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Decarbonization Paths for the Dutch Aviation Sector

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Abstract: To reduce aviation's climatic impact, there are international, regional and national policies in place and under development. The most firm policy measure to reduce net CO_2 emissions from aviation is ReFuelEU Aviation, requiring 70% of fuel tanked in the EU to be net CO_2-free in 2050. Considering the technological options available, expected improvements in airline operational efficiency and aircraft efficiency, as well as considering behavioral factors that influence aviation travel demand, a path for the complete decarbonization of the Dutch aviation market is provided. The path implies increasing the share of CO_2-free energy carriers to 100% in 2050 for all departing and arriving flights. Methodologically, first, the aggregate ticket price increase as a result of this policy is estimated. Second, demand price elasticity factors are applied to the price increase to estimate the impact of complete decarbonization on the number of passengers carried by the Dutch aviation sector in 2050. The findings outline that a shift to exclusively CO_2-free energy carriers will result in a 15% reduction in the number of passengers in 2050 compared to the market development under ReFuelEU Aviation obligations. The Dutch aviation sector will still grow from 81 million passengers in 2019 to between 98 and 138 million in 2050, but the growth rate will be significantly lower than before 2019. The expected sustainable energy requirements will be 171 PJ per year in 2050, with a likely range between 146 and 206 PJ, representing no substantial change from the 2019 level of 166 PJ.

Keywords: aviation decarbonization; aviation CO_2 emissions; decarbonization policy analysis; sustainable aviation fuels; aviation system efficiency; travel demand analysis

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1. Introduction

Global aviation is responsible for about 2.4 percent of global CO_2 emissions [1]. The vast majority of these emissions are not the responsibility of individual countries. Based on the IPCC agreements, countries only have to include emissions from domestic activities in their emission totals; international aviation does not belong to the scope of domestic activities. Aviation emissions, therefore, fall outside the scope of national emission targets, such as the Dutch target to reduce greenhouse gas emissions by at least 55 percent by 2030 compared to 1990 [2].

Dutch aviation is an important contributor to the climate challenge. In 2019, the last year before the COVID-19 pandemic, CO_2 emissions from aviation in the Netherlands were approximately 12 megatons measured by the amount of tanked fuels [3]. These CO_2 emissions from the aviation sector are comparable in volume to the emissions from passenger car traffic in the Netherlands. In addition, the non-CO_2 climate effects related to emissions of nitrogen oxides, soot particles, sulfate and condensation trails at cruising altitude also have a substantial influence on the climatic system.

The growth rate of aviation has been high, which means that if this growth continues into the future, the share of aviation in the climate problem will increase sharply. Specifically for the Netherlands, the transport volume in aviation has increased by 85% in the twenty years between 1997 and 2017 [4], much more than the 20% growth in road traffic in the same period [5]. Such strong growth cannot be kept up with efficiency improvements only. The demand for aviation transport services can continue to grow in the Netherlands; however, the growth and its limits depend on the policy space that regulates the aviation sector.

The key questions that this paper looks at are the following: Within the realm of climatic policies, is a complete decarbonization of the Dutch aviation sector possible by 2050? (This paper defines the decarbonization of the Dutch aviation sector as the execution of flights departing from the Netherlands and the execution of flights departing from foreign locations, both in EU and non-EU countries, using CO_2-free energy carriers. The decarbonization of the Dutch aviation sector, thus, applies to all flights departing from and coming into the Netherlands, irrespective of aircraft registration and carrier domicile). What will it mean for the demand for aviation services? What will be the demand for sustainable energy carriers? What is the scope to reduce the climatic effects of non-CO_2 emissions? Simple aggregate methods were used to quantify the impact on transport demand and estimate the necessary amount of energy carriers needed to decarbonize aviation under the projected aircraft efficiency improvements and technologies that will support the transition to carbon-neutral aviation.

A serious complicating factor for national and European aviation policy is the fact that aviation operates on a global scale. Decarbonization policies require technological shifts, such as changes in aircraft technology and the use of sustainable aviation fuels (SAFs). These technological shifts entail substantial extra costs. If policy is applied at national or European levels, there will be leakages to other jurisdictions. Carbon leakage implies reducing the competitiveness of domestic sectors without achieving the full mitigation objective [6]. Passenger behavior and the behavior of airlines will determine the size of the leakage [7]. The authors strongly acknowledge the possibility of carbon leakages beyond the Dutch aviation sector as a result of national decarbonization policies; this will be dealt with in a follow-up study.

2. Problem and Context

The size of the national aviation sector is measured by its passenger and freight transport volumes. In the Netherlands, the Aeolus model has been developed for the purpose of policy analyses and prognoses [8], which is based on the observed transport volumes related to the Netherlands. Aeolus is a global strategic aviation model, which can be used to estimate the number of air passengers, the amount of air freight and the number of air transport movements at Dutch airports [9].

According to the Aeolus model, for the Netherlands, aviation freight transport is mostly intercontinental, while passenger transport, expressed as the number of passengers, is mostly intra-European transport. European destinations represent the largest number of flights and the largest number of travelers. However, 70% of CO_2 emissions can be attributed to intercontinental flights. Based on the data from the Aeolus model for the basis year of 2017, Table 1 provides an indication of the number of air trips, the distance traveled and the associated CO_2 emissions of Dutch citizens, foreign visitors and transfer passengers via Dutch airports.

The CO_2 emissions of aviation are determined by three aspects: the transport volume, the (energy) efficiency of aircraft and the type of energy carrier used. Between 1997 and 2017, the transport volume increased by 85%, an average growth of approximately 3% per year [4]. At the same time, efficiency (due to more fuel-efficient aircraft, a higher occupancy rate and a higher passenger density measured as the number of passengers per m^2 of space available on the aircraft) improved by approximately 39% in that period or by an average of 1.7% per year. As a result, fuel sales increased by 33% in the same period or by 1.4% per year. Until now, flights have been carried out almost entirely using fossil Jet-A1 fuel; thus, the total emissions have also increased by 1.4% per year.

Table 1. Main quantitative indicators of the Dutch commercial aviation sector (Aeolus data).

Type Transport		Number of Passenger Trips, mln	Distance Flown Per Passenger, km	Total Distance Flown, Gpax-km	CO_2 Emissions, kg CO_2/pax	Total Emissions, Mton CO_2
Dutch		**38**	**3000**	**113**	**275**	**10.4**
Of which	Within Europe	29	1300	38	183	5.2
	Intercontinental	9	8100	75	561	5.2
Of which	Business-related	9	2600	22	247	2.1
	Non-business	29	3100	91	284	8.3
From, to or via Dutch airports		**63**	**3800**	**243**	**333**	**21.2**
Of which	Within Europe	42	1200	52	174	7.3
	From/to or via Europe	21	9000	191	649	13.8
Of which	Business-related	18	3400	63	309	5.7
	Non-business	45	4000	181	343	15.5
Of which	O/D passengers	50	2900	143	266	13.3
	Transfer	13	7900	100	624	7.9

The expectation is that the size of the aviation sector, measured in the number of passengers and tons of cargo (also expressed in passenger–kilometers and freight ton–kilometers), will continue to grow. The main Dutch airport, Schiphol, will probably remain slot-restricted with a maximum number of aircraft movements per year determined by government policy. Thus, there is a distinction between the number of aircraft movements and the transport volume, which could still grow, even if the number of flights is restricted due to larger aircraft being deployed at and to Schiphol.

Not only do the CO_2 emissions from aviation impact the climate, there are estimations of the impact of non-CO_2 emissions on the climate [10]. Contrails and emissions of nitrogen oxides (NO_x) are considered to have a strong warming effect; emissions of NO_x are also detrimental to human health. The uncertainty of the warming effect of non-CO_2 emissions is large; however, it is reasonable to assume that at least the short-lived effects of non-CO_2 emissions could be high. NO_x and water vapor emissions are inherent in the technology of the jet engine where fuel is burnt. It is argued later in the paper that the warming effect of the contrails can be reduced substantially at a relatively small penalty of extra fuel burn, as aircraft can be made to avoid regions where long-lived contrails can form.

Further growth of the volume depends on supply and demand. The supply side is partly determined by the limitation of aviation; the demand is mostly determined by population size, economic growth and the costs of aviation services. Both the population and the economy are expected to grow long term, as are the costs related to decarbonization efforts. In addition to systemic studies on the decarbonization of the EU transport system [11], to our knowledge, there is no scientific contribution that assesses the impact of the complete decarbonization of aviation, taking into account policies that are already in place and accounting for the uncertainty in the demand growth, especially in the context of the national Dutch aviation sector. The main research question this paper addresses is, therefore, the following: Based on the current understanding of the known future aviation policies, the technological development of both aircraft and energy systems, population and economic development, behavior change, and under the condition of CO_2 neutrality of the Dutch aviation sector in 2050, what is the expected impact on the passenger transportation volumes, and what are the energy requirements for the provision of sustainable aviation energy carriers?

3. Current Aviation Policy Context

For Dutch aviation, as a part of the global aviation system, policy can be split into three levels: international policy, European policy and domestic policy.

International policy: In the Paris Climate Agreement, the climate task for international aviation has been laid down by the International Civil Aviation Organization (ICAO). The ICAO has drawn up the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) climate plan to tackle the climate challenge, which includes funding for reforestation and renewable energy projects worth approximately 2% of annual revenues. Recently, the ICAO has adopted a long-term global aspirational goal (LTAG) for international aviation of net zero carbon emissions by 2050 in support of the Paris Agreement's temperature goal [12]. The Netherlands is a member of the ICAO, and the LTAG agreements apply to the Dutch aviation sector. Net zero carbon emissions by 2050 may be achieved by many means, including emission offsets; therefore, the climatic impact of these policies will strongly depend on how these measures are implemented and the implementation quality.

European policy: In 2021, the EU proposed an ambitious climate policy package in the form of the FitFor55 program. For aviation, it includes three major components: the ReFuelEU Aviation initiative that mandates the share and type of SAFs in jet fuel; the participation of aviation in the EU Emission Trade System (EU ETS) with no free emission permits for intra-EU flights; and the inclusion of jet fuel into the EU Energy Taxation Directive (ETD). The obligations under ReFuelEU require a 34% share of SAFs in 2040 and 70% in 2050, with SAFs estimated to cost three times more than conventional fossil jet fuel; the EU ETD may establish a tax of EUR 0.37 per liter of fossil jet fuel; and the EU ETS may add EUR 0.24 per liter at the current (July 2023) permit prices of EUR 90 per metric ton of CO_2. Once fully implemented, these policy measures together will have a strong impact on fuel costs and, thus, transportation unit costs, making flying passengers and freight substantially more expensive than without these policies.

Dutch policy: The national policy is centered on voluntary agreements (Duurzame Luchtvaarttafel) to limit emissions [13], the taxation of air tickets [9,14], and capacity restrictions to reduce noise pollution for the local population [15], mainly in the form of limiting the number of flight movements at Amsterdam Schiphol Airport [16]. The implemented national policy, therefore, does not have a direct impact on the emissions of the Dutch aviation sector. To control emissions from the aviation sector, some new policy measures are under study and development, such as capping the allowable emissions of departing flights through the so-called "CO_2 ceiling" set at each airport [14].

4. Available Decarbonization Solutions

The complete decarbonization of aviation means the use of sustainable net zero CO_2 sources of energy and energy carriers. As these sustainable energy carriers, at least in the near term, are scarce and expensive, improvements in efficiency (aircraft and operational efficiency) and demand reduction for air transport may expedite the achievement of the goals of decarbonization. Further, as not only CO_2 emissions impact the climate system, a way of mitigating non-CO_2 climatic effects is discussed.

For the foreseeable future, the propulsion technological options available can be split into two categories, namely, classical ones based on turbine engine architecture where fuel is burnt internally to drive propulsion systems and electrical drives for propulsion.

I ***Classical turbine engine architecture*:** This is the established technology that is used on almost all currently flying commercial aircraft. Decarbonization paths for turbine engines include the replacement of fossil-based fuel with fuels that do not emit CO_2 into the atmosphere (net zero CO_2) through the complete life cycle. The use of these net zero CO_2 fuels may require some adjustments to engine technology to account for specific fuel properties; however, these adjustments can be relatively easily achieved in State-of-the-Art systems. There are essentially three possible alternatives:

1. **Bio-based fuels:** The climate neutrality of bio-based fuels relates to the fact that CO_2 molecules released during combustion come from the atmosphere in the first place when the bio-feedstock grew, as opposed to fossil fuels, where carbon atoms, and hence CO_2, come from underground sources. Ignoring the possible emissions of CO_2 during the production and distribution cycle, bio-based fuels can be said to have net zero CO_2 emissions along their life cycle. There are a number of ways to produce bio-based fuels [17,18], of which hydro-processed esters and fatty acids (HEFAs) are the dominant ones at the moment. As used cooking oil is the main feedstock for the HEFA process, it has a limited scale-up potential. The technology based on gasification and the Fischer–Tropsch process provides a scale-up potential as it may use forestry residues, (wheat) straw and other abundant cellulose sources as the input. The European Renewable Energy Directive (RED II) limits the use of crops suitable for consumption as an energy source for transport [19]; therefore, only feedstocks that do not compete with food production chains or result as a byproduct or waste from these chains can be seen as a long-term suitable source for the production of aviation biofuels. For example, the author of [20] makes a case for low-cost cellulosic-based SAF production from hybrid poplars (wood) using the pyrolysis process. The costs are estimated to be around USD 8 per gallon (around EUR 2 per liter);
2. **Synthetic fuels** (also called e-fuels): Synthetic jet fuel can be made from hydrogen (produced via electrolysis from renewable electricity) and a carbon source, which is usually CO_2. Electrolysis, as a source of hydrogen, gives these fuels alternative names, such as e-fuel and e-kerosine. ReFuelEU mandates that 35% of SAFs in 2050 should be based on e-fuels. The advantage of e-fuels is that they are not bio-based and, thus, do not have a bottleneck in the form of bio-feedstock availability. On the downside, synthetic fuels require large quantities of green energy (e-fuel's production process efficiency is limited) and a source of CO_2. In the advanced stages of decarbonization, CO_2 sources such as flue gasses will be scarce, and the technology may rely on obtaining CO_2 from the atmosphere through the direct air capture (DAC) process. The DAC process has not yet reached commercial maturity; it also requires substantial energy input. The path of synthetic fuel production and scale up is, thus, challenged by the limits in efficiency, energy availability, sources of CO_2 and technological immaturity;
3. **Hydrogen:** Hydrogen can be produced from water in electrolyzers using renewable electricity. The efficiency of commercial or near-term technologies is within 59–82%, measured as the percentage of thermal hydrogen output to electric energy input in the electrolysis process [21]. Although the current generation of jet engines can burn hydrogen (requiring relatively small adjustments to account for hydrogen combustion properties), the storage of hydrogen on an aircraft requires new aircraft designs. For example, hydrogen cannot be stored in the wings; a voluminous storage tank has to be put in the fuselage. There is also the issue of hydrogen distribution at airports, which is presently non-existent.

II ***Electric engine architecture*:** An electric engine can be used to generate mechanical energy to drive propulsion systems. There are potentially two onboard sources of electricity for this architecture:

  1. **Energy stored in onboard batteries**: The battery–electric aircraft concept is developing quickly, with some niches that can already be filled by this concept. However, without a breakthrough in battery technology, electric aircraft will be very limited in their operation scope, mainly due to the energy density of the batteries, 265 Wh/kg for batteries compared to 11,950 Wh/kg for jet fuel [22]. This factor 45 difference in energy density between batteries and jet fuel, even taking into account the higher efficiency of the battery–electric propulsion chain, will be the limiting factor for the large-scale deployment of battery–electric aircraft;

2. **Electricity produced on board in fuel cells:** The low-energy density of batteries can be supplemented with the production of electricity on board using fuel cells. This will require a hybrid solution, where electricity from fuel cells is supplemented with battery power in peak demand moments, such as takeoff and go-around. Le Bris [23] makes a case for hybrid battery–hydrogen aircraft as a stepping stone to fully hydrogen aircraft; ZeroAvia is planning the commercial exploitation of this solution with a 19-seat aircraft flying between Rotterdam and London [24]. The hybrid solutions still have the infrastructural limitation of the hydrogen infrastructure chain. Fuel cell solutions come with a large weight penalty of their own; the current generation fuel cells weigh 0.625 kg per kW of power [25]. For the cruise phase of the flight, a typical B737 or A320 needs around 10–15 MW, which would add 10 tons to the aircraft weight to only integrate the fuel cells. (The empty weight of the current generation of this type of aircraft is between 40 and 50 tons.) A hybrid solution would, thus, require much heavier aircraft designs; thus, the scale-up potential of this technology to larger aircraft is not clear at this moment.

Based on these considerations, the evidence points out that net zero CO_2 drop-in sustainable fuels will be the main decarbonization means for aviation until 2050. There seem to be enough sustainable feedstocks available in the EU that fulfill the sustainability criteria and could be utilized to meet the short- and medium-term SAF targets; however, there will be a lack of actually available biomass in the EU in 2050 [26], and the emphasis may shift toward synthetic fuels. Hydrogen can play a role in commercial aviation after 2040; still, its role will be limited to short–medium-haul operations and the availability of the infrastructure on both ends of the flight. It is assumed that the costs of sustainable energy carriers, both liquid SAFs and hydrogen, will be three times higher than the cost of fossil-based jet fuel on a per energy unit basis. The uncertainty is high in this estimation; there are some types of SAFs that are estimated to cost less, and some types of SAFs that cost more [27]. The present cost estimations do not explicitly take into account the volatility in fuel prices, as well as the fact that not only aviation will have to decarbonize; other sectors such as long-distance shipping and industry will compete for these resources too. Thus, the price will be driven by demand and supply for sustainable energy carriers.

The non-CO_2 emissions of aircraft operation contribute to the climatic effects of the aviation industry. A comprehensive summary of these effects can be found in Lee et al. [10]. Although uncertainty with respect to the quantification of the climatic effects of non-CO_2 emissions is large, the most important contributors to climate change are NO_x emissions and long-lived condensation trails (contrails) that aircraft leave under certain atmospheric conditions. NO_x emissions are intrinsic to the high temperatures of burning fuels; only electrical designs (battery and fuel cell–battery) avoid it completely. The contrails can be dealt with efficiently and at relatively low additional operational costs by avoiding areas of airspace where long-lived contrails can form. If the vertical boundaries of contrail-forming areas are known, an altitude change of 300 m would be sufficient to avoid about 50% of the areas where contrails are formed [28]; an elevation change of 600 m would be enough to avoid about 80% of the areas. In addition, 50% of long-lived contrails can be avoided with a 1% increase in fuel consumption [29]. The main challenge of this approach currently is the unavailability of precise and complex data about humidity levels at higher flight levels, which are necessary for the prediction of ice-supersaturated regions [30]. However small the operational cost penalty is, the economics of airline operations do not suggest voluntary avoidance of areas where contrails can form. There is a need for a policy that would shift the economic balance of airline operations toward avoidance of these areas.

Improvement in efficiency

Improvement in efficiency can be split into two forms, operational efficiency and aircraft efficiency. Operational efficiency is related to how efficiently aircraft capacity is used (the number of people per m^2 of floor space as a function of seat density, load factor, and cargo load factor) and route efficiency.

The evidence suggests that improvements in operational efficiency have a rather limited potential. In recent years, full-service carriers (FSCs) have shown a tendency to match the seat layout density of the economy class to that of low-cost carriers (LCCs). For instance, the cabin of the KLM Boeing 737–800 now contains 186 seats, while the cabin of RyanAir of the same aircraft type contains 189 seats, which is the legal exit limit for this type of aircraft. The aircraft utilization rates with respect to passenger loads also reached the limits; according to carriers' public reports, load factors for LCCs such as EasyJet and RyanAir reached 93% and 96%, respectively, in 2019. KLM, as an example of an FSC, reached an 89% load factor. Given the natural variability in travel demand, passenger load factors cannot reach 100%; in other words, the potential to increase load factors in the future is likely to be limited. Cargo load factors are generally lower than those of passengers; cargo shows trade imbalance, as in one direction (e.g., from Asia to Europe), there is, on average, more cargo than in the other direction (from Europe to Asia). Cargo load factors may also be restricted by aircraft operational limits, as a full cargo load may substantially reduce the maximum flight distance, and hence, on longer routes, aircraft cannot be 100% utilized without a need for a fuel stop.

The efficiency of aircraft is expected to increase. Grewe et al. estimate [31] that the generation of aircraft that enters service in 2035 will be 22% (single-aisle) and 18% (double-aisle) more efficient than the current State-of-the-Art generation (Boeing 737-Max and Airbus 320 NEO for single-aisle; Boeing 787 and Airbus 350 for double-aisle type). For 2050, the authors [30] project an improvement of 38% for single-aisle and an improvement of 25–34% for conventional double-aisle aircraft designs, with possibly an improvement of up to 44% for the most advanced future designs. Given the fleet renewal cycle, an approximation of fuel economy development suggests that the Dutch aviation sector will consume 71% of energy per passenger–kilometer compared to 2019.

Reduction in demand for aviation transport services

In the Dutch aviation market, there are two factors that would probably reduce demand for travel with respect to the autonomous demand growth trend. The first factor is behavioral, namely, the long-term shift in business practices related to the COVID-19 pandemic. Businesses are now used to teleconferences as a substitute for physical meetings, as well as a more broad populational awareness of the environmental impact of aviation. The second factor is purely economical, as the higher ticket prices due to the use of more expensive SAFs will reduce demand for air travel.

For **the behavioral factor**, there is quite a lot of uncertainty. A McKinsey report [32] estimated that business travel will take longer to recover from the pandemic, and even then, it will only likely recover to around 80% of pre-pandemic levels by 2024. Using US national-wide panel survey data of 2973 respondents, the authors conclude [33] that 41% of pre-COVID-19 business travelers expect to take fewer flights after the pandemic, while only 8% anticipate more flights compared to pre-pandemic. Videoconferencing provides a clear way to save costs and time related to meetings, however, at the expense of the travel experience and social bonding. Based on a sample of 245 business travelers, the authors [34] show that the predicted decline in business travel volume of 20–30% might be realistic. The decision between videoconferencing and face-to-face meetings depends on the meeting type and the objective of the business person who is to meet people in remote locations. For the leisure traveler, a change in social norms can impact the decisions on how to travel or even whether to travel to far-away destinations. "Flight shaming" is an established term; however, it is still too early to draw conclusions on its impact on the volumes of global aviation. Based on an online survey [35] conducted in Germany with 1000 participants, a conclusion is drawn that although respondents do not report a significant change in travel behavior, a two-third majority of respondents indicate support for market-based measures increasing the cost of flying, as well as policies forcing airlines to reduce emissions and legislation abolishing subsidies. There is some evidence that if costs are increased due to the carbon price, fewer people will fly than when the same price increase is a result of an operational price increase, suggesting environmental awareness may play a role in the decision to fly [36]. This implies that positive policies requiring the decarbonization of aviation and entailing ticket price increases may be broadly supported population-wise.

For **the economic factor**, an increase in ticket price reduces demand for air travel. For aggregate estimations, price demand elasticity is a useful tool for the estimation of the impact of higher prices on air travel demand. There is a substantial body of literature on price demand elasticity at the micro level, the level of individual airlines and routes, for example [37], as airlines are interested in these estimations for their pricing policies. However, for the purpose of understanding how ticket prices impact aggregate demand for air travel, aviation system-wide elasticity estimations are necessary. Similar to the behavioral factor, the uncertainty is high. The authors of [38] provide an overview of the elasticity literature, showing a high degree of variability in elasticity estimations. For the purpose of this study, however, Aeolus model elasticities are used as presented by Romijn, Blom and Hilbers [39]. These estimations of the aggregate price demand elasticity for air travel are -1 for the leisure traveler and -0.5 for the business traveler.

5. Quantitative Estimation

The expectation is that around 2024, Dutch aviation will be back at the level of 2019 in terms of transport volume. The Climate and Energy Outlook (KEV) 2022 [2] expects aviation to grow again after that, by an average of 2% per year; the quantitative estimation presented in this paper builds upon data and assumptions as specified in the KEV [2]. There is an uncertainty in the estimation of autonomous growth for the demand for aviation services. Depending on population growth, economic growth, cost trends and propensity to fly, this autonomous growth could be higher (2.6% per annum) or lower (1.5% per annum). The current estimations provided in the KEV [39] include the restraining effect of the current policy, which is air passenger tax, CORSIA, ETS and SAF blending obligation in accordance with FitFor55 and ReFuelEU.

The combination of more fuel-efficient aircraft and more efficient operations will lead to annual improvements in fuel consumption per unit of transport activity in the coming decades. The Aeolus model assumes a trend-wise improvement in aircraft efficiency (from fleet renewal with new generations of more economical aircraft and operational improvements). The Aeolus model's aircraft efficiency path is in line with Grewe et al. (2021) [31], meaning that in 2050, aircraft energy consumption per unit of transport activity (passenger–kilometer, ton–kilometer) will be 71% of energy consumption in 2021.

Combining aircraft efficiency improvement data with the expected autonomous growth in air transportation demand (including the restraining effect of the now-in-place policy regulations) and applying these to the starting point of the total energy demand of Dutch aviation in 2019 of 167 PJ, the central estimation of aviation energy demand in 2050 is around 200 PJ. Given the uncertainty in the autonomous demand growth, the annual energy needs may lay between 170 and 240 PJ in 2050 (see Figure 1). Note that the stabilization of the number of passengers in the period of 2019–2030 is attributed to the effects of the COVID-19 pandemic and the introduction of a flight ticket tax for departing passengers from the Netherlands. Similarly, the same projections can be calculated for the number of passengers handled at Dutch airports. Starting with 81 million passengers in 2019, the central estimation is 134 million passengers in 2050, with low and high bands of 115 and 162 million passengers, respectively (see Figure 2). Note that these estimations include only currently known policy measures limiting emissions; as discussed further, full decarbonization will restrict further energy demand and the number of passengers.

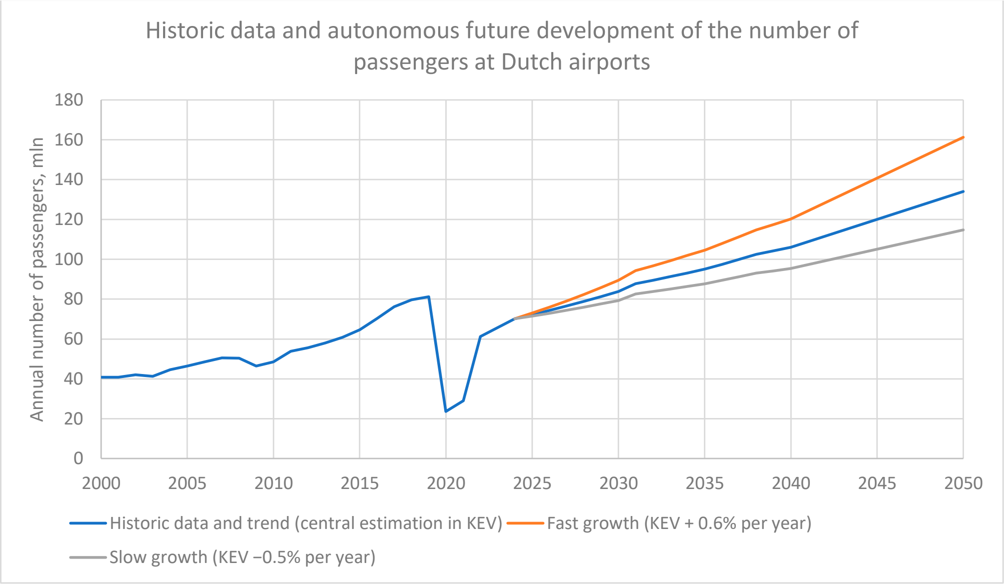

Figure 1. Autonomous development of the number of passengers at Dutch airports on the basis of current policy measures.

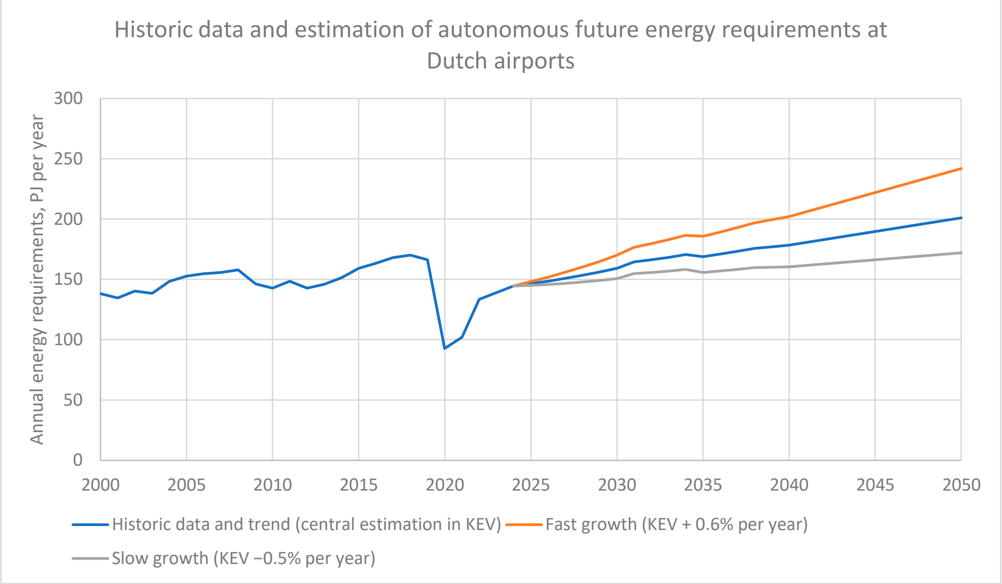

Figure 2. Estimation of energy requirements for Dutch aviation's autonomous development on the basis of current policy measures.

The complete decarbonization of the Dutch aviation sector by 2050 means additional requirements for sustainable energy carriers beyond the requirements of FitFor55 and ReFuelEU. The share of SAFs for intra-EU flights and flights departing from the EU has to increase in this case from 70% to 100%. Moreover, the ReFuelEU does not mandate any blending obligations for flights departing outside of the EU, as these flights cannot be regulated by the EU and fall under the scope of the ICAO agreements (CORSIA and LTAG). Therefore, the obligatory share of SAFs to power flights from non-EU countries to EU countries has to increase from 0% to 100%.

The share of aviation fuel in Dutch aviation that is covered by ReFuelEU (intra-EU flights and flights from the EU to foreign destinations) is 65%. Therefore, in 2050, for this 65%, the share of SAFs has to increase from 70% to 100%. For the remaining 35% of fuel related to flights back from non-EU countries, the share of SAFs will have to increase from

0% to 100%. On the basis of the KEV data [2], a 100% SAF requirement on all flights will add 17% to the ticket price, which only includes ReFuelEU blend obligations, assuming that SAFs are three times more expensive than fossil-based jet fuel.

An increase in ticket prices will reduce demand for air transport services. Using Aeolus demand price elasticities [40] and taking into account the weighted average share of business travelers of 28% in the Dutch market, the average elasticity for all types of travelers is estimated to be −0.86. Taking into account the higher SAF costs compared to fossil Jet-A1 fuel, the application of Aeolus elasticity factors determines the impact of higher ticket prices on travel volumes.

A more stringent decarbonization policy compared to ReFuelEU leading to zero CO_2 flying in 2050 will result in 4%, 11% and 17% higher ticket prices with respect to the KEV path in 2030, 2040 and 2050, respectively. Hence, a demand reduction of −4%, −10 and −15% in 2030, 2040 and 2050, respectively, is to be expected with respect to the KEV path, which is based on the current regulations. The cost increases related to the complete decarbonization of the Dutch aviation sector are in line with the cost increase estimations provided by Dray et al., 2022 [29]. The estimation in [29] is that to reduce lifecycle aviation CO_2 emissions by 89–94% compared with 2019 levels (and despite a 2–3-fold growth in demand by 2050), the aviation sector could manage the associated cost increases, with ticket prices rising by no more than 15% compared with a no-intervention baseline leading to demand suppression of less than 14%.

The complete decarbonization of the Dutch aviation sector in 2050 will still result in growth, even in the slow autonomous growth scenario. Under the condition of the extra costs of complete decarbonization, the application of Aeolus elasticities results in the number of passengers being between 98 and 138 million in 2050, which is higher than 81 million passengers in 2019 (see Figure 3). Decarbonization results, therefore, in a slower growth rate than before 2019. On the energy demand side, the requirement for net zero energy carriers at Dutch airports will be between 146 and 206 PJ per year in 2050 (167 PJ in 2019). The most likely central estimation shows an energy requirement of 171 PJ, which is essentially the same amount as in 2019. The slow growth scenario results in energy requirements consistently under the 2019 level, staying around 145–146 PJ annually in the whole period of 2030–2050 (see Figure 4).

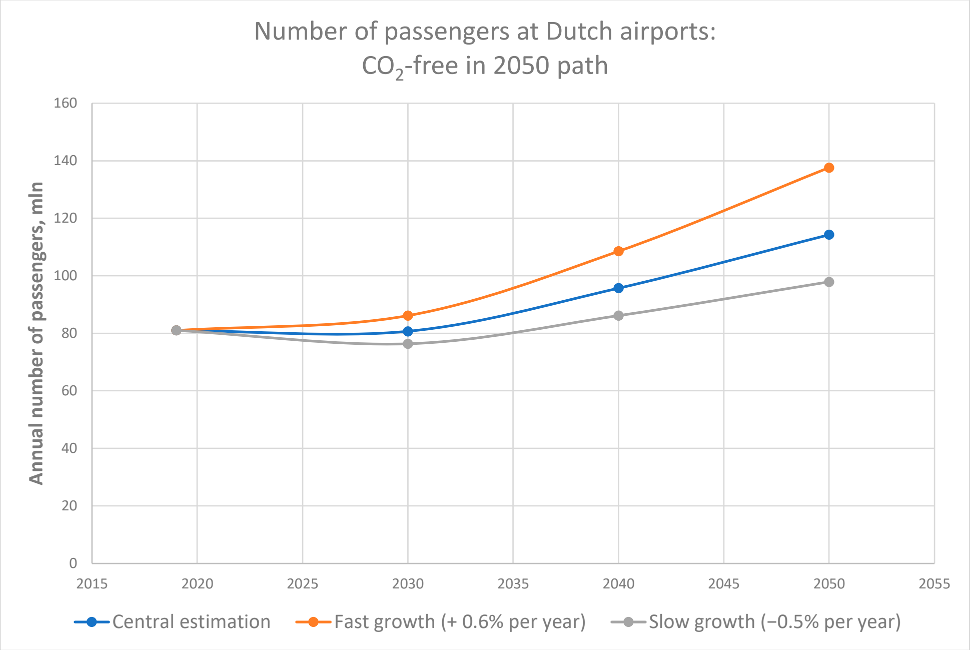

Figure 3. Estimation of the number of passengers at Dutch airports on the path to CO_2-free flying in 2050.

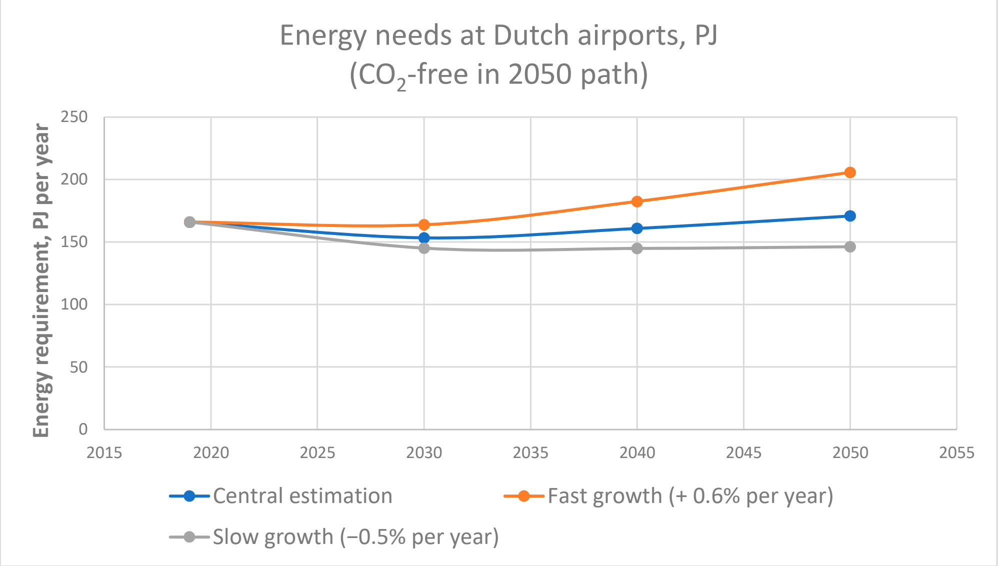

Figure 4. Estimation of energy requirements for Dutch aviation on the path to CO_2-free flying in 2050.

6. Conclusions

The aviation industry is under the challenge of reducing its climatic impact. There are international, European and Dutch policies in place that require a substantial reduction in carbon emissions. The European FitFor55 and ReFuelEU regulations set the sector on a strong decarbonization path toward 2050 through the obligation of blending 70% of SAFs into the fuel tanked at European airports. This paper considers the impact of an extension of this policy to 100% SAFs in 2050 at Dutch airports and the requirement that the flights back from EU and non-EU countries are also powered by CO_2-free energy carriers.

Considering technological solutions that can be scaled up to completely decarbonize aviation, the evidence suggests that SAFs (bio-based and e-fuels) will be the main solution for the task. Hydrogen solutions might be commercially viable closer to 2050, but the greatest share of the decarbonization effort will still be achieved by liquid drop-in fuels.

A strengthening of the decarbonization policies toward net zero CO_2 emissions will reduce the growth in aviation transport volumes. Nonetheless, the expected passenger volumes will still grow in the period of 2019–2050, from 81 million passengers in 2019 to between 98 and 138 passengers in 2050. This growth is 15% less strong than it would be without the strengthening of the ReFuelEU regulation. In line with other estimations [7], it should be acknowledged that if international aviation is more lightly regulated, there will be a substantial leakage of passengers and emissions to foreign carriers.

The analysis of this paper is based on the assumption that, on average, SAFs are three times more expensive than fossil-based jet fuel. The results are sensitive to the SAF cost multiplier as it determines the growth in ticket price. The market price of SAFs is determined by the matching of supply and demand, where demand is determined by how strongly the decarbonization policies are executed, and supply depends on the availability of raw materials and production capacity. Therefore, the success or failure of decarbonization depends on policy execution, including the timely availability of SAFs in the market and enforcing SAF blending obligations in reality.

For future research, two questions stand out. The first question is related to the availability of sustainable energy carriers for the aviation sector: will there be sufficient quantities of sustainable energy to achieve the decarbonization goals by 2050? Although the computations of this paper assume that CO_2-neutral energy carriers will be available in 2050, the reality may be different, especially given the need to decarbonize other sectors of the economy. Aviation will compete for sustainable energy with other transport modes, such as international maritime shipping, as well as industries that heavily use energy.

The second question is related to the possible leakage effects of emissions and passengers. Decarbonization will increase the costs of flying, and hence, these costs will be passed on to the passengers in the form of higher ticket prices. If other regions move slower on the decarbonization path, those regions will gain a cost advantage over the regions that pursue a faster decarbonization path. This may result in passengers shifting to carriers from the lower-cost regions, thus shifting CO_2 emissions to them. Moreover, this shift may result in less optimal routings and the use of less energy-efficient aircraft. Therefore, the amount of leakage effects should be investigated together with the question of what policy measures can ensure a level playing field and prevent leakages.

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