technology or on hydrogen-powered aircraft, except possibly for all-electric urban air vehicles (electric vertical take-off and landing, eVTOL, vehicles) (Airbus, et al., 2021). The latter are not considered in this study. Moreover, the industry is in a very dynamic development phase, and changes occur frequently, e.g., in the plans of the Swedish Heart Aerospace, which has gone from producing a 19-seat AEA to a 30-seat hybrid with a back-up system in the form of two turbo generators powered by SAFs (Heart Aerospace, 2022).

The assumptions about AEA development used in this study are based on two sources. The first are known AEA projects under development in May 2022 and what is known of these: the Heart Aerospace's ES-19, Bye Aerospace's e-Flyer 800, and Wright Spirit. The known existing projects are listed in Table 1, including some information about these projects. The second is previous literature: both Grimme et al., (2020) and Justin and Mavris (2022) analyze 19-seat AEAs, and Gnadt et al. (2019) develop a design concept for a series of optimized 180-passenger aircraft based on the Airbus A320neo configuration. They study the properties of five different configurations with specific energy of the battery pack varying from 400 to 2000 Wh/kg, with 400 Wh/kg increments. Gnadt et al note, however, that the 400 Wh/kg configuration did not converge in the simulations, and Wright Electric (2021, p. 9) notes that 750 Wh/kg is "considered the mass specific energy at which electric single-aisle aircraft such as the A320 become viable."

The on-going projects can be used to make educated guesses about the state-of-the-art to 2030. For an estimate beyond that, we need an estimate of probable battery development over time. Historical development of batteries, from the introduction of lithium-ion (Li-ion) batteries in 1991 to the present day and a prognosis to 2026 is shown in Figure 2.

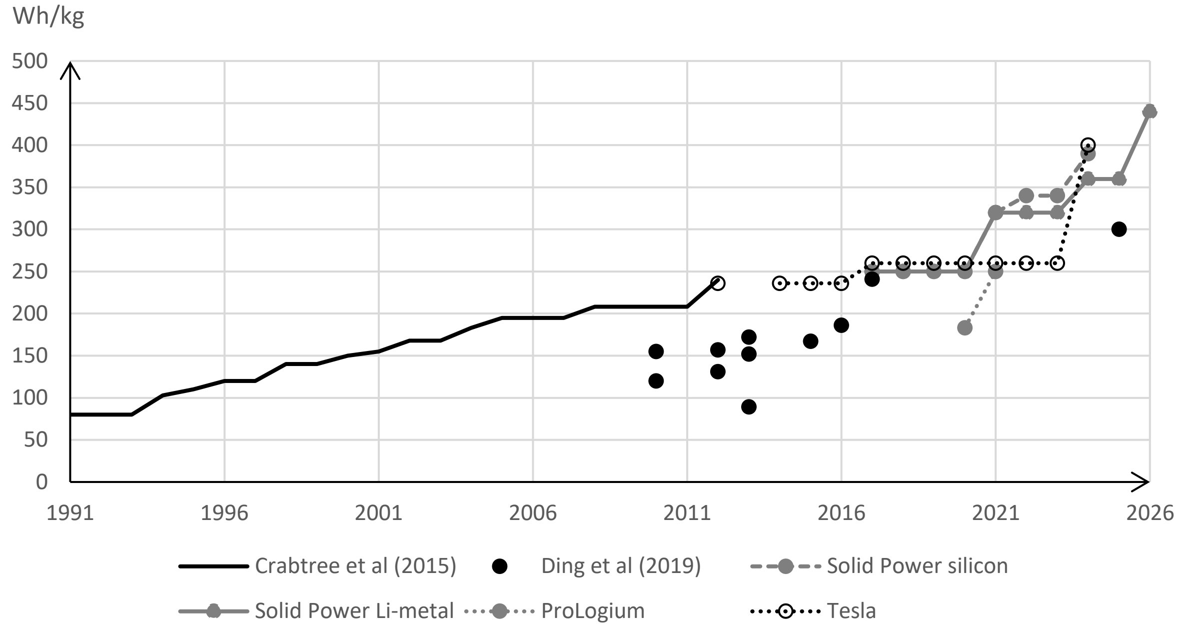
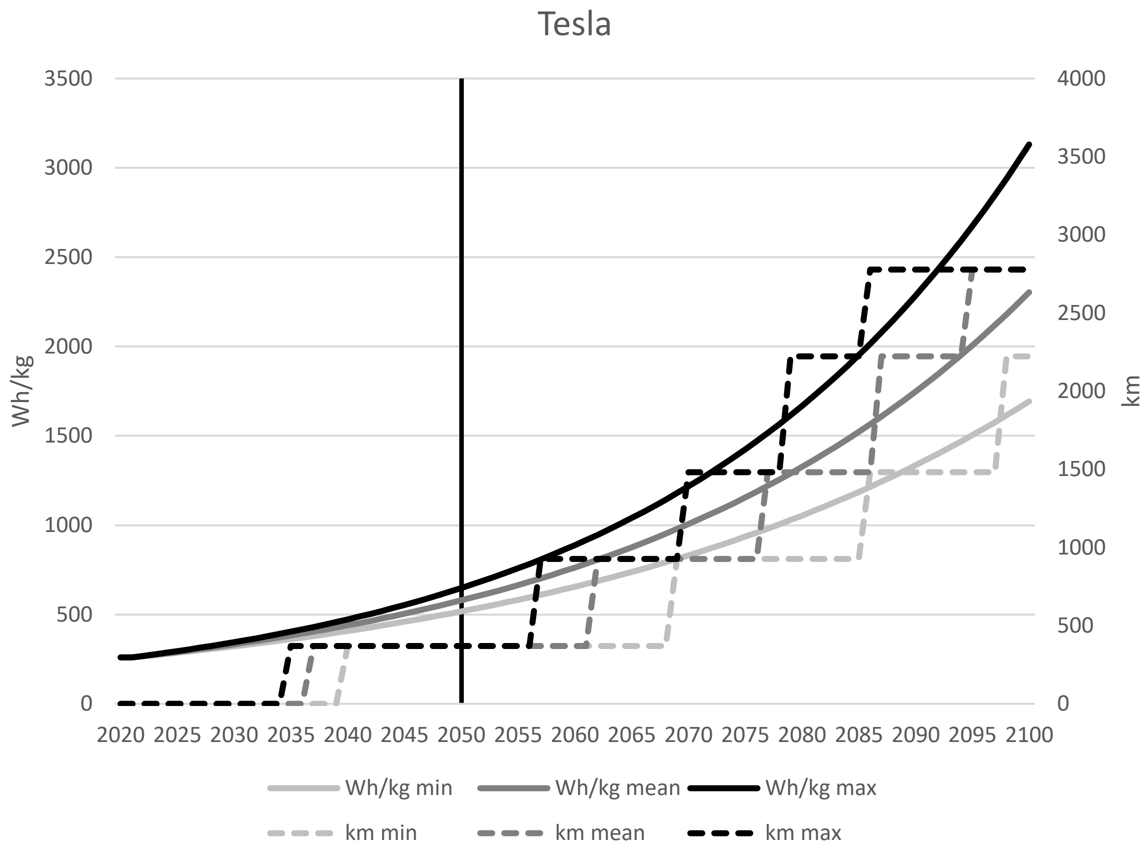


Figure 2. Development of battery technology, in Wh/kg, from 1991 to an estimate of 2026. Sources: Crabtree et al. (2015), Ding et al. (2019), Solid Power (2021), ProLogium (2021).

Taking the state-of-the art in battery development in 2020 as a starting point, we use the values for Tesla and Solid Power batteries as two possible starting points. Then we combine the aircraft configurations from Gnadt et al. with historical rates of battery development from Koh and Magee (2008) to calculate the possible range of a 180-seat airliner based on Airbus 320neo configuration. The combination of estimated battery development, using the minimum, mean, and maximum rates of technological development from Koh and Magee, and the range this yields according to Gnadt et al. is shown in Figure 3 for two starting values of battery development: Tesla's 260 Wh/kg in 2020 and 2021, and Solid Power's 250 Wh/kg in 2020 and 320 Wh/kg in 2021. The figure does not consider possible physical limits in Wh/kg that may exist for battery development.



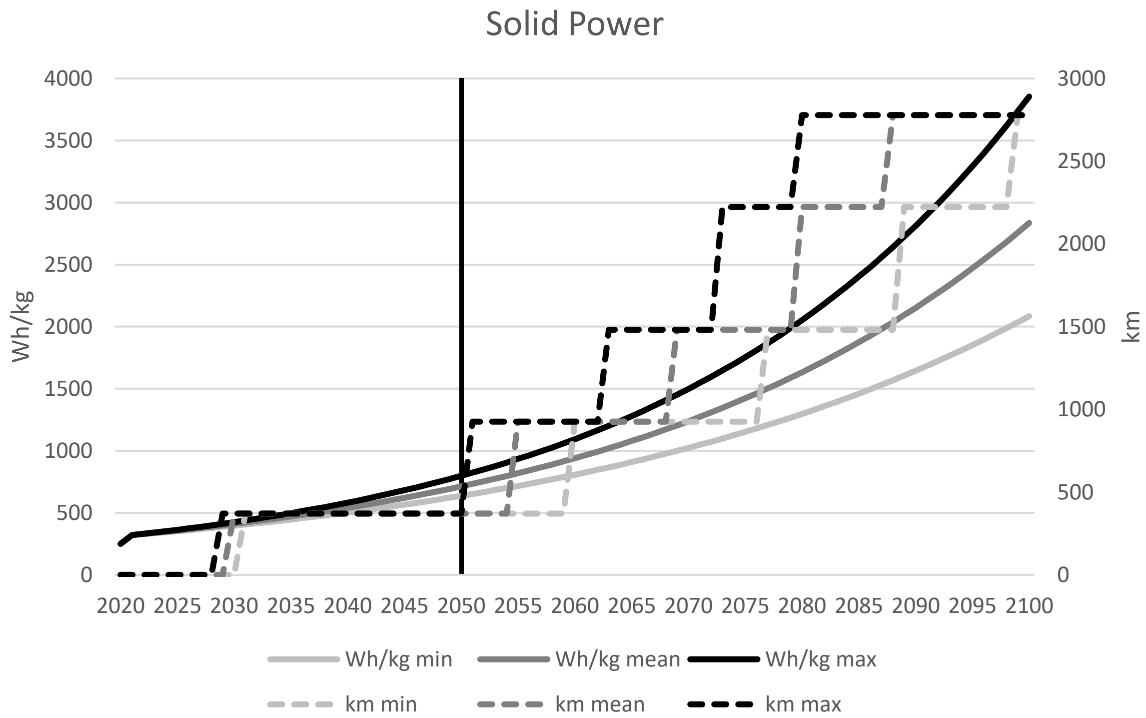


Figure 3. Two scenarios for the development of batteries, based on the extrapolated energy storage density from Tesla (260 Wh/kg in 2020) and Solid Power (250 Wh/kg in 2020, 320 Wh/kg in 2021 using technological development trends from Koh and Magee (2008), on the left-hand axis. On the right-hand axis, the flying range of a 180-seat aircraft depending on the available energy density, based on Gnadt et al. (2019). Years from 2020 to 2100. 2050 has been marked with a vertical line.

A final question that must be considered is the continuous cost of batteries: how often the batteries will have to be replaced, and at what cost? According to Christoffer Levandowski (2021), the innovation chief at Heart Aerospace, they count on the batteries of their then-planned ES-19 to be changed every two years, which is the approximation we will use.

Figure 4 shows a prognosis for battery price development in EUR per kilowatt hour up to 2050 on the right-hand axis, and the discounted biannual investment cost on batteries for the three types of aircraft under study. The battery replacement costs were calculated using cost estimates presented by Mauler et al., (2021). In doing this we assume a constant battery size, i.e., that aircraft will not be fitted with more powerful batteries as time goes by, and that its energy needs are constant over time. The battery annuity is calculated assuming that the aircraft available in 2030 has 8 batteries, that available in 2040 has 23 (the average between the two extremes) batteries, and the AEA-800 has 39 batteries of 1,260 kg each, the total weight of batteries in the plane being 48.7 thousand kilograms according to Gnadt et al., (2019). From 2050 onwards we have kept the cost of batteries constant at their 2050 level in EUR/kWh, for lack of better information.

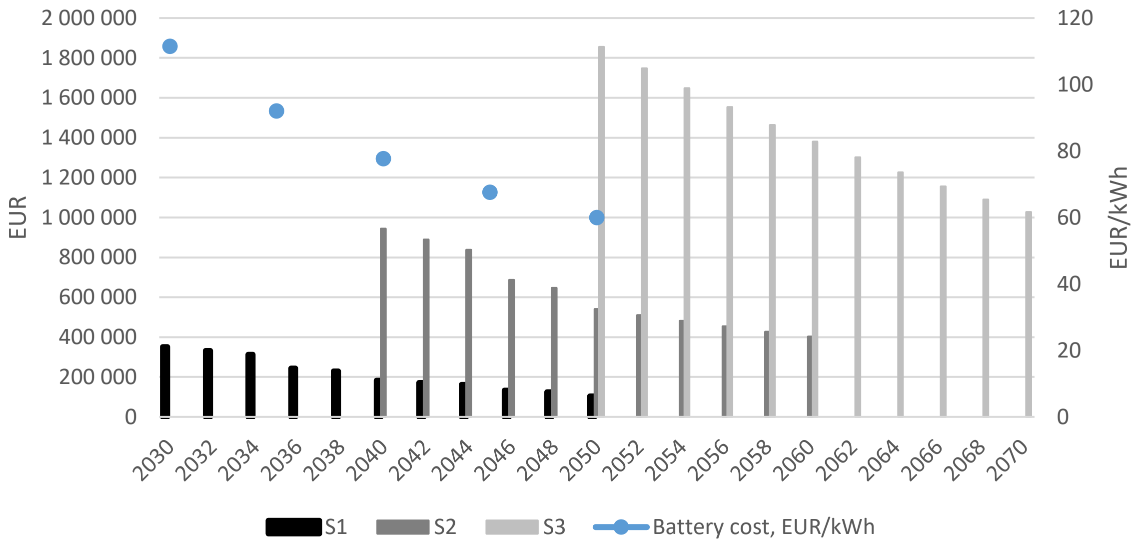


Figure 4. A prognosis for the development of battery prices in EUR/kWh (right axis), and the annual cost of battery change (left axis) for three types of AEAs: S1 is assumed to be available in 2030, S2 in 2040, and S3 in 2050 (see Table 4 below). Source: Mauler et al. (2021), own calculations.

3.2. Conventional airplanes, fuel efficiency and SAF use

In order to calculate the benefits from reduced emissions of greenhouse gases, NO_X, CO, HC, smoke, non-volatile particulate matter (nvPM), and noise, and changes in fuel cost due to the introduction of AEAs, we need information about the conventional airplanes that AEAs replace. The data comes from several sources. From the Swedish Transport Agency, we have obtained a data set containing all flights to and from Swedish airports 2019. For each flight the data includes information on takeoff airport, landing airport, type of aircraft, registered number of seats, date, time, type of flight (regular traffic, charter, air taxi, postal), and number of passengers. In total we have information of a close to 380,000 flights covering almost 38 million passengers.

For aircraft carbon dioxide emissions, we use information from the Master emissions calculator 2019 and the LTO emissions calculator 2019 (European Environment Agency, 2019). These are developed and released along with the EMEP/EEA air pollutant emission inventory guidebook and can be used by EU members to establish national inventory reports.[1] Information about the emissions of NO_X, HC; CO, smoke, and nvPM from different engines, fuel flow, the number of engines, MTOW, and noise levels was obtained from EASA (2022). Of particular use have been the EASA/ICAO Aircraft Engine Emissions Databank and the EASA Certification Noise Levels.

Information from the European databases was complemented by publicly available sources on the Internet to find information about common engine types, the price of different airplanes, number of crew, and in some cases, maximum take-off weight (MTOW).[2] Given the large number of the types of airplanes in use (112 in total), the data is not complete, and for 40 airplane types used on only one or two routes, we have not collected any data at all. Table 2 summarizes some information for the five most used types of airplanes.

Table 2. Characteristics of the five types of airplanes most used on the routes considered in this study. Emission figures pertain to the landing-and-take-off cycle, noise is the cumulative noise level from lateral, flyover and approach.

ICAO-CODE	NAME	ENGINE	# EN-GINES	MTOW TON	NO_X KG	CO KG	HC G	NVPM MG	NOISE EPNDB
B738	Boeing 737-800	CFM56-7B27	2	75	10.6	5.4	337	11.9	275.3
A320	Airbus A320	IAE V2500 or CFM56-5B	2	73	10.4	6.4	690	9.6	272.3
AT76	Aerospatiale / Alenia ATR 72-600	PW127M, PW127N or PW814GA	2	23	6.3	1.6	6	1.0	254.9
B737	Boeing 737-700	CFM56-7B20/22/24/26/27	2	66	9.4	6.0	474	9.3	272.3
CRJ9	Canadair Regional Jet 900/ Bombardier CRJ 900	CF34-8C5	2	36	4.6	2.1	18	2.5	264.6

In order to estimate fuel-use up until 2050 we will have to take two things into consideration. The first is the increase in fuel efficiency in conventional aircraft. We follow Rutherford (2011), and calculate that fuel use will even in the future fall by 0.2 percent per year on seat kilometre basis (0.3 percent in ton-kilometre basis). Secondly, we assume that the use of SAFs develops in the way set out by the European Commission (2021d), Annex I, and shown in Table 3.

[1] Sweden uses a system developed by the Swedish Defence Research Agency based on calculations with PIANO (Project Interactive ANalysis and Optimization).

[2] The most used sources are www.aerocorner.com, www.flugzeuginfo.net, and Wikipedia.

Table 3. Volume shares of sustainable aviation fuels (SAFs) required by the proposed EU legislation. Source: European Commission (2021d), Annex I.

FROM 1 JANUARY OF YEAR	A MINIMUM SHARE OF SAF, PERCENT	BIO-BASED SAFS	SYNTHETIC AVIATION FUELS (RFNBOS)[3]
2025	2	2	
2030	5	4,3	0,7
2035	20	15	5
2040	32	24	8
2045	38	27	11
2050	63	35	28

3.3. Routes

Given the information in Section 3.1, based on existing routes and data of these from the Swedish Transport Administration, we have calculated possible AEA routes trafficking Swedish airports in 2030, 2040, and 2050, respectively. We have done this for three scenarios, which are shown in Table 4.

Table 4. The expected range and number of passengers a given year. Background information for the choice of routes for AEA.

SCENARIO	YEAR	NUMBER OF PASSENGERS	RANGE, KM
S1	2030	19	400
S2	2040	100	650
S3	2050	180	926

3.3.1. Calculation of flying distances

Using coordinates for each of the airports in the data from the Swedish Transport Agency we have calculated a great circle distance (GCD) between each pair of airports using equations (3) and (4).[4] If (φ_i, λ_i) and $(\varphi_{i+1}, \lambda_{i+1})$ represent latitude and longitude (in radians) for two geographical points i and $(i+1)$, then the central angle, $\Delta\sigma$, between these points is given by the spherical law of cosines

[3] European Commission (2021b) notes that these are renewable fuels of non-biological origin (RFNBOs) in the meaning of Article 2(63) of the Renewable Energy Directive. They are also known as "synthetic fuels".

[4] Coordinates has been gathered from https://openflights.org/ and if not available from Google Maps.

(3) $$\Delta\sigma = \cos^{-1}(\sin\varphi_i \cdot \sin\varphi_{i+1} + \cos\varphi_i \cdot \cos\varphi_{i+1} \cdot \cos(|\lambda_{i+1} - \lambda_i|)),$$

and the distance d, the arc length, is given by (2):

(4) $$d = R \cdot \Delta\sigma,$$

where R is the mean radius of the earth.

To account for stacking, traffic, and weather-driven corrections these distances have been modified by a factor defined by (5). This is being used for all GCDs longer than or equal to 135 kilometers otherwise the factor is set to zero.

(5) $$Corr_{factor} = 32.123ln(d) - 148.16$$

The formula for the correction factor has been estimated using information from two different sources. In (ICAO, 2018) a factor is used in three discreate steps as shown in Table 5.

Table 5. ICAO correction factor used to cover distance flown in excess of the GCD

GCD	*Correction*
Less than 550 km	+ 50 km
Between 550 and 500 km	+ 100 km
Over 5 500 km	+ 125 km

The second source is a Swedish study by Mårtensson et al., (2016). The authors found radar measured distances for domestic flights to be, on average, 7.8 percent longer than the great circle distances.

Using Mårtensson et.al. for GCDs up to 800 kilometers and otherwise the ICAO (2018) recommendations, we can fit function (5), as illustrated in Figure 5.

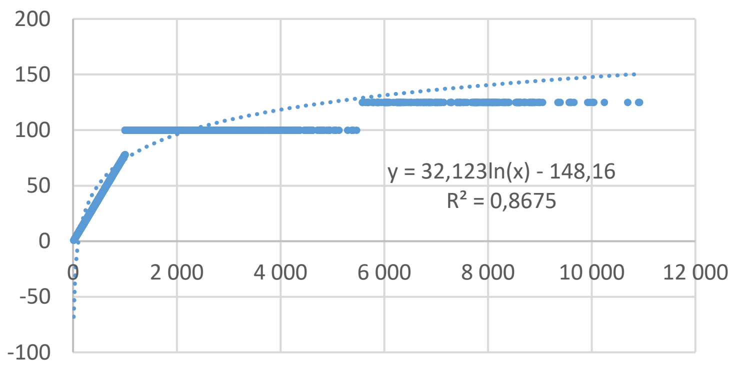


Figure 5. Function used to correct GDC distances.

3.3.2. Flight times

To account for changes in travel time we need estimates of average flight times for different planes on different routes. We need an estimate that captures how average speed is affected by distance traveled. This has been done using information on departure and arrival times for domestic movements in the data from the Swedish Transport Administration (departure and arrival times are not available for international flights). The relationship between average speed and distance traveled is well described by a logarithmic function as illustrated by the examples in Figure 6.

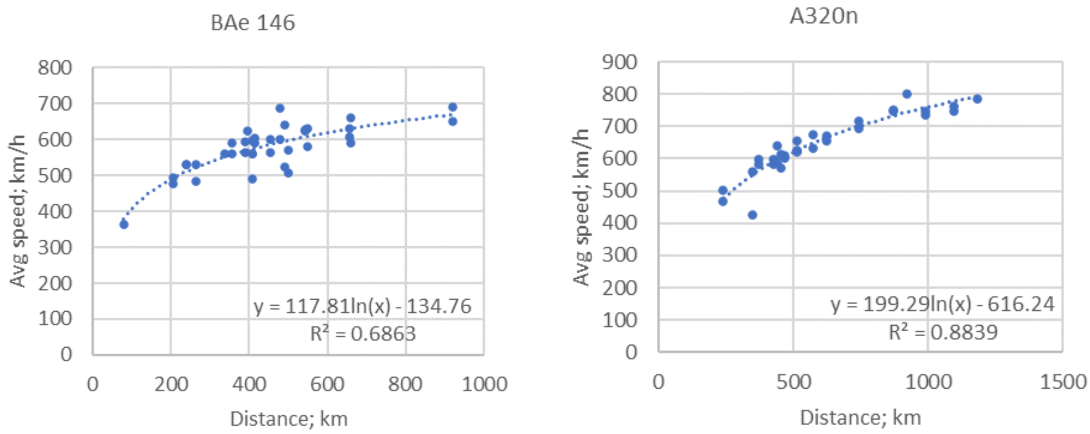


Figure 6. Estimated relationship between distance flown and average speed for a BAe 146 and a A320neo.

To calculate average flight times for the electric planes we can use the estimated relationship for similar planes, in fuselage, wingspan, size, etc. and rescale the functions to reflect lower cruise speeds. In doing so, the 19-seater has been modeled as a British Aerospace Jetstream 32, the 100-seater as a British Aerospace 146 and the 180-seater as an Airbus 320 neo. The reason for using BAe 146 and Airbus 320 neo for the larger electric planes is that it is difficult to find similar sized turbo prop planes in the data. Furthermore, the 100-seater proposed by Wright Electric is being built on the British Aerospace 146 platform. For smaller turbo prop planes the relationship between average speed and distance is not as clear as for larger planes since smaller planes will be more affected by weather conditions. The results for the 19-seater will therefore be more uncertain. For larger turbo prop planes, as the ATR 72-500, we get a better fit, see Figure 7.

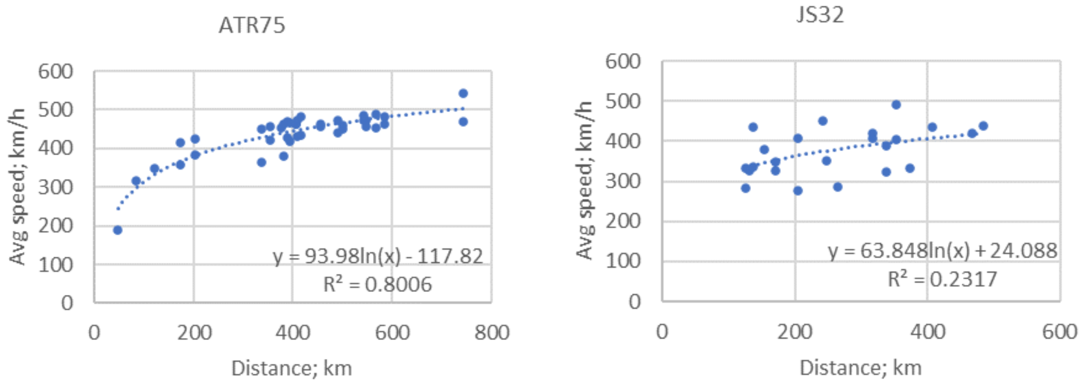


Figure 7. Estimated relationship between distance flown and average speed for an ATR-72-500 and a BAe Jetstream 32.

The functions used for the electric planes are presented in Table 6.

Table 6. Estimated relationship between average speed and distance in kilometers for the electric planes being considered for 2030, 2040 and 2050.

Scenario	*Electric plane*	*Function*
S1	19 passengers	Avg_speed = $44.0 \ln(distance) + 16.6$
S2	100 passengers	Avg_speed = $94.6 \ln(distance) - 108.2$
S3	180 passengers	Avg_speed = $198.3 \ln(distance) - 613.3$

The share of business passengers has been set according to information from the Swedish Transport Administration. For lines not covered by this information we have used an average based on the data.

As it turns out, the cruise speed for the AEA used for 2050 (described in Gnadt et.al. (2019)) is in line with the planes currently operating routes possible to electrify. We only get travel time losses for 2030 and 2040. The results, given in person hours, are presented in Table 7. Travel time losses enter the analysis as a determinant of demand and consequently, impact the consumer surplus.

Table 7. Travel time loss in person hours per year due to electrification of aviation.

	Domestic		*International*		*All*	
Year	2030	2040	2030	2040	2030	2040
Business	15,035	206,473	6,093	100,582	21,128	307,055
Private	14,515	203,340	8,043	134,509	22,558	337,849
Total	*29,550*	*409,813*	*14,136*	*235,091*	*43,686*	*644,904*

The cost of increased travel time can be calculated using valuation of time according to ASEK 7.0. Following the recommendation in ASEK, half of the cost of increased travel time on international flights are to be considered in a Swedish CBA. This yield results according to Table 8.

Table 8. Values of travel time lost due to slower cruise speed of AEAs. EUR.

	Domestic		*International*		*All*	
Year	2030	2040	2030	2040	2030	2040
Business	654,791	10,387,636	132,669	2,548,871	787,460	12,936,507
Private	234,991	3,800,426	65,110	1,250,032	300,101	5,050,458
Total	889,782	14,188,061	197,778	3,798,903	1,087,561	17,986,965

3.3.3. Future demand

Travel demand is assumed to develop according to forecasts done by the Swedish Transport Agency and the Swedish Transport Administration. This information has been used to calculate possible routes to electrify, and changes in emissions.[5] The Transport Agency has published a forecast considering the effects of the pandemic (Swedish Transport Agency, 2021). Three outcomes are presented: low, medium, and high. According to the medium forecast, passengers on international flights will not be back to pre-pandemic levels until after 2027. With the higher recovery rate pre-pandemic levels will be reached by 2025. Domestic passenger numbers will not reach pre-pandemic levels, not even in the high scenario. Based on this, we use the same passenger counts for 2030 as in 2019. After 2030 we use a growth rate of 0.68 percent per year for domestic passengers and 2.63 percent per year for passenger on international flights, based on (Trafikverket, 2020). The outcome is illustrated in Figure 8 and Figure 9.

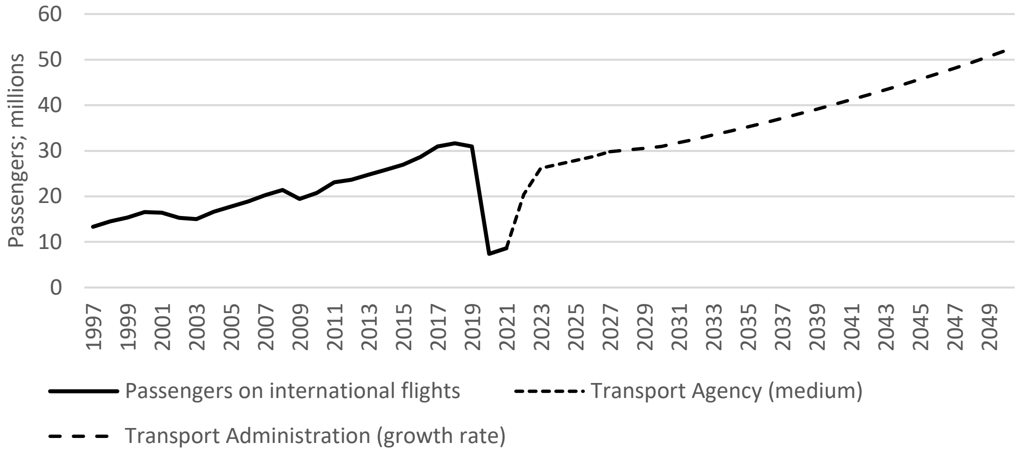


Figure 8. Passengers on international flights as reported by Swedish airports 1997 to 2020, forecast for the period 2021 to 2027 by the Swedish Transport Agency and yearly growth rate according to a pre-pandemic forecast by the Swedish Transport Administration. Source: The Swedish Transport Agency (2021) and the Swedish Transport Administration (2020).

[5] When calculating PS and CS, these prognoses are not used since supply and demand in these calculations is determined by changes in the explanatory variables, and travel demand does not enter directly in the supply or demand curves.

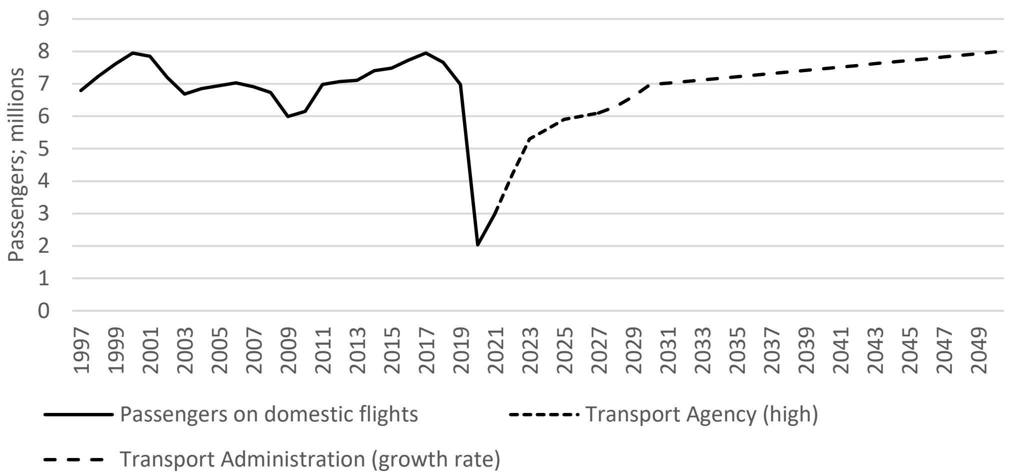


Figure 9. Passengers on domestic flights as reported by Swedish airports 1997 to 2020, forecast for the period 2021 to 2027 by the Swedish Transport Agency and yearly growth rate according to a pre-pandemic forecast by the Swedish Transport Administration. Source: The Swedish Transport Agency (2021) and the Swedish Transport Administration (2020).

For lack of information to assume otherwise, we assume a uniform growth rate across routes, plane types, and departure times. The passenger growth numbers are used to determine routes that are interesting to electrify in 2030, 2040, and 2050.

3.3.4. Routes suitable for electrification

In forming scenarios for routes suitable for electric aviation 2030, 2040 and 2050 we have used a set of basic rules:

1) Flight distance must be under the specified range of available electric planes at given year

2) Given 1, if the passenger capacity is enough for the plane to cover the demand for at least 80 percent of the flights on a specific route, this route is considered all electric. The remaining demand is considered too low for traditional planes to compete.

3) If under the share specified by 2, airlines using electric planes is still allowed to compete for a share of the market on other routes. To be economically feasible the plane type must be able to cover the demand for at least two return flights per week. We have ignored the fact that some low passenger flights might be due to re-positioning of planes.

The scenarios assume that AEAs will be able to produce seats at a cost comparable to conventional aircraft on the market.

In selecting possible routes or a share of departures we take into consideration that growing demand may alter the selection. In doing so we use the forecasts presented in section 3.3.3 and assume a uniform growth rate across routes, plane types, and departure times.

For 2030, the potential for electric flights has been calculated based on a capacity of 19 passengers and a range of 400 km.[6] We mainly consider commercial traffic. Adding smaller aircraft, e.g., an 8-seater with 900 km range, will cover some additional chartered flights but not significantly affect the calculation on CO_2 savings and travel time losses. Half of the identified routes are part of a public

[6] The assumption of 400 km range was made before it stood clear for us whether this includes the airplane's safety margin or not. Therefore, the scenario should be taken for what it is: a hypothetical scenario for a given type of AEA that may, or may not, be available.

service obligation (orange lines) and the second half shorter lines covering traffic to/from Stockholm and Gothenburg. We estimate that a share of the traffic between Gothenburg and Oslo and between Gothenburg and Copenhagen might be electrified by 2030. The thickness of the lines is set proportional to number of passengers 2030.

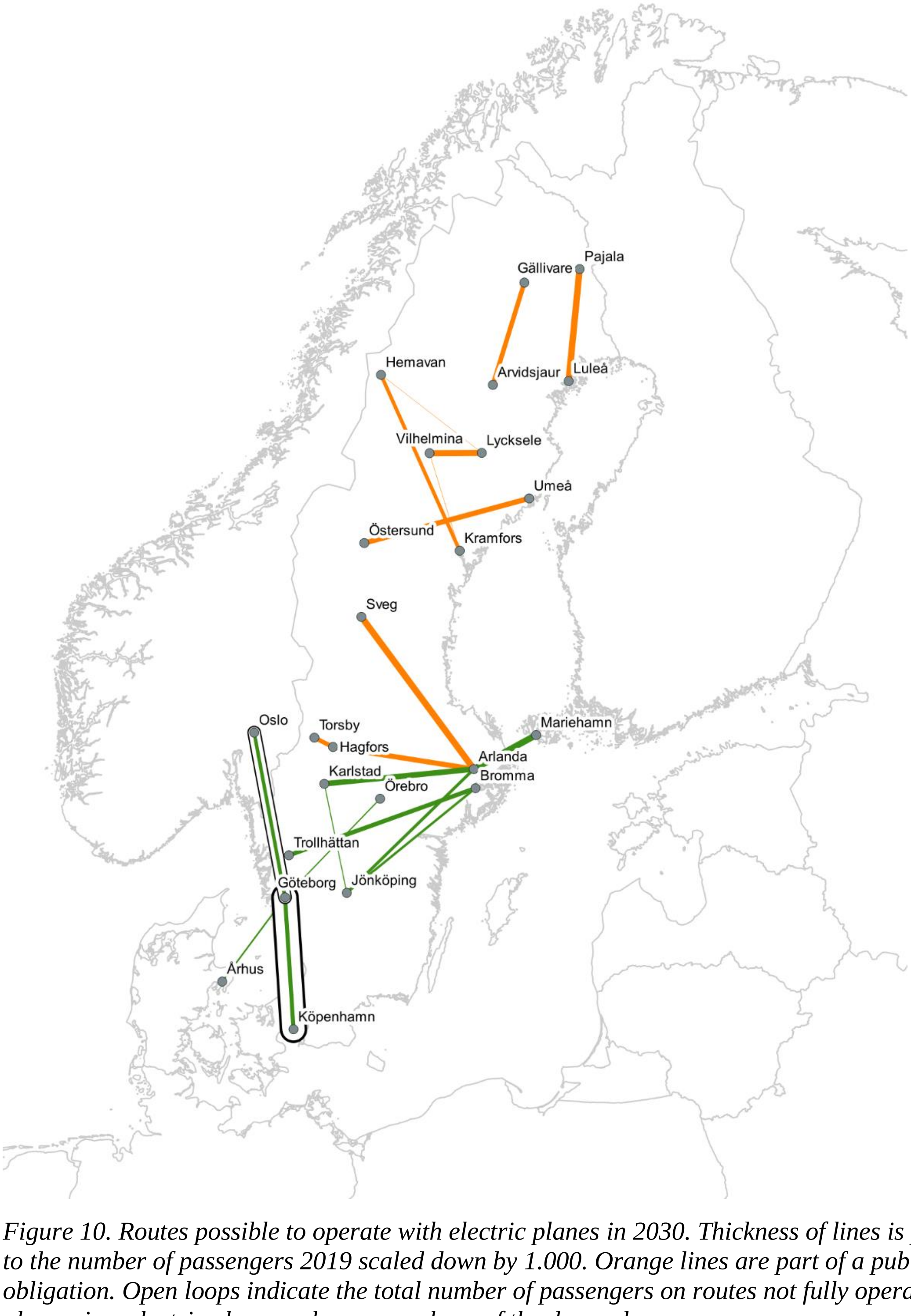


Figure 10. Routes possible to operate with electric planes in 2030. Thickness of lines is proportional to the number of passengers 2019 scaled down by 1.000. Orange lines are part of a public service obligation. Open loops indicate the total number of passengers on routes not fully operated by electric planes, i.e., electric planes only cover a share of the demand.

By 2040 we are considering larger AEAs carrying up to 100 passengers and with a range of 650 km. This will likely require other types of batteries. For example, Wright Aerospace is considering the use of aluminum-air batteries, using chemical reactions between aluminum and air. Unlike lithium-ion batteries, these are not rechargeable but need to be “re fueled” with new aluminum anodes. This will in turn require another type of ground infrastructure and most likely a battery swapping technique. This development is therefore more uncertain. In this scenario we get more of a traditional hub pattern and apart from Copenhagen, flights between Stockholm and the capitals of the other Nordic countries can be partially covered by electric planes. Gothenburg-Oslo and Gothenburg-Copenhagen can now be completely electrified. The more pronounced hub pattern will put pressure on charging capacity on the Stockholm airport Arlanda and Bromma and this is a second reason why a battery swapping technique might be required. A couple of longer public obligation routes to/from Stockholm can also be electrified. We also find it possible to electrify some smaller international routes covering Vaasa, Tampere, Turku (Åbo in the map), Tallin, Riga, Gdansk, Hamburg, and Bergen. Please note that scale for the line thickness differs from the 2030 map.

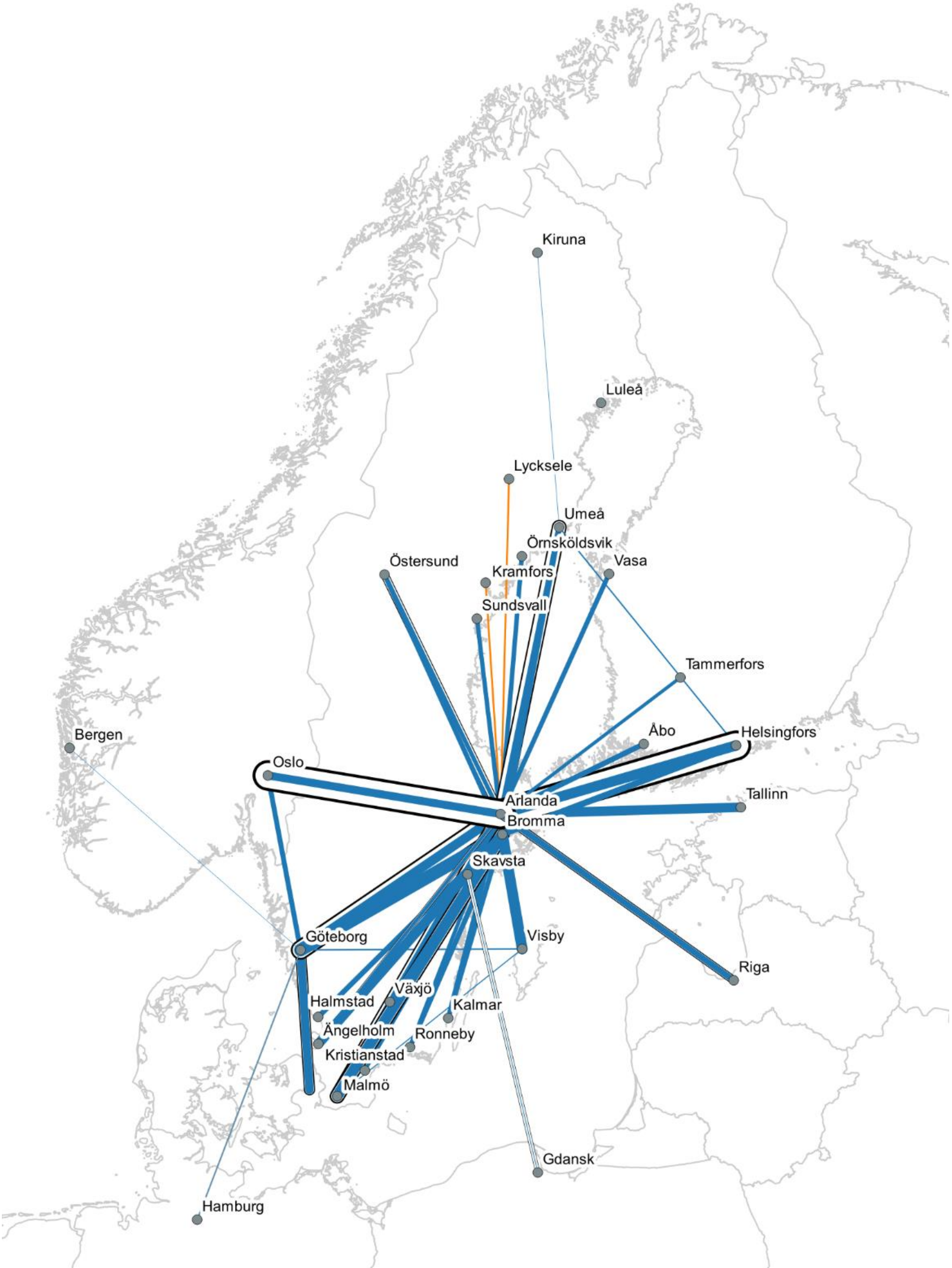


Figure 11. Routes in addition to those in 2030 that could be operated with AEAs in 2040. Thickness of lines is proportional to the estimated number of passengers in 2040 scaled down by 3.000. Orange routes are part of a public service obligation. Open loops indicate the total number of passengers on routes not fully operated by AEAs, i.e., AEAs only cover a share of the demand.

For 2050 we consider a 180-passenger plane with 926-kilometer range as suggested in Gnadt et.al. (2019). This will allow for an almost complete coverage of the bigger domestic routes and add a few more international routes as possible to electrify.

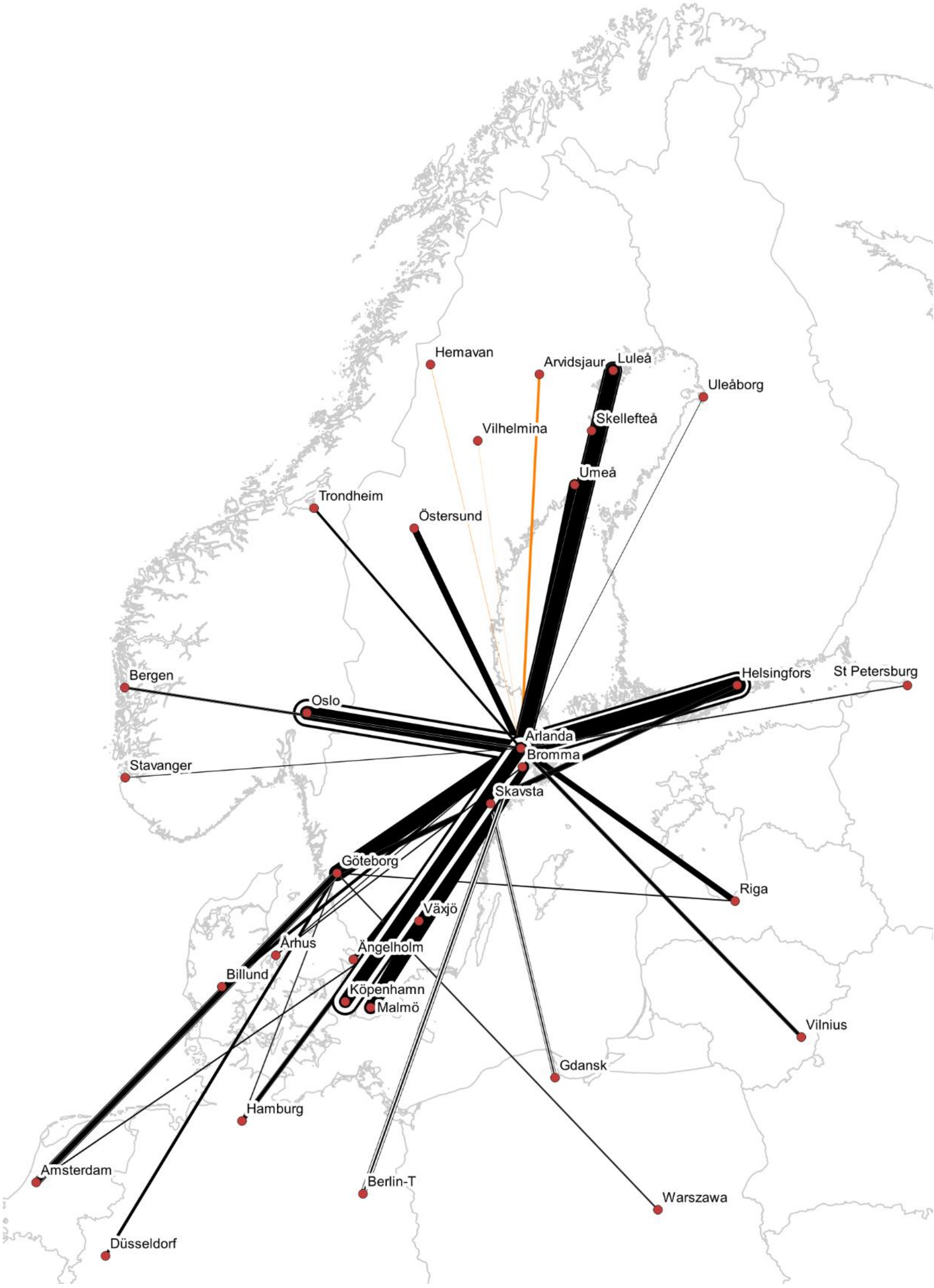


Figure 12. Routes in addition to those in 2030 and 2040 that could be operated with AEAs in 2050. Thickness of lines proportional to number of passengers 2050 scaled down by 3.000. Orange lines are part of a public service obligation. Open loops indicate the total number of passengers on routes not fully operated by AEAs, i.e., AEAs only cover a share of the demand.

3.4. Fuel costs and CO_2 emissions

Fuel cost prognoses used in this report come from several sources. We use information from Statista.com (2022a) to calculate the average (Brent) oil price for 2021, at 70.40 USD per barrel. The average jet fuel price in 2021 is obtained from IATA (2021), at 599.70 USD per ton. We use the difference in the average jet fuel and oil prices to calculate a price premium for jet fuel over crude oil, at 0.033 EUR per liter. We assume this price premium to be constant over time and use it to create a jet fuel price prognosis from an oil price prognosis obtained from the Swedish Energy Agency (2021).

The Swedish Energy Agency (2021) presents scenarios for the future of the Swedish energy system, including a prognosis for (ground-transport) biofuel prices. It is also the source for the electricity price prognosis (for electricity area 3 in Sweden). The prices of jet-biofuels are obtained from Capaz et al. (2020), however. The Swedish Energy Agency (2021) assumes constant prices of biofuels over the period, while Capaz et al. calculate the minimum selling price given production possibilities, feedstocks etc. in Brazil, without any consideration to future changes in production costs. We lack data to challenge these assumptions and given that two opposing forces can be expected to influence the prices of biofuels, namely increased demand raising prices while learning-by-doing and technological development lowering prices, we, too, assume constant prices over the period.

The price of hydrogen is obtained as the mean price reported by Statista.com (2022b), at 3.15 EUR per kg. The price prognosis for EU-ETS is obtained from the European Commission (2021c). The basic prices used, CO_2 equivalent emissions, and specific energy assumptions are shown in Table 9.

Table 9. Price prognoses, specific energy CO_2-equivalent emissions, and data sources.

	JET FUEL (A-1)	**ELEC-TRICITY**	**HEFA**	**FISCHER-TROPSCH**	**ALCOHOL-TO-JET**	**HTL**	**HYDROGEN**
Year	EUR/kg	EUR/MWh	EUR/kg	EUR/kg	EUR/kg	EUR/kg	EUR/kg
2021	0.51	36.12	1.96	1.71	1.78	0.92	3.15
2030	0.63	24.60					
2040	0.72	33.99					
2050	0.87	37.77					
MJ/kg	43.15		44	44	42.8	24.7	
gCO_2-eq/kWh	320.4	47 (2020)	73	11	96	38	9.13
Source:	Swedish Energy Agency (2021)		Capaz et al (2020); specific energies from Neste (2020) and Mathanker et al (2020).				Statista.com (2022b), Capaz et al (2020)

Assumptions about the use of biofuels and renewable fuels of non-biological origin (RFNBOs) are based on policy option C1 from European Commission (2021b), and were reproduced in Table 3. This option, along with policy option C2, is deemed more “economically flexible” by the commission, therefore constituting a least-cost alternative compared to the other policy options (A1-B2) evaluated. Moreover, option C1 is the Commission’s preferred option.

Since it is not feasible within this study to make a prognosis of SAF availability on the world market, we cannot determine which of the jet-biofuels, HEFA, Fischer-Tropsch, or alcohol-to-jet (ATJ), that lies on the margin and therefore determines the biofuel price.[7] For this reason, we make three calculations of weighted jet fuel prices to 2030, 2040, and 2050, respectively, one for each SAF (bf). The weighted average jet fuel price per kg fuel is calculated as follows:

$$p_t = \left(1 - \left(s_{t.bf} + s_{t.rfnbo}\right)\right) p_{t.f} + s_{t.bf} p_{t.bf} + s_{t.rfnbo} p_{t.rfnbo},$$

where p_t is the weighted average price at time t, and $s_{t,i}$ denotes the share of biofuels (bf) and renewable fuels of non-biological origin ($rfnbo$), respectively. $p_{t.f}$ is the price of fossil jet fuel at time t, and $p_{t.bf}$ and $p_{t.rfnbo}$ are the prices of the biofuels and hydrogen, respectively. Since the jet fuel price obtained from IATA (2021) is exclusive handling costs, and the biofuel prices are the minimum selling prices, we multiply p_t by 1.25 to take account of transport and other handling costs.

Jet fuel price p_t is exclusive the cost of emissions allowances from the EU-ETS. To take account of this, and to account for the emissions arising from the biofuels, we also calculate the weighted average cost of EU-ETS emission allowances per kg fuel:

$$c_{t,ETS} = \left[\left(1 - \left(s_{t,bf} + s_{t,rfnbo}\right)\right) e_f + s_{t,bf} e_{bf} + s_{t,rfnbo} e_{rfnbo}\right] p_{t,ETS}.$$

Here, $c_{t,ETS}$ is the cost of an emission allowance per kg of fuel, and e denotes the emissions from respective type of fuel, $i \in \{f, bf, rfnbo\}$. Fuel for airplanes is not subject to the VAT (3 chapter 23§ Mervärdesskattelag (1994:200)). Table 10 shows the jet fuel price depending on the marginal biofuel for years 2030, 2040, and 2050, respectively, broken into its fuel cost and emission allowance cost components, and in total. As a comparison, the average jet fuel price in 2021 was 0.51 EUR per kg, excluding handling costs, or 0.62 EUR per kg including the cost of emissions allowances.

Table 10. Jet fuel price, the cost of emission allowances, and the total cost of fuel in 2030, 2040, and 2050, respectively. EUR_{2021}/kg_{fuel}.

YEAR	HEFA	FISCHER-TROPSCH	ALCOHOL-TO-JET	HTL
2030	0,88	0,87	0,87	0,82
2040	1,29	1,24	1,25	1,09
2050	2,35	2,24	2,27	1,90
Cost of EU-ETS				
2030	0,14	0,14	0,14	0,14
2040	0,36	0,35	0,36	0,35
2050	0,80	0,75	0,81	0,76
Total cost of fuel, EUR_{2021}/kg_{fuel}				
2030	1,02	1,00	1,01	0,96

[7] In Table 9, even HTL has been included, since Capaz et al., (2020) also studied the minimum selling price of this SAF. HTL has not been approved as a SAF and will not be included in the consequent analyses.

2040	1,65	1,59	1,62	1,44
2050	3,15	2,99	3,08	2,65

Sources: IATA (2021), Capaz et al., (2020), European Commission (2021c).

3.5. Other costs

3.5.1. Airport charges

There is no uniform standard for airport charges. Some of the fees are set by national agencies, while for example landing and take-off fees are determined by respective airport themselves. However, according to ICAO rules all airlines must be treated equally and fees should be set according to actual costs. Airports are required to account for all costs covered by a fee in a transparent way (ICAO, 2006; ICAO, 2001; Directive 2009/12/EC).

Within set regulations it is possible to differentiate fees to, for example, promote a shift towards planes with lower emissions. In general, fees will depend on type of plane, type of engine, and number of passengers and cover operation and maintenance of terminals and runways, handling of passengers, luggage, and security. Most airports also charge for noise and NO_X emissions.

In this report, we have attempted to calculate the airport charges for the Swedish airports included in the data. For the ten airports belonging to the state-owned company, Swedavia, we have used the fees and the calculation methods given in Swedavia (2022). For the other 25 airports included in the study, we have used price lists available at the airport’s webpage or by request. Two airports, those in Sveg and Vilhelmina, did not answer to our request of price lists. Moreover, we have not attempted to replicate the airport fees for non-Swedish airports, of which there are 30 in our data. The price lists usually apply for single take-offs and landings and for regular routes, the airports have negotiated prices. We have not been able to account for these, however.

Table 11 gives examples of charges for a Boeing 737-800 departing from Gothenburg and Arlanda. The table shows own calculations based on Swedavia (2022) and the results obtained using a calculator at Swedavia’s homepage, given similar assumptions about the airplane and number of passengers. For some reason, the individual components of the calculations differ from one another in some cases, but the total sum is of the same order of magnitude. Since we use the sum of all charges in the regression model in Section 4.1, we deem the differences to be of negligible importance.

In Table 11, the own calculation for the baggage facility charge also includes the passenger handling infrastructure charges and the ramp handling infrastructure charge. Since the CO_2 emission charge is a fee-rebate system, which is revenue neutral for Swedavia, we did not include it in the calculations. Instead, we assume that the external effect caused by the burning of jet fuel and the climate gas emissions arising from it are internalized by the flight’s inclusion in the EU ETS. In our data, there is only one route that is not an intra-EU or European Economic Area (EEA) one, namely one to St Petersburg. This route, at the time of writing, is defunct because of the EU sanctions against Russia for invading Ukraine.

Table 11. Examples of airport charges at Gothenburg (GOT) and Stockholm/Arlanda (ARN) airports, assuming a plane of the model B738 with two CFM56-7B27 engines, MTOW of 74,908 kg, 113

departing passengers from GOT and 103 passengers from ARN, no transfer passengers and no use of SAFs. EUR_{2021}.

	AIRPORT			
	GOT		ARN	
	Own calculation	Swedavia	Own calculation	Swedavia
Take Off Charge	409	335	354	283
Terminal Navigation Charge	129	114	241	213
Noise Charge	56	32	56	32
NOx Emission Charge	104	124	104	125
Passenger Charge - Local Departing Passengers	745	746	919	924
Assistance Service Charge (PRM-Charge)	71	71	51	52
Baggage Facility Charge	263	136	253	226
Passenger Handling Infrastructure Charge (invoice to handling agent)		49		20
Ramp Handling Infrastructure Charge (invoice to handling agent)		77		7
CO_2 Emission Charge		14		18
Security charge: 40 SEK/dep pax (invoiced by Swedish transport agency)	445	446	404	406
Slot Coordination Charge	2	2	2	2
TOTAL	**2223**	**2146**	**2384**	**2310**

Sources: own calculations based on Swedavia (2022) and Swedavia's calculator at https://www.swedavia.com/about-swedavia/airport-charges.

Airlines are also charged for air navigation. The charge is to cover costs incurred by air navigation facilities and services, the system for levying charges, and costs for operating the system. In Europe EUROCONTROL collects route charges on behalf of its Member States through its Central Route Charges Office (CRCO). We do not include this charge separately in our calculations, however.

3.5.2. External effects

To calculate the value of external effects, we use either the values given in the ASEK 7.0 report (Swedish Transport Administration, 2020) or in European Commission (2019), or both. Moreover, to calculate the external effect arising from the high-altitude effect of CO_2 emissions, we have used both the value of climate emissions from ASEK 7.0 (0.69 EUR/kg CO_2-eq), and the prognosticated price of emissions allowances within the EU ETS (0.037 EUR/kg CO_2-eq in 2030, 0.098 EUR/kg CO_2-eq in 2040, and 0.18 EUR/kg CO_2-eq in 2050). We used the latter as a "reality check" against the quite high value used in ASEK 7.0.

As a proxy for PM 2.5 emissions, we use the NMVOC emissions reported by EASA (2022). To calculate the value of emissions of PM2.5, we use values from the European Commission (2019). For the value of emissions of nitrous oxides, we use values from both ASEK 7.0 and European Commission (2019).

The noise emitted by AEAs is not a well-researched issue. In order not to completely lose this aspect of AEA introduction, we use noise levels for a Beaver aircraft versus an electric version of the same aircraft (magniX, 2021). We calculate the noise from respective type of AEA by using the formula given in equation (6), where dB denotes the noise level of plane $i = \{b, eb, f, a\}$ where b stands for a conventional Beaver aircraft, eb for an e-Beaver, f for a conventional airplane and a for an AEA, at phase $j \in \{takeoff, cruise, landing\}$ of flight. f consists of three airplanes: Dassault Falcon with 17 seats, BAe Jetstream 61 with 53 seats, and Airbus A320neo with 190 seats, which are used as the "noise proxies" for the three types of AEA.

(6)
$$dB_{a,j} = \frac{dB_{eb,j}}{dB_{b,j}} dB_{f,j}$$

Thus, we scale down the noise level for the existing aircraft by the relative noise level of an e-Beaver to a conventional Beaver aircraft. For noise, we only include the value of the calculated difference in noise values for AEA minus the conventional aircraft it would replace at respective route, using the valuation of noise obtained from Schroten and de Bruyn (2019), and do not calculate the change in producer- or consumer surplus that would result from a correct pricing of the noise externality.

There are some external effects that we do not consider. These include accidents, which happen very seldom and are therefore not priced for air transport in Sweden. We attempted to calculate the cost of crowding using the definition and values from ASEK 7.0, but the results indicate that there is no crowding on airplanes. This is quite intuitive considering that the cabin factor never exceeds one, and that crowding is defined as cabin factors exceeding certain percentages, starting from 0.5 to 0.75, 1, and so on. EASA (2022) also reports emissions of hydrocarbons (HC), but we have not found a monetary valuation of these either in ASEK 7.0 or in European Commission (2019), and consequently the impact is ignored.

3.6. Other parameter values

We assume the depreciation period for capital assets, i.e., the airplane, to be 20 years. This is the approximate mean depreciation time indicated by IATA (2016) and corresponds, e.g., to the useful life expectancy of Lufthansa's new commercial aircraft. The value varies from 3 years for Boeing 767 for Kenya Airlines to 30 years for the core parts by Air China. Moreover, based on the same source, we assume residual value of 5 percent. Even for this parameter, there is considerable variation from zero to 60 percent, the latter figure pertaining to Qatar Airways executive jets.

We assume engine maintenance costs according to information obtained in an interview with Christopher Lewandowski of Heart Aerospace (Levandowski, 2021). Thus, we assume that an electric airplane motor has a yearly maintenance cost of EUR 845, a turboprop engine of EUR 126,743, and a turbofan engine of EUR 278,834 per engine.[8]

3.7. Data

To calculate the change in the producer- and consumer surpluses arising from the introduction of AEAs, we started by estimating a simultaneous equations model for supply and demand for air transport. Summary statistics for the variables used are shown in **Fel! Hittar inte referenskälla.**, their construction was discussed in Section 2.1.

Table 12. Summary statistics.

VARIABLE	OBS	MEAN	STD. DEV.	MIN	MAX
ln(seats)	1,428	7.08	2.81	1.79	13.48
ln(pax)	1,204	6.49	3.23	-0.69	12.99
r(ticket)	1,046	220.2	186	0	1012
ln(r(ticket))	888	5.21	1.13	-3.42	6.92
p(ticket)	1,066	504.70	272	83	1791
ln(p(ticket))	1,066	6.08	0.56	4.42	7.49
fees	1,145	115.4	1,913	0	46,521
ln(fees)	794	3.34	0.88	1.74	10.75
p(fuel)	1,428	0.029	0.028	0.007	0.196
ln(p(fuel))	1,428	-3.79	0.64	-4.92	-1.63
w(pilot)	1,356	1.62	2.64	0.00	17.88
Ln(w(pilot))	1,134	0.01	1.04	-1.95	2.88
CAPEX	1,364	13,045	28,721	0	234,098
ln(CAPEX)	1,364	7.31	2.62	-7.96	12.36
foreign	1,448	0.33	0.47	0	1
ln(ttime)	980	-5.82	1.55	-7.74	0.69
ln(catchment)	1,154	7.64	3.85	-1.08	16.47
Charter	1,448	0.24	0.43	0	1

[8] USD 1,000, 150,000, and 330,000 respectively.

4. Results

4.1. Regression results

Results from estimating the translog supply and demand functions, equations (1) and (2), are summarized in Table 31 in Appendix 1. We use the translog form of the equation in order to remove skewness in the variables, as is apparent from Table 12. We estimated the equations using Stata's reg3 command for a three-stage estimation for systems of simultaneous equations. Column (1) of Table 31 reports results from the full model. The preferred model, where we have removed the insignificant coefficient for $\ln\left(p(fuel)\right)^2$, is model (2). This means that we retain a number of variables with insignificant coefficients in the model. The exclusion of the quadratic fuel price variable ascertains marginal effects with "correct" signs, however.

According to Table 12, we have at most 1,448 observations of some variables. The regression models in Table 31 are run with a considerably lower number of observations, 505, however. This is partly due to a lack of data on some variables, most notably $p(ticket)$, but also $fees$. As noted above, we do not have airport fees for foreign airports. Thus, on routes with a foreign origin or destination, a route is only included in one direction, when it starts in Sweden.

Due to the large number of interactions, the regression results are not immediately transparent. For this reason, we have calculated marginal effects at mean values of the variables, which are shown in Table 13. The marginal effects of the variables are in general as expected. Thus, an increase in revenue per seat increases supply, while an increase in the ticket price depresses demand. The impact of ticket prices on supply is significant only at 5 percent level, however. The impact of airport fees is insignificant. The rest of the variables have the expected signs and are statistically significant at a very high level: thus, higher fuel prices, pilot costs, and CAPEX all reduce supply. Likewise, a longer travel time decreases demand. Finally, demand on chartered flights is lower than that on scheduled flights.

Table 13. Marginal effects at the mean values of variables of the model in column (2) of Table 31.

	DY/DX	***STD. ERR. (DELTA METHOD)***	***Z***	***P>|Z|***	***95% CONF. INTERVAL***	
Supply						
ln(r(ticket))	0.23	0.10	2.22	0.026	[0.03 –	0.43]
ln(fees)	0.10	0.15	0.66	0.507	[-0.20 –	0.40]
ln(p(fuel))	-1.20	0.25	-4.77	0.000	[-1.70 –	-0.71]
ln(w(pilot))	-1.57	0.10	-15.3	0.000	[-1.77 –	-1.37]
ln(CAPEX)	-0.88	0.04	-24.2	0.000	[-0.95 –	-0.81]
Demand						
ln(p(ticket))	-0.94	0.13	-7.18	0.000	[-1.20 –	-0.69]
ln(ttime)	-0.56	0.06	-9.7	0.000	[-0.67 –	-0.44]

Charter = 1	-0.91	0.23	-4.01	0.000	[-1.36 –	-0.47]

The next step is to use the regression results to calculate the producer and consumer surpluses (PS and CS, respectively). We now turn to this.

4.2. Business-as-usual vs AEAs

In this section we start by calculating the business-as-usual (BAU) producer and consumer surpluses (PS and CS) assuming constant demand. The BAU scenario is one where only conventional aircraft will be used, but where increasing amounts of SAFs will be blended into the jet fuel, and where the prices of EU ETS allowances increase over time. We then compare the BAU scenarios against the AEA scenarios described in Table 4.

Table 14 summarizes variable values for AEAs used in the analyses. The table corresponds to **Fel! Hittar inte referenskälla.**; those variables in the former table not shown in the latter have the same value both for AEAs and conventional flight in the ensuing calculations. We will, in the calculations, use two alternative ways to define the electricity cost for AEAs. The first is based on design mission electricity use, i.e., $\ln\left(p\left(fuel_{design}\right)\right) = \ln\left(p_{el} \times number\ of\ flights \times kWh_{design\ mission}/seats \times distance\right)$. The second is based on calculated fuel use in conventional aircraft in 2019. We assume fuel use efficiency of 40 percent, and thus calculate $\ln\left(p\left(fuel_{fossil}\right)\right) = \ln\left(p_{el} \times kWh_{fossile}/seats \times distance\right)$. t-tests of equal means indicate that the latter, fossil fuel consumption-based electricity costs, exceed the former in all three years in a statistically significant manner. Thus, using both measures can be seen as a sensitivity test to variations in electricity costs.

Table 14. Summary statistics for AEA-variables.

VARIABLE	YEAR	OBS	MEAN	STD. DEV.	MIN	MAX
ln(fees)	All	794	3.50	0.74	1.37	8.39
ln(p(fuel)): design mission	2030	82	0.0046	0.0045	0	0.016
	2040	686	0.0037	0.0042	0	0.045
	2050	1,428	0.011	0.012	0	0.078
ln(p(fuel): fossil kWh	2030	1,428	0.0008	0.0047	0	0.060
	2040	1,428	0.0080	0.013	0	0.083
	2050	1,428	0.014	0.013	0.0034	0.093
ln(w(pilot))	All	1,154	0.53	1.33	-1.30	3.82
ln(CAPEX)	2030	1,274	8.44	2.96	2.67	13.65
	2040	1,274	8.49	2.93	2.67	13.65

	2050	1,274	8.50	2.93	2.72	13.64
ln(ttime)	2030	32	-3.45	1.86	-6.46	-0.42
	2040	542	-4.71	1.54	-7.33	0.84
	2050	1,204	-5.69	1.61	-7.77	0.84

4.2.1. Change in producer surplus

We use the regression results from the previous section to calculate the PS for conventional flight and AEAs given the predicted development of jet fuel prices, electricity prices, battery replacement costs, the cost of ETS allowances, and EU's SAF blending mandate for 2030, 2040, and 2050. We calculate the impact of the SAF mandate on fuel prices for three SAFs as described in Table 10. We calculate the producer surplus for conventional flights and AEAs using the results from Table 31, substituting in the calculated OPEX (airport fees, fuel price, and pilot cost) and CAPEX (annualized capital and battery replacement cost, engine maintenance) for AEAs in the results.

As was explained in section 2.1, PS is given by the integral under the $S(p)$ function between $p_{min} = 0$ and $p_{max} = 1011.721$: $\int_0^{1011} S(r)dr$. This results in the following function for the PS:

$$\begin{aligned} PS = 5988.79\gamma_1 + 36461.8\,\gamma_2 & \\ & + 1011.72\{\gamma_3 \ln(fees) + \gamma_4 \ln(fees)^2 + \gamma_5 \ln(pfuel) + \gamma_6 \ln(w) + \gamma_7 \ln(w)^2 \\ & + \gamma_8 \ln(CAPEX) + \gamma_9 \ln(CAPEX)^2\} \\ & + 5988.79\{\gamma_{10} \ln(fees) + \gamma_{11} \ln(pfuel) + \gamma_{12} \ln(w) + \gamma_{13} \ln(CAPEX)\} \\ & + 1011.72\{\gamma_{14} \ln(fees) \ln(CAPEX) + \gamma_{15} \ln(pfuel) \ln(CAPEX) \\ & + \gamma_{16} \ln(w) \ln(CAPEX) + \gamma_{17} \ln(fees) \ln(pfuel) + \gamma_{18} \ln(fees) \ln(w) \\ & + \gamma_{19} \ln(pfuel) \ln(w) + \alpha_s\} \end{aligned}$$

The results are shown in Table 15.

Table 15. Producer surplus: mean values, standard deviation, minimum and maximum in EUR_{2021} per year. Calculated for conventional flight in 2019 using jet fuel only, conventional flight using a mixture of SAFs and jet fuel for 2030, 2040, and 2050, and for AEAs using two different ways to calculate the electricity cost, again for 2030, 2040, and 2050.

MARGINAL SAF	YEAR	OBS	MEAN	STD. DEV.	MIN	MAX
Baseline	2019	691	11,618	11,384	1,045	192,209
HEFA	2030	63	6,012	5,332	1,879	36,869
FT	2030	63	6,053	5,359	1,924	37,017
ATJ	2030	63	6,039	5,350	1,908	36,966
Electricity: design mission	2030	9	9,980	25,998	-3,270	78,613

Electricity: fossil kWh	2030	9	9,847	23,587	-1,541	72,335
HEFA	2040	309	8,022	3,973	458	32,160
FT	2040	309	8,108	4,009	568	32,527
ATJ	2040	309	8,068	3,992	517	32,356
Electricity: design mission	2040	321	15,174	13,460	-9,505	80,618
Electricity: fossil kWh	2040	321	12,057	10,457	-4,778	68,732
HEFA	2050	658	6,536	3,022	-3,427	32,093
FT	2050	658	6,672	3,042	-2,926	32,709
ATJ	2050	658	6,591	3,030	-3,222	32,344
Electricity: design mission	2050	680	12,887	11,216	-11,004	95,592
Electricity: fossil kWh	2050	680	12,873	10,271	-5,003	117,394

The results in Table 15 indicate that, on average, electric aviation in 2030 overperforms compared to conventional aircraft. The number of routes is low, however, only nine, and the least profitable routes generate a loss. Moreover, t-tests of equal means indicate that the PS for AEAs, independent of the measure of electricity cost, and conventional flight using SAFs is equal. This changes from 2040 onwards, when t-tests indicate that the mean PS for AEAs, again regardless of the measure of electricity cost used, is higher than that for conventional, SAF-using aircraft at a very high level of statistical significance. However, the PS for AEAs based on the fossil fuel use-based electricity cost is lower than PS based on design mission energy use. Moreover, the standard deviation of AEA-PS is much higher than that for conventional aircraft and consequently, on the least profitable routes, the PS is negative throughout the studied period. It is interesting to note that in 2050, the least profitable routes have a negative PS even for conventional aircraft.

To further examine the possible benefits and excess costs of electric aviation, we conduct a series of t-tests of equal means for the variables included in the regression model. These are shown in Table 16.

Table 16. t-tests of equal means of variables pertaining to conventional aircraft versus AEAs. The fuel price for conventional aircraft is based on Fischer-Tropsch as the marginal fuel.

VARIABLE	YEAR	OBS	MEAN CONVEN-TIONAL	MEAN AEA	T	PR(T<T)	PR(T>T)
fees	All	1,145	115.4	44.7	1.28	0.8987	0.1013

p(fuel)[9]: design mission	2030	82	0.062	0.0046	6.7	1.0000	0.0000
	2040	686	0.088	0.0037	24.4	1.0000	0.0000
	2050	1,428	0.12	0.011	32.4	1.0000	0.0000
p(fuel): fossil kWh	2030	82	0.062	0.014	6.55	1.0000	0.0000
	2040	686	0.088	0.017	24.01	1.0000	0.0000
	2050	1,428	0.124	0.014	35.42	1.0000	0.0000
w(pilot)	All	1,356	1.62	3.50	-15.16	0.0000	1.0000
CAPEX	2030	74	24,546	118,340	-5,23	0.0000	1.0000
	2040	648	16,896	91,362	-12,71	0.0000	1.0000
	2050	1,364	13,045	63,794	-15,08	0.0000	1.0000
- capital cost	All	1,384	7,058,531	11,600,000	-16.67	0.0000	1.0000
- engine maintenance	All	1,364	3,343	188	16.00	1.0000	0.0000
- engine maintenance + battery replacement	2030	74	5842	112,828	-9,22	0.0000	1.0000
	2040	648	5106	335,661	-34,92	0.0000	1.0000
	2050	1,364	3343	611,601	-50,72	0.0000	1.0000

The difference in the mean airport fees paid by AEAs and conventional aircraft is insignificant, despite us having set certain fees, such as a NO_X-charge and noise charges equal to zero for AEAs. The reason for the fees nevertheless being about equal is probably to be found in the fact that many airport fees are based on the weight of the airplane (MTOW, maximum take-off weight), or on the number of passengers. The latter we have assumed is the same for both types of aircraft, and then, naturally, both pay equal fees. MTOW, however, is higher for AEAs, the mean for the entire sample being 66,850 kg for AEAs and 55,369 kg for conventional aircraft. The difference is statistically significant with a $t = -6.4$, at a very high level of statistical significance.

The rest of the differences are as expected. The fuel cost of AEAs is lower than that for the conventional aircraft, despite us having compared the fuel cost of AEAs with the SAF most favorable for conventional aircraft, namely Fischer-Tropsch. AEAs have a higher cost for pilots, which is due to the longer flight time due to slower aircraft. AEAs also have much higher CAPEX.

In order to look more deeply at the differences in CAPEX, we broke up the variable. Thus, AEAs have a much higher annualized capital cost than conventional aircraft. This is partly due to us having imputed the cost of an aircraft for the S2 and S3 type of planes (see Table 4 for the scenarios) by taking the corresponding conventional aircraft and adding a surcharge of 10 percent. However, the result remains even if we only look at the aircraft assumed to be available in 2030, where we have an

[9] The marginal SAF is assumed to be Fischer-Tropsch.

independent guess of the cost of the aircraft. In fact, that comparison indicates that the 10 percent surcharge is insufficient, the mean capital cost of AEAs for that year being almost a factor of 5 higher than that for corresponding conventional aircraft.

The other component of capital costs that we have included is the engine maintenance cost. The cost of engine maintenance as such is much lower for the AEAs, which was expected. If, however, we add the cost of replacing the aircraft batteries every second year, as described in Section 3.1, the tables are turned and the cost of engine maintenance and battery replacement in AEAs becomes much higher than that in conventional aircraft.

We have not considered changes in ticket prices, but in order to get a feel for this, we calculate the costs per seat provided. The mean values for conventional aircraft and AEAs are shown in Table 17. The costs included are all in per seat terms, the number of seats used being that from 2019. Costs included in the marginal costs in Table 17 include the cost of fuel, pilot cost, airport fees, the cost of engine maintenance per year, and for AEAs, the biannual battery replacement cost. The capital cost of aircraft is not included since we do not have data on all use of an airplane. Including the capital cost raises the cost per seat provided to a level that is not covered by the ticket price; the average cost in 2019 is calculated at 13,021 EUR/seat for conventional aircraft while the revenue per seat is on average 220 EUR/seat.

Table 17. t-tests of marginal costs of conventional aircraft using Fischer-Tropsch as the marginal SAF versus AEAs. Costs included in marginal costs include the cost of fuel, pilot cost, airport fees, the cost of engine maintenance per year, and finally, for AEAs, the biannual battery replacement cost. All costs are per seat produced in 2019, in EUR_{2021}.

VARIABLE	YEAR	OBS	MEAN CONVEN-TINAL	MEAN AEA	T	PR(T<T)	PR(T>T)
Marginal cost vs ticket revenue/seat	2019	998	22.6	219.7*	34.2	0.0000	1.0000
Marginal cost: p(fuel): design mission	2030	73	28.2	11.5	5.2	1.0000	0.0000
	2040	637	49.8	16.1	20.1	1.0000	0.0000
	2050	1,351	73.1	19.4	30.2	1.0000	0.0000
Marginal cost: p(fuel) fossil kWh	2030	73	28.2	14.7	4.86	1.0000	0.0000
	2040	637	49.8	21.9	19.36	1.0000	0.0000
	2050	1,351	73.1	20.6	33.13	1.0000	0.0000

* Mean ticket price in 2019.

Table 17 and the calculations underlying it reveal interesting detail. For one, AEAs are throughout much cheaper to run on a per seat basis than conventional aircraft, regardless of the way to calculate the electricity cost. Secondly, the marginal cost of running a conventional aircraft on SAFs raises the marginal cost to a level more than three times higher than that in 2019 by 2050. The marginal cost of AEAs in turn start low at about 15 (12) EUR/seat for the fossil kWh measure of electricity cost (design mission-based cost), rise to about 22 (16) EUR/seat in 2040, and then fall back a bit to 21 EUR/seat according to the fossil kWh calculation of electricity costs in 2050 (rise to 19 EUR/seat according to the design mission based electricity cost). Based on these calculations, given that the technology is available at the prices used in this study, AEAs would thus be able to carry their costs, probably including the higher cost of capital, and still turn a handsome profit. Table 32 in Appendix 1 shows more detail for all electrified routes in 2030, and for the ten routes with the highest, and ten routes with the lowest PS for 2040 and 2050, respectively.

4.2.2. Change in consumer surplus

CS is obtained by integrating under the $D(p)$ curve between the minimum and maximum ticket prices, $p_{min} = 83$ and $p_{max} = 1790.5$.

(7)
$$CS = \int_{p=83}^{1791} d(p)dp = 11337\beta_1 + 76159\beta_2 + 1708[\alpha_d + \beta_3 \ln(ttime) + \beta_4 1.charter + \beta_5 \ln(catchment)].$$

The consumer surplus for conventional flight and AEAs at the three given years, 2030, 2040, and 2050, respectively, are shown in Table 18. The upper panel refers to scheduled flights, while the lower panel contains CS for chartered and taxi flights.

Table 18. Consumer surplus for scheduled flights and chartered or taxi flights, respectively. The 2019 figures are the base scenario and refer to consumer surplus arising from conventional aircraft. The figures for 2030, 2040, and 2050 are for AEAs. EUR.

Scheduled flights					
Year	**Obs**	**Mean**	**Std. Dev.**	**Min**	**Max**
2019	933	10,362	4,621	-4,449	18,584
2030	30	6,796	4,867	-3,480	13,624
2040	527	8,318	5,127	-4,588	17,730
2050	1,154	9,861	4,707	-4,588	18,590
Charter and taxiflight					
2019	933	8,801	4,621	-6,010	17,023
2030	30	5,235	4,867	-5,041	12,063
2040	527	6,757	5,127	-6,150	16,168
2050	1,154	8,300	4,707	-6,150	17,029

As was expected, CS on average falls for the slower AEAs. However, we have assumed that later generations of AEAs become faster (Gnadt, et al., 2019), which is visible in the rise of CS over time from 6,800 EUR/route in 2030 to 9,900 EUR/route in 2050. We examine the question further by conducting pair-wise t-tests of equal means for conventional flights and AEA flights for the three years studied. The results are shown in Table 19.

Table 19. t-tests of equal means of consumer surplus from conventional aircraft versus AEAs.

YEAR	OBS	MEAN CONVEN-TIONAL	MEAN AEA	T	PR(T<T)	PR(T>T)
Scheduled flights						
2030	24	6,747	6,222	15.82	1.0000	0.0000
2040	404	8,963	8,844	12.96	1.0000	0.0000
2050	933	10,362	10,318	9.23	1.0000	0.0000
Chartered and taxi flights						
2030	24	5,186	4,661	15.82	1.0000	0.0000
2040	404	7,402	7,283	12.96	1.0000	0.0000
2050	933	8,801	8,757	9.23	1.0000	0.0000

The results in Table 19 are not surprising. Thus, the difference in mean CS is statistically significant, and the CS for AEAs is lower than that for conventional flight for all three years studied, and both for scheduled flights and for charter. We then conclude that consumers lose some CS with the introduction of longer flight times.

4.3. Total surplus

In order to gauge the total benefits from going electric, we summarize the PS and the CS, and compare the mean levels of this sum for conventional flight versus AEAs. Summary statistics for the sum of PS and CS are shown in Table 20.

Table 20. Summary statistics for the sum of PS and CS for conventional flight in 2019, marginal SAF Fischer-Tropsch, and for AEAs. Separate values apply for scheduled and charter/taxi flight.

FUEL	YEAR	OBS	MEAN	STD. DEV.	MIN	MAX
Scheduled flights						
Conventional	2019	653	22,755	11,621	2,258	189,034
Fischer-Tropsch	2030	62	9,348	5,570	2,978	39,613
	2040	296	18,086	6,992	2,593	35,123

	2050	620	17,806	5,726	643	33,874
AEA: design mission	2030	8	17,227	26,483	1,603	80,787
	2040	309	24,705	15,892	-5,991	83,155
	2050	645	23,466	12,799	-7,924	97,345
AEA: fossil kWh	2030	8	16,862	24,007	2,991	74,509
	2040	309	21,601	12,851	-1,283	70,907
	2050	645	23,415	11,833	-3,249	119,147
Charter and taxiflight						
Conventional	2019	653	21,194	11,621	696	187,473
Fischer-Tropsch	2030	62	7,787	5,570	1,417	38,052
	2040	296	16,525	6,992	1,032	33,562
	2050	620	16,245	5,726	-918	32,313
AEA: design mission	2030	8	15,666	26,483	42	79,226
	2040	309	23,144	15,892	-7,552	81,594
	2050	645	21,905	12,799	-9,485	95,784
AEA: fossil kWh	2030	8	15,301	24,007	1,430	72,948
	2040	309	20,040	12,851	-2,844	69,345
	2050	645	21,854	11,833	-4,810	117,586

Table 20 contains interesting information. First, the total surplus for conventional, scheduled flights is more than halved from 2019 to 2030, when more SAFs are blended into the fuel mix. For the chartered and taxi flight it falls by almost two-thirds. The total surplus grows over time as more flights are included in the sample, however, even though it never reaches back to the level in 2019. These changes are statistically significant at a very high level of significance.

Table 21 reports results pertaining to the difference that is of most interest here, namely the difference in total average surplus between conventional, SAF (Fischer-Tropsch) driven aircraft and AEAs. The results from the t-tests confirm the findings from Table 20, namely that the total surplus from AEAs exceeds that from conventional, SAF-driven flight in 2040 and 2050, regardless of the measure of electricity cost used. The results for 2030 are insignificant, probably due to the very small sample size.

Table 21. t-tests of equal means of total surplus from conventional aircraft versus AEAs

	YEAR	OBS	MEAN CONVEN-TIONAL	MEAN AEA	T	PR(T<T)	PR(T>T)
Scheduled flights							
p(fuel): design mission	2030	7	15,410	18,477	-0.47	0.3276	0.6724
	2040	261	18,473	26,402	-12.49	0.0000	1.0000
	2050	561	17,627	24,108	-17.80	0.0000	1.0000
p(fuel): fossil kWh	2030	7	15,410	17,943	-0.46	0.3307	0.6693
	2040	261	18,473	23,129	-9.84	0.0000	1.0000
	2050	561	17,627	24,078	-22.03	0.0000	1.0000
Chartered and taxi flights							
p(fuel): design mission	2030	7	13,849	16,915	-0.47	0.3276	0.6724
	2040	261	16,912	24,841	-12.49	0.0000	1.0000
	2050	561	16,066	22,547	-17.80	0.0000	1.0000
p(fuel): fossil kWh	2030	7	13,849	16,382	-0.46	0.3307	0.6693
	2040	261	16,912	21,568	-9.84	0.0000	1.0000
	2050	561	16,066	22,517	-22.03	0.0000	1.0000

4.4. Sensitivity analyses

We conduct a number of sensitivity analyses on the assumptions on AEAs. We start by doubling the fuel cost of AEAs per passenger kilometre. After this we calculate what would happen if the engine maintenance cost of AEAs was the same as the corresponding conventional aircraft. This would be the case if, e.g., the inspection regimes on aircraft engines were not relaxed for AEAs. Finally, we consider the impact of capital costs and raise the capital cost of the AEAs introduced in 2040 and 2050 to a level similar to that assumed in 2030, namely, we assume that the cost of capital for all AEAs is 5 times that assumed above.

It is not surprising that the PS falls for AEAs when the electricity price doubles, the difference being statistically significant in 2040 and 2050 as shown in Table 22. In 2030 there are probably too few observations for the difference to be statistically significant. Alternatively, the routes are so short that the electricity use does not constitute a major part of the operating cost, and the means really are approximately the same.

Table 22. The impact of a doubling of the electricity cost on producer surplus from AEAs. t-tests of equal means, the main scenario being conventional aircraft using Fischer-Tropsch as the marginal SAF, alternative scenarios for the two definitions of electricity use.

YEAR	OBS	MEAN MAIN SCENARIO	MEAN ALTERNA-TIVE SCENARIO	T	PR(T<T)	PR(T>T)
Alternative scenario p(fuel): design mission						
2030	8	8,818	10,417	-0.337	0.3729	0.6271
2040	272	8,250	14,330	-12.19	0.0000	1.0000
2050	595	6,657	10,972	-14.59	0.0000	1.0000
Alternative scenario p(fuel): fossil kWh						
2030	8	8,818	10,166	-0.354	0.3671	0.6329
2040	272	8,250	11,057	-8.087	0.0000	1.0000
2050	595	6,657	10,994	-19.84	0.0000	1.0000

The results in Table 22 indicate AEAs, even after a doubling of the cost of electricity, still have a higher PS than conventional, SAF-driven aircraft, even though the result is not statistically significant in 2030. It is very highly so in 2040 and 2050, respectively, however. Moreover, we have attempted to raise the electricity cost of AEAs up to a level 20 times that assumed in the main scenarios. Even with this very high electricity cost, the PS from AEAs exceeds that from conventional aircraft, ceteris paribus. Thus, our result of AEAs having a higher PS than the SAF-driven conventional aircraft holds even if the electricity price would rise considerably.

Turning to the engine maintenance costs, we examine how the PS from AEAs would change if they had an engine maintenance cost equal to that for conventional aircraft. The results from comparing the PS for AEAs with higher engine maintenance costs against conventional aircraft using Fischer-Tropsch as the marginal SAF are shown in Table 23. Again, the results for 2030 are insignificant, probably due to the small number of observations. For 2040 and 2050 the results indicate that the higher engine maintenance cost do not suffice to reduce the PS from AEAs sufficiently for the conventional aircraft to have a higher PS. That is, AEAs still have a higher PS than conventional aircraft, even if they paid as much for engine maintenance.

Table 23. The impact of a higher engine maintenance cost on par with conventional aircraft on producer surplus from AEAs. t-tests of equal means, alternative scenario against the main AEA scenario and conventional aircraft using Fischer-Tropsch as the marginal SAF.

YEAR	OBS	MEAN MAIN SCENARIO	MEAN ALTERNA-TIVE SCENARIO	T	PR(T<T)	PR(T>T)
Main scenario: Fischer-Tropsch, alternative scenario p(fuel): design mission						

2030	8	8,818	11,033	-0.381	0.3571	0.6429
2040	272	8,250	16,176	-12.97	0.0000	1.0000
2050	595	6,657	13,050	-18.47	0.0000	1.0000
Main scenario: Fischer-Tropsch, alternative scenario p(fuel): fossil kWh						
2030	8	8,818	10,781	-0.403	0.3496	0.6504
2040	272	8,250	12,903	-10.24	0.0000	1.0000
2050	595	6,657	13,071	-23.03	0.0000	1.0000

In the final sensitivity analysis, we increase the annualized capital cost of AEAs fivefold in 2040 and 2050. The results are shown in Table 24. Unsurprisingly, the PS falls compared to the main AEA scenario. Even this change does not suffice to make the SAF-driven conventional aircraft have a higher PS than the AEAs, however.

Table 24. The impact of a five-fold increase in the annualized capital cost of AEAs in 2040 and 2050 on producer surplus from AEAs. t-tests of equal means, alternative scenario against the main AEA scenario and conventional aircraft using Fischer-Tropsch as the marginal SAF

Year	*Obs*	*Mean main scenario*	*Mean alternative scenario*	*t*	*Pr(T<t)*	*Pr(T>t)*
Main scenario: Fischer-Tropsch, alternative scenario p(fuel): design mission						
2040	272	8,250	14,214	-9.36	0.0000	1.0000
2050	595	6,657	11,472	-13.54	0.0000	1.0000
Main scenario: Fischer-Tropsch, alternative scenario p(fuel): fossil kWh						
2040	272	8,250	11,593	-7.01	0.0000	1.0000
2050	595	6,657	11,638	-17.06	0.0000	1.0000

We conclude that the results in Section 4.2.1 regarding the PS of AEAs being higher than that from the SAF-driven conventional aircraft are quite robust, at least with regard to changes in single costs. It thus seems that at least from 2040, assuming our assumptions about the available technology hold, AEAs would be a valuable addition to the aircraft fleet, helping to keep costs down.

5. Extensions

5.1. External effects: the high-altitude effect

As was noted in Section 3.5.2, we have data on three types of external effects: the high-altitude effect, emissions of PM2.5 and NO_X. However, these effects have been included in the monetary valuation, and therefore in the regression model only so far as they have been internalized in the airport fees. Thus, a monetary valuation of the high-altitude effect or PM2.5 is not included in the calculation of PS in Section 4.2.1. For this reason, in this section, we calculate the possible benefits from reduced high-altitude effect. Emissions of particles and NO_X are at least partly included in this calculation.

Since aviation within Europe is covered by the EU ETS, CO_2 emissions are considered internalized and should not be a part of the CBA. However, in calculating potential savings due to reduced high altitude effects, which should be included in the CBA, we do get an estimate on potential savings in CO_2 emissions. Since potential CO_2 savings can be of interest to study in relation to politically set goal for CO_2 emissions, we have chosen to include these results in the report.

To be able to calculate the reductions in CO_2 emissions and high-altitude effects for different scenarios of AEAs we have built a database with bottom-up calculations of emission from each of the close to 380 000 flights to/from Swedish airports in 2019 that we have data for. This has been done by using information in the Master emissions calculator 2019 and the LTO emissions calculator 2019 published by the European Environment Agency.[10] These calculators contain estimates of fuel use and emissions for different planes during take-off and landing and during flight. The estimates have been done by EUROCONTROL based on their Fuel Burn and Emissions Inventory System (FEIS), using among others their Base of Aircraft Data (BADA) and their Advanced Emissions Model (AEM). An overview of the method used by EUROCONTROL is given in the EMEP/EEA air pollutant emission inventory guidebook 2019, section 1.A.3.a, 1.A.5.b Aviation, Annex 4. (EMEP/EEA, 2019) The method used in this paper follows the Tier 3 inventory methodology outlined in the guidebook.

5.1.1. Emissions from landings and take-offs

The landing and take-off (LTO) part of a flight, see Figure 13, covers emissions due to movements under 3,000 feet. Calculations are based on engine thrust and duration during different phases of an LTO cycle. Standard cycle emissions are calculated based on figures in Table 25.

[10] 1.A Combustion — European Environment Agency (europa.eu)

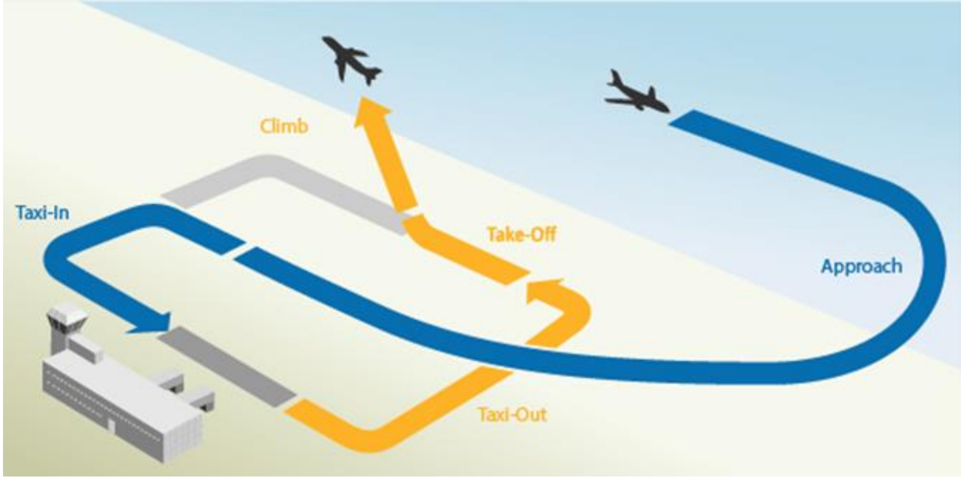


Figure 13. ICAO LTO cycle (Europeiska unionens byrå för luftfartssäkerhet, 2019).

Table 25. Engine use in the ICAO standard cycle for LTO emissions.

PHASE	THRUST	DURATION (MIN)
Take-off	100 %	0.7
Climb out	85 %	2.2
Approach and landing	30 %	4.0
Taxi	7 %	26.0

Source: (EMEP/EEA, 2019).

For each plane type there are calculations based on LTO cycles for all Swedish airports – all airports present in the flight data from the Swedish Transport Administration. However, some of the airports share settings, and some are set equal to the standard cycle giving us unique calculations for 25 out of 38 airports in the data set. Since it is time consuming to access detailed data from the LTO emissions calculator and the data must be processed to match other data needed in the calculations we have chosen to use the standard LTO cycle for all airports outside of Sweden.

To be able to make calculations for one-way flights, not only return flights, information on emissions from take-offs (Taxi-out, take-off and climb out) and landings (approach, taxi-in) are handled separately.

5.1.2. Emissions from climb, cruise, and descent

Fuel consumption and emissions during the CCD phase (climb, cruise, and descent) are, for each plane type, given for a discrete number of flight distances. In calculating emissions for a specific flight distance, we use linear interpolated values between these points. The EMEP/EEA database also lack information on some of the aircraft in operation to/from Swedish airports, mostly smaller planes under 20 passengers. In these cases, we have used data for similar plane types in the EMEP/EEA database.

5.1.3. CO2 savings

Given the scenarios outlined above we get estimated fuel savings according to Table 26. If we assume a uniform passenger demand growth, the same amount of fuel efficiency gains and the same level of alternative fuels over all routes and aircraft types, a calculated share of total fuel saved could reasonably well capture the potential CO_2 savings. These shares can be used against forecasts of fuel use and/or emissions.

Even with a positive view on the technical development of AEAs we find that, from a climate perspective, the benefits lie mostly in the domestic market. The first generation of aircraft is estimated to only cover 2.8 percent of the fuel used on domestic flights in Sweden. A 2050 scenario, as described above, could allow for savings of up to 86 percent in the domestic market. For international flights AEAs are only calculated to, depending on year, cover between 0.2 and 7.1 percent of the total fuel consumption. In total we find a potential to save 21 percent of the fuel used by flights to/from Swedish airports by 2050. If technology allows for smaller AEAs only, as assumed for 2030, the CO2 savings from investing in electric aviation will be small. Furthermore, the potential is likely slightly overestimated since the EEA/EMEP data is calculated based on average load factors. Fuel use on routes with low demand will therefore be overestimated (for empty flights only half of the fuel used is accounted for).

Since domestic flights are reported twice, both as leaving and arriving, we have used data only for domestic flights leaving Swedish airports. For international flights only half of the savings are considered as “Swedish”. We need an estimate of “Swedish” benefits when relating total social benefits to investments in Swedish airports. For total savings these figures will have to be doubled.

Table 26. Estimated fuel savings according to AEA scenarios for 2030, 2040 and 2050. Flights to/from Swedish airports; percent.

	DOMESTIC			**INTERNATIONAL**			**ALL**		
Year	2030	2040	2050	2030	2040	2050	2030	2040	2050
Charter	7.0	44.2	48.4	0.2	0.2	0.4	0.3	1.2	1.5
Scheduled	2.7	48.7	86.4	0.2	2.9	8.3	0.7	11.9	23.6
Taxi	7.6	39.8	41.0	0.2	1.2	2.7	2.0	10.6	12.0
TOTAL	**2.8**	**48.6**	**85.6**	**0.2**	**2.5**	**7.1**	**0.6**	**10.6**	**20.9**

In calculating CO2 savings, we must handle the expected increase in passengers given by the forecasts presented above. Controls made for 2040 reveal that current capacity will cover the expected increase in demand. However, by 2050 there are routes where demand must be met with more departures or a shift to larger planes. In this context we use a basic scaling factor to account for the increase in demand. The scaling factor for 2040 and 2050 respectively is given by:

$$SF_{2040} = \frac{TW_{2040}}{TW_{2019}}, \text{and} \tag{4}$$

$$SF_{2050} = \frac{TW_{2050}}{TW_{2019}} \tag{5}$$

where TW is total weight defined in KG as (Nbr of seats * 50) + (Nbr passengers * 100) + Freight[11] for each year.

[11] Freight includes weight due to postal service.

For fuel efficiency gains we use a fall in fuel consumption by 0,2 percent per seat kilometre and year, as suggested in (Rutherford, 2011). The share of sustainable aviation fuels is set according to Table 3. Factors of emissions have been set according to Table 9; i.e., 3.84 kg CO_2-eq per kg fuel used for traditional jet fuel, 0.72 kg CO_2-eq per kg fuel used for bio-based SAF (an average over HEFA, Fischer-Tropsch and Alcohol to jet). CO_2 emissions from synthetic aviation fuels have been set to zero assuming these will be produced using renewable electricity. Since production plants for electricity are part of the EU ETS their emissions should be considered internalized. The results are shown in Table 27.

Table 27. Estimated CO_2 savings in tons in 2030, 2040, and 2050, respectively, accounting for fuel efficiency gains and increased use of sustainable aviation fuels.

	DOMESTIC			**INTERNATIONAL**			**ALL**		
Year	2030	2040	2050	2030	2040	2050	2030	2040	2050
Charter	696	3,268	2,137	790	778	884	1,485	4,046	3,021
Scheduled	16,659	230,443	250,286	4,531	61,865	123,664	21,189	292,308	373,950
Taxi	139	542	337	12	56	82	151	599	419
TOTAL	**17,493**	**234,254**	**252,760**	**5,333**	**62,699**	**124,630**	**22,826**	**296,953**	**377,390**

5.1.4. High altitude effects

Climate effects that should be a part of a CBA are those related to emissions of water vapor, soot and other particles, formation of contrails and NO_X emissions at high altitude. They are called high altitude effects because they only take effect when the emissions occur on altitudes higher than 8,000 or 9,000 meters. These effects are not covered by the EU ETS.

To establish a scheme for calculating CO_2 equivalents for high altitude effects we have created a relationship between these effects and CO_2 emissions from jet planes on high altitude. This allows us to differentiate high altitude effects over different types of flights. Turbo prop planes are not considered to cause high altitude effects due to lower flight trajectories. The distance flown on high altitude has been approximated with total distance (corrected distance) reduced by 195 kilometers, a distance assumed to be covered during ascending and descending from high altitude. Both (Azar & Johansson, 2012) and (Lee, et al., 2021) suggest that CO_2 emissions should be multiplied by a factor of 1.7 (GWP_{100}) to get total CO_2 equivalents accounting for high altitude effects on a global scale. Using this we can estimate a factor to use on the high-altitude CO_2 emissions that will give us a total high-altitude factor of 1.7. This has been done according to:

$$F_{ha} = \frac{0.7CO2_{tot}}{CO2_{ha}} \tag{6}$$

where F_{ha} is the factor to use on high altitude CO_2 emissions, $CO2_{tot}$ is total CO_2 emissions from flights to/from Swedish airports and $CO2_{ha}$ is CO_2 emissions at high altitude according to the definition above. The factor F_{ha} turns out to be very close to one. It is calculated to 0.9942. CO_2 emissions at high altitude, calculated as suggested, will thereby give us the CO_2 equivalents needed for a total high-altitude factor of 1.7.

Using this simplified approach, we get estimated savings in high altitude effects (CO_2-eq), according to Table 28. Increased passenger demand is dealt with in the same manner as for CO_2 emissions and we account for a fuel efficiency gain of 0.2 percent per year as previously described. We do not have any information on what type of SAFs will be most common, and we lack information on how alternative fuels will affect emissions of water vapor, soot and other particles, formation of contrails and NOx emissions at high altitude. CO_2 equivalent high-altitude effects are therefore calculated as if using jet fuel.

The CO_2 equivalents from reduced high-altitude effects are much smaller than 70 percent of CO_2 savings since most planes being replaced by electric planes in our scenarios are turbo prop planes not causing any high-altitude effects.

Table 28. Estimated savings in CO_2 equivalent high-altitude effects in 2030, 2040, and 2050, respectively; accounting for fuel efficiency gains and an increase in demand but not increased use of sustainable aviation fuels.

	DOMESTIC			INTERNATIONAL			ALL		
Year	2030	2040	2050	2030	2040	2050	2030	2040	2050
Charter	31	785	924	124	199	581	155	984	1 505
Scheduled	241	71,411	176,428	458	17,264	96,656	700	88,675	273,083
Taxi	10	211	221	2	23	71	13	234	291
TOTAL	**282**	**72,406**	**177,572**	**585**	**17,486**	**97,307**	**867**	**89,892**	**274,879**

Calculating the valuation of the high-altitude effect using the social cost of carbon from ASEK and EU ETS respectively, we get the results presented in Table 29. The effects of the first generation AEAs will be small, with a benefit per year valued to around 600,000 EUR according to ASEK (0.73 EUR per kg CO_2) and 32,000 EUR if valued according to the price prognosis for the EU ETS 2030 (0.037 EUR per kg CO_2). This is because the first generation AEAs will mainly replace turbo prop planes not causing any high-altitude effects. If it will be possible to construct and operate AEAs with higher capacity, the benefit will be larger. The scenario for 2040 give us benefits valued to 63 million EUR per year, if valued using ASEK (same value as for 2030), and 9 million EUR per year, if valued according to EU ETS (estimated to 0.098 EUR per kg CO_2). The scenario for 2050 gives us benefit of over 197 million EUR per year according to ASEK (same value as for 2030) and 53 million EUR per year if valued according to EU ETS (estimated to 0.184 EUR per kg CO_2).

Table 29. The value of a reduction in the high-altitude effects due to the use of AEAs instead of conventional aircraft. EUR

	VALUED ACCORDING TO ASEK (EUR)			VALUED ACCORDING TO EU ETS (EUR)		
Domestic	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
Charter	21,390	552,001	663,782	1,141	78,560	177,123
Scheduled	166,290	50,268,016	126,698,144	8,874	7,154,066	33,808,114

Taxi	6,900	148,350	158,700	368	21,113	42,348
Total	***194,581***	***50,968,368***	***127,520,626***	***10,383***	***7,253,739***	***34,027,585***
International	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
Charter	85,560	140,070	416,761	4,566	19,935	111,208
Scheduled	316,021	12,153,003	69,411,428	16,864	1,729,597	18,521,736
Taxi	1,380	15,870	51,060	74	2,259	13,625
Total	***403,651***	***12,308,943***	***69,879,250***	***21,540***	***1,751,790***	***18,646,569***
All	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
Charter	106,950	692,762	1,080,543	5,707	98,593	288,332
Scheduled	483,001	62,420,329	196,110,262	25,774	8,883,565	52,330,034
Taxi	8,970	164,220	209,071	479	23,372	55,788
Total	***598,232***	***63,277,312***	***197,399,876***	***31,923***	***9,005,529***	***52,674,154***

5.2. New routes

If smaller AEAs can produce trips at a much lower cost than today's smaller planes, we must consider the possibility of new routes opening. To investigate this possibility, we have used data from the Swedish national model system for traffic forecasts, SAMPERS. The SAMPERS system is divided into several modules and/or models covering different steps of the procedure, e.g., car ownership, travel demand, route choice etc. and different levels of detail, e.g., international, national, and regional travel. For our purpose we have used results from the national model, covering domestic long-distance trips (over 100 km).

From the SAMPERS system we get estimated number of trips and travel time (including waiting time) by car, train, bus, and plane between 682 regions for the years 2017 and 2040. These trips and travel time estimates have then been aggregated into flows between Swedish municipalities. Travel time as a weighted average based on population numbers for each region according to:

$$W_{ij} = \frac{P_i}{\sum_{i \in M}^{n} P_i} \frac{P_j}{\sum_{j \in N}^{n} P_j} \tag{7}$$

where W_{ij} is the weight for the data relating to journeys between SAMPERS region i and j , P is population, M is the municipality in which i resides, and N the municipality in which j resides.

Estimated total number of long-distance trips in 2017 and 2040 are shown in Table 30.

Table 30. Total number of long-distance trips 2017 and 2040 according to SAMPERS.

	CAR	BUS	TRAIN	AIRCRAFT

Year	2017	2040	2017	2040	2017	2040	2017	2040
Business	10 009 235	12 044 315	127 604	137 797	2 558 526	3 670 936	1 809 720	1 511 170
Private	50 580 225	61 365 232	5 238 189	6 044 732	7 623 167	10 530 078	1 060 420	1 423 599
Commute	6 954 615	9 499 636	511 808	662 727	3 230 159	5 076 894	538 706	555 533

The possibility of new routes is only considered for all-electric planes being ready for traffic by the year 2030, i.e., planes with up to 19 seats and a range of 400 kilometres. Larger planes need higher demand to be profitable and will to a higher degree compete with solutions on already established routes. We also only consider traffic between already established airports. Besides airports that were hosting scheduled traffic 2019, we have added three airports that are certified as public airports (Borås, Eskilstuna, and Skövde). If traffic will be large enough to justify the cost of keeping an airport open is left out of this analysis.

To identify new routes, i.e., routes where there was no scheduled traffic in 2019, that could be operated with a smaller electric plane, we have used the following steps:

1. Identify relations with airports that are at least 170 kilometers driving distance a part (the approximate distance in which electric airplanes could compete in travel time with road traffic given an average driving speed of 70 km/h, see Baumeister et al., (2020) for an explanation for this assumption) and under 400 kilometers great circle distance apart (the assumed maximum distance for an AEA).
2. Given the relationship between average speed and distance for a S1 AEA, as presented in Table 6, and assuming an additional time for travel to/from the airports, check in, security, boarding and taxi-times of 110 minutes, we only consider relationships that allows for time savings of at least 60 minutes compared to the fastest alternative.
3. We only consider relationships with an estimated travel demand of at least (on average) 3 individuals per day. In the case an airport serves two or more municipalities, e.g., Åre/Östersund, Sundsvall/Timrå or Trollhättan/Vänersborg, we have used both municipalities in calculating demand.

Besides this we have added four international routes suggested in a study by the Swedish Agency (Traffic Analysis, 2020). This gives us possible routes according to Figure 14. In total this amounts to 55 domestic routes and 4 international routes.

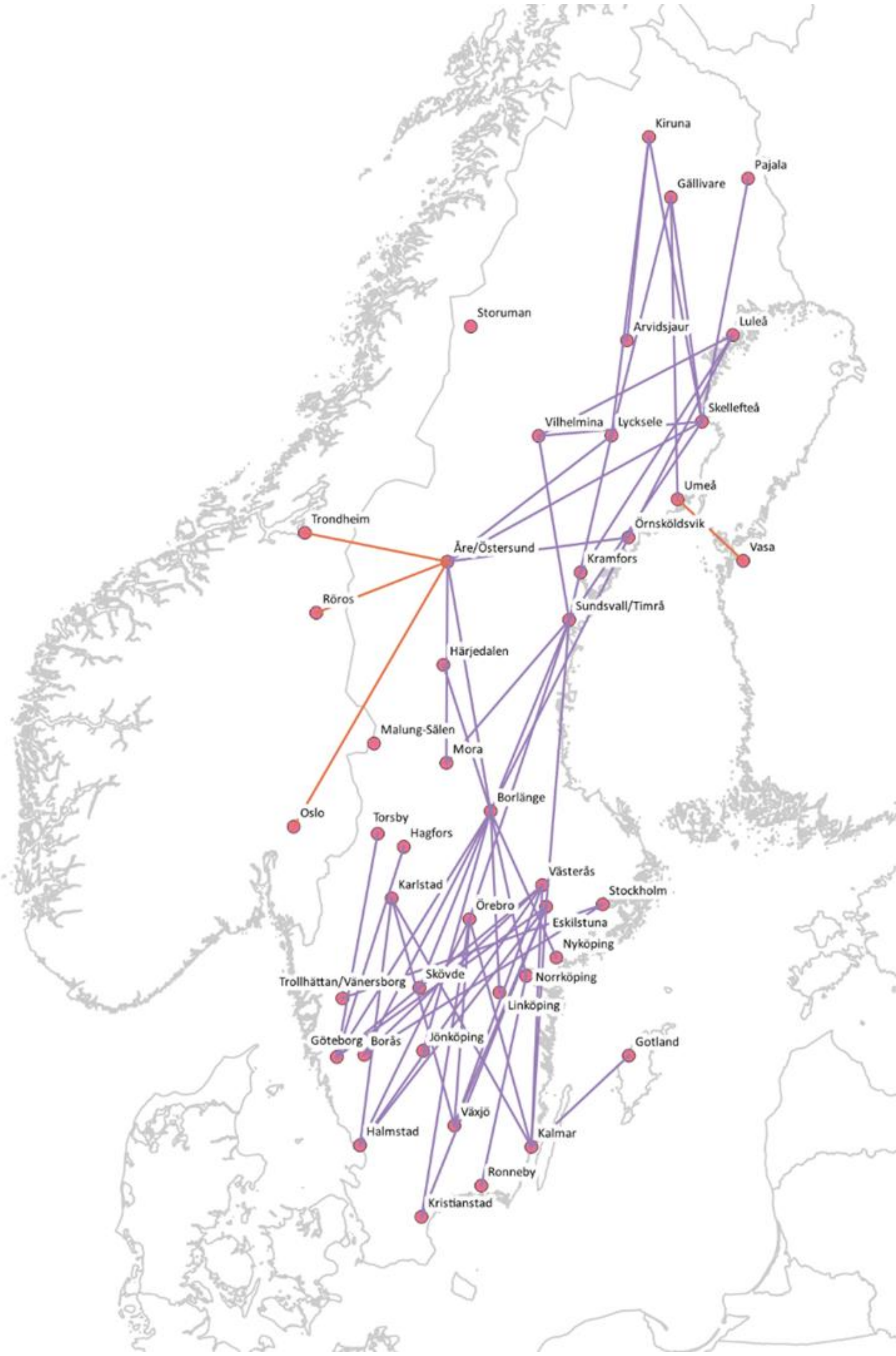


Figure 14. Possible new routes for a 19-passenger, 400 km, airplane.

We have also identified 26 routes that could be operated depending on the season. In the southern parts of Sweden this will, to a large extent, be trips to Gotland and in the northern parts trips to mountain and ski resorts, see Figure 15.

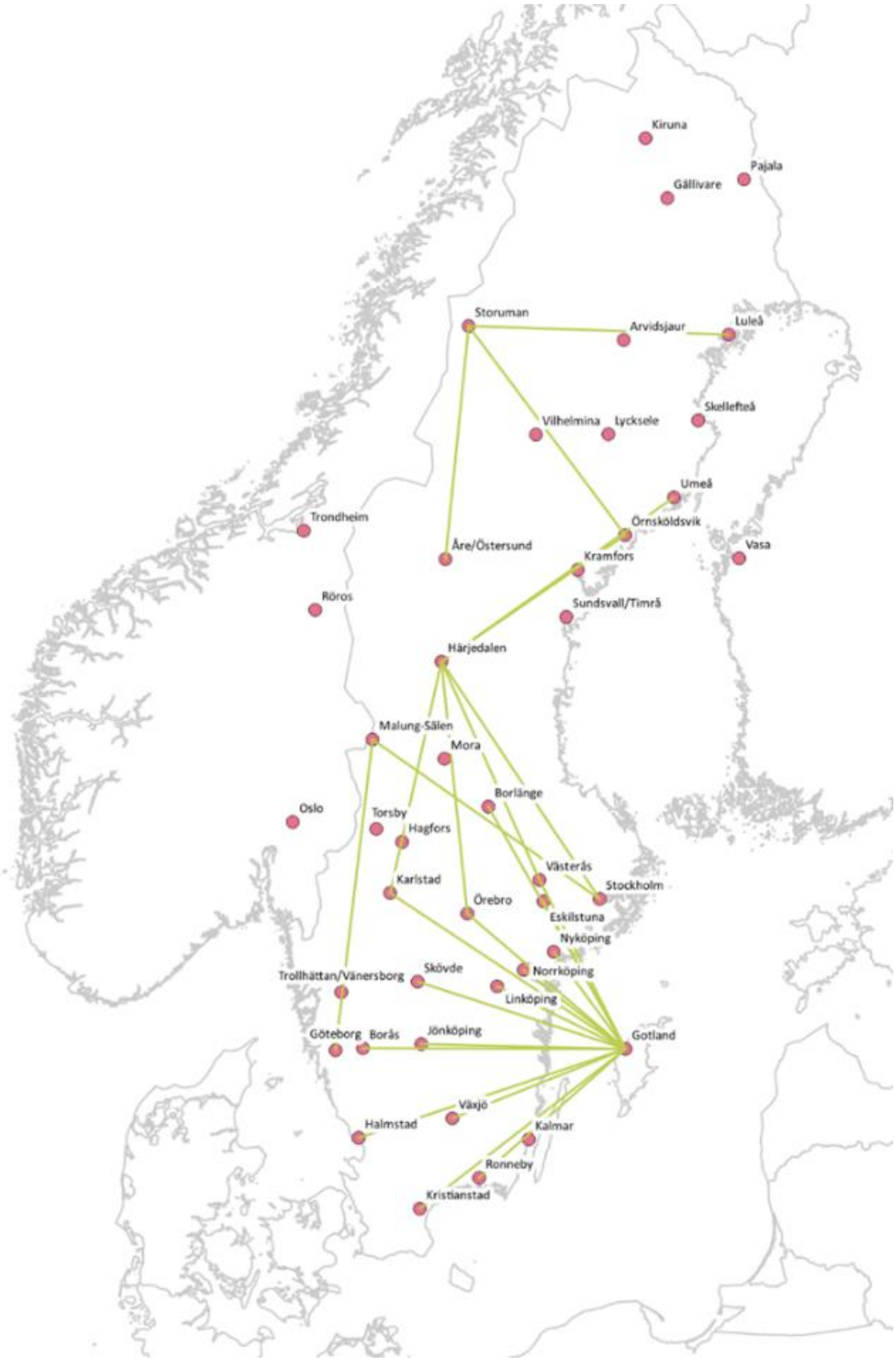


Figure 15. Possible new seasonal routes for a 19-passemger, 400 km, airplane.

The possibility to operate these routes will be dependent on the production cost per seat for an AEA. This will also affect the benefit associated with the operation. If comparing the generalized cost of driving with the generalized cost of flying assuming on average two passengers per car trip, 12 passengers per flight, two return flights per day six days a week (seasonal routes only operates for 15 weeks per year) and that half of the car trips will be run with electric cars, we get the outcome in Figure 16. At a cost of 100 EUR, for a single fare, travel to/from the airport, parking etc., we estimate the benefit to 12.1 million EUR per year and that 35 of the selected routes will be in operation. At 150 EUR this falls to 3.2 million EUR in benefit and 15 routes.

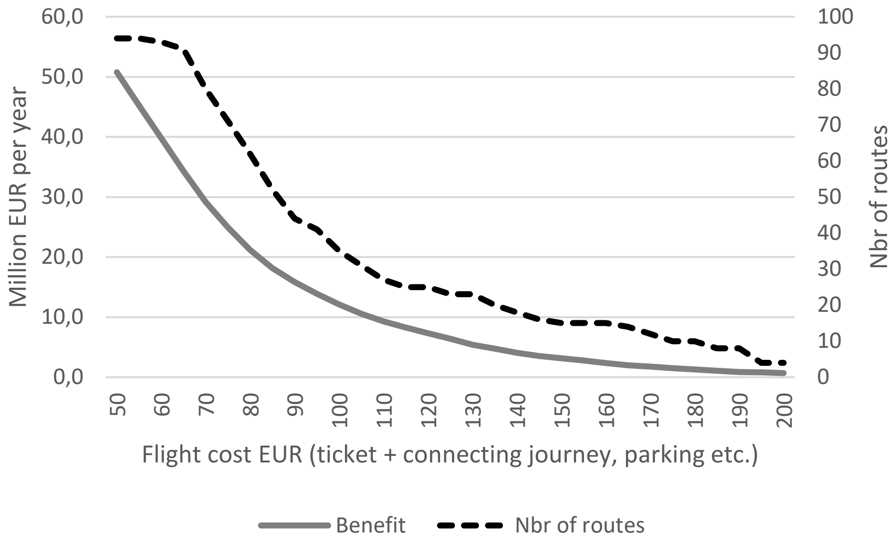


Figure 16. Estimated value of shorter travel time and CO2 savings, and the number of routes that will be operational, given different levels of cost of flying on new routes.

6. Conclusions

In this study, we have attempted to do a first cost-benefit analysis (CBA) for all-electric aviation (AEA) in Sweden and its near-abroad. The main result is that if the technology of AEAs can be made to work in the way we have assumed, they lead to a robustly higher total surplus than the SAF-driven conventional aircraft, at least from 2040 onwards. AEAs could in an important way improve the producer surplus of airlines compared to conventional aircraft using SAFs. The results are robust to changes in the most important underlying variables, namely electricity price, capital cost, and engine maintenance cost, all else equal. Given that the AEAs are slower than conventional aircraft, at least until the A320neo-lookalike is introduced in 2050, consumer surplus falls due to the longer travel time, however. The results indicate that the airlines could compensate the consumers for this by lowering the ticket prices and still retain a higher producer surplus than by running conventional aircraft on SAFs on the routes that could be electrified.

This leads to our second main conclusion pertaining to the introduction of policies to support AEAs. Since the AEAs, if the technology works, are not disadvantaged compared to conventional aircraft with regard to the running costs, the most important thing is to get the technology to work. To this end, public subsidies to technological development may be useful. We have not done an own analysis of an appropriate level of research and development (R&D) subsidies. However, a literature studying directed technical change endogenizes the decision by private companies to invest in a certain type of technology: clean or conventional. Especially the question of how to forward R&D in renewable electricity production has been studied. This literature is summarized in three recent papers by Hémous and Olsen (2021), Dechezleprêtre and Hémous (2022), and Greaker and Popp (2022), and results in a conclusion that new, energy efficient technologies need public subsidies to be able to attract enough private capital for technical change to take off.

This work with a CBA for all-electric flight has not been without challenges: doing a CBA for a technology that, at present, only exists at a very small scale is not easy. On the positive side, we have had access to very good data on take-offs and landings, including data on seats supplied, number of passengers etc. What we lack is corresponding data on prices, especially ticket prices on different routes. Moreover, much data does not really exist, for which reason our analysis relies on many assumptions. These include the range of an AEA, the capital cost of such an aircraft, the development of battery capacity and cost over the next 30-odd years, the flying speed, and fuel costs, both for the BAU scenarios and for the AEA. Even the BAU-scenarios rely on many assumptions and uncertainties, starting from the cost of an aircraft, fuel efficiency improvements, use of SAFs etc.

The enormity of the task of collecting and collating such disparate data has necessitated the exclusion of a number of important questions and impacts. Thus, we have not considered the investment costs required of airports to accommodate AEAs. Our analysis of the reduced cost of the high-altitude effect gives some insight into the magnitude of additional benefits from electrification of aviation, however. If the investment cost is lower than the benefits from internalizing the external effects of conventional aviation, then such investment would be beneficial from a societal point of view. Given that the benefits start low in 2030, with few routes to be electrified, our recommendation is to start the investment at the airports with most potential for hosting, from a private point of view, profitable routes. These airports could then act as testbeds for the technology. According to our results, airports that would be interesting to include in the batch of early adopters include the airports in Jönköping, Pajala, Luleå and Gothenburg. Even the Oslo Gardemoen airport would, according to our calculations, be of interest for early electrification from a Swedish point of view.

Another issue related to the investment costs required of airports is that the analysis of routes that are possible to electrify by 2040 indicates a return to a hub-system. If this is the case, investment costs and energy needs in the hub-airports will grow very large. This will necessitate higher investments in new energy infrastructure, possibly to a very high cost, on these airports.

Yet another important question which we have started to answer but where we have not come with a definitive answer pertains to the new routes that might be possible to create if AEAs fulfill their promise of cheaper and quieter flight with less emissions. One problem with such analyses is how to create sensible estimates of ticket prices. By necessity, the analysis becomes in some way circular: based our results, if it is possible to back out the number of potential passengers it would be possible to use the demand function to calculate a willingness to pay for a flight between an origin-destination pair. Interpreting the willingness to pay as ticket price, it would then be possible to use the supply function to calculate the profitability of the route to the airlines at the implied price. If the producer surplus was positive given the willingness to pay, then, it might be possible to introduce electric flight on the route. If not, the next question would be to examine how demand would change if the ticket price were high enough to cover the airlines' costs.

In order to do the iterative analysis of new routes, it would be important to estimate the supply and demand functions with more data: a longer time series combined with better price data, especially better data about the ticket prices. The usage of a panel of data would make it possible to include a measure of GDP-growth in the model, too, and in that way use the model to prognosticate future demand and supply of flight in a better way than what has been done in the present study.

A further question that might benefit from future enquiry is the discrepancy between our results, and the results from studies examining the possibilities for regional markets for electric flight (Grimme, et al., 2020; Roy, et al., 2021). The market studies indicate that AEAs will not be commercially viable if the airplane cannot be automated, i.e., if the cost of personnel is not reduced considerably. According to our results, automation is not necessary for AEAs to replace conventional aircraft using SAFs. However, we have not included all costs in the calculation of marginal costs, e.g., we did not include the cost of the cabin personnel. At the same time, the results in Table 17 show that the calculated mean unit cost in 2019 is almost ten times lower than the average ticket price, and even more for AEAs in the future years studied, which leaves marginal for unaccounted-for costs. On the other hand, the market studies (Grimme, et al., 2020; Roy, et al., 2021) did not compare AEAs to SAF-using conventional aircraft but assumed, instead, the continued use of fossil jet fuel. Considering the large fall in PS expected when the share of SAFs blended into jet fuel increases, this may explain the discrepancy.

Finally, we have excluded hybrid flight from the present study. There are two main reasons for this: first, to calculate the share of hybrid versus battery-driven flight time at the present level of knowledge is very difficult. Such an analysis would increase the uncertainties present in the study further. Second, if hybrids are used to extend the range of a flight, i.e., combustion is used during the cruise-phase of the flight, for flights flying at an altitude higher than 8,000 meters, the high-altitude effect would not be eliminated. Given that the climate externality from intra-EU flights, excluding the high-altitude effect, has been internalized with the inclusion of flight into the EU ETS, hybrids will not contribute to a reduction in the climate impact from flight. In future studies, it would nevertheless be valuable even to include hybrid aircraft.

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Appendix 1

Table 31. Estimation results for supply and demand. Dependent variables: ln(number of seats produced in 2019/2) for supply and ln(number of passengers in 2019/2). The model in column (2) is the preferred one.

	(1)	(2)
Supply		
ln(r(ticket))	-38.72***	-44.43***
	(-3.93)	(-4.72)
ln(r(ticket)) # ln(r(ticket))	1.488***	1.649***
	(4.12)	(4.82)
foreign=0 # ln(fees)	-47.81***	-52.71***
	(-4.20)	(-5.17)
foreign=0 # ln(fees) # ln(fees)	2.577***	2.552***
	(5.13)	(5.82)
ln(p(fuel))	10.90	22.63***
	(0.96)	(3.60)
ln(p(fuel)) # ln(p(fuel))	-0.679	
	(-0.98)	
ln(w(pilot))	5.555**	7.007*
	(2.61)	(2.41)
ln(w(pilot)) # ln(w(pilot))	-0.207+	-0.186+
	(-1.67)	(-1.80)
ln(CAPEX)	4.087	-2.257
	(1.15)	(-0.58)
ln(CAPEX) # ln(CAPEX)	-0.0705**	-0.0273
	(-2.94)	(-0.99)
foreign=0 # ln(r(ticket)) # ln(fees)	3.942***	4.135***
	(4.66)	(5.39)
ln(r(ticket)) # ln(p(fuel))	-2.673***	-2.988***
	(-3.87)	(-4.83)
ln(r(ticket)) # ln(w(pilot))	-0.196	-0.307+
	(-1.17)	(-1.93)
ln(r(ticket)) # ln(CAPEX)	-0.0438	0.288
	(-0.22)	(1.24)
foreign=0 # ln(fees) # ln(CAPEX)	-0.0759	0.409

	(-0.26)	(1.27)
ln(p(fuel)) # ln(CAPEX)	0.907**	0.297
	(2.60)	(0.89)
ln(w(pilot)) # ln(CAPEX)	-0.0568	-0.0301
	(-1.31)	(-0.82)
foreign=0 # ln(fees) # ln(p(fuel))	-2.694***	-2.907***
	(-3.65)	(-4.90)
foreign=0 # ln(fees) # ln(w(pilot))	-0.469+	-0.659*
	(-1.95)	(-2.51)
ln(p(fuel)) # ln(w(pilot))	1.098***	1.199**
	(3.35)	(2.95)
Constant	197.2**	264.0***
	(2.75)	(4.24)
Demand		
ln(p(ticket))	12.24***	12.35***
	(4.39)	(4.40)
ln(p(ticket)) # ln(p(ticket))	-1.073***	-1.081***
	(-4.62)	(-4.63)
ln(ttime)	-0.569***	-0.556***
	(-9.91)	(-9.70)
Charter=1	-0.882***	-0.914***
	(-3.87)	onl
ln(catchment)	-0.553***	-0.555***
	(-25.87)	(-25.96)
Constant	-26.67**	-26.96**
	(-3.24)	(-3.26)
Observations	505	505
AIC	3326.0	3178.1
BIC	3440.1	3288.0

t statistics in parentheses

+ p<0.1, * p<0.05, ** p<0.01, *** p<0.001

Appendix 2

Producer surplus from electrified routes, all routes in 2030, the ten routes with the highest and the lowest PS in 2040 and 2050, respectively. Producer surplus in EUR_{2021}/route and year for conventional flight using Fischer-Tropsch as the marginal fuel, and for AEAs, respectively. In 2030, only four electrifiable routes have a positive PS.

Table 32. Mean producer surplus and the 95 percent confidence intervals, EUR_{2021}/route and year. Calculated for 2019, conventional flight using Fischer-Tropsch as the marginal fuel, and AEAs with two definitions of electricity consumption, for 2030, 2040, and 2050, respectively.

Year 2030

Origin	Destination	Airplane	PS 2019	95% Conf. Interval		PS FT	95% Conf. Interval		PS AEA design miss.	95% Conf. Interval		PS AEA fossil kWh	95% Conf. Interval	
			Mean	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**
Jönköping	Oslo/ Gardemoen	BE20	41 647	25 748	57 546	37 017	22 992	51 041	78 613	40 951	116 275	72 335	37 995	106 674
Pajala	Luleå	BE20	5 980	4 014	7 947	4 910	1 734	8 087	7 065	5 153	8 976	6 302	5 037	7 566
Luleå	Pajala	BE20	6 070	3 996	8 144	5 090	1 803	8 378	5 913	4 231	7 595	5 505	4 433	6 576
Göteborg/ Landvetter	Oslo/ Gardemoen	CL35	4 973	2 650	7 297	3 216	1 146	5 287	3 866	-4 390	12 122	2 767	-808	6 342
Göteborg/ Landvetter	Århus/ Tirstrup	SW4							1 555	-251	3 362	2 368	1 131	3 604
Göteborg/ Landvetter	Oslo/ Gardemoen	FA7X	7 433	3 959	10 906	5 492	3 115	7 869	-210	-7 659	7 240	1 178	-1 318	3 674

Stockholm/ Arlanda	Sveg	BE20	6 289	4 247	8 331	6 686	3 723	9 650	-466	-2 761	1 829	1 234	-230	2 699
Umeå	Åre Östersund	BE20	3 716	3 113	4 320	4 061	3 387	4 735	-3 246	-7 499	1 008	-1 528	-4 286	1 231
Åre Östersund	Umeå	BE20	3 722	3 120	4 324	4 073	3 398	4 747	-3 270	-7 514	973	-1 541	-4 291	1 208
Year 2040	**The ten routes with the highest PS**													
Origin	**Destina-tion**	**Air-plane**	**PS 2019**	**95% Conf. Interval**		**PS FT**	**95% Conf. Interval**		**PS AEA design miss.**	**95% Conf. Interval**		**PS AEA fossil kWh**	**95% Conf. Interval**	
Göteborg/ Landvetter	Stockholm/ Arlanda	F50	38 967	28 542	49 391	29 369	21 932	36 806	80 618	55 211	106 026	67 804	46 954	88 654
Stockholm/ Arlanda	Göteborg/ Landvetter	F50	39 730	29 055	50 405	30 017	22 366	37 669	80 210	54 943	105 477	67 439	46 713	88 165
Jönköping	Oslo/ Gardemoen	BE20	41 647	25 748	57 546	32 527	20 232	44 821	75 012	39 277	110 746	68 732	36 301	101 164
Stockholm/ Arlanda	Riga/ Skulte	GLEX	37 692	23 760	51 623	27 823	17 504	38 141	72 728	40 609	104 848	50 253	28 973	71 534
Hemavan/ Tärnaby	Lycksele	SF34	35 042	22 005	48 080	26 724	17 162	36 285	67 282	38 361	96 204	61 659	35 434	87 884
Lycksele	Hemavan/ Tärnaby	SF34	31 850	19 977	43 722	24 022	15 471	32 573	64 243	36 418	92 069	58 790	33 606	83 974
Jönköping	Karlstad	SF34	22 117	16 033	28 201	15 194	11 296	19 093	55 542	35 260	75 824	49 940	31 966	67 914

Hemavan/ Tärnaby	Lycksele	F50	22 983	18 123	27 842	15 449	12 444	18 454	50 936	35 610	66 262	42 112	29 885	54 339
Lycksele	Hemavan/ Tärnaby	F50	21 541	17 162	25 921	14 342	11 692	16 992	48 862	34 256	63 468	40 292	28 693	51 891
Jönköping	Stockholm/ Arlanda	SF34	17 543	13 837	21 249	11 235	9 346	13 124	48 792	34 890	62 693	40 560	29 494	51 627
	The ten routes with the lowest PS													
Stockholm/ Bromma	Copen-hagen	C680							-5 558	-11 513	396	-863	-2 805	1 079
Göteborg/ Landvetter	Hamburg	C650							-6 209	-13 058	640	-1 612	-4 001	777
Stockholm/ Arlanda	Helsinki	C25A	3 938	2 867	5 008	4 464	2 115	6 813	-6 231	-12 226	-237	-2 038	-4 388	311
Stockholm/ Bromma	Helsinki	FA7X	3 749	2 381	5 117	2 015	-68	4 098	-6 463	-11 645	-1 281	523	-674	1 720
Stockholm/ Arlanda	Oslo/ Gardemoen	C25A	3 877	2 456	5 297	4 715	1 962	7 469	-6 617	-12 147	-1 087	-1 974	-4 038	90
Stockholm/ Arlanda	Helsinki	FA7X	2 668	1 700	3 635	2 065	-1 091	5 222	-6 755	-12 582	-928	221	-1 014	1 456
Stockholm/ Arlanda	Copen-hagen	GLF6							-7 471	-14 468	-473	62	-1 103	1 227
Stockholm/ Bromma	Copen-hagen	BE40							-7 928	-13 683	-2 174	-2 853	-5 324	-381

Stockholm/ Arlanda	Copen- hagen	E135							-8 710	-15 261	-2 160	-1 999	-3 929	-69
Stockholm/ Bromma	Århus/ Tirstrup	P180							-9 505	-15 728	-3 283	-4 778	-8 009	-1 546
Year 2050	**The ten routes with the highest PS**													
Origin	**Destina- tion**	**Airpla ne**	**PS 2019**	**95% Conf. Interval**		**PS FT**	**95% Conf. Interval**		**PS AEA design miss.**	**95% Conf. Interval**		**PS AEA fossil kWh**	**95% Conf. Interval**	
Malmö	Stockholm/ Arlanda	B733							95 592	62 816	128 368	117 394	76 535	158 253
Stockholm/ Arlanda	Malmö	B733							91 389	60 074	122 703	112 680	73 456	151 904
Göteborg/ Landvetter	Stockholm/ Arlanda	F50	38 967	28 542	49 391	22 787	17 059	28 515	79 262	54 377	104 148	66 439	46 097	86 780
Stockholm/ Arlanda	Göteborg/ Landvetter	F50	39 730	29 055	50 405	23 357	17 443	29 272	78 859	54 112	103 606	66 078	45 859	86 297
Jönköping	Oslo/ Gardemoen	BE20	41 647	25 748	57 546	26 273	16 160	36 385	73 834	38 731	108 937	67 554	35 747	99 361
Stockholm/ Arlanda	Riga/ Skulte	GLEX	37 692	23 760	51 623	21 055	12 700	29 410	71 588	40 119	103 056	49 093	28 417	69 770
Hemavan/ Tärnaby	Lycksele	SF34	35 042	22 005	48 080	21 019	13 620	28 418	66 080	37 820	94 339	60 452	34 878	86 026

Lycksele	Hemavan/ Tärnaby	SF34	31 850	19 977	43 722	18 654	12 155	25 153	63 078	35 902	90 255	57 621	33 075	82 167
Jönköping	Karlstad	SF34	22 117	16 033	28 201	10 447	7 496	13 399	54 401	34 654	74 149	48 794	31 343	66 245
Göteborg/ Landvetter	Billund	A320	50 926	31 165	70 686	32 709	20 535	44 883	53 722	32 395	75 048	72 619	42 774	102 464
	The ten routes with the lowest PS													
Stockholm/ Arlanda	Billund	C25A	2 462	1 631	3 292	2 834	768	4 900	-7 070	-14 913	774	-3 312	-7 472	847
Stockholm/ Arlanda	Copen-hagen	GLF6							-7 171	-13 911	-432	359	-757	1 475
Stockholm/ Bromma	Berlin	CL60							-7 186	-15 653	1 281	-1 875	-4 886	1 135
Stockholm/ Bromma	Copen-hagen	BE40							-7 578	-13 093	-2 064	-2 504	-4 787	-221
Stockholm/ Arlanda	Copen-hagen	E135							-8 357	-14 647	-2 067	-1 647	-3 402	107
Stockholm/ Bromma	Århus/ Tirstrup	P180							-9 108	-15 069	-3 147	-4 381	-7 384	-1 379
Stockholm/ Bromma	Berlin	C560	2 354	1 264	3 444	3 537	1 657	5 417	-9 327	-17 121	-1 532	-3 405	-6 683	-128
Stockholm/ Bromma	Berlin	C56X	2 886	1 913	3 859	3 433	1 638	5 229	-9 397	-15 223	-3 572	-2 784	-5 173	-394

Stockholm/ Arlanda	Vilnius	BE20	1 045	-100	2 191	4 427	2 959	5 896	-9 507	-16 575	-2 440	-4 832	-8 602	-1 063
Göteborg/ Landvetter	Düsseldorf	C550							-11 004	-18 049	-3 959	-5 003	-8 373	-1 633