PERSPECTIVES FOR AERONAUTICAL RESEARCH IN EUROPE

PARE

CHAPTER 18

Decarbonisation of Aviation by 2050

Final Report

WWW.PAREPROJECT.EU

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 769220. This publication [communication] reflects the views only of the author, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

Table of Contents

List of Figures

List of Tables

Chapter 18 – Objective Decarbonization of Aviation by 2050

18.1 Executive Summary

Objective and scope

According to ICAO, aviation is responsible for 2% of global CO2 emissions. However, it is expected to occupy an increasingly large share, if it continues to grow as foreseen (5% annually), as other sectors are seeking to reduce their emissions in line with their carbon budgets. Although international aviation community aspire to a 2% annual fuel efficiency improvement and a carbon-neutral growth from 2020, the achievement of this goal is still at risk; and even if achieved, aviation will still produce by 2050 a significant amount of CO2, that might endanger the achievement of the goals of the Paris Agreement.

ICAO 2019 report quantified emissions of the aviation sector over the period 2016-2050 between 56 GtCO2 in a business as usual scenario and 12 GtCO2 in an optimistic, but unlikely to meet, a scenario with technological improvements and 100% of biofuels use. These figures would imply that aviation emissions, from 2016 to 2050, could consume between the 27% and 12% of the remaining carbon budget to keep global temperature rise below 1.5C above preindustrial levels.

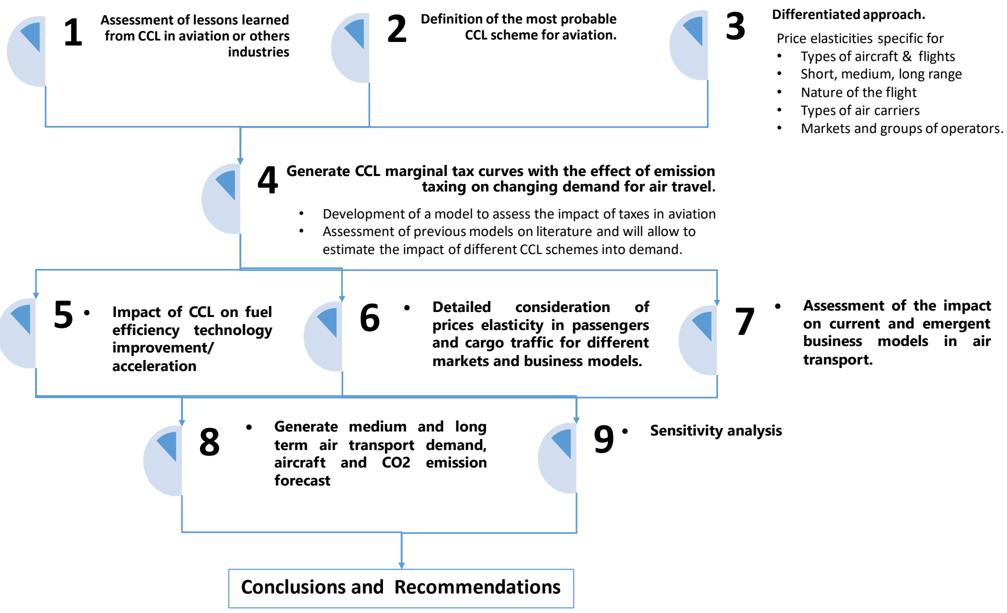
In an attempt to provide insight into the best solutions for aviation decarbonisation and to inform future policy, research, and business strategies, ACARE has defined a set of long-term air transport scenarios. To accommodate the study of these scenarios within the PARE project remaining working time and effort, this pilot what-if study tackles the first of them: Scenario 1 - TAX scenario. Therefore, although other relevant measures to reduce aviation CO2 emissions are tackled in this study, the core part of this pilot what-if analysis pretends to gather analytics and insights to answer how taxing CO2-emissions (Climate Change Levy schemes) will imply significant changes in the aviation industry, including aviation demand, industry and markets structure and emission reduction.

ACARE aviation decarbonization long-term air transport scenarios

Methodology

The methodology proposed in this pilot case study follows a qualitative and analytical approach typical of the market and exploratory studies, with the following main steps:

- Overall assessment of possible solutions and alternatives for aviation decarbonisation.
- Assessment of lessons learned from the implementation of CCL in aviation or other industries.
- Definition of the most probable CCL scheme for aviation.
- Development of a simple and generally applicable model to assess the impact of taxes on aviation.
- Generation of CCL marginal tax curves and its effect on changing demand for air travel. The model and CCL curves consider price elasticities of demand specific for different markets.
- Assessment of CCL impact on fuel efficiency technology improvement and the acceleration of its entry into service.
- Analysis of CCL impact on the evolution of the short, medium and long-range markets.
- Sensitivity analysis.



Methodology for the "pilot what if" study on the Aviation Decarbonisation case.

Climate Change levy schemes.

Recent reports claimed that the expected technology and operations improvements will not mitigate the expected fuel demand and emissions growth from aviation, and that to significantly reduce the expected fossil fuel demand and ultimately eliminate it from the sector would require further measures. For those authors, carbon pricing needs to play a central role in bringing forward further reductions in fuel demand. At this stage, much attention has been devoted to the climate change levy schemes, mostly at the national and local level.[1]

The primary rationale for environmental taxation is the externalities argument. Carbon taxes are a type of Pigouvian tax, this type of taxes seeks to correct a negative or positive externality, in this case, the decarbonization of aviation. By leaving a tax on the pollution-generating activity, the social costs of pollution

[1] In general, this category can be instantiated as charges, taxes, and levies. The term charge usually refers to a mandatory payment of an amount related to carbon emissions, whether implemented as a tax or as a levy. By a tax usually is meant a compulsory payment that is not fully required to those paying it. By levy usually is meant a charge that is fully rebated to the payer, in cash or in kind. For the sake of this study all the three terms are consider equivalents and referred indistinctively.

can be 'internalised' to the agent (who must pay the tax) and the socially optimal level of pollution would occur.

If the tax is expected to cover the social cost of pollution it is necessary to estimate the environmental cost of the emission of one tonne of CO_2. Although this measure is generally recognised as positive, there is no yet a clear agreement on what could be the most convenient type of tax, what should be its value, and what would be the expected impacts. CCL schemes are based on the consideration of the price elasticity of aviation. Assuming an elasticity close to 1, an increase of 1% in price would imply a 1% reduction on the demand. Under different considerations of the price elasticity of aviation, certain authors have recently proposed different tax values. Some authors claim that a tax of € 150/ton CO_2 could be an effective measure to reduce air transport demand and therefore aviation emissions. Others consider a uniform, globally applied CO2 price of $25 per tonne. This emissions price corresponds to the medium damage scenario studied by AGF and is consistent with the US 2010 inter-agency assessment of environmental damages per tonne. Authors claim that a $25 per tonne emissions price would add about US 6 cents per litre, or about 8 percent, to the price of jet fuel. The latest study of Delf for the EU considers the effects of a fuel excise duty on kerosene, equivalent to 330 €/kilolitre, as a 10% increase in the average ticket price and an 11% decline in passenger demand at European level.

Aviation may be subject to different types of taxes, being the most common i) Ticket taxes, ii) distance-based ticket tax, iii) Frequent Flyer Levy (FFL), iv) Value added tax, v) Taxation on aircraft fuel, vi) Environmental taxes and vii) 5. Taxes for air cargo. Although in many countries' aviation is exempted from all taxes, a significant number of countries levy taxes on certain aviation activities. For example, in the European Union, VAT or taxes on domestic flights are the most prevalent and applied in at least 17 states. Six EU states applied some kind of taxes on international aviation, normally in the form of passenger's ticket taxes departing from airports in the country. Outside the EU, 13 countries (including Australia, Canada, USA, Hong Kong, Brazil and Japan) tax aviation activities, in most of the cases in the form of ticket or departure taxes, normally a fixed amount per passenger, depending on the destination or travel class. A small number of countries applies VAT or sales taxes (a levy proportional to the value of the ticket), for example, Japan, Mexico, USA, and Canada. Additionally, commercial air transport, both passengers and cargo operation, is subject to various charges and fees that are not seen as taxes, as these are levied to cover the costs of provided services.

However, aviation is currently under-charged from an environmental perspective. This low charge regime is even more important for international aviation. When it comes to the taxation of aircraft fuel different schemes are applied. Fuel on domestic flights is sometimes taxed (e.g. in the USA or France that charges air freight with a tax of € 1.33 per ton of freight). In contrast, the fuel used on international flights is generally exempt from fuel taxes due to international convention. Unlike domestic transportation fuels, they are subject to no excise tax to reflect environmental damages in fuel prices.

ICAO recommends not to tax the intake of jet fuel based on reciprocity, a practice that is followed by most countries and generally mentioned in bilateral Transport Agreements. In Europe, aircraft fuel for commercial air transport operations is exempt from excise duty; although States may abolish this exemption for intra-Community and domestic flights. The Energy Tax Directive establishes a minimum excise duty rate for kerosene of € 330/1,000 L, a value that is normally taken as a reference to quantify the magnitude of the jet fuel tax exemption.

ICAO (policy doc 8632), and also IATA, recommends, that "international air transport is [to apply a] zero [VAT] rate", to guarantee an equitable treatment for international aviation throughout the many jurisdictions into which it operates. However, domestic air transport is often subject to VAT. States may also impose VAT on fuel, or charges such as airport charges, air navigation charges or service fees. At European level, States may exempt passenger transport from VAT or apply a zero VAT rate, and add some activities for commercial air traffic on international routes should be exempt

from VAT (such as the supply of goods for the fuelling and provisioning of aircraft and other activities). The ICAO Council is strong of the view that any environmental levies on air transport should be in the form of charges rather than taxes, with these directly related to the costs of the resulting damage to the environment. Besides, they argue that any funds collected should be used to mitigate the environmental impact of aircraft emissions.

Modelling the impacts of Aviation Climate Change levy schemes.

As part of the study, a model to calculate CCL marginal curves has been developed. This is an easy to use and generally applicable model that could be employed to assess the effects of the introduction, change or abolition of aviation taxes or aviation-specific tax exemptions. Basic rationally behind the model is that because the various CCL schemes (taxes) affects the price of flying, the first impact is on the aviation demand. The extent to which the demand is changed is given by the price elasticity of demand. The change in demand results in a change of supply, i.e. the number of flights and the RPK changes. This also has an impact on fuel consumption and emissions. The change in demand causes also a change in the output of the aviation sector which has an impact on the cost of flying, fiscal revenue, direct and indirect jobs and value-added, and ultimately in GDP. These impacts are calculated by input-output analysis. Hence, the following impacts can be modelled and projected up to 2050:

- CCL schemes and derived impact on the cost/price of flying.
- Passenger demand.
- Change in RPK and number of flights.
- Change in fuel consumption
- Change in C02 emissions.
- Increase in the flight cost and Fiscal revenue from the aviation sector.

The granularity of the model goes down to flight modelling. Each flight is modelled considering its origin and destination, airline, aircraft model, aircraft model fuel consumption, aircraft passenger's capacity, occupation factor and average ticket price for each flight. The model applies the hypotheses and variations in parameters down to the level of the flight and allows further aggregation of results by route, country, or region, so impacts of taxes can be studied at the level required by the user. Additionally, the model allows projecting the demand, traffic and impacts up to 2050. Reference yearly growth rates are taken Boeing and Airbus forecasts.

The model allows defining three different CCL schemes: taxes on fuel, on VAT and ticket prices. It allows modelling average airport charges departure and flight range, (e.g. different departure airport charges can be modelled at an airport for short, medium, and long-range flight). It also accounts for the specific VAT of any country in the world and allows to define specify VAT tax for each country. Any value of fuel tax could be modelled. Exceptions to the taxes could be modelled also to certain extend. The model will allow making different assumptions on fuel consumption and economic impact of the taxes for different companies if necessary.

Concerning the price elasticity of demand, the model is based on Intervistas [1] study, where several elasticities are provided. These are applied to each flight. Reference year for traffic, demand in RPKs and CO2 calculations of the model was 2018. CO2 calculation has been calibrated by comparing with the actual values of fuel consumption and CO2 emissions in Europe and worldwide for the year 2018. Additionally, results have been found coherent in magnitude to previous studies by ICAO and other sources. CO2 impacts are considered for each flight taken into account the distance of the route and the specific aircraft model fuel consumption. Improvements in fuel efficiency can be incorporated for each flight or a set of flights, allowing to model improvements in fuel consumption technology, removal of a fleet or the introduction of a new and more efficient aircraft model.

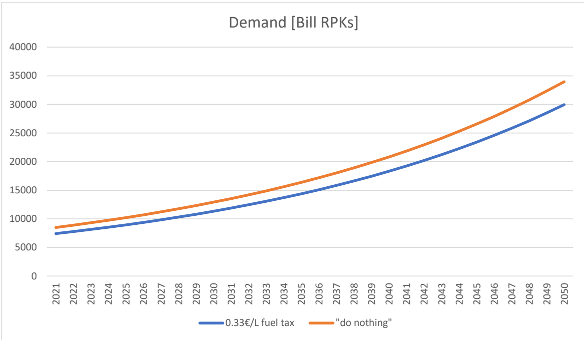
Application of the model.

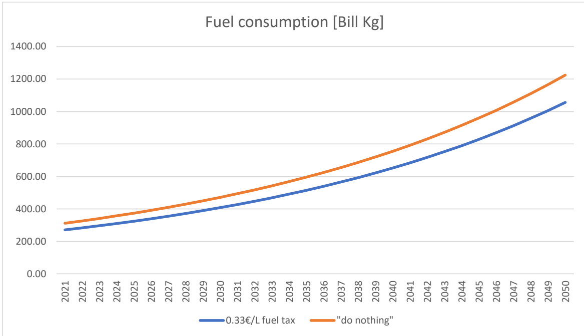
Although the possible applications of the model are broader, in this study it has been used to try to answer some questions about CCL implementation not broadly tackled in the previous work available in the literature. All the following cases are illustrated for a tax on fuel CCL scheme equivalent to the current fuel excise duty of 0.33 € per litre of fuel (equivalent to 0.4€ per Kg of fuel[2]), that will apply in 2021. This value of tax has been selected to easy comparison with the most recent and relevant studies. Note that for the sake of the calculations COVID effect is not considered and traffic in 2021 is calculated as a projection of industrial figures in 2018.

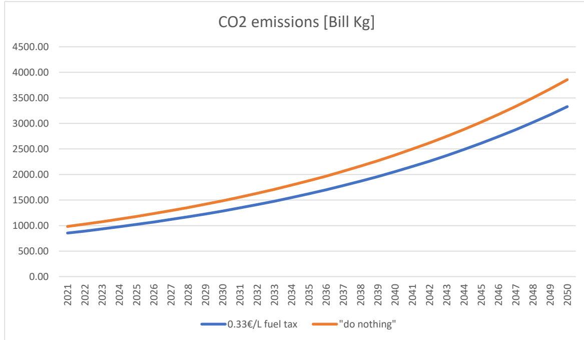
- Overall results: demand, fuel, CO2, and fiscal revenue.

As a starting point, the Figure 18. 7 presents the overall results of applying the mentioned fuel tax in terms of demand, fuel consumed and CO2. These results correspond to a worldwide application projected up to 2050. For the whole period 2021-2050, the application of the tax implies a global 12% reduction of demand, as well as a reduction on 13% tone of fuel and CO2 produced concerning the, do-nothing scenario. Additionally, the overall fiscal revenue obtained from the tax application is estimated to be 108 Bill € in 2021 and increases progressively up to 422 Bill€ in 2050. Detailed figures for each year are provided in the table below. This figures and values obtained are coherent with other previous studies. Delft study considers a fuel tax of 0.333€/l but applied only to European International flights, with a 10% increase in the average ticket price, 11% decline in passenger demand and 27 Billion € for the year of application.

[2] Density of aviation fuel considered as 0.825 Kg/L. Density is normally in the range of 0,775 – 0,840 kg/l [210]







	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Demand [Bill PRKS] "do nothing"	8490.88225	8890.70919	9310.62861	9751.69971	10215.0394	10701.8256	11213.3004	11750.7738	12315.6277	12909.3194
Demand [Bill PRKS] 0.33€/L Fuel Tax	7426.93597	7779.0633	8148.98646	8537.64759	8946.04027	9375.21249	9826.26957	10300.3775	10798.7661	11322.733
Fuel consumption [Bill KG] "do nothing"	311.69	326.19	341.40	357.36	374.12	391.72	410.20	429.60	449.97	471.37
Fuel consumption [Bill KG] 0.33€/L Fuel Tax	270.75	283.19	296.24	309.95	324.34	339.45	355.31	371.98	389.49	407.88
CO2 emissions [Bill KG] "do nothing"	981.84	1027.49	1075.41	1125.70	1178.49	1233.92	1292.12	1353.23	1417.41	1484.82
CO2 emissions [Bill KG] 0.33€/L	852.88	892.05	933.17	976.33	1021.66	1069.26	1119.24	1171.74	1226.88	1284.81

	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
Demand [Bill PRKS] "do nothing"	13533.3864	14189.4505	14879.2225	15604.5075	16367.2098	17169.3389	18013.0149	18900.4752	19834.0806	20816.3229
Demand [Bill PRKS] 0.33€/L Fuel Tax	11873.6469	12452.9521	13062.1723	13702.9152	14376.8774	15085.8491	15831.7196	16616.4828	17442.2428	18311.2206
Fuel consumption [Bill KG] "do nothing"	493.85	517.47	542.28	568.35	595.74	624.53	654.80	686.60	720.05	755.20
Fuel consumption [Bill KG] 0.33€/L Fuel Tax	427.20	447.50	468.84	491.26	514.82	539.59	565.64	593.01	621.80	652.07
CO2 emissions [Bill KG] "do nothing"	1555.63	1630.02	1708.17	1790.29	1876.59	1967.28	2062.60	2162.81	2268.14	2378.89
CO2 emissions [Bill KG] 0.33€/L	1345.68	1409.63	1476.83	1547.46	1621.69	1699.72	1781.75	1868.00	1958.68	2054.03

	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Demand [Bill PRKS] "do nothing"	21849.8314	22937.3814	24081.9022	25286.4853	26554.3945	27889.0747	29294.1626	30773.4975	32331.1326	33971.3472
Demand [Bill PRKS] 0.33€/L Fuel Tax	19225.7606	20188.3369	21201.5616	22268.1919	23391.1386	24573.4744	25818.4437	27129.4718	28510.1752	29964.3724
Fuel consumption [Bill KG] "do nothing"	792.17	831.04	871.92	914.92	960.15	1007.72	1057.77	1110.43	1165.84	1224.14
Fuel consumption [Bill KG] 0.33€/L Fuel Tax	683.91	717.39	752.61	789.66	828.64	869.64	912.79	958.20	1005.99	1056.28
CO2 emissions [Bill KG] "do nothing"	2495.34	2617.79	2746.56	2882.00	3024.46	3174.32	3331.98	3497.86	3672.39	3856.06
CO2 emissions [Bill KG] 0.33€/L	2154.32	2259.79	2370.73	2487.43	2610.21	2739.38	2875.30	3018.33	3168.85	3327.28

Overall results of a 0.33€/L fuel tax.

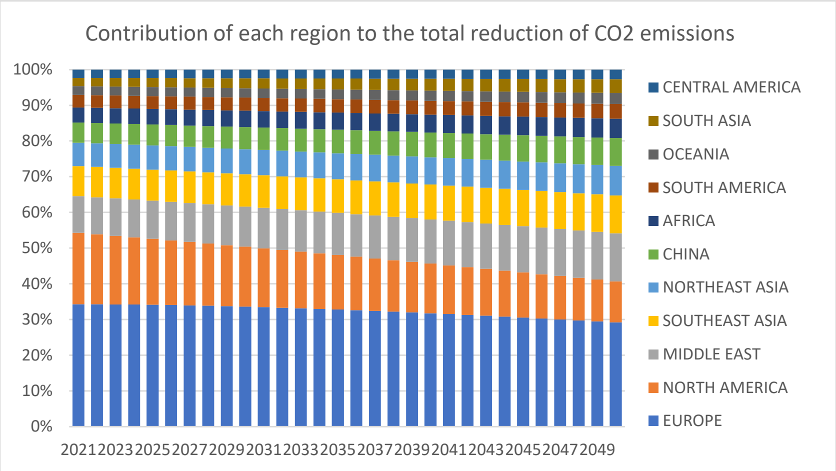
- Impact on operational cost and in the air transport industry activity.

It is possible to extract some conclusions about the impacts of a 0.33€/L tax fuel policy in the operational cost of the airlines by observing what has been the effect of effective fuel cost increase for the air transport in past periods. A tax of fuel of 0.33 per litre (0.4€ per kg) is indeed a big increase in the price of fuel. As of January 2020, the price of Jet A1 was approximately €0.55 per kg. The 0.4€ per kg fuel tax will imply a high 72% increase in the price of fuel respect to the prices in 2019. Global fuel consumption by commercial airlines reached an all-time high of 161.5 Billion € of fuel cost in 2019 (96 billion gallons at a 0.55€/kg means). Being fuel the 23.5% of the airline total expenditure, the operational cost of airlines for the same year is estimated at 687.5 billion of euros.

The application of the proposed tax might imply an increase in the percentage of fuel in the total expenditure of the airlines higher than the levels in 2012 (rough calculation lead to 40%). That could mean a decline in air transport activity to levels much worse than those of 2012/2013. This calculation, although approximate, illustrates that although 0.33€/L has been proposed at European level as fuel tax for European aviation (and used in this study for comparative purposes), this tax will not be sustainable worldwide. Additionally, if implemented only in Europe it could be too detrimental for European aviation and imply a significant loss of competitiveness against other regions of the world.

- Regional contribution and cooperation.

As stated by most authors the effectiveness of a fuel tax will depend very much on the homogeneity of its application. It is expected then that this tax could be applied globally worldwide. Next figureFigure 18. 11 illustrates how 70% of the reduction in CO2 emissions will be produced by aviation with origin in just 4 regions: Europe, North America, Middle East and Southeast Asia. By applying the 80/20 Pareto's law, (which states that for many phenomena 80% of the result comes from 20% of the effort), it would be necessary that at least these regions would agree on the implementation of the tax in order to obtain a significant CO2 saving. A worldwide agreement less than that could lead to an insignificant CO2 saving and at the same time produce a negative counter effect of the economy, air transport and tourism.



Contribution (in %) of Regions to the reduction in CO2.

Additionally, there is an underlying fear that unilateral taxation would harm local tourism, trade, and domestic carriers, increase import prices, decrease the demand for exports, and in addition leading fuelling to take place in countries without similar policy measures. Because of all those reasons international coordination is needed.

- Compensating developing countries.

One of the concerns of implementing carbon charges for aviation is that developing countries are made no worse off by the global adaption of such charges, and up to what extent this could be avoided through reasonably practicable compensation rules. Compensating developing countries for the economic harm they might suffer from such charges—ensuring that they bear “no net incidence”—is widely recognized as critical to their acceptability

The IMF (Internationally Monetary Fund) found that combining a global charge with targeted compensation provides an effective way to pursue both efficiency and equity objectives, however, it will withdraw a significant part of the potential CO2 savings. Such compensation seems to require—at most—40 percent of global revenues. With a gross estimation by 2020, a globally implemented carbon charge of $25 per tonne of CO2 on international aviation fuel could have raised in 2020, with no COVID 19 incidence, around $12 billion. 40% of this amount would leave about $7 billion for compensating developing economies and will therefore withdraw from climate finance. Developing countries might use this compensations funds to subside local aviation, jeopardizing the CO2 reductions provided by the tax itself. There is an important trade-off here: the more extensive is compensation, the less public revenue will remain for climate finance or other productive purposes.

- Impact on Oil prices: Partial pass-through of charges to fuel prices.

A critical issue when setting a CCL scheme is how far charges on jet would be passed on to purchasers. Jet fuel prices might not rise by the full amount of any new charge on their use. Some portion of the real burden is likely to be passed back to oil refiners and oil producers. However, if refiners can shift production from these fuels to other oil products fairly easily (which seems plausible), this pass back is likely to be modest. Supposing that the share of aviation in global oil demands is 11% and international fuel taxes are implemented globally then a fuel tax of 10 cents per litre imposed on all aviation fuel demand would reduce the world oil price by around 0.55 cents and, conversely, increase the price to fuel purchasers by around 9.4 cents per litre.

Also taxing the use of oil in some particular use results in a fall in its prices in other uses. Thus, low-income oil-importing countries, for instance, would derive some benefit to the extent that prices of fuels in other uses fall. This effect also means that total emissions fall by less than do those in the affected sector since the reduced price in other sectors leads there to higher emissions.

- Fuel efficiency improvement.

It is also claimed that emissions pricing would induce other mitigation options beyond this demand reduction. These include more efficient operations and improved efficiency of new planes. Based upon historical data some authors have quantified jet aircraft fuel efficiency historical improvement at a rate of 1.2-2.2% per year on a seat/km basis. International aviation community aspire to a 2% annual fuel efficiency improvement and a carbon-neutral growth from 2020.

To comparatively assess the effect of CCL against this effect a simulation has been run under different hypothesis from 2% up to 4% of fuel efficiency improvement, in addition to de do nothing and 0.33€/L fuel tax scenarios. Data showed that a 2-4% yearly fuel efficiency improvement does not provide a significant CO2 emissions improvement when compared to a 0.33€/L fuel tax.

- Implementation

Some key challenges need to be considered for implementing globally coordinated charges in international aviation.

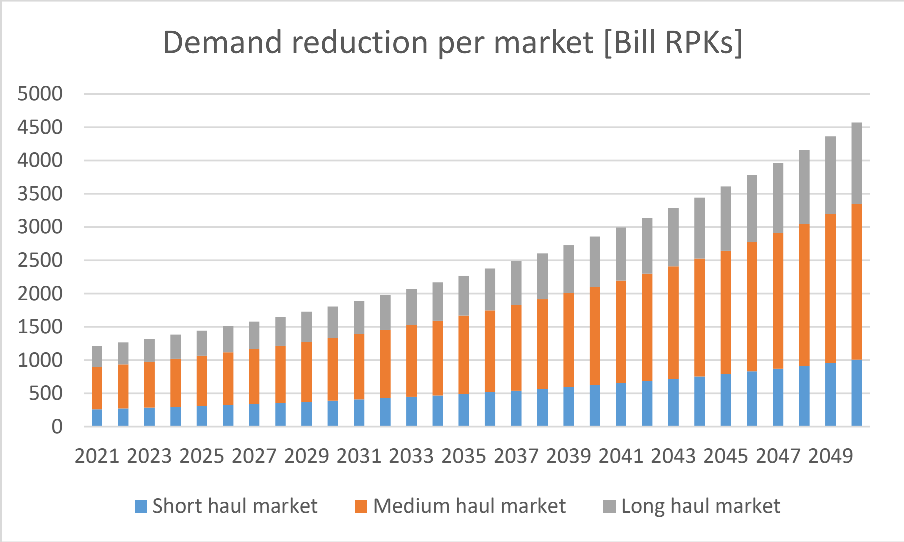
- New frameworks. New frameworks would be needed to govern the use of funds raised to determine how and when charges (or emissions levels) are set and changed; to provide appropriate verification of tax paid or permits held, and to monitor and implement any compensation arrangements.

  While the EU experience indicates that taxation agreements can be reached, it also shows how sensitive are the sovereignty issues at stake. One possibility is to link an emissions charge on international transportation to the average carbon price of the largest economy-wide emission reduction scheme, for instance, so limiting the need for a separate decision process.

- Implementation costs. The familiarity of operators and national authorities with fuel excises suggests that implementation costs would be lower with a tax-based approach than with an ETS (Emissions Trading System). Collecting fuel taxes is a staple of almost all tax administrations, and very familiar to business; implementing trading schemes is not. Ideally, taxes would be levied to minimize the number of points to control—which, broadly, means as upstream in the production process as possible. If taxation at the refinery level is not possible, the tax could be collected as fuel is disbursed from depots at airports and ports, or directly from aircraft and ship operators. Implementation would be simplest—and environmental efficiency greatest—if no distinction were made between fuels in domestic and international use. Indeed, eliminating the differentiation imposed at present should in itself be a simplification.
- Administration model. Policies could be administered nationally, through international coordination or in some combination of the two—with the appropriate institutions for monitoring and verification depending on the approach taken.
- Multilateral agreements: The current aviation fuel tax exemptions are built into multilateral agreements within the ICAO framework and bilateral air service agreements, which operate on a basis of reciprocity. Though consideration of the challenges is needed, amending the Chicago Convention and associated resolutions would remove these obstacles, although the EU experience on intra-union charging seems to suggest the possibility of overcoming them without doing so.

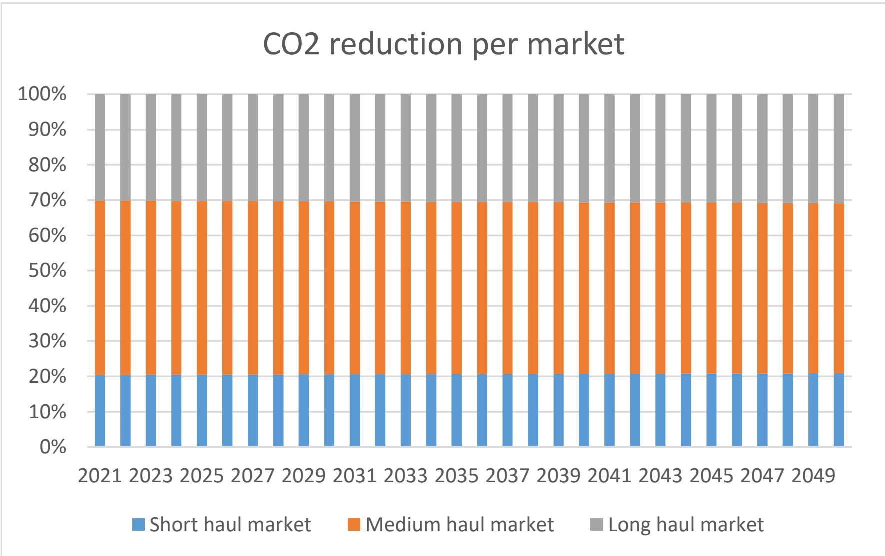
  - Impact on different markets.

The fuel tax may affect differently the short, medium, and long-range markets. In this regard two key questions need to be evaluated: which market results more affected in terms of demand and which market might contribute the most to the CO2 emissions reduction. Next figure illustrates how the demand is reduced in each of the markets in terms of RPKs. It can be appreciated how the biggest reduction takes place in the medium-haul market with an initial reduction of around 634 Bill RPKS in 2021 and a final of 2340 Bill RPKs by 20250. For the short-haul market the initial reduction by 2021 is around 260 Bill RPKS and by 2050 is around 1007 Bill RPKs. For the long-haul market, the reduction is of 316 Bill RPKs by 2021 and 1225 Bill RPKs by 2050. In average it means an 11% yearly reduction for the short-haul market, a 16% yearly reduction for the medium-haul market and a 14% yearly reduction for the long-haul market.



Reduction in demand for short, medium, and long-haul market

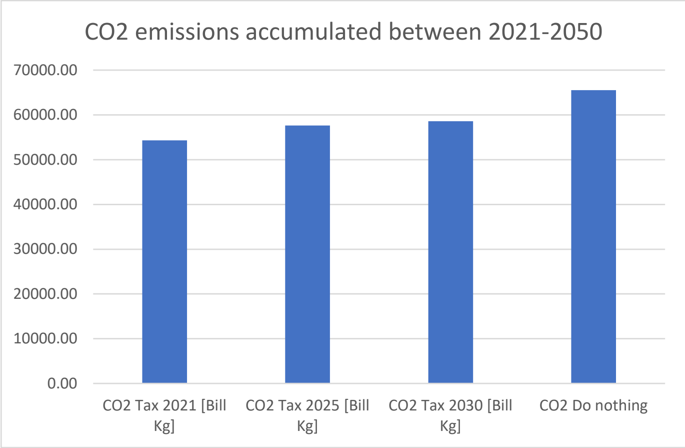
Next figure shows how each market contributes to the global reduction of CO2. It can be observed that the biggest reduction of CO2 is expected in the medium-haul market, which will account for 49.5% of the total reduction with 68 Bill Kg CO2 by 2021 and 252 Bill Kg CO2 by 2050. The short-haul market accounts for 20.5% of the global reduction with 28 Bill Kg CO2 by 2021 and 109 Bill Kg CO2 by 2050. The short-haul markets account for 30% of the global reduction with 41 Bill Kg CO2 by 2021 and 161 Bill Kg CO2 by 2050.



Contribution of each market in % to the global CO2 reduction

- Implementation year.

The next analysis shows the effect of implementing the tax in 2021 or delaying its application up to 2025 or even 2030. Next figure presents the accumulated CO2 emissions between 2021 and 2050 in Bill Kg for the three different implementation dates in contrast with the accumulated CO2 emission for the do-nothing scenario. Implementation of the fuel tax in 2030 instead of 2021 would imply the emission of 3304 Bill Kg more of CO2, whereas implementing the tax in 2025 instead of 2021 would imply the emission of 950 Bill Kg more of CO2.

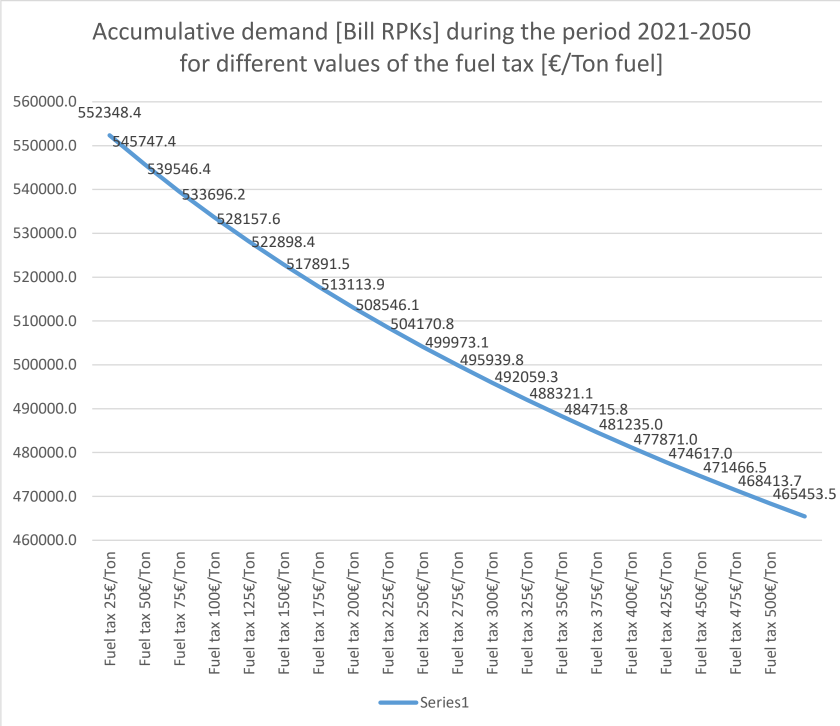


CO2 emissions by 2050.

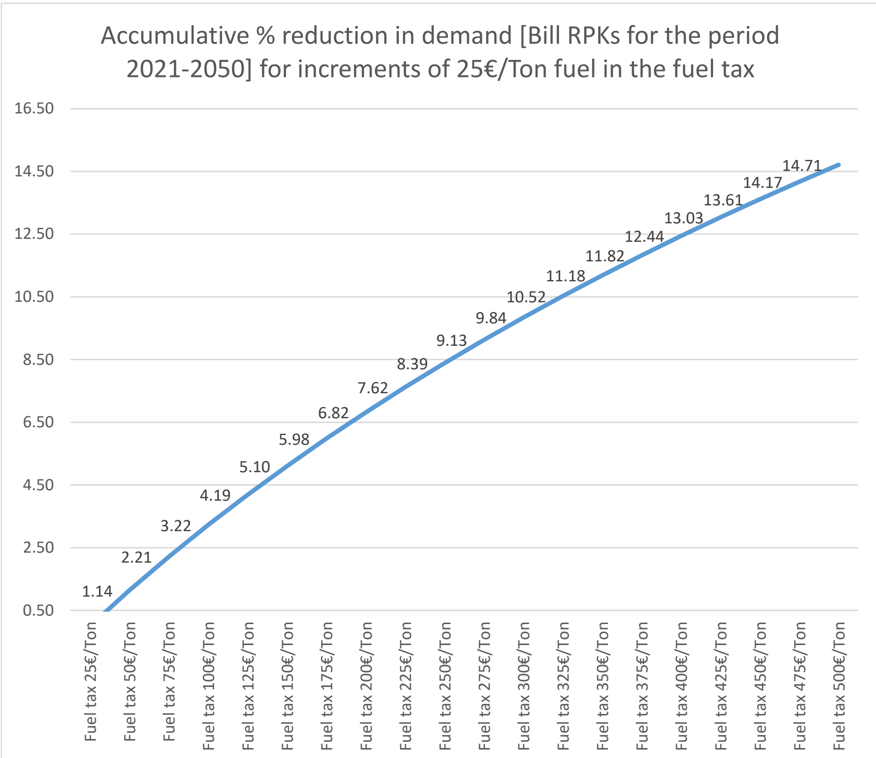
Generation of the marginal CCL curves.

As discussed in the previous sections a fuel tax of 0.33€/L applied worldwide will imply a very high increase in the price of fuel. At the same time, there is no yet an agreement among the different sources and studies of what might be the optimum value for such a tax, these figures varying depending on the study consulted. Those studies are not always easy to compare as they do not reproduce the same scenarios or considerer a local/ regional application of the tax.

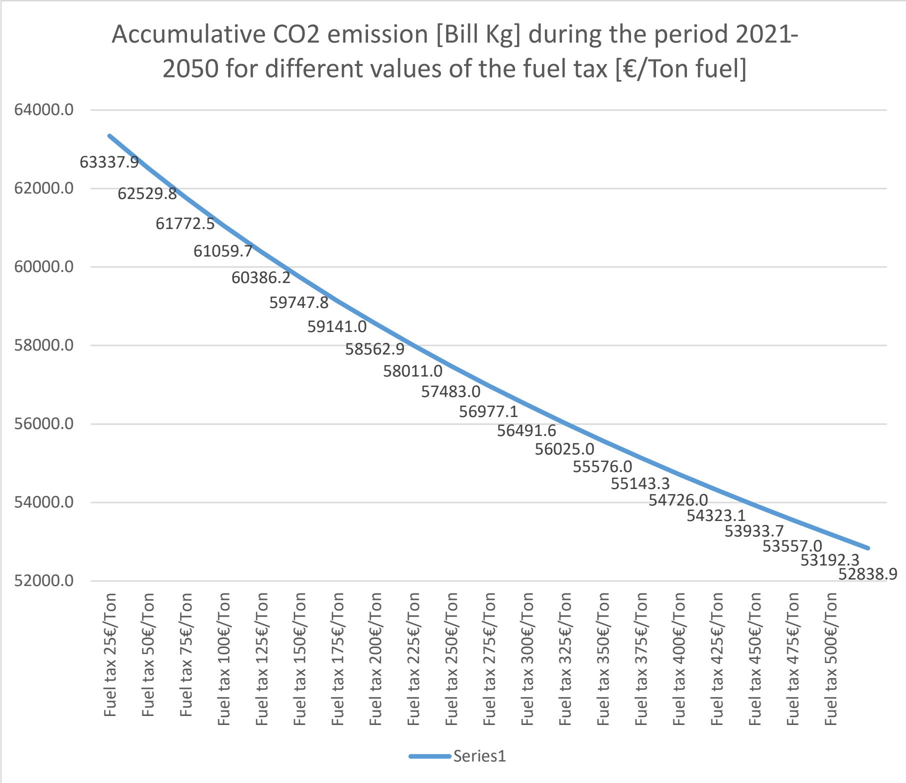
To help to solve these problems we construct in this analysis marginal curves that represent the effect in demand and CO2 for different values of a global fuel tax, ranging from 0 to 500€/Ton of fuel in intervals of 25€/Ton. Being the value of 400€ /Ton (333€/KL) the tax equivalent to the excise of duty study that has served for comparison in the previous analysis. By expressing this information in accumulative percentages we obtain the marginal CCL curves in Figure 18. 18, which give straightforward the % of reduction for the worldwide demand in the period 2021 to 2050 for any given tax. This marginal curve can be used as criteria for design. Similar abacus can be constructed for each region in the world o for each market segment (Short, medium, long haul). Similar abacus is provided for fuel consumption and CO2 emissions.



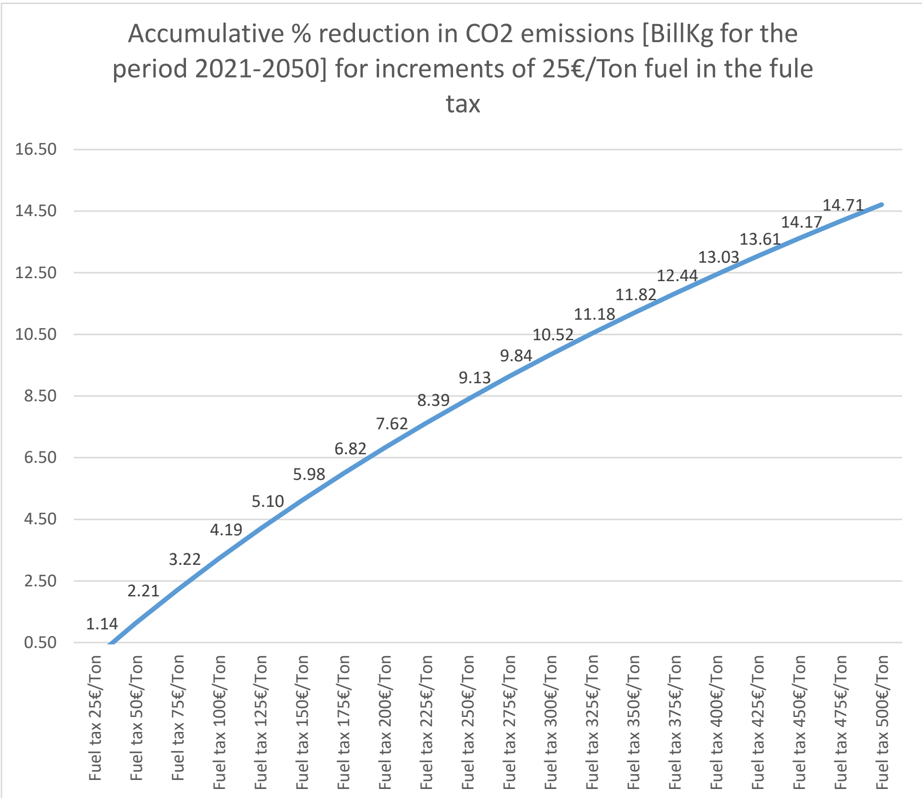
Accumulative demand during the period 2021-2050 for different values of the fuel tax.



Fuel tax marginal curve: accumulative % reduction in demand for the period 2021-2050 for increments of 25€/Ton in the fuel tax.



Accumulative fuel consumption during the period 2021-2050 for different values of the fuel tax.



Fuel tax marginal curve: accumulative % reduction in fuel consumption for the period 2021-2050 for increments of 25€/Ton in the fuel

18.2 Introduction

The PARE project assesses progress, gaps and barriers, and proposes suitable measures to close the remaining gap to support the achievement of the Flightpath 2050 goals in a broad variety of key areas of aeronautical research which are essential for the development of the aerospace sector in Europe.

As part of this process, the project has the task of identifying the actions required in the coming future for the proper development of the aerospace research sector that can benefit from a detailed and rigorous analysis of possible political, social and industrial scenarios by carrying out What-if analysis.

The experience of the consortium and its capabilities, as well as the work, is done analysing the state of the art, and future forecasts and needs in each of the project's areas of interest, have allowed the identification of highly relevant case studies for the evolution of the sector.

During the second year of the project, two what-if studies were developed. The first what-if study "China's New Airliners" analysed China's ability to certify and produce commercial aircraft efficiently, economically and on time to take advantage of the country's anticipated development, and how that could influence the international scenario and impact on the current balance of the aerospace industry. The second what-if study "The NMA case" focused on the analysis of competition among the main aircraft manufacturers in a segment that has captured the attention of both in recent years, the Middle of the Market segment.

During the third and final year of PARE project what-if studies will seek to shed some light into two different and relevant topics from evolution of aviation in Europe and worldwide.

The first of these topics is the assessment of long-term aviation scenarios to explore the possible paths and course of action of aviation towards decarbonisation and the consequences for different aviation markets (short, medium and long haul markets). The study focus on key technological, economical, market and business questions about the aviation CO2 emissions and derived impacts, and possible solutions and alternatives to minimise and reduce those impacts, the focus being on research and development, innovation and acceleration of entry into service of new products and solutions.

Finally, because of the long-term horizon of the aviation decarbonisation target, the second topic of the study refers to the workforce that will be required by this future green aviation. In particular, the emphasis is put into the new skills and knowledge that the industry will require from aerospace and aeronautical engineers and other aviation professionals; and what practical educational policies might be required to support the green social ambitions. New technologies and innovation will be key for achieving the aviation cero emission goal.

The PARE consortium has delineated a proposal for two comprehensive what-if studies to address the topics outlined in the previous paragraphs. Both what if proposals are based on the combination of a qualitative and analytical approach typical of the market and exploratory studies, complemented with the application of Bayesian Belief and Causal Networks models to evaluate the overall effects of solutions and uncertain hypothesis in the various scenarios under analysis. The full extension of these two proposals can be consulted in detailed at references [1] and [2], including objectives, scope, methodology and table of contents.

However, because of their complexity, those two studies cannot be accomplished in its full extension during the last year of the PARE project activity. Nevertheless, both topics are considered of primary interest in the sustainable future of aviation in Europe. In an attempt to collaborate and provide support to the ACARE WG5 activities, the PARE project has outlined one small scale study that will serve as a pilot case, to show the potential of the more ambitus original what-if analysis. This “pilot case” is outlined hereafter and developed through this document.

18.3 Scope and context of the pilot What-if study

Understanding and minimising the environmental impacts of aviation and protecting of the environment is a long-term commitment to aviation in Europe. The European Flightpath 2050 goals consider environmental protection a key challenge for the future of the aviation industry. Flightpath 2050 vision aims to continuously reduce the environmental impact in the face of continuing expansion in demand for aviation. It is envisaged that towards 2050, the forecast growth in the aviation industry will drive the need to deliver revolutionary technology solutions at an increasing rate and secure the path to sustainable energy supplies that can displace today’s fossil fuels to mitigate fully the potential impact on the atmosphere. This vision has been translated into 5 ambitus goals. The ambition settled in the Flightpath 2050 document for CO2 reduction is that in 2050 technologies and procedures available will allow a 75% reduction in CO2 emissions per passenger kilometre to support the ATAG; and some phases of the aircraft operation, such taxiing, will be emission-free.

According to ICAO, aviation is responsible for 2% of global CO2 emissions. International aviation community aspire to a 2% annual fuel efficiency improvement and a carbon-neutral growth from 2020. However, aviation is expected to occupy an increasingly large share, if it continues to grow as foreseen (5% annually), as other sectors are seeking to reduce their emissions in line with their carbon budgets. The achievement of this goal is still at risk; and even if achieved aviation will still produce by 2050 a significant amount of CO2, that might endanger the achievement of the goals of the Paris Agreement.

ICAO 2019 report quantified emissions of the aviation sector over the period 2016-2050 could be between at 56 GtCO2 in a business as usual scenario and 12 GtCO2 in an optimistic, but unlikely to meet, the scenario with technological improvements and 100% of biofuels use. As claim by CrabonBrief, these figures would imply that aviation emissions, from 2016 to 2050, could consume between the 27% and the 12% of the remaining carbon budget to keep global temperature rise below 1.5C above preindustrial levels.

Additionally, carbon dioxide is not the only way aviation affects the climate. Aircraft emit other gases and aerosols that change the composition of the atmosphere, such as NOx and water vapour. They also produce “contrails”, which affect the cloudiness of the sky and how much solar radiation reaches the surface of the Earth. The extent to which these extra factors amplify the CO2 effect is still poorly understood and not captured in ICAO’s estimates of aviation’s impact on the climate.

Consequently, experts and studies are calling aviation community attention towards the need to establish even more ambitus goals for aviation CO2 emissions in the path to decarbonize the aviation sector by mid-century. Aviation is being challenged to immediately start to reduce its in-sector emissions, then sharply reduce its CO2 emissions and fully decarbonize toward the second half of this century.

Governments, the aviation industry, international and research institutions, private sector, and civil society must do more to harness viable technological and policy solutions to face this challenge.

Particularly, from research and technology, development of aviation climate neutrality might require a combination of research at low TRL and in uptake into new products that enter the market. ACARE (Advisory Council for Aviation Research and Innovation in Europe) is committed to shedding some light towards the possible alternatives and best combination of solutions. ACARE has stressed the importance of not focusing only on short term issues but to support the entire R&I chain, as no single solution will be able to solve all problems, and different approaches might be required for short, medium and long-haul air transport markets.

In an attempt to provide insight into the best solutions for aviation decarbonisation and to inform future policy, research, and business strategies, ACARE has defined a set of long-term air transport scenarios. A brief description of these scenarios is provided hereafter:

- Scenario 1: Tax scenario
  Rationale:
  The price elasticity of aviation is in practice close to 1. This means the moment the price will go up by 1% the demand will go down by 1%. By taxing the CO_2-emissions significantly there will be a change in demand. An order of magnitude of € 180/ton CO_2 was mentioned as an effective measure.
  Questions:
  - What would such a tax mean for the demand in short, medium, and long-range flights?
  - What would be possible alternative developments ((high speed) surface transport)?
  - Will there be negative growth?
  - Low cost has driven price and demand for the last decades. How will this change and how will the sector remain competitive?

- Scenario 2: Tech will fix it scenario
  Rationale:
  By putting an extra effort in technical development, we could try to speed up the environmental performance of aircraft. Let us assume we can innovate fast enough to meet the demands of society for climate neutrality.
  Questions:
  - What do we need to do to achieve this?
  - Where are the highest chances for success?
  - Would it still be possible to deliver mass transport?
  - Do we need to make a better integration with other modes of transport?
  - Once climate neutrality is no longer an issue because that problem is solved, what will make the difference (travel time, easiness, comfort, price, etc.)?
  - Will society walk away from aviation if we fail to deliver?
  - Would it still be possible to fail without serious consequences for the sector/company?

- Scenario 3: Megacities and teleworking
  Rationale:
  There is an ongoing trend in the world towards urbanization. It is expected that there will be a lot of megacities where people live and work. Transportation within megacities will not be done via air. Transport between megacities can probably also best be done via high frequency, high-speed surface transport (e.g. high-speed rail, Hyperloop, etc.). Consequently, only specific branches of aviation will remain. Furthermore, the internet infrastructure will become so good that teleworking with frequent teleconferencing becomes the norm. Face-to-face meetings will become less common.
  Questions:
  - Which branches of aviation will remain and which ones will disappear?
  - How will we take care of the energy needed for all modes of transport?
  - In how far will teleworking/teleconferencing take over?

- Scenario 4: War on carbon

Rationale:
It is considered no longer acceptable to emit large quantities of CO_2. The world will start an aggressive war against carbon emissions. This will lead to disruptive changes comparable to large volcanic eruptions that can stop aviation almost immediately.
Questions:
- Will this lead to disruptive changes in aviation, if yes, how quickly will this take effect?
- Will this lead to continentalisation where every continent is "on its own" without extensive intercontinental transport of people and goods?
- What will be an acceptable level of carbon emissions?
- Will there be a (personal) carbon budget?
- Who will decide on this?

- Scenario 5: Global unrest, crisis, or war
  Rationale:
  A situation of unrest/crisis/war develops in the world. This will cut off air travel in significant parts of the world for a number of years.
  Questions:
  - Will long haul air travel suffer so much that it almost disappears?
  - What will happen to short and medium-haul flights?
  - Who will decide on what will happen in air travel?
  - Will fuel supplies also be interrupted?
  - What will be the consequences for the cost of air travel?
  - What will be the consequences for the demand for air travel?

The detail definition of these scenarios; the analysis of possible economic, political, and technological solutions to reduce aviation environmental impact in each of them; as well as the breakdown of the consequences of each scenario for aviation and air transport, will enlighten the discussion. They will offer a more clear and informed view on the possible course of action to tackle aviation decarbonisation challenge. It is expected that the analysis of these scenarios will help to:

i) provide external strategic advice, in an inclusive and representative manner, on real value-adding research areas;
ii) minimize no significant impact or non-adding value research;
iii) focus on impact in the shortest possible term having in mind, of course, the aviation cycles; and
iv) identify synergies with other sectors and national funding programs.

However, because of their complexity in this pilot what-if study, only the first scenario will be addressed during the last year of the PARE project, as an illustration of what a bigger study could provide.

18.4 The objective of the reduced pilot case.

The main objective of this "what if" study is to further detail and analyse the long term scenarios defined by ACARE to explore the possible paths and course of action of aviation towards decarbonisation; to provide insight into the consequences and final outlook of these scenarios for different aviation markets (short, medium and long haul markets), and to inform future policy, research and business strategies through a set of synthetic conclusions and recommendations.

To accommodate that main objective within the PARE project remaining working time and effort a pilot study is proposed, limiting part of the activities and the range of scenarios. The pilot study will accomplish in detail the analysis of a set of possible decarbonisation measures that can be enunciated under the category of "Market Based Measures". The pilot study will concentrate in the extensive analysis of the first of the ACARE WG 5 scenarios, the **"Tax Scenario"** and the impacts of Aviation Pricing and Climate Change Levy; and it will be complemented with the assessment of other regulatory/legislation options in the decarbonisation roadmap, such as emission trading scheme, strengthening CORSIA, revisiting aviation subsidies, fiscal measures, technology-forcing efficiency standards, strengthening ICAO CO2 standards or stricter fuel efficiency standards and incentives on aviation fuel suppliers.

Although the Pilot Study focused on Market Based Measures, particularly in Climate Change Levy measures, other important aspects, that could be covered in a future more comprehensive study, will be highlighted, such as near and long term technology solutions; transformative, breakthrough clean aviation technologies; new mobility solutions to support modal shift; new business models for the aviation industry; stricter fuel efficiency standards and incentives on aviation fuel suppliers; sustainable alternative fuels; advanced biofuels or synthetic fuels, electro fuels, synthetic kerosene.

This pilot will be developed like a first exploratory analysis of the impacts for aviation and air transport of the main hypothesis included in this scenario. To the light of the results of the pilot study, a broader and more complete study could be tackled, considering the impacts for aviation in the whole set of 5 ACARE scenarios.

18.4.1 Coordination with ACARE WG5

To achieve the objective of the study close cooperation will be established with ACARE WG 5 with the aim of jointly gather analytics and insights to answer key political, technological, economical, market and business questions about the aviation CO2 emissions and derived impacts, and possible solutions and alternatives to minimise and reduce those impacts, the focus being on research and development, innovation and acceleration of entry into service of new products and solutions.

Coordination with ACARE WG5 will facilitate

- The detail definition of the ACARE scenarios, as well as the breakdown of the consequences of each scenario for aviation and air transport, and other modes of transport.
- Provide sustained answers to the particular questions raised at each scenario making the best out from data and expert information covering markets structure, forecast and uncertainties, technology prospects, fuel efficiency-related research and aviation environmental impacts studies, land-based infrastructure alternatives and impacts or synergies with other industries, economic information, etc., ...
- The analysis of possible economic, political and technological solutions to reduce aviation environmental impact in each of the scenarios; including the identification of the best combination of solutions for each of the three main aviation markets (short, medium and long flights), and the evaluation of the associated uncertainties.
- The assessment of the achievements in fuel efficiency up to now and the understanding of what might be feasible from the combination and integration of different solutions and scenarios.
- The provision of a more clear and informed view on the possible course of action to tackle aviation decarbonisation challenge.
- Identification of impacts and consequences for R& D strategies to concentrate into real value-adding research areas, minimize no significant impact or non-adding value research; focus on impact in the shortest possible term having in mind, of course, the aviation cycles; identify synergies with other sectors and national funding programs, and find a balanced combination of research at low TRL and in uptake into new products that enter the market.

18.5 Methodology

As stated before, although other relevant topics will also be tackled in the study, the core part of the pilot what-if analysis pretends to gather analytics and insights to answer how taxing CO2-emissions (Climate Change Levy schemes) will imply significant changes in the aviation industry, including aviation demand, industry and markets structure and emission reduction.

Recent reports claimed that the expected technology and operations improvements will not mitigate the expected fuel demand and emissions growth from aviation, and that to significantly reduce the expected fossil fuel demand and ultimately eliminate it from the sector would require further measures [2]. For those authors, carbon pricing needs to play a central role in bringing forward further reductions in fuel demand.

This scenario is based on the consideration of the price elasticity of aviation. Assuming an elasticity close to 1, an increase of 1% in price would imply a 1% reduction on the demand. Under this consideration, some authors [3] have estimated that introducing fiscal measures that combined represent a carbon price equivalent to € 150/ton CO2 can moderate demand growth from the sector through incentivising a combination of design and operational efficiency improvements and modal shift. Other measures highlighted by this report include stricter fuel efficiency standards and incentives to speed up fleet renewal. All that, combined, these measures could cut fuel demand by some 12 Mton, or 16.9% in 2050 compared to a business as usual scenario.

The primary rationale for environmental taxation is the externalities argument. By leaving a tax on the pollution-generating activity, the social costs of pollution can be 'internalised' to the agent (who must pay the tax) and the socially optimal level of pollution would occur.

If the tax is expected to cover the social cost of pollution it is necessary to estimate the environmental cost of the emission of one tonne of CO_2. Although several figures have been produced during the last years, one accepted figure stands for 180 euros per ton of CO2 (according to calculations published by Germany's Federal Environment Agency (UBA) [4]. This figure is in the order of magnitude of the 150/ton CO2 equivalent carbon price analysed in [3].

Two main impacts of taxing would be analysed in this study. On one side, because of price elasticity, as far as the tax is translated to the user, it is expected to have an impact on demand, aviation markets and emissions. At the same time, the pressure of environmental taxation can also be a trigger for companies, airlines, and manufacturers, to increase fuel efficiency by changing technology, and become a driver for competition.

In deciding at what rate to set a green tax, it is necessary to take into account the cost of abating pollution (either from changing technology or from curbing activity altogether) and the value (in terms of our welfare) of the reduced damage resulting from lower pollution. The socially optimal level of pollution is that where the marginal abatement cost (i.e. the cost to the polluter of eliminating an extra unit of pollution) is equal to the marginal damage cost (the net social damage caused by that last unit).

A key aspect, therefore, will be to figure out how an emission tax might affect aviation will be the balance between the abatement cost for a company derived either from the reduction of its activity (demand reduction), or the abatement cost derived from the migration to more fuel-efficient technologies. Particular relevant in valuing abatement costs, although difficult to estimate, will be the expected impact of R&D in new abatement or production technologies.

The effect of taxes will be also different depending on the business model of the companies. The trade-off for this uncertain outcome is that taxes will provide incentives for low-cost abaters to reduce pollution more and high-cost abaters to reduce pollution less, preferring to pay extra tax than incur the higher costs of pollution reduction. The hypothesis that taxes provide ongoing incentives to reduce pollution and therefore tax liability by investing in new clean technologies, is generally referred to as "dynamic efficiency".

Emissions trading schemes provide an alternative approach to the problem: the total level of pollution is guaranteed by the number of permits allocated and then the permits are traded such that more efficient abaters can sell excess allowances to less efficient abaters, giving a certain outcome at the lowest cost. Both taxes and emissions trading schemes, therefore, offer efficiency advantages over simple regulation. With taxation, policymakers effectively set the pollution price but leave the resulting emissions level uncertain, whilst with trading the level is fixed and the resulting price uncertain, determined by the market trading patterns.

Different schemes can be established for aviation CCL (Climate Change Levy): a tax on jet fuel, distance-based air passenger's tax, quota obligation for biofuels, etc... Today, almost all countries have taxes on fossil fuels for road transport and this has proved to be an effective instrument for decreasing emissions as well as financing the public sector. Few countries have a tax on jet fuel: Norway and Japan are two exceptions.

An alternative to using fuel as the tax base is to tax tickets. The UK was an early adopter and implemented an Air Passenger Duty in 1994. Today, many countries have implemented similar taxes, including Germany, Sweden, France, Norway, Austria and South Africa. These taxes are for both domestic and international air traffic, and the rates are usually differentiated based on distance.

For the road sector, many countries in the EU have biofuel quota obligations, sometimes called a biofuel mandate, to meet the EU target that 10% of fuels for road transport must be renewable by 2020. These instruments are designed to ensure that fuel suppliers for road transport have to sell an increasing proportion of low carbon fuels.

To analyses the implication of this scenario, the pilot study will perform the following tasks and analysis:

- An overall assessment of possible solutions and alternatives for aviation decarbonisation. Aviation industry approach has relied on four pillars of climate action: reducing fuel use (and CO2 emissions) through new technology and alternative fuels; better operations of existing aircraft; and infrastructure improvements. For all emissions that cannot be reduced through these pillars, global market-based measures, in particular climate change levies, could be used to offset the remaining emissions in order to meet the targets set by the industry.

- Assessment of lessons learned from the implementation of CCL in aviation or other industries. In particular, attention will be devoted to the inventory of taxes and tax exemptions that apply to aviation in Europe.

- Definition of the most probable CCL scheme for aviation. The most probable schemes under application or discussion today for aviation will be outlined, either tax on jet fuel, distance-based air passengers' tax, quota obligation for biofuels, etc...

- Development of a simple and generally applicable model to assess the impact of taxes on aviation. The model will be based upon previous models available on literature and will allow estimating the impact of different CCL schemes into demand.

  The main aim of this model is to generate CCL marginal tax curves and its effect on changing demand for air travel. The model will use a differentiated approach, taking into account the types of aircraft and types of flights, the distance they are operated (short, medium, long-range), the nature of the flight - regular, charter, passenger, freight, passenger and express – and different types of air carriers (low cost, traditional, etc…). The model will also consider price elasticities of demand specific for different markets.

- The model and CCL curves should consider price elasticities of demand specific for different markets.

- Assessment of CCL impact on fuel efficiency technology improvement and the acceleration of its entry into service. As discussed previously the introduction of a CCL tax could encourage airlines to upgrade their existing fleet with more efficient models and technologies. The pilot study will include an assessment of the potential fuel saving for a new generation of aircraft and engines recently introduced, about to enter the market, or available in the medium timeframe. This information will be used to estimate how CCL could accelerate the migration to new aircraft models with better fuel efficiency. Tax saving and the cost of new technologies will be evaluated. These estimates will be used to complete the CCL model and adjust the impact of CCL in demand in the medium timeframe.

- Using detailed air transport statistics from past years, global air transport and aircraft production forecasts and the outcome of the previous CCL model and curves, the pilot study will generate medium- and long-term air transport demand, aircraft and CO_2 emission forecast. When possible it will also estimate the change in flights and connectivity, economic impacts such as GDP, jobs and fiscal revenues.

  Particular attention will be paid to the evolution of the short, medium, and long-range markets and to the evaluation of CO_2 emissions (considering both the effect of CCL on price and demand, as well as on the adoption of new technologies.)

- Sensitivity analysis. The pilot study will include sensitivity analysis to estimate the effect of some external hypothesis and uncertainties such as the evolution of the fuel prices or the impact of third countries that do not join CCL taxation measures.

The methodology proposed in this pilot case study follows a qualitative and analytical approach typical of the market and exploratory studies to better understand what is happening and what could happen in the medium and long-term future. Figure 18. 1 illustrates the main steps in the whole process.

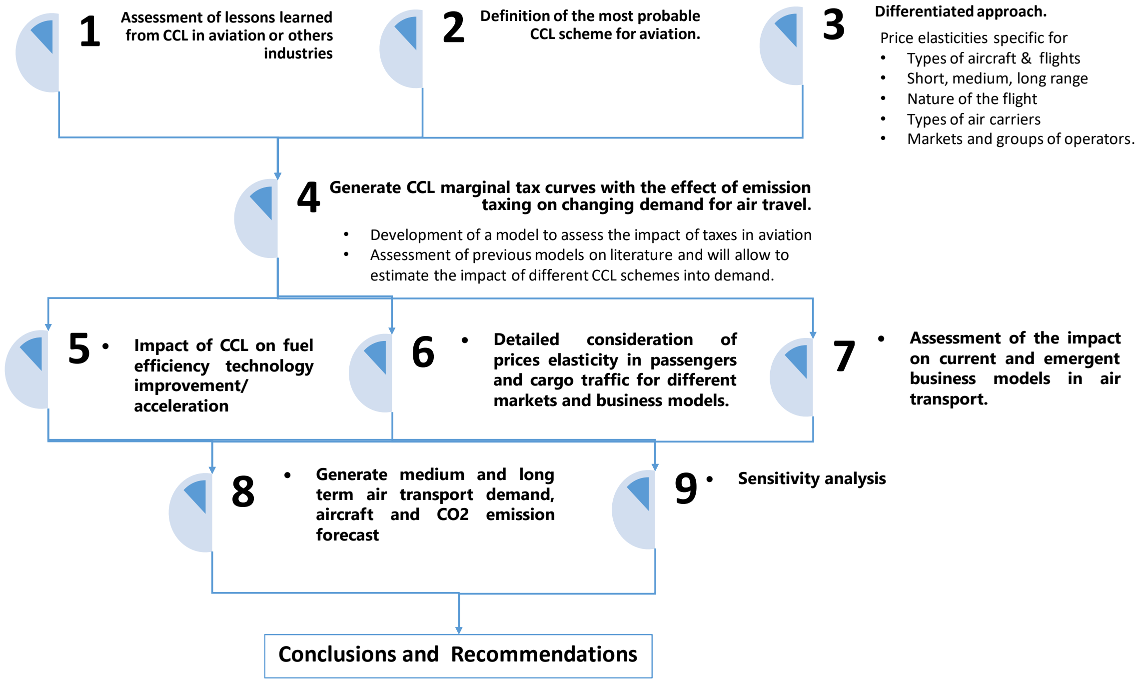


Figure 18. 1. Methodology for the "pilot what if" study on the Aviation Decarbonisation case.

Finally, the results of the whole process will allow us to understand how possible future scenarios and possible solutions will impact the evolution of air transport in the coming years. It will also help us to understand how the introduction of CO_2 reductions measures could imply changes in a today aviation and air transport industry, or how it will incentive the development and introduction of new technologies and aircraft improvements.

The whole approach will allow testing policy options to determine their outcomes in a competitive market, based on the assumptions in the valuation model.

18.6 Assessment of potential CO2 reduction actions/alternatives

This chapter outlines and summarises possible solutions and alternatives for aviation decarbonisation. Up to now, the aviation industry approach focuses on four pillars of climate action: reducing fuel use (and CO_2 emissions) through new technology and alternative fuels; better operations of existing aircraft; and infrastructure improvements. For all emissions that cannot be reduced through these pillars, global market-based measures could be used to offset the remaining emissions in order to meet the targets set by the industry.

Alternatives have been identified in different domains including technological and or operational solutions, economic or trading solutions, political and social solutions and have been grouped according to the categories in the next figure. Detailed inventory and analysis of each one of them are provided in the annexes of this document.

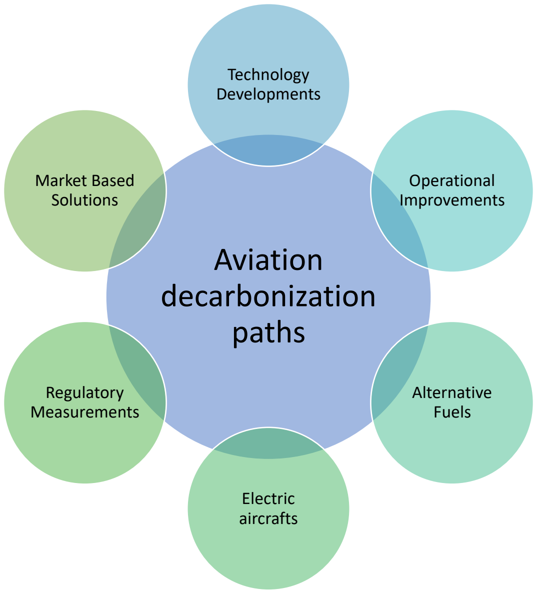


Figure 18. 2. Potential CO2 reduction actions/alternatives.

18.6.1 Market-Based measures

Market-based measures are instruments designed to address the climate impact of aviation, beyond what operational and technological measures or sustainable aviation fuels can achieve [5]. They are part of the comprehensive approach needed to reduce aviation's emissions, as technological and operational measures alone are currently not sufficient to tackle the growing impact of the aviation sector on climate change. Market-based measures, comprising both cap and trading as well as offsetting schemes, are designed to mitigate climate change through sector emission reductions or through incentivizing efforts outside of the aviation sector.

Market-based instruments are indirect regulatory instruments, which influence actors' behaviour by changing their economic incentive structure. Costs from environmental externalities, such as greenhouse gas (GHG) emissions, are usually not reflected in consumption or investment decisions but are nonetheless imposed on third parties. Putting a price on greenhouse gas emissions is important to harness market forces and achieve cost-effective emission reductions. Therefore, these types of policies work by reflecting the environmental impact of a certain action by attaching a cost to it, to signal and provide an incentive to the polluter to reduce this impact.

Market-based solutions are the main concern of this study. Figure 18. 3 shows the breadth of market-based instruments used in the EU. The most important instrument types here are:

- emissions trading schemes, and
- climate change levy schemes.

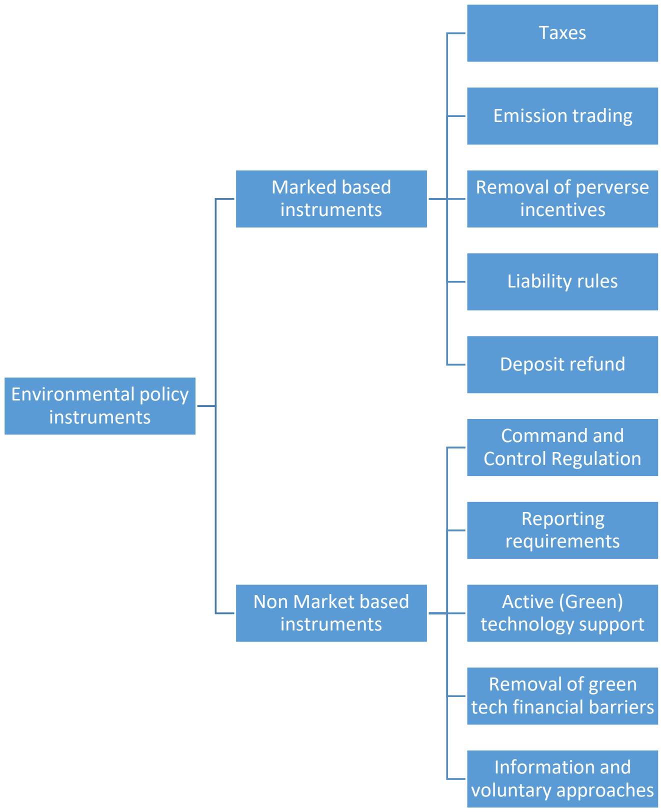


Figure 18. 3. Taxonomy of climate policy instruments [6]

Both taxes and emissions trading schemes, therefore, offer efficiency advantages over simple regulation and technological solutions. With taxation, policymakers effectively set the pollution price but leave the resulting emissions level uncertain, whilst with trading the level is fixed and the resulting price uncertain, determined by the market trading patterns. Both of them are discussed below in more detail,

Regarding the removal of perverse incentives, this instrument refers to the removal of subsidies for environmentally harmful activities and products, such as subsidies for the extraction or production of fossil fuels, exemptions from energy taxes, or fossil fuel subsidies to keep the price level low. Furthermore, this also includes the removal of further incentives rewarding harmful activities, such as the abolition of liability exemptions [6]. Regarding the extent of these so-called perverse incentives, the environmental impact of their abolishment can be potentially large, as the following example shows: In 2012, the total support provided by the EU Member States to coal power generation (hard coal and lignite) summed up to some EUR 10 billion (not including historic support), improving the profitability of the investment, mainly in the form of investment grants, exemptions from fuel taxes and support to decommissioning and waste disposal. Meanwhile, the total external costs of coal power generation are estimated at EUR 86 billion [7].

Also of relevance are liability instruments which "impel concerned parties to internalize external costs through the threat of consequential costs" [6]. Deposit refund systems charge consumers an upfront payment for improper waste disposal. The refund is a reward for returning the waste to the right collection point.

18.6.1.1 Emission trading systems

Cap and trade systems generate economic incentives to change the behaviour of societal actors and reduce pollution. The starting point in a cap and trade system is a limit on the physical emission quantity (cap) of a harmful substance, introduced by a regulatory authority, which issues emission allowances according to the maximum limit it has defined. This is either done by grandfathering (free allocation according to certain criteria, such as past pollution) or auctioning, which generates revenue for the governments. The emission allowances can be traded on a market and polluters can buy and sell them according to their needs, with the allowance price determined by supply and demand. Polluters carry out mitigation actions until it is cheaper to buy an allowance on the market than to mitigate a further emission unit. As a result, those polluters with the cheapest mitigation options will reduce the most.

Therefore, the environmental outcome of an aviation emissions trading system is determined by the emissions cap. Aircraft operators are able to use allowances from outside the aviation sector to cover their emissions. The absolute level of CO2 emissions from the aviation sector itself can exceed the number of allowances allocated to it, as the increase is offset by CO2 emissions reductions in other sectors of the economy. In emissions trading schemes the total level of pollution is guaranteed by the number of permits allocated to the companies. Then the permits are traded such that more efficient abaters can sell excess allowances to less efficient abaters, giving a certain outcome at the lowest cost.

Cap and trade systems theoretically guarantee the most cost-effective mitigation pathway for society [8] and are more dependable than taxes since emissions are capped. However, in real applications market design can become very complex. Furthermore, the demand for allowances also depends on the economic situation. In a recession, economic activity will decrease and thereby emissions, which will drive down allowance prices. The low allowance price will not serve as an incentive to invest in low carbon technologies and which can create a lock-in effect, as no further action is required to achieve the emission cap. This can make future emission reductions more expensive, threatening the theoretical cost-effectiveness of an emissions trading system (ETS).

Cap and trade systems have been most developed worldwide through exemplary programs such as CORSIA at the international level, or ETS at European level. This alternative however may not deliver sufficient CO2 emissions reductions to address the problem of aviation decarbonization.

- CORSIA: Among ICAO's measures, the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), is the first global market-based measure for any sector. Detailed analysis of this measure is provided in Annex 1. CO2 offsetting is calculated as the operator's annual emissions multiplied by a growth factor determined by ICAO as a combination of the individual operator and the sector performances.

  The success of the implementation of CORSIA relies on the establishment of robust and transparent monitoring and the eligible offset credit programs.

  By 2020, global international aviation emissions are projected to be around 70% higher than in 2005 and the International Civil Aviation Organization (ICAO) forecasts that by 2050 they could grow by a further 300-700%. [9]

  During the period 2021-2035, and based on expected participation, the scheme is estimated to offset around 80% of the emissions above 2020 levels. This is because participation in the first phases is voluntary for states, and there are exemptions for those with low aviation activity. All EU countries will join the scheme from the start.

  However, despite the great international effort involved in CORSIA, according to the Air Transport Action Group (ATAG), CORSIA shouldn't have any real impact on the growth of air traffic (i.e. on passenger demand), as the global scheme was developed as a way to help ensure aviation growth continues (to drive economic development through international trade and tourism), whilst also taking care of its environmental responsibility [10].

Before the establishment of CORSIA, in 2012, ICAO assessed the impacts of the implementation of three Global Market-Based Measure (GMBM) options – global mandatory offsetting, global mandatory offsetting with revenue and global emissions trading. The following assumptions were considered: (i) impacts would be assessed from 2020 to 2036; (ii) the future per tonne prices of CO_2 (emissions units to be purchased) would be $30 in 2020, $40 in 2030 and $45 in 2040; and (iii) the costs resulting from purchasing emissions units would be passed through to ticket prices (i.e. 100% cost-pass-through). Considering a GMBM without revenue (the modelling did not distinguish between offsetting and emissions trading), which is CORSIA's case, and the assumptions above, the estimated air traffic demand (measured in revenue tonne-kilometres (RTK)) would be reduced by 1.2% and the profits for the international aviation sector would be $0.4 billion or 1.2% lower in 2036 [11].

Assessment \ Scenario	Without GMBM scheme (baseline)		With GMBM scheme
	2020	2036	2036
Air traffic demand, billion RTK	743	1561	1543
Operating results, billion $ (profit)	16.2	33.7 (2.8%)	33.3 (2.7%)

Table 18. 1. Results of ICAO's 2012 GMBM assessment.

The assessment also demonstrated that the differences between GMBM impacts by world regions or groups of States were marginal. For example, the GMBM impacts on traffic demand and operating results (profit) in the six regions (Europe, Asia/Pacific, North America, Latin America, Africa and the Middle East), were generally consistent with the global average of a 1.2% reduction for both. The Middle East would be the region with higher reduction in traffic demand (of 1.4%), whereas Africa and Asia/Pacific would have slightly better results in profitability, lowered by 1%.

A more recent assessment [12] made by ICAO's Committee on Aviation Environment Protection (CAEP) suggests that, in a scenario of high carbon prices in the future ($33 per tonne in 2025 and $40 per tonne in 2035) and industry CO2 growth, the CORSIA scheme (i.e. the purchasing of carbon offsets) will cost airliners $12.4 billion in 2030 (approximately around 1.1% of the projected annual industry revenue) and $23.9 billion in 2035 (~1.8% of projected annual industry revenue).

Another recent study [13] made by CE Delft considers similar carbon prices (compared to previous ICAO's assessments), based on World Energy Outlook (WEO) New Policies Scenario, and estimates lower yearly costs for the aviation sector resulting from buying carbon offsets.

Year	WEO – New Policies Scenario		
	2020	2030	2040
Carbon prices, € $_{2015}$ per tonne of CO_2	18.0	33.4	45.1
Total costs to industry (in billion € $_{2015}$)	-	7.9	14.0

Table 18. 2. Result of the CE Delft 2016 GMBM assessment.

In any case, considering that in 2015 the aviation industry spent around $181 billion on fuel (around a third of operating costs), the overall financial impact or burden to the industry will be relatively insignificant and a lot less than the cost of fuel for any airline (and less than a tax). This figure also reflects on the insufficient contribution of CORSIA to meet the 2ºC target under the 2015 Paris Agreement [14].

However, for each airline individually, the burden will vary depending on the airline's business model as well as its share of international flights, growth rate, fleet age, and operational efficiency. Airlines that grow fast (being the majority of low-cost carriers) and with high greenhouse gases (GHG) emissions will be affected more by CORSIA. Strategies for monitoring, reporting and verification, as well as biofuel and other efficiency measures, may impact reported performance significantly [15]. It is to note that, according to data from the EU's Transport & Environmental group in 2019, Ryanair has become the first airline to be included in a list of Europe's top polluters, which had until now been exclusively occupied by coal plants [16].

In these circumstances, it will be necessary to wait until reliable information about the effectiveness of the program might be available after the pilot phase, which applies from 2021 through 2023 to States that have volunteered to participate in the scheme.

- EU Emissions Trading System: The EU Emissions Trading System (EU ETS) is the cornerstone of the European Union's policy to tackle climate change, and a key tool for reducing greenhouse gas emissions cost-effectively, including from the aviation sector. It operates in 31 countries: the 28 EU Member States, Iceland, Liechtenstein and Norway. It is the first and so far the biggest international system capping greenhouse gas emissions: it operates in 31 countries: the 28 EU Member States, Iceland, Liechtenstein and Norway and around 500 commercial and non-commercial aircraft operators that fly between airports in the European Economic Area (EEA). European Council Conclusions of October 2014 [17] expect that the EU ETS will be the main European instrument to achieve the EU's binding 2030 target of an at least 40% domestic reduction of greenhouse gases compared to 1990 [18]. EU countries have amended the original legislation several times as the system has evolved. The most recent changes were agreed in March 2018. Detailed analysis of this measure is provided in Annex 1.

  The working principle is based on a "cap", or limit, on the total amount of certain greenhouse gases that can be emitted by the factories, power plants, other installations, and aircraft operators in the system. Within this cap, companies can sell to or buy emission allowances from one another. The limit on allowances available provides certainty that the environmental objective is achieved and gives allowances a market value, in line with the 2015 Paris Agreement on climate change.

  For aviation, the cap is calculated based on the average emissions from the years 2004-2006 and was originally set at 210 MtCO2e/year (at 97% of the historical emissions, the mean between emissions of 2004, 2005 and 2006). This cap was meant to reflect the initial inclusion of all flights from, to, and within the EEA in the EU ETS. However, following the "stop the clock" temporary suspension until the end of 2016, the number of aviation allowances put into circulation in 2013-2016 was significantly lower than the original cap. In 2017, the intra-EEA scope for aviation was prolonged until 2023. The adjusted approach for determining the annual aviation cap still applies. PHASE 4 (2021-2030): A linear cap reduction factor of 2.2% (48.4 million allowances) annually for both stationary sources and the aviation sector. The linear reduction factor does not have a sunset clause and the cap will continue to decline beyond 2030.

  Aircraft Operators are entitled to free allocation based on an efficiency benchmark, but this might not cover the totality of emissions. The remaining allowances need to be purchased from auctions or the secondary market. The system allows aircraft operators to use aviation allowances or general (stationary installations) allowances to cover their emissions.

With the inclusion of intra-European flights in the EU ETS it has delivered around 100 MT of CO_2 reductions/offsets between 2012 and 2018. The total amount of annual allowances to be issued will be around 38 million, whilst verified CO_2 emissions from aviation activities carried out between aerodromes located in the EEA has fluctuated between 53.5 MT CO2 in 2013 and 61MT in 2016. This means that the EU ETS is now contributing more than 23 MT CO2 of emission reductions annually [19], or around 100 MT CO2 over 2012-2018, partly within the sector (airlines reduce their emissions to avoid paying for additional units) or in other sectors (airlines purchase units from other ETS sectors, which would have to reduce their emissions consistently). While some reductions are likely to be within the aviation sector, encouraged by the EU ETS's economic incentive for limiting emissions or use of aviation biofuels, the majority of reductions are expected to occur in other sectors.

Target the EU's 2030 economy-wide target commits the bloc to achieve an emissions reduction target of -40% against 1990 levels. That target is a combination of emission reductions under the bloc's ETS and targets for each member state for sectors of their economy not covered by ETS under the Climate Action Regulation. In establishing the ETS target, the Council of the EU included outbound aviation emissions i.e. emissions from all flights departing EU airports to any destination either within the EU or beyond the EU, with a target of 111 Mtons by 2030 (Council of the EU, 2017). As outbound aviation emissions are currently (2017) estimated to be 174 Mtons (UNFCCC), that target is a reduction of over 36% from current emissions. It should be noted that while the initial target includes all emissions from outbound aviation, the scope of aviation's inclusion in EU ETS has been limited to outbound flights within Europe until at least 2024.

By contrast, the CORSIA target has been set to stabilize emissions from international aviation at 2020 levels, allowing airlines to continue growing their emissions. Setting aside how each measure will achieve their respective target (airlines purchasing allowance reductions from other sectors covered by ETS, and airlines purchasing offsets approved by ICAO under CORSIA), the CORSIA target is a weaker target than the EU 2030 target. Therefore, any move to replace the existing ETS target with the CORSIA target would represent a regression in Europe's climate ambition, a move which the Paris Agreement explicitly prohibits.

A further distinction between the EU 2030 targets and the CORSIA scheme is that the former is to be solely achieved through reductions within the EU and therefore does not recognise the use of international credits. In contrast, CORSIA is built explicitly around the use of such international credits.

As a result, implementation of CORSIA into EU law, in a manner which replaces existing EU legislation, risks creating a situation where all sectors of Europe's economy, bar aviation, are legally obliged to achieve emission reductions without offsetting. As the commitment to domestic reductions was stated in Europe's NDC, which explicitly states "No contribution from international credits" backtracking on this for any part of its economy would, like with a weaker target, count as backsliding which the agreement prohibits.

Due to the weaker target and the use of offsets, implementing CORSIA in EU law in a manner which replaces existing legal commitments would weaken Europe's overall climate ambition. According to independent research commissioned by T&E, over the period 2021-2030, Europe's aviation emissions would increase 683.8 Mtons CO2 (TAKS, 2019), which is equivalent to the 2017 CO2 emissions of Poland and France combined (Global Carbon Atlas, 2019). [20], [21], [22], [23]

18.6.1.2 Climate Change levy schemes: carbon-based charges, taxes, and levies.

At this stage, much attention has been devoted to the other main market-based instrument, the climate change levy schemes, mostly at the national and local level. In general, this category can be instantiated as charges, taxes, and levies. The term charge usually refers to mandatory payment of an amount related to carbon emissions, whether implemented as a tax or as a levy. By a tax usually is meant a compulsory payment that is not fully required to those paying it. [3] By levy usually is meant a charge that is fully rebated to the payer,

[3] Thus payment for a service, including to a public agency, is not a tax if it covers the cost of providing that service: such payments are user fees'.

in cash or kind. For the sake of this study, all three terms are considered equivalents and referred indistinctively.

The primary rationale for environmental taxation is the externalities argument. By leaving a tax on the pollution-generating activity, the social costs of pollution can be 'internalised' to the agent (who must pay the tax) and the socially optimal level of pollution would occur.

Carbon-based taxes generally refer to taxes on aviation jet fuel through price signals to airliners (through higher fuel costs) and/or consumers (through higher ticket prices). There is also the air passenger tax, which in practice imply altering the price relationship between air travel and other transport modes, along with other categories of consumption. If the air passenger tax is distance-based, it incentivises customers to opt for shorter flights.

Although this measure is generally recognised as positive, there is no yet a clear agreement on what could be the most convenient type of tax, what should be its value, and what would be the expected impacts. Under different considerations of the price elasticity of aviation, certain authors have recently proposed different tax values as effective MBI. At [14] authors claim that a tax of an order of magnitude of € 150/ton CO_2 could be an effective measure to reduce air transport demand and therefore aviation emissions. At [24] a uniform globally applied CO2 price of $25 per tonne is considered. This emissions price corresponds to the medium damage scenario studied by AGF [25] [26], and is consistent with the US 2010 inter-agency assessment of environmental damages per tonne. Authors claim that a $25 per tonne emissions price would add about US 6 cents per litre, or about 8 percent, to the price of jet fuel. At [27] the effects of a fuel excise duty on kerosene, equivalent to is 330 €/kilolitre are estimated to result in in a 10% increase in the average ticket price and an 11% decline in passenger demand at European level.

In this study, we complement the available information by gathering analytics and insights to answer how taxing CO2-emissions (Climate Change Levy schemes) will imply significant changes in the aviation industry, including aviation demand, industry and markets structure and emissions reduction.

It is important to note that, according to Article 24 of the International Civil Aviation (Chicago Convention), jet fuel for international commercial flights (e.g. kerosene) is legally exempt from taxes (and therefore only with bilateral agreements between two or more countries it would be possible to introduce a tax on jet fuel for international flights [28], [29]Error! Bookmark not defined..

Chicago Convention provides that fuel and lubricating oils on board that are carried on an aircraft of a Contracting State when they reach the territory of another Contracting State and are still on board such aircraft when it leaves said State shall be exempt from the payment of customs duties, inspection charges or other similar taxes and fees, if national or local [30]. Besides, in Chicago Convention was prohibited the application of taxes to kerosene so as not to slow down the development of international traffic. However, 76 years after the Chicago Convention, the aviation sector contributes more than 2% of global CO2 emissions and is expected to exceed 20% by 2050.

Nevertheless, even with these bilateral agreements, studies consider that a carbon tax would only be effective in reducing demand if it is common and equal among countries as airlines could change their operational behaviour to remain competitive (e.g. changing airports of choice and/or relocating to "low-tax" countries) [27]. Every country would be better off with taxes on aviation, in the sense that these would lead to a socially optimal air traffic level [31]. The problem is that there are some incentives for a country to reduce or not introduce taxes in aviation and thus increase its participation in the aviation market. Besides, tax evasion measures taken by tax subjects (for example, travelling to airports in neighbouring non-tax countries or refuelling abroad) can reduce the positive environmental impact of aviation taxes [31].

Therefore, the main drawback to using taxes as a global climate policy instrument is the need for consensus between States regarding their introduction, as well as the detailed policy design e.g. tax rates and tax bases. Despite all these considerations, the introduction of aviation taxes into an internationally coordinated movement should be possible. For example, the international harmonization of aviation taxes within the European Union or the EU minimum tax rates for energy products used for heating, as a fuel or as electricity in the Energy Taxation Directive. Regarding energy product taxation, however, many Member States apply exemptions or reductions. Moreover, these minimum tax rates are not based on the carbon content of the fuels but mainly on weight or volume. However, some Member States apply an explicit carbon tax on top of the regular energy excise duties. In 2012, energy taxes accounted for 75% of environmental tax revenues in the EU. Vehicle taxes include registration taxes, ownership taxes and road use charges in form of vignettes or distance-based toll systems. In 2012, transport taxes accounted for 21% of environmental tax revenues in the EU.

Carbon taxes are a type of Pigouvian tax [32], this type of taxes seeks to correct a negative or positive externality, in this case, the decarbonization of aviation. Therefore, the imposition of carbon taxes would increase the price of a flight, which could lead to a reduction in demand.

In order to be environmentally effective, air traffic taxes should provide incentives for:

- Reducing fuel consumption and therefore pollution using more reliable aircraft.
- Shift the fuel mix to less emission-intensive sources.
- Optimize aircraft loads and thus decrease fuel consumption and emissions per passenger as well as reduce the number of flights. [33]
- Avoid very short and very long distances.

Environmental effectiveness also depends on the susceptibility of the tax on the fiscal competition and the possibilities of passengers and carriers to avoid it by flying from or by tanking in third low or no-tax countries. The various aviation tax choices vary in their ability to set certain incentives.

In terms of exposure to the impacts of climate change, economic development rates and contributions to international aviation pollution, the different circumstances and respective capacities of developing countries need to be considered also. By introducing a carbon tax in the purchase of airline tickets, it is understood that all passengers can pay such a tax, both passengers in developing countries and those in non-developed countries, which means that countries would have to establish a tax at an appropriate level according to their economic circumstances.

In this context, a carbon fuel tax would reduce flight demand and supply, particularly for very short and very long-haul flights, and it can also be expected to contribute to aircraft load optimization. Carbon-based flight ticket tax offers less environmental benefits than carbon-based fuel tax, as it provides little incentive for airlines to raise aircraft loads and reduce fuel use.

Although there have not been numerous research related to carbon taxes in aviation, every factor that can cause a tax to have a negative or positive effect on different variables such as employment, GDP or costs and benefits should be studied before implement any carbon tax [34]. These factors could be the following:

- It is likely that there is lower employment, lower GDP, and an impact on the economy, since it may take time for the economy to adapt to such a change as the imposition of a carbon tax. Despite this, it is difficult to determine how a change in aviation tax will truly impact the economy. On the other hand, carbon taxes in aviation can also result in lower real wages, and this will therefore lead to a reduction in unemployment as well as GDP will increase and tax benefits will come in.

- An aviation tax would impact both inbound and outbound tourism. When visitors pay more for the goods and services than they cost, taxes account for at least part of that difference. A country will be exporting taxes so that national income and net benefits will increase.
- If a country depends on taxation on its goods and services, for example, VAT, all goods and services would usually be taxed. If there is a service like international aviation that is not regulated, welfare will be boosted by imposing to aviation a tax that is not very different from other taxes, resulting in a national income and net benefits increase [35].
- If an externality exists, such as greenhouse gas emissions, taxing the emissions will increase net benefits, but not necessarily national income. An aviation tax, regardless if it is a tax on fuel or a tax on tickets, will have that positive effect. In the case of emissions, the beneficiary will be the planet rather than country population.
- The carbon tax will reduce the use of aviation, and if aviation has broader economic benefits, it will reduce national income and will affect the economy.

Considering that taxes on aviation jet fuel can only be levied on domestic flights, the following analysis will consider the impact of (both existent and potential) carbon taxes in European countries, Japan and the United States. Other countries also tax domestic aviation fuel, but no studies have been found regarding its impact on the country's aviation sector.

18.6.1.2.1 Impact in Europe

A study [27] made by CE Delft for the Directorate-General for Mobility and Transport (DG MOVE) of the European Commission (EC) assessed the impact of the introduction or abolition (*i.e.* in the case the country already has a tax) of a ticket tax, Value Added Tax (VAT) on tickets or a fuel excise duty on 24 EU MS through the development of a model. The model estimated the impact of each taxation alone by holding constant the current VAT and excise duty scheme of the country. The base year used in the study was 2015 and the ticket tax and VAT rates were based on Germany's rate values (as of May 2018), as the country levies ticket taxes and VAT (only on domestic flights) and it provided a good example. Moreover, the study assumed that, in the base case, international flights were exempt from VAT and excise duties. To estimate the impact on demand, the study considered different elasticities per passenger group and types of flights. For this study, a short-haul route was defined as a route with a stage length shorter than 3,500 km. Short-haul flights generally have a higher elasticity in absolute terms (i.e. lower) relative to long-haul flights since the likelihood of inter-modal substitution is greatest in case of a fare increase as the car or train can act as a substitute. For long-haul flights there are no alternative modes of transport, hence passengers are relatively less price sensitive. At the same time, passengers that travel in first/business class are less price-sensitive than those who travel in other classes. Considering this, the resulting elasticities in the study were:

Geographic Zone	Domestic (intra-Europe short-haul flights)		Europe (intra-Europe long-haul flights)		Intercontinental	
Passenger group	First/business class	Economy class & other classes	First/business class	Economy class & other classes	First/business class	Economy class & other classes
Elasticity	-0.68	-1.23	-0.57	-1.12	-0.25	-0.8

Table 18. 3. Passenger groups and elasticities considered in the study

The study also considered that a 1% change in the passenger demand will lead to the same percentage change in the number of flights. Regarding the cost pass-through, the model assumed that airlines would pass on the VAT/ the fuel excise duty to passengers for 100%.

Ticket tax: The ticket tax to be introduced in the model (for countries that don't levy a tax on tickets) was based on the German Air Transport Tax for short-haul flights (since the majority of passengers within a country fly to destinations within Europe in economy class and other classes), which is 7.47€ per passenger, and the model assumed that it was only levied in the country of departure. In contrast to VAT (as modelled in the study), the tax also applied to inbound passengers which paid the ticket tax on their return leg.

The calculated impacts on ticket prices range from 3-19%, although in most MS it is close to 10%. The differences are partly due to the different level of ticket prices and share of international transfer passengers or freight flights in the EU MS. In most countries, a 10% increase in ticket prices resulted in a 9-11% lower demand (and a similar reduction in the number of flights). In general, the introduction of a tax that increases ticket prices by 10% has no net impacts on jobs. The negative impacts on employment in the aviation sector and suppliers are offset by positive impacts in other sectors caused by increased fiscal revenue, which either results in higher government spending or results in lower taxes and increases the demand of households or businesses.

VAT on flight tickets: In the study, VAT was modelled as an ad-valorem tax on the purchase of a ticket, meaning that the tax was applied/levied in the country where the ticket is sold and not on the country of departure. The VAT rate was based on Germany's standard value, which is 19%.

In EU-wide (considering 28 MS), the introduction of Germany's VAT rate of 19% on tickets for domestic flights for all destinations, the model estimated that the demand for flights by passengers and the resulting number of flights would decrease by 18% compared to the current situation. This would result in a reduction of the number of direct jobs and the value-added (percentage of revenue created by adding value) by the aviation sector of 18%, although the overall effect on jobs and GDP is negligible. The introduction of the VAT would increase the aviation-related fiscal revenue EU-wide from € 10 billion to € 40 billion.

Fuel excise duty on kerosene: The same tax rate was considered in all countries, corresponding to the minimum rate for kerosene (the basic fuel used in modern civil aircraft) from the Energy Taxation Directive (which exempts kerosene used in international aviation) that **is 330 €/kilolitre and that would increase the** ticket price.

The introduction of this duty in EU-wide (considering 28 MS) would result in a 10% increase in the average ticket price and an 11% decline in passenger demand. The aviation-related fiscal revenue would increase from € 10 billion to € 27 billion (an increase of 1,7%), while on the other hand there is a relative reduction of 11% in the number of direct jobs and the value added by the aviation sector. The introduction of excise duty on fuel would have an impact of less than 0.1% for most MS, although some outliers have a contraction of GDP by 0.6% or an increase of 0.7%. Thus, the impacts of this particular excise duty are found to be smaller than for the VAT on flight tickets, and higher than for the (oppositely directed) abolition of the ticket tax.

Overall, the analysis showcases that new or increased aviation taxes would have a negative impact on the aviation industry economic growth (lower direct employment and direct value-added) but its impact on the overall employment within an MS, on fiscal revenue and GDP would be close-to-zero.

18.6.1.2.2 Impact in Japan

Between 1972 and 2013, the Japanese Aviation Fuel Tax was levied on aviation fuel for domestic flights, amounting to JPY26000/kilolitre (approximately 193€/kilolitre, considering an exchange rate of 1 EUR = 135 JPY) until April 2011. Afterwards, the Japanese government implemented a 30% reduction in the tax, resulting in a fuel tax of JPY18000/kilolitre (approximately 133€/kilolitre or 3$/ton CO2).

A study [36] authorsError! Bookmark not defined. analysed the effect that this tax had on the national demand for aviation fuel, using a Bayesian structural time series model, based on monthly observations of fuel consumption between 2004 and 2013, and domestic data aviation provided by the Japanese government.

From 1994 to 2013, the real-term price of jet fuel quadrupled, approximately doubling each year and accordingly, airlines' operational costs attributable to fuel increased from 13.6% in 2003 to 33.1% in 2013. However, the price of airline tickets remained relatively unaltered for the same period, probably due to a low-cost pass-through assumed by airlines. Consequently, between 1991 and 2013, Japan's domestic revenue RTK grew at an average annual growth rate of 13% and the volume of passengers increased by 23 million.

Despite the increase in fuel costs, during this period, Japan also had a positive evolution of fuel efficiency. With the tax adjustment in April 2011, the study estimated that there was an increase of 9.7% in fuel consumption until December 2013 [37], [38].

18.6.1.2.3 Impact in the United States

Another study [39] made by the National Technical University of Athens analysed the impact of the introduction of a carbon pricing policy (i.e. a tax on CO_2 emissions for domestic flights) on the competitive U.S. air transport in the year of 2012. The carbon price at the time was 10$ per ton CO_2 and to account for the uncertainties related to carbon price (and the recommended levels of a carbon price to achieve the goals of the Paris Agreement), the study considered three scenarios for the carbon price: (i) low scenario, 10$ per ton CO_2; (ii) medium scenario, 20$ per ton CO_2; (iii) high scenario, 50$ and 100$ per ton CO_2. Regarding the carbon cost pass-through, the study assumed that ticket prices would be adjusted as a response to the carbon emissions cost, based on the profit maximization behaviour of airline.

The following table presents the simulation results obtained. The findings of the study suggested that on average U.S. airliners would pass the full carbon cost to passengers. On average the ticket prices increase by 1.07-10.73% and the passenger demand decreases by 1.47%-13.50% depending on the carbon price set, respectively. Within-group market shares, on average an itinerary, may lose from 0.22%-2.23% of its market due to ticket price changes among the competitors. These relatively low percentage changes in the conditional market share could be additionally explained by the lack of competitive transport options in the U.S. (i.e., no high-speed rail).

Effect \ Scenario	Low 10$/ton CO_2	Medium 20$/ton CO_2	High 50$/ton CO_2	100$/ton CO_2
Average carbon cost imposed to the airline for each passenger (Δcost)	4.75	9.51	23.77	47.53
Average price increase (%Δprice)	1.07%	2.15%	5.36%	10.73%
Average demand change of within-group connections (%ΔMSyx)	-0.22%	-0.45%	-1.13%	-2.23%
Reduction in total air travel (%Δpassengers)	-1.47%	-2.91%	-7.07%	-13.50%

Table 18. 4. Effects of the carbon pricing policy in the U.S. domestic airline network

The study also assessed the reduction in air carbon emissions, which accounted for 17.05% for the higher carbon price scenario. Considering the aviation industry ambitious goal to reduce net aviation CO_2 emissions by 50% until 2050 (relative to 2005 levels), the study concluded that the carbon price should be as high as 295$/ton CO_2. With this price, the simulation estimated an intense increase in ticket prices of about 32% and a reduction in total passenger demand of about 39.6%.

On an airline-level analysis, the results of the study indicate that the effects differ depending on the airline type and that low-cost airlines, except Southwest Airlines, face the largest increase. Considering the medium scenario, low-cost airlines would face a price increase between 1.9% and 3.4%, being the average price increase of 2.15% considering legacy airlines. Nevertheless, the study concluded that the considered carbon policy wasn't expected to influence the competition between U.S. airlines.

18.6.2 Regulatory and policy measurements.

18.6.2.1 Revisiting existing aviation subsidies

There is a link between the aviation industry's development and its fiscal framework, and there are not many public data on financial support that airlines and stakeholders receive from governments and institutions. Several papers discuss the effects and design of specific subsidies, such as the provision of air transport services to remote regions but only a few studies in some countries with a more comprehensive approach quantify subsidies to the aviation industry. Apart from a limited number of academic papers, environmental agencies, non-governmental organizations (NGOs) or aviation lobby organizations have also been addressing the issue of aviation subsidies.

Talking about subsidies, these are a form of economic intervention that can be found in practically all sectors and play an important role globally, even in aviation. Subsidies in aviation have a long history and have been a source of controversy for over half a century. The 1938 Civil Aeronautics Act governed "subsidy payments in support of scheduled domestic and international air services" in the United States. Subsidies were enhanced based on claims of defining aviation as an "infant industry" and in favour of "national defence", although it was noted that aviation could no longer be defined as an "infant industry" by 1950 [40]. Subsidy payments in the United States continued to rise in the following years and exceeded US$ 60 million in the year 1960 but the Airline Deregulation Act sought to end US airline subsidies by 1978. European flag carriers also received support from governments, with subsidy policies dating back at least until 1919. The European Commission first attempted to define subsidies in the 1980s compared to' government measures, as concerns were growing about levels of 'permissible state aid' and 'overcapacity in the European airline industry'. Yet, despite these discussions, governments have continued to provide aid to airlines.

The two main elements of air transport infrastructure are air traffic control services and airports. Air traffic control services are generally financed through user fees or assigned taxes, which allows an almost complete recovery of costs. Besides, the size of an airport is relevant, since most large airports cover their total costs and even generate profits for their shareholders, while smaller airports are generally not profitable. In some countries, like Norway and Spain, most airports belong to a group of publicly owned airports. If the group covers its costs, there is no subsidy for the air transport industry, but a cross-subsidy within the industry is possible. In other countries such as Germany, for example, smaller airports are often owned by regional or local municipalities, forcing respective governments to cover losses. However, most passengers depart from large and often profitable airports, generally leading to cost recovery.

Additionally, governments often also pay for airport access infrastructures, including road and railway systems. For example, a large portion of airport financing in the US is based on the Airport Improvement Program, which is funded through taxes on aviation, and also provides funds for smaller airports.

In some cases, selling duty-free goods at airports or onboard an aircraft could be considered as a subsidy due to the tax exemption allows the airline, the airport operator or a franchise to sell goods at a higher margin and therefore have higher profits.

On the other hand, fuels for use in international aviation are not subject to taxes. This clause can usually be found in bilateral air services agreements. While Article 24 of the Chicago Convention only prohibits taxes on fuel found on board an aeroplane when it reaches a contracting state, fuel used on domestic flights is usually exempt as well from general fuel tax in many countries.

Governments have been financially involved in the sector's development since the start of commercial aviation, extending a wide range of subsidies to manufacturers, transportation infrastructure providers and airlines, which could have been legal or illegal under various trade agreements and legislation, both local and multinational. A conceptual description of the aviation subsidies is provided in the following table. Airlines were found to receive most types of subsidies. This can be explained by the fact that airlines are the most exposed to competition, and that governments have often tried to protect domestic airlines for reasons of domestic economic growth as well as national priority reasons.

	Manufacturers		Infrastructure Providers		Airlines
	Aircraft	Suppliers	Air Traffic Control	Airports	
Grants:					
Research and development	X	X	X		
Exports	X	X			
Investments	X	X	X	X	X
Loss coverage				X	X
Equity infusions	X		X	X	X
Loans and loan guarantees	X	X		X	X
Grants to provide air transport services to remote regions				X	X
Dedicated transfers to Residents buying tickets					X
Hidden subsidies:					
Reduced infrastructure fees	X			X	X
Cross-subsidisation				X	X
Monopoly rights				X	X
No or reduced taxes:					
Fuel					X
Value Added Taxes					X
Frequent flyer programs					X

Table 18. 5. Overview of subsidies extended to aviation. Source: GÖSSLING, S.; FICHERT, F.; FORSYTH, P. (2017), "Subsidies in Aviation" (online: https://www.mdpi.com/journal/sustainability)

The empty spaces in the table do not necessarily imply that a specific type of subsidy does not exist in practice. Some subsidies are specific by design or definition, for example, only airlines offer frequent flyer programs. Also, some airports can also be expected to receive subsidies related to the provision of airport infrastructure or other programs such as renewable energy generation. And there may be some more subsidies, but they have not been identified due to lack of transparency.

When subsidies constitute undue economic advantages under competition and trade agreements or national legislation (for example, open skies agreements; EU rules on state aid), the definition of what constitutes a subsidy is crucial. Temporary subsidies should be also taken into account as they are often linked to specific and extraordinary events such as an external crash, the bankruptcy of an airline or a significant investment in the airport. On the other hand, although subsidies to aircraft manufacturers are often related to specific activities such as the development of a new type of aircraft, these are provided regularly, which makes them permanent and non-temporary examples of state aid.

Land grants, low-interest loans and direct grants to airports and operators are among the many forms of inappropriate state aid that distort competition with other modes, exacerbate aviation's climate effects and do little to improve connectivity as the low-cost carrier experience has clearly shown [41]. One policy approach to moderate demand for air travel could be to phase out these direct (passed on to aircraft manufactures, airports or airlines) and indirect (provided to customers) subsidies, which also include subsidies for airport expansion and operational aid to airlines or tax exemptions – both energy and CO_2 taxes [42], [43]. The European Green New Deal [44], launched last year, reinforces the need to end global fossil fuel subsidies, phasing-out financing by multilateral institutions of fossil fuel infrastructure, strengthening sustainable financing and phasing out all new coal plant construction, besides putting an end to tax exemptions in the aviation sector.

Subsidies should only be given in the most exceptional cases, i.e. where there is a clear need to maintain appropriate scheduled air services on routes which are vital and/or improve connectivity to remote regions. Public service obligations (PSOs) are designed to do just that. For example, in PSOs, in case no air carrier is interested in operating the route on which the obligations have been imposed, the Member State concerned may restrict the access to the route to a single air carrier and compensate its operational losses resulting from the PSO [45]. At an MS level, this operational aid given to airlines has the most distortive effect on competition [3].

A report made by the Economic and Social Research Institute analysed the economic and environmental impacts of the removal of eight different fossil fuel subsidies in Ireland by using the Ireland Economy-Energy-Environment (I3E) model. The model estimated both the impact of the removal of each subsidy alone by holding the other subsidies constant (as it was made in the CE Delft study) and the impact of the removal of all subsidies in 2020. The base year (for comparison) used in the report was 2014. Also, the model considered a separate set of scenarios in which the removal of each subsidy is accompanied by a gradual increase (of 6€ per year starting from 2020) in the level of the carbon tax (which was estimated to increase from 20 €/ ton CO_2 in 2014 to 26€/ ton CO_2 in 2020) to quantify the combined effects of these different policy instruments.

In the report, the removal of sectoral fossil fuel subsidies is translated into increases in the production tax rates, whereas the elimination of subsidies on the energy commodity is translated as increases in the sales tax. For the aviation sector, the removed subsidies considered were the excise exception on aviation fuel (represented by the indicator PT_ATS and accounted as a fuel production tax rate) and the excise exception on the commodity of kerosene (represented by the indicator ST_KRS and accounted as a sales tax rate). Removing the entire PT_ATS subsidy (€ 425.9 million in 2014) paid to the aviation sector would increase its production tax rate by 212.07% and, for the ST_KRS subsidy (€ 460.1 million in 2014), its removal would correspond to a 31% sales tax rate on kerosene. The higher production rate and introduction of sales tax lead to a reduction in the transportation (TRP indicator) sectoral real value-added (i.e. its contribution to GDP). In 2030, removing the entire PT_ATS subsidy, the aggregate transportation sector's real value-added would shrink by almost 10% (the largest impact in the transportation sector with the removal of one subsidy alone) as the production tax rate of the aviation sector would triple, relative to business-as-usual (BaU), and its value-added constitutes more than half of the aggregate value-added of the transportation sector. In the cases of removing the fossil fuel subsidies on commodities, the impacts are the largest for the transportation and electricity (ELC indicator) production sectors when the subsidy on kerosene is removed. As expected, the sectoral impacts become larger in absolute terms when the subsidy removal process is accompanied by an increase in the level of the carbon tax (scenarios PT_ATS_tax and ST_KRS_tax).

Scenario	Sectoral Real Value –added in 2030		Real GDP in 2030	Consumer Price Index in 2030	
	ELC	TRP		Energy	Non-energy
PT_ATS	-0.26%	-9.84%	-0.34%	-0.18%	0.27%
ST_KRS	-2.28%	-3.30%	-0.23%	2.86%	-0.26%
PT_ATS_tax	-2.48%	-13.18%	-0.66%	9.60%	-0.06%
ST_KRS_tax	-4.41%	-7.03%	-0.82%	13.04%	-0.50%
ALL	-6.10%	-14.31%	-1.32%	8.73%	-0.53%
ALL_tax	-8.08%	-17.22%	-1.83%	19.94%	-0.61%

Table 18. 6. Sectoral and macroeconomic impacts (in percentage change compared to the BaU scenario) of subsidy removal and carbon tax addition in Ireland.

In macroeconomic terms, removing the PT_ATS and ST_KRS subsidies would lead to a reduction in the overall economic activity (measures by real GDP, in 2014 prices) by 0.34% and 0.23%, respectively, in 2030, compared to BaU scenario. Regarding the average price changes of the energy commodities, which are measured by the energy consumer price index (CPI), they would be mainly positive (i.e. the energy inflation would be higher relative to BaU level), with the removal of fossil fuel subsidies on diesel and kerosene having the highest impacts across all scenarios. This is due to the estimated higher production cost that would lead to increased domestic fuel prices and consequently decrease the national firm's profits and competitiveness in international markets.

However, overall, the report concluded that removing the subsidies one-by-one (in 2020) would not generate a significant decrease in the overall economic activity in 2030. Even if all subsidies were removed simultaneously (scenario represented by the indicator ALL), real GDP would be only 1.3% lower in 2030, compared to its BaU level. With the addition of the carbon tax (scenario ALL_tax), in 2030, the GDP would be 1.83% lower and the level of inflation would be 1% higher, compared to BaU level.

In Japan, based on the tax reform decided on 2012, the government established the introduction of a Special Tax for Climate Change Mitigation (JPY289/ton CO_2 or approximately 2.1€/ton CO_2), which was added to the existing Petroleum and Coal Tax (that is JPY760/KL or approximately 5.6€/ton CO_2 for crude oil or oil products) that covers all fossil fuels and was intended to be used for the introduction of renewable energy, among other purposes. An analysis made by the Japanese Ministry of the Environment estimates that new carbon tax's impact on Japan's GDP was an increase of between 0.04% and 0.1%.

18.6.2.2 Fiscal measures

Besides revising existent aviation subsidies, a greater use of green fiscal measures or instruments is needed to help to redirect public investment, consumption, and taxation to green priorities and away from harmful subsidies. Even though today there are several commercial-size plants in operation producing aviation biofuel, the consumption is very low due to several barriers that are limiting market uptake, such as the cost relative to conventional aviation fuel and the low priority in most MS's national bioenergy policies. In global terms, the International Environmental Agency (IEA) [46]estimates that, in 2018, aviation biofuel production was about 15 million litres and accounted for less than 0.1% of total aviation fuel consumption/demand. In 2017, it is estimated that EU had a potential bio-based aviation fuel output or production capacity of 0.335 million tonnes per year, which accounts for approximately 0.6% of the total EU conventional fossil fuel demand, and that the current consumption of SAFs or bio-based aviation fuels is below 1% of total EU aviation fuel consumption [46].

Considering this, it is fundamental to create fiscal incentives (subsidies) to increase the global uptake of SAFs. For instance, at the international level, ICAO's CORSIA will allow aircraft operators to reduce their offsetting obligations by using SAFs and fossil-based 'lower-carbon aviation fuels', which will decrease the costs resulting from purchasing emissions units, and thus, the estimated burden for the aircraft operator. However, countries have more control over policy support for domestic than international aviation, and the introduction of national policy mechanisms to facilitate SAF consumption is also gathering pace. The US, the EU, the Netherlands, the United Kingdom and Norway have all recently established policy mechanisms which will support the use of aviation biofuels. In EU, following the European Green New Deal, a review of the European economic governance framework will include a reference to green public investment in the context of the quality of public finance, which will allow improving EU fiscal governance.

According to IEA's Sustainable Development Scenario (SDS), which anticipates biofuels reaching around 10% of aviation fuel consumption/demand by 2030 and close to 20% by 2040, subsidising the consumption of SAF envisaged in the SDS scenario in 2025, around 5% of total aviation jet fuel demand, would require about $6.5 billion of subsidy (based on closing a cost premium of USD 0.35 litre between HEFA-SPK and fossil jet kerosene at USD 70/ barrel (bbl) oil prices). This is far below the support for renewable power generation in 2017, which reached $143 billion.

A report [47] from the UK's Sustainable Aviation (SA) estimates that in 2035 there may be between 14.5 and 30.9 million tonnes per year of SAFs produced globally. This would correspond to 4%-8% of global aviation fuel use. If UK production were to grow in line with global production, SAFs produced in the UK could provide between 3.3% and 7.8% of the UK's 2035 aviation fuel demand. For this, it would be necessary to develop up to 14 full commercial-scale plants until 2035, which corresponds to a new plant every 1.3 years and around £4 billion (approximately 4.4 billion EUR) of total investment. By 2035, the development of a domestic industry for the production of SAFs could generate a Gross Value Added (GVA) of up to £742 million (approximately 823 million EUR) annually and support up to 5,200 UK jobs. A further 13,600 jobs could be generated from the growing market for SAFs through global exports.

18.6.2.3 CO2 standards

Achieving emissions reductions through technical standards is a fundamental element of ICAO's basket of measures to address aviation emissions. The sector remained the last major transport mode without vehicle emission standards, so the intensive CAEP work over the past six years was an important opportunity for ICAO to deliver on its stated climate goals [48]. In 2017 the 36-State ICAO Council has adopted a new aircraft CO2 emissions standard which will reduce the impact of aviation greenhouse gas emissions on the global climate. Contained in a new Volume III to Annex 16 of the Chicago Convention (Environmental Protection), the aircraft CO2 emissions measure represents the world's first global design certification standard governing CO2 emissions for any industry sector [49] [48] [50]. The Standard will apply to new aircraft type designs from 2020, and aircraft type designs already in production as of 2023. Those in-production aircraft which by 2028 do not meet the standard will no longer be able to be produced unless their designs are sufficiently modified [48] . Detailed information about the standards is provided in Annex 3.

Fuel efficiency is central to aviation's business and sustainable growth strategy — as evidenced by the huge gains in fuel efficiency over the decades. The formalisation of a CO2 Standard for aircraft is an important part of the sector's overall basket of measures for climate action and is complementary to the significant work already underway in the sector: new aircraft and alternative fuels technology; optimising operational procedures; and improved infrastructure. Each new generation of aircraft is roughly 15-20% more efficient than the model it replaces. The CO_2 Standard mandates that these improvements continue. The Standard will ensure that all newly-developed aircraft and engines incorporate the latest commercially-available proven technologies, mindful that no single technology can be applied across the entire range of new aircraft and engine models from small regional and business aircraft to the very large capacity long-range commercial aircraft.

CO_2 differs fundamentally from ICAO's noise and NOx standards because fuel efficiency has always been a major aircraft design parameter whereas noise and (to a large extent) engine emissions abatement measures, are not in themselves inherent to building aircraft – at least until the regulation was introduced. While those measures simply add costs, every fuel efficiency improving technology has both costs and savings. [51]

The CO_2 Standard focuses on cruise flight performance. For each aircraft type, depending on its size and weight, the CO_2 Standard defines a maximum metric value (fuel burn per flight kilometre) that may not be exceeded [52]. This CO_2 metric system intends to equitably reward advances in aeroplane technologies (e.g. propulsion, aerodynamics and structures) that contribute to reductions in aeroplane CO_2 emissions and differentiate between aeroplanes with different generations of these technologies. As well as accommodating the full range of technologies and designs which manufacturers can employ to reduce CO_2 emissions, the CO_2 metric system has been designed to be common across different aeroplane categories, regardless of aeroplane purpose or capability

18.6.3 Alternative fuels

When considering alternative fuels, two main alternatives can be outlined: renewable hydrocarbon biofuels and synthetic fuels, electro fuels and synthetic kerosene.

Renewable Hydrocarbon Biofuels: The use of biofuels is needed according to accredited forecasts to contribute to the reduction of CO_2 emission by 2050. Research initiatives and certification paths are detailed in Annex 5.

Due to the high cost of aircraft and the long fleet replacement time, and also to limit infrastructure changes, the aviation sector is likely to rely on liquid fuels similar to kerosene to 2050 and possibly beyond and is currently looking to drop-in sustainable fuels to the conventional, crude based, jet fuel.

According to ICAO, today the situation of distributing blended alternative fuels is as follows [53]:

- 185,000 commercial flights since 2011
- 5 technical SAF pathways certified & 4 more pre-2020
- Growing locations offering daily flights
- 2018 SAF volume = approximately 0.01% of total fuel demand
- A number of major construction announcements in the past 18 months
- Approximately 6 billion SAF litres in a forward purchase agreement
- More than 40 airlines have developed experience using SAF

However, sustainable Aviation Fuels (SAF) production capacity requires large industrial investments in a moment when SAF is not yet economically competitive with Conventional Aviation Fuels (CAF). Additionally, decarbonizing the aviation bringing new fuels in commercial flights requires to go through a long and expensive route encompassing certification,

Renewable jet fuel, also called *biojet* or *aviation biofuel*, is a biomass-derived fuel that can be used interchangeably with petroleum-based aviation fuel. Certain biojet fuels can be blended up to 50% with conventional commercial and military jet (or aviation turbine) fuels. The composition of these new fuels is currently mostly paraffinic, being known as Synthetic Paraffinic Kerosene (SPK) or iso-paraffins. It can be blended in variable amounts up to 50%, depending on the fuel type with conventional commercial and military jet (or aviation turbine) fuel while synthetic kerosene with aromatics (SKA) fuels can be used interchangeably with fossil fuels. Blending is required with SPK fuels because they lack sufficient aromatic hydrocarbons, which are present in conventional jet fuel. While aromatic hydrocarbons are limited in jet fuel to prevent smoke formation during combustion, a minimum aromatic content is needed to cause elastomer swell in aircraft fuel systems and increase fuel density. Once blended, SAF has the same characteristics as fossil jet fuel.

There are 5 major fuel routes approved by the ASTM D7566 standard:

- Hydrogenated esters and fatty acids (HEFA) fuels derived from used cooking oil, animal fats, algae, and vegetable oils (e.g., camelina) (HEFA-SPK)
- Fischer-Tropsch (FT) fuels using solid biomass resources (e.g., wood residues) (FT-SKA)
- FT fuels with aromatics using solid biomass resources (e.g., wood residues) (FT-SKA)
- Synthetic iso-paraffin (SIP) from fermented hydro processed sugar, formerly known as direct-sugar-to-hydrocarbon fuels. Blends of up to 10% are permitted for this fuel (SIP-SPK)
- Alcohol-to-jet (ATJ) fuels produced from isobutanol and blended to a maximum level of 30% (ATJ-SPK).

The blend is then re-certified as Jet A or Jet A-1. It can be handled in exactly the same way as regular jet fuel. There are other 7 routes currently under approval process, plus other 15 waiting to enter the process [54]. Sustainability of those pathways depends upon the feedstock and way of production. Feedstocks considered by the aviation industry[4] are lipids such as waste oils like used cooking oil (UCO), residual animal/vegetable oils from industries, vegetable oils like camelina oil, algae, cellulosic material such as tobacco, jatropha, sugars from sugarcane, lignocellulosic material, lignin residues, municipal solid wastes (MSW), dedicated energy crops. Wastes and residues that do not require land to be produced usually have fewer sustainability concerns. Drop-in fuels could also be produced from electric power (power-to-liquid (PTL) or sunlight (STL)). Beside the assessment of the current technical potential, an appraisal of the maturity level of the various production pathways is summarised in a database, which Joint Research Centre (JRC) updates, in Annex 5.

Table 18. 7 provides a summary on the state of the art of alternative fuel use in aviation.

Jet Engines	SPK (FT, HEFA, FT/A)	SIP	ATJ	HEFA+	LNG
How much is used and why?	Not used in Europe on a large scale, there is a growing interest in developing these fuels as they are considered large contributors for decarbonisation of air transport in the short and medium-term[5]. More than 1600	Used at Lab'line demonstration project and some Airbus delivery flights, but not	Recently approved, no use reported in Europe.	HEFA+ refers to upgrading from the conventional green diesel (HVO) to the aviation quality standards (cold	Not used.

[4] The feedstocks types cannot be considered sustainable per se. Sustainability should be demonstrated along the production chain. Those mentioned above have been used in aviation because in particular production chains they have been found as sustainable according to internationally recognized standards like RSB (www.rsb.org) or ISCC (www.iscc-system.org) and the Directive 2009/28/EC.

[5] ICAO (2013) "ICAO environmental report 2013. Aviation and climate change". Available at: http://cfapp.icao.int/Environmental-Report-2013/files/assets/common/downloads/ICAO_2013_Environmental_Report.pdf

Jet Engines	SPK (FT, HEFA, FT/A)	SIP	ATJ	HEFA+	LNG
	commercial flights have been done using sustainable fuel blends from 20-50%[6]. Use at the airport as non-segregated fuel has started in January 2016 in Oslo[7] increasing the number of flights, but the volumes needed to keep continuous supply are a challenge. There is no continuous production of drop-in fuels for aviation in Europe. Use outside Europe, mostly in the USA, has been promoted by military contracts and now starting from private companies.	used continuously.		temperature properties, density...). Not yet approved for commercial aviation, but testing is ongoing.	
How is it used?	Synthetic paraffinic kerosene, once it has been blended, can be used as drop-in jet fuel. Maximum blend ratios accepted for commercial aviation are FT-SPK (50%), HEFA-SPK (50%) and FT-SPK/A (50%)[8]. Once the fuel has been blended and approved according to the ASTM D7566 standard, it can be used in all civil aircraft and infrastructures using conventional jet fuel without any segregation.	It can be used blended with fossil jet fuel up to 10% v/v.	Can be used blended with fossil jet fuel up to 30% v/v.	HEFA is approved up to 50%. HEFA + could be probably used blended with fossil jet fuel up to 10% v/v.	It is not drop-in, requires a radical change of airframe and combination with electricity still not in the market.
Trends	The technology is at an early commercial stage and the production capacity is still limited, which is mainly due to economic reasons. However, HEFA is an industrially mature technology. Recently a production facility in Los Angeles (CA, USA) has started continuous production of HEFA, able to produce about 30,000 t of HEFA-SPK per year. Besides, outside Europe, there are several offtake agreements from airlines or governments, but considering facilities still not running. In Europe, potential production capacity according to the EU Flightpath and the latest updates could reach 15,000 t of sustainable fuel (FT-SPK) per year in France from 2018[9].	The technology is at an early commercial stage with low availability.	The technology is at an early commercial stage with low availability.	The technology is a commercial-stage with high availability. It could be easily adopted with some 'minor' adaptations. HEFA (Green Diesel) is well developed for ground transport fuels but the extension of HEFA+ is still to be approved.	Possibilities of using LNG as jet fuel are being explored

[6] Ecofys (2016) "Accounting methods for bio jet fuel. Final report". Available at: http://www.ecofys.com/files/files/ecofys-2015-accounting-methods-for-biojet-fuel.pdf

[7] ITAKA project (2016) "Press release. ITAKA provides sustainable fuel for worldwide's first biojet supply via hydrant system at Oslo Airport". Available at: http://www.itaka-project.eu/Shared%20Documents/20160122_ITAKA_airportusage_start.pdf

[8] ASTM (2016) "ASTM D7566-16, Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons". Available at: http://www.astm.org/Standards/D7566.htm

[9] EU Biofuels Flightpath (2016) "2 million tons per year: A performing biofuels supply chain for EU aviation". Available at: https://ec.europa.eu/energy/sites/ener/files/20130911_a_performing_biofuels_supply_chain.pdf

Jet Engines	SPK (FT, HEFA, FT/A)	SIP	ATJ	HEFA+	LNG
Challenges & opportunities	There are almost no challenges due to their drop-in characteristics at the defined blend ratios, but to reach pure use is still not possible (but could potentially be). Minimum content in aromatics related to fuel system seals is one of the limitations to unblended use while it has been identified that there the nvPM emissions lower when aromatics are also lower. Different aerosols, nvPM and shoot combustion profiles from SPK suggest different nonCO_2 effects at high altitude that would need better understood to know the real decarbonisation potential. Use of low blend ratios of green diesel (as HEFA+ for aviation) SPK could suddenly increase the production capacity and would increase the uptake but there is still some fuel system testing required.	This is a unique molecule vs the incumbent what is more complex. It has reported that the 10% blend ratio could be difficult to be higher.	Same as SPK, but blend ratio unlikely to be enlarged.	Use of low blend ratios of green diesel (as HEFA+ for aviation) SPK, if approved, could suddenly increase the production capacity and increase the uptake in the short term, but there is still some fuel system testing required to know the limits. It wouldn't be a long term solution due to the low blend ratios.	Non-drop-in is not feasible in the time frame for a real implementation but it could be a solution for the future.

Table 18. 7. State of the art on alternative fuel use in aviation

Synthetic fuels, electrofuels and synthetic kerosene: Electrofuels are those that use renewable energy for fuel synthesis and that is carbon-neutral concerning greenhouse gas emission. Some potential electrofuels respect to the potential application as aviation fuels are n-octane, methanol, methane, hydrogen, and ammonia. The physical and combustion properties significantly differ from jet fuel, except for n-octane. Different electrofuels perform differently concerning important aspects such as fuel and air mass flow rates. (See annexe 6 for more detailed information).

- Electrofuels: Electrofuels are produced by combining hydrogen with carbon extracted from CO_2. Ideally, the hydrogen would be produced by electrolysis using renewable electricity to obtain it from water, and this would be combined with CO_2 sucked from the atmosphere to make a drop-in fuel. If such a process was implemented on a large scale, it would be effectively carbon neutral, but it with present time technology would cost up to six times more than jet fuel[10].
- Hydrogen from Water Electrolysis: The electrolysis of water to produce hydrogen has been well known since the end of the 18th Century11. The energy efficiency of the water electrolysis is already high (70–80%12). Hydrogen is an almost ideal electrofuel 13, it possesses the highest gravimetric energy density of all fuels. However, hydrogen has a very low volumetric energy density and a high diffusion coefficient, which makes hydrogen difficult to store. Compression and liquefaction are the main ways to store hydrogen effectively, but hydrogen compression consumes 15.5% of the

[10] 'Electrofuels' that increase plane ticket price by 60% only way to clean up air travel, report finds, Josh Gabbatiss October 2018, The Independent

[11] Salem, R.R. The electrolysis of water. J. Electroanal. Chem. 1999, 476, 92–93.

[12] Gülker, F. Production of hydrogen (Herstellung vonWasserstoff). Patent DE446488 (GB), July 1927.

[13] Crabtree, G.W.; Dresselhaus, M.S.; Buchanan, M.V. The Hydrogen Economy. Phys. Today 2004, 57, 39–45.

hydrogen's inner energy content and liquefaction up to 45%14. The use of hydrogen in a combustion engine or its oxidation in a fuel cell ("cold combustion") currently yields efficiencies from 40% (combustion) up to 55% (fuel cell).

- Power-To-X: Due to the obstacles in using hydrogen as a fuel, molecular hydrogen is generally rather used as a chemical intermediate for the production of easily manageable liquid or gaseous fuels, such as methane ("power-to-gas") and longer chained hydrocarbons ("power-to-liquid") from carbon dioxide, or for the production of ammonia from nitrogen ("power-to-ammonia"). All three conventional "power-to-X" technologies share the combination of the electrolytic hydrogen synthesis and subsequent catalytic conversion of the hydrogen gas with carbon dioxide or nitrogen.

New one-step reactions are needed to bypass the production and the storage of hydrogen to raise energy efficiency further. Electrochemical pathways can be, given the appropriate technology readiness, more efficient than conventional processes and are needed to steer the demand for electricity in a way that new regenerative energies can handle. All electrochemical pathways are, in terms of technology readiness, far behind, but have the potential for the creation of tailor-made emission-free aviation fuels with renewable energies.

In Table 18. 8 five representative electrofuels: n-octane, methanol, methane, hydrogen, ammonia are compared with conventional jet fuel (Jet A-1) regarding some selected properties of importance for the utilization as potential sustainable aviation fuels.

Physical Property	Jet A-1	nC_8H_{18}	CH_3OH	LCH_4	LH_2	LNH_3
Flash point (°C)	38	12	11	-	-	-
Autoignition temperature (°C)	210	205	455	595	560	630
Specific energy (MJ kg^{-1})	43.2	44.64	19.9	49	120	18.6
Energy density (MJ L^{-1})	34.9	33.2	15.9	21.2	8.4	13.6
Density (g cm^{-3})	0.808 *	0.70 †	0.796 †	0.58 ‡	0.071 ‡	0.73 ‡
Boiling point (°C)	176	126	65	−162	−252	−33
Melting point (°C)	−47	−57	−98	−182	−260	−77.7
Vapor pressure at 20 °C (hPa)	3	14	129	n/a	n/a	8573
Lower explosive limit (vol %)	0.6	0.8	6.0	5.0	4.0	15.0
Upper explosive limit (vol %)	6.5	6.5	50.0	15.0	77.0	28.0
Mass fraction of hydrogen (-)	n/a	0.16	0.13	0.25	1.00	0.18
Mass fraction of carbon (-)	n/a	0.84	0.38	0.75	0.00	0.00
Mass fraction of oxygen or nitrogen (-)	n/a	0.00	0.49	0.00	0.00	0.82

Table 18. 8. Comparison of physical and chemical properties of Jet A-1 and different potential electrofuels (L = liquefied; * at 15 _C; † at 20 _C; ‡ at boiling point)[15].

All investigated electrofuels, except n-octane, differ significantly from jet fuel regarding their combustion properties. The mass flows of air for combustion and cooling the burned hot gases are nearly the same, whereas the mass flow of fuel differs due to the specific energy. Mixture approaches (ammonia/hydrogen mixture) might be of special interest, where more research is needed. The design of combustors has to be adapted to the fuels, requiring basic research on flame stabilization and emission. Although this process will need great effort, it provides the chance to reduce the emission of soot and nitrogen oxide, if the combustion were based on more advanced approaches, like lean premixed or partially premixed combustion.

Fuel choice influences turbine performance. Higher power output and higher shaft speed are observed, therefore, the alternative electrofuels may be used in current turbine designs without major performance

---

[14] Sap, K.A.; Demmers, J.A.A.; Nimit Patel, G.R.The energy efficiency of onboard hydrogen storage. Intech 2012, 6, 111–133.

[15] IFA. Gefahrstoffe—Datenbanken (GESTIS). Available online: http://www.dguv.de/ifa/gestis/index.jsp

impacts. Concerning the aerothermodynamics of the hot gas path, they can even be used with current designs. Regarding the turbomachinery design, however, the increase in rotor speed changes the mechanical loads and thus requires modifications in the mechanical design. The fuels, therefore, are not drop-in options but appear to be alternatives worth further evaluation regarding the upstream fuel supply chain and, if that turns out promising, concerning a more detailed component design for the compressor, the combustor and the turbine of the aero-engine.

The emission reductions resulting from the use of electrofuels depend mainly on what electricity is used to produce the hydrogen and the choice of the source of CO_2 leads to different impacts. Using CO_2 from a fossil carbon origin, such as the one being emitted in a steel or a power plant, means the fuel is not carbon circular because the CO_2 ends up in the atmosphere anyway. In a 2050 timeframe, the alternative is to use CO_2 captured directly from the atmosphere that is a more expensive process but ensures the electrofuels is fully circular. Despite these cost impacts, as fuel efficiency improvements will not decarbonise aviation, and with sustainable advanced biofuels unable to meet all of aviation fuel demand in 2050, if the sector wishes to decarbonise, it must steadily and in a sustainable manner increase electrofuels production to meet the remainder of its fuel demand. At least until more radical technology breakthroughs become available[16].

However, the cost implications of electrofuels will remain substantial. The fact that electrofuels production requires enormous quantities of electricity means that its cost will likely exceed that of untaxed kerosene. It is unlikely that, even with carbon pricing, electrofuels will reach cost parity with kerosene. As a result, policies will need to be put in place to ensure the uptake of electrofuels. Any policy which requires airlines to purchase a more expensive fuel will result in an overall increase in operational costs. At least some of that increase can be expected to be passed onto consumers, increasing the price of tickets, and thereby reducing demand. Electrofuels uptake will have an impact on overall electricity demand: meeting aviation fuel demand with electrofuels will require 912 TWh. This amount is equivalent to 28.2% of Europe's total electricity generation of 3234 TWh in 2015, or 94.4% of the 966 TWh of renewables generation. This electricity used in the production of electrofuels will have to be renewable and additional for the resulting fuel to be considered zero carbon.

Also, other sectors, such as industry, are expecting to use some types of electrofuels as a way to decarbonise. These competing demands for additional renewable electricity need to be taken into account to assess the realistic amounts of electrofuels which could be used in aviation. In the production of electrofuels, only a portion will be suitable for use in the aviation sector (for example 80%, a very optimistic assessment).

On the other side, hydrogen presents several key advantages for aviation:

- Elimination of CO2 emissions in flight and along the entire life cycle if produced carbon-free.
- Its usage in fuel cells allows for zero-emission propulsion (including NOx and particles).
- Very low particle emissions, when burnt in a turbine engine.

However, considering non-CO2 emissions at high altitude, is still to be assessed how the use of hydrogen in a thermal (combustion) engine can lead to different emissions and consequently a change in the global environmental impact. Additionally, to scale H2-powered aircraft, several technological unlocks need to happen.

[16] Roadmap to decarbonizing European aviation, October 2018, Transport & Environment

Non-drop-in-fuel will require parallel technology developments to increase the maturity of the key building blocks, still at a very low TRL. The aerospace industry is planning to collaborate to develop the necessary onboard technologies, widespread availability of new fuels (e.g. H_2, LNG). Recharging/refuelling infrastructure, together with low CO2 means of production, will be key for the overall success of this approach.

18.6.4 Technological innovations

18.6.4.1 Deploying near term technologies

Aviation decarbonization the "*revolutionary*" technology solutions imply longer and riskier development, probably to be implemented by 2050 (Blended Wing / Body Aircraft, Open Rotor Engine and Hybrid and fully Electric Propulsion, etc.)

Of the *evolutionary* technology solutions, some provide marginal gains over the existing performance, gains that can cumulate into non-negligible values. Those technologies are "slowly evolutionary". If the current generation of airliners is N, the *slowly evolutionary* solutions had already been introduced on N-1, or N, or are expected to be introduced or refined on N+1. Other technologies provide rather visible steps, bringing larger measurable generational differences. They will be called "fast evolutionary". However, due to saturation in exploiting the classical configuration of aircraft, the *evolutionary* technologies are not expected to achieve more than 30-35% reduction in fuel burn compared to 2010 levels, according to IATA [3]

A few main directions are currently available to improve the fuel efficiency in aviation, as well as its emissions footprint. The technologies used in the design and manufacture the machine can provide the most important source of that improvement. In the case of *evolutionary* technologies, three fields can provide the most promising results: powerplants performance, aircraft aerodynamics and weight reduction.

For improving aerodynamics, the following aspects offer most prospects.

- High aspect ratio designs. Limitations of the stress in current wing configurations can be overcome either using lightweight structures and stronger materials or introducing new shapes. In the latter kind of solutions, a very thin and long wing will provide less induced drag and consequently less fuel burn and higher speeds. A strut or truss braced wing could offer such advantages. A Boeing project [7] designated SUGAR (Subsonic Ultra Green Aircraft Research) powered by an advanced turbofan, with a 900 nm mission a 29% (further optimisation up to 53%) fuel economy compared to a Boeing 737-800 and possible Entry into service (EIS) by 2030-2035[1]. The configuration with a parasol wing also provides a suitable accommodation of a large diameter Ultra High Bypass Rotor or even an Open Rotor engine. Such a solution, however, should deal with the challenge of designing a foldable wing to respond to ICAO airport limitations. Measured on NASA TRL scale SUGAR is probably reaching TRL3-4, other similar designs being considerably behind.
- Boundary layer ingestion. The PFC (Propulsive Fuselage Concept) [1] places the propulsive fan on the axis of the tail of the fuselage so that thrust is generated using ingested slower boundary layer airflow. It decreases the drag and necessary thrust while the forces are distributed on the main structure and not transmitted via nacelles and wings, with an estimated fuel reduction of 7-12% and TRL3. The advantage of the configuration is enhanced when turbo-electric propulsion is chosen; in this case, a "distributed propulsion" might be preferable, i.e. one of the three or more electrically driven fans would be placed on the aircraft tail to absorb the boundary layer.
- Laminar flow control revisited. Maintaining laminar flow by controlling the pressure distribution on an airfoil, Natural Laminar Flow (NLF), is a promising solution but lack of cost motivation and difficulties in a compromise between the necessary shape and the mass increase prevented a commercial application. A solution obtained by adding to the wing shaping (NLF) some boundary

layer suction on the front part of the wing is called Hybrid Laminar Flow Control (HLFC). The result is the increasing of Reynolds numbers at which turbulent flows appear. Flows can be organised with surface suction through a multitude of very small holes. Some proposals for applying such solutions on large aircraft were submitted during the 60s and 70s the projects were never funded. Eventually extending HLFC effect on the whole surface would create an all laminar aircraft, but this is unlikely to happen before 2050. A successful NLF Control experiment was achieved by BLADE (Breakthrough Laminar Aircraft Demonstrator in Europe, started in 2017 as part of the Clean Sky Programme. Other Clean Sky II tests are prepared to demonstrate HLFC on horizontal tail of an Airbus A320. TRL 4-5 can be assumed both for NFL and for HLFC, promising application on the next generation of airliners (N+1). To obtain a laminar flow wing, a high precision profile and surface properties needs to be achieved and this became less difficult when using composite materials. The suction system involved in the HLFC solution creates an even stronger challenge for engineering. And the solution is not expected to function at speeds over M 0.8 which makes it applicable on short- and medium-range aircraft and less on widebodies. However, great expectations for benefits in fuel economy are already built over LFC.

- Active flow control. The simple idea of reducing the size (and consequently the mass and the induced drag) of the tail to the normal operation (non-emergency) necessities will bring fuel efficiency benefits. For special requirements, like the situation of failure of one engine, the airflow on the rudder surface can be enhanced by turning on a system blowing some supplementary flow air. A testing programme was successfully performed by Boeing, showed that the aerodynamic effectiveness of the rudder for the testing selected manoeuvres was increased by 14% [17]. That can permit a 17% scale down of the vertical tail, with reduced mass and drag, which can lead to a half per cent fuel economy [15].

Regarding weight reduction, the following aspects offer most prospects.

- Advanced Composite Structures. They offer good mechanical characteristics combined with a very low density (high strength-to-weight ratio); accessible aerodynamics profiles – encouraging NLFC, better comfort for passengers due to higher cabin pressure, improved maintainability, the feasibility of smart structures etc... Initially, major control surfaces were introduced about 40 years ago then gradually larger structural elements as wings, tails and fuselage sections could be manufactured once the technology developed. The A350 XWB airframe is made out of 53% composites, carbon fibre reinforced plastic (CFRP) for the outer and centre wing box (covers, stringers, spars), fuselage (skin, frame, keel beam, and rear fuselage) and the empennage (horizontal and vertical tailplanes). The continual rise in the content of composites is relevant for the maturity of the technology achieved during the last decades, TRL might be considered above 7.
- Smart Intelligent Structures. Smart structures are considered the systems of Structural Health Monitoring (SHM) already introduced in newer designs, up to the Morphing Structures (MS) which are still in a TRL 2-3 range. SHM is already used in a rather primitive form on some types of helicopters and aircraft engines. It enables condition-based maintenance, and a lighter structure can be used with benefits in terms of fuel consumption, besides the obvious gains in life cycle cost. Next step is the currently rather remote perspective of surface morphing, i.e. using smartness to control, optimise and rearrange the shape of the wing to better adapt to different flight conditions. DARPA Smart Wing Project was aimed to evaluate a SM wing concept equipped with a hinge less trailing edge control surface and its results were particularly promising. However, this research identified issues to be addressed in future designs: aeroelastic behaviour, the fatigue life of the structure, the need for compact power sources, etc. There is less chance that SM to become production standard during the next several decades.
- Additive manufacturing. Parts produced with this method are already beginning to appear on the latest generation of aircraft, producing components that weigh 30-55% less than traditional metal

parts [15]. Less weight reduces fuel burn and CO2 emissions. 3D Polymer components, such as ramps used to attach electrical harnesses to the aircraft structure, saving 2.4 kilograms per plane, will be equipping the A350XWB [15]. Additive manufacturing challenges, too. Additive manufacturing machines are expensive, sometimes hundreds of thousands of dollars. One of the biggest challenges, though, is making sure that your final part has good properties. If powders do not quite sinter together, it forms defects that lead to failure. Expected component weight gains will increase once the technology is growing in maturity and the costs of the process will decrease.

18.6.4.2 Combination of design and operational efficiency improvements.

Today, the objectives of improving operational efficiency are directly related to improving economic performance and increasing the competitiveness of aircraft. At the same time, technical efficiency is determined in aircraft development by optimizing its aerodynamic characteristics, new design solutions, power plant parameters by optimizing flight conditions under given restrictions and operating conditions. If we neglect the issues of aircraft reliability and the associated costs of maintenance, repair and flight delays, the economic efficiency of a transport aircraft will primarily be determined by the available commercial load and the required fuel costs. The payload determines the amount of the airline potential income per flight, and fuel costs are one of the main expense items.

The efficiency of traditional schemes of modern aircraft engines and airframes is approaching its maximum limit. It is impossible to drastically improve their performance and reduce CO2 emissions without developing alternative engine designs and new airframe layouts. The use of new fuels is also a prerequisite. [55] [56]

To conduct studies on coordination the design of the aircraft and improve operational efficiency, groups of aircraft, which are represented by configurations No. 1-6 were formed. Development paths with different options for improving operational efficiency have been identified for the selected aircraft groups. [57], [58] [59], [60]. The main content of the research is the forecast for aircraft configurations improvements and their control systems over timeframes to track the time history of their characteristics [61], [62]

Configuration No.1. Aircraft that start operation in 2020 and will fly until 2050 are under consideration. The general structural layout of the airframe and power plant will not change until 2050. The power plant consists of turbofan engine of traditional configuration with a direct fan drive, from 2030 configuration with geared fan drive will be used, from 2040 a hybrid power plant will be used. For 2020, all achievable technologies have been introduced. The implementation of innovative products is 2%, from 2030 – will be 10%, from 2040 – will be 30%.

Configuration No.2. The development of aircraft is supposed to be similar to configuration No. 1. The difference in the trend is the number of aircraft released on the world market and the cost of their maintenance.

Configuration No.3. "Flying wing" type aircraft, which will begin operation in 2030, is under consideration. In 2020 the development of new airframe designs type "flying wing" is equal to TRL = 9 (for military aircraft). The development of a new passenger aircraft configuration is TRL = 5. From 2030, the power plant will include a hybrid engine. From 2035, a distributed power plant and a hybrid engine will be used; from 2045 a fully electric motor will be in operation. For 2030, the implementation of innovative products will be 35%, from 2040 – 70%.

Configuration No.4. In 2020 the development of new airframe configuration for supersonic aircraft has a value of TRL = 5. The operation of this type of aircraft is expected from 2030. The power plant includes a turbofan engine or ramjet engine. From 2040, a distributed power plant will be used. In 2030, the implementation of innovative products will be 40%, from 2040 – 70%.

Configuration No.5. Aircraft that start operation in 2020 and will fly until 2050 are under consideration. The general structural layout of an airframe and a power plant changes according to technology readiness. The power plant consists of turboprop of a traditional configuration. From 2030, a hybrid engine with propeller will be in operation. From 2040, a power plant with a fully electric motor will be used. In 2030, the implementation of innovative products will be 35%, in 2040 – 80%.

Configuration No.6. Aircraft that will be in operation from 2040 are under consideration. The design layout of the airframe and power plant changes according to technology readiness. In 2020, the development of new airframe designs type "flying wing" with adaptive functions (transformation technologies) for passenger aircraft is TRL = 2. It is expected to have TRL = 6 from 2030. The power plant consists of fully electric motors or engines of non-traditional configuration. In 2030, the introduction of innovative products will be 55%, in 2040 – 90%.

Analysis of the data demonstrates that the development paths of new aircraft are not monotonic. By 2050 the best result can be shown by "flying wing" type aircraft with transformation technologies and morphing technology of airframe elements. Of course, such developments are accompanied by the use of electric motors, the introduction of fully nanostructured materials and other advanced technologies.

"Flying wing" type aircraft will become more profitable than traditional aircraft, such as the Boeing 777 or Airbus A350. This is due to the best aerodynamic characteristics and improved integration properties of the airframe and power plant of a new aircraft configuration. The rational use of distributed power plant with fully electric motors will significantly improve the operational characteristics of "flying wing" type aircraft.

Supersonic commercial aircraft show the worst result. This is due to the fact that flying at supersonic speeds has negative environmental impacts. Supersonic aircraft still have serious limitations in terms of noise and economy. These problematic issues will persist for a long time.

At the same time, the use of biofuels promises a reduction in carbon dioxide emissions in the range of 36-85%. This greatly depends on the type of soil on which a particular plant will grow. Although the hybrid biofuel-kerosene mixture was certified for use in aviation in 2009, the industry does not hurry to introduce a new product. There are certain technical obstacles and difficulties towards increasing biofuel production to commercial scale. But the main factor is the price that will be compared with traditional kerosene in only a few decades.

The introduction of aircraft as per configurations No. 1 and No. 2 will lead to a reduction in CO_2 by 16% in 2030, by 28% in 2040, by 45% in 2050. Implementation of configuration No. 3 can contribute to a reduction in CO_2 by 45% in 2040 and by 90% in 2050. Implementation of configuration No. 4 can lead to a reduction in CO_2 by 15% in 2040 and by 35% in 2050. The application of configuration No. 5 can contribute to a reduction in CO_2 by 45% in 2030 and by 80% in 2050. The application of configuration No.6 will completely remove CO_2 emissions by 2050 based on the introduction of all innovative products and with the use of electric motors and systems.

15.1.1.1 Review of the ways of technical development of radically new aircraft designs

The review of the technical development of the structural and layout schemes of modern and promising passenger and transport aircraft showed that a new generation of aircraft would be created according to a new aerodynamic scheme. Significant reserves to improve the aerodynamic perfection of aircraft are laid in the integration processes and new layout schemes. Modern aircraft, such as Boeing B787 and Airbus A350, will be the last generation to be created by the traditional scheme. The next generation of aircraft will completely exhaust the reserve of improvement of this layout and no matter how much effort is spent, it will be practically impossible to obtain significant results.

In the medium and long term prospect, the main directions of technological improvement of aircraft will be the creation of aircraft with a long duration and flight range based on improving the mass-dimensional characteristics of special and general aircraft equipment, increasing the aerodynamic feature and weight perfection of the airframe design, as well as the use of promising power plants based on electric and hybrid engines. It is planned that the introduction of such revolutionary innovations will take about 20...to 25 years. Experts predict the appearance in the operation of radically new aircraft designs at the turn of 2040.

The main task of civil aviation for the period up to 2050 is the transportation of people that determines the improvement of civil aircraft in the direction of upgrading safety, ecology, efficiency, comfort, etc. The practical impact of these factors is expressed in the studies carried out in the following areas:

- Increasing the speed performance of traditionally designed aircraft (supersonic and subsonic aircraft and helicopters).
- Increasing the speed performance of an aircraft by combining traditional design solutions (a combination of the advantages of an aeroplane and helicopter flight principle, when creating high-speed vertical take-off vehicles).
- Practical mastering of new flight power ratings (hypersonic aircraft).

The main directions in the development of material technology for the implementation of a new aircraft generation are:

- Self-healing materials and coatings.
- Self-organizing regulatory structures and systems.
- Sensor and active elements with improved performance.
- Composites based on polymers, ceramics, adhesives with new properties.
- Graphene-based structures.

The most likely features in creating a new aircraft generation will be:

- Remote control of aircraft elements.
- Use of "smart" structural materials and coatings.
- Possibility of adaptive variations in the geometry of flight vehicle planes.
- Application of engines with a variable cycle and with an integrated electric generator.
- Application of new physical principles in the operation of electronic computing equipment (photonics, fibre optic signal transmission, etc.).

Despite these development directions, all scientific and technical studies of world air companies are reduced to two areas:

- Improving the fuel efficiency of the power plant using new workflow cycles.
- Improving the aerodynamic characteristics of the design of the flight vehicle airframe based on the use of radically new aircraft designs.

These two directions contain a common sense in integrating a flight vehicle airframe and its power plant into a single complex technical system to ensure the specified operational performance of a new aircraft. We review separately these two extensive challenges.

18.6.4.2.1 Ways to improve the fuel efficiency of the power plant

Researchers and engineers strive to develop new concepts and technologies. According to the IATA Technology Roadmap [63], [64], 24 potential airframes and power plants were determined that may be available for sustainable aviation in 2050 as for the level of technology readiness. As part of NASA's N-plus USA programs, several innovative airframe technologies were determined to reduce emissions [65], [66]. However, IATA and NASA researchers concluded that technology development alone could not achieve the desired goals in emission reduction.

Researchers from the University of Cambridge summarized various new aircraft concepts proposed by the aeronautical research communities and concluded that ACARE and NASA emission reduction goals could not be achieved without developing new concepts for the transformation of the aircraft conceptual design [67] .

Achieving the specified indicators requires solving a number of complicated challenges, developing advanced technologies, and can only be realized with an integrated approach by improving the performance of the engine and aircraft, as well as improving the air traffic control system.

Compared with the fifth-generation engines (PW1000G, LEAP, GEn [68]x, Trent), the maximum reduction in specific fuel consumption with increased flight and thermal efficiency (while increasing cycle parameters and the bypass ratio) can be 25...30 % for a propfan engine or distributed power plant (DPP).

The decrease in specific fuel consumption for a turbofan engine with direct or reduction fan drive or a turbofan engine with a complex thermodynamic cycle (for example, with intermediate cooling) with increasing cycle parameters and the bypass ratio to m =14...18 can be 15...20 % [69] [70] .

Based on a comparison of the efficiency of engines of various structural schemes to achieve the required flight speed (Figure 45), today we discuss the development of technologies for:

- Turbofan engine of the traditional scheme with direct (m<14) or reduction gear (m>14) of a fan.
- Propfan engine ("open" rotor).
- Distributed power plant.
- Engine for supersonic aircraft.
- Hybrid powerplant.
- Fully electric motor.

From the point of view of technologies for creating engines, the main technological trends that will lead to the achievement of these goals are:

1. Increasing the bypass ratio *m*, which increases propulsive efficiency and thereby reduces specific fuel consumption.
2. Increase in turbine inlet temperature (TIT) and overall pressure ratio (OPR), which increases thermal efficiency.
3. Increasing the efficiency of engine elements, that is, the polytropic efficiency of fans, compressor stages and turbines.
4. Reducing the weight of the engine structure based on the use of lightweight materials with increased strength, which will lead to a decrease in specific fuel consumption.
5. The use of built-in electric generators to increase the efficiency of propulsors.
6. Today, the most economical engine option is a turboprop scheme.

The most promising engine in terms of emissions is a fully electric engine. However, the transition to a fully electric motor is a long way, which requires the development of new technologies. Taking this into account, NASA offers a phased approach to creating an electric engine for aircraft of various purposes. [71]

It is planned that for regional aircraft with a capacity of up to 50 people the necessary equipment (electric motors of acceptable weight with a capacity of 1...2 MW) will be available within the next 10 years, for 100-seater aircraft (electric motors with a capacity of 2...5 MW) within 20 years, and B737 / A320 class aircraft (electric motors with a capacity of 5...10 MW) for 30 years [72].

In addition to electric motors and generators, the development of accumulators and converters of electric energy, as well as on-board electrical networks for high power, is required. In this case, the weight efficiency of all elements of electrical equipment (except for superconducting ones) significantly decreases with the growth of their power. Besides, the storage of energy in the form of fuel is considerably more efficient than any existing electrical energy storage system. Therefore, all-electric light and ultralight aircraft, although they exist, have an extremely limited flight duration.

The hybrid scheme, which assumes the generation of electricity onboard using a heat engine (piston or gas turbine), circumvents this limitation and is at the current stage of development of the most promising for various types of aircraft, including for light aircraft with no more than 12 passengers, and shortly for regional aviation.

Based on the studies on ways to increase the fuel efficiency of aircraft engines of different world companies, a group of researchers in the work presented a change in the bypass ratio of a turbofan engine for airplanes with a maximum take-off weight of more than 100 tons and airplanes with one aisle. Analysis of the research results implies that the maximum possible efficiency of the engine elements is practically achieved in those time periods that are being analysed. During this period, advances in production processes and materials science will develop. Possible improvements in the efficiency of engine elements of modern structural schemes do not have great prospects. It is supposed that technology is a more limiting factor for improvement, for example, the use of additive manufacturing to create more complex geometries with more efficient cooling systems.

Analysis of the results of the study of technical concepts shows that the revolution in fuel efficiency that commercial air transport has experienced over the past 60 years is amazing and has helped airlines become interested in acquiring new aircraft with high fuel efficiency. However, development efforts are currently showing diminishing returns, increasing interest in more radical concepts.

Large turbofan engines create thrust with an overall efficiency of about 40%. Significant improvements should still be possible, if the remaining major losses can be influenced by more radical design concepts.

It is commonly known that the main sources of losses in modern gas turbine engines are the irreversibility of the combustion chamber, the heat loss of the exhaust gases of the active area and the kinetic energy of the exhaust gases. Together, they make up more than 80% of the total losses (Fig. 14). Industry is already reducing kinetic energy losses by introducing engines with reduction gears with ultra-high bypass ratios, and concepts with an "open" rotor are being considered.

Around 30% reduction in CO2 is estimated to occur from the radical innovations that are now at a lower TRL level. Due to EU projects: VITAL, NEWAC, DREAM, LEMCOTEC, E-BREAK and ENOVAL, ULTIMATE partners have gained in Europe the most comprehensive experience in the development and evaluation of advanced aircraft engine architectures. Existing tools, knowledge and models will be used for joint optimization and evaluation in accordance with the SRIA goals for the successful improvement of technologies up to TRL 2.

Forecasts until 2050 without these breakthrough technologies can reduce CO_2 emissions by 45% for long-range aircraft with advanced turbojet engines and 59% for short-range aircraft with open rotor engines. These values are compared to operating aircraft in 2000. But ACARE goals require a 75% reduction, with 68% for aircraft, and the rest for operational improvements.

It is supposed that the concept of a new engine will provide about 12% improvement in fuel combustion compared to conventional 2050 engines. It is shown that the inclusion of intermediate cooling provides more compact combustion systems with a constant volume, reducing the weight of the system and facilitating engine integration.

The combined-cycle engine concept has a supercharged gas generator and two rows of four-stroke V-10 piston engines. Secondary liquid heat exchangers provide more efficient heat recovery of exhaust gases and ensure an additional degree of freedom in the design. Additional ULTIMATE technology with the innovative BOXPROP low-noise propeller will result in a quieter powerplant. The "open rotor" drive is operated by an ultra-compact gas generator with intermediate cooling, which uses pulsed detonation combustion. Significant performance improvements with ULTIMATE technology should help to achieve ACARE goals. However, to achieve the goal of significantly reducing CO_2 emissions, it is necessary to use biofuels or more radical aircraft designs.

18.6.4.2.2 Analysis of the development of radically new aircraft designs

Based on existing information available in the public domain in the promising directions of development of radically new aircraft designs until 2050, the following basic concepts can be distinguished:

- "Transforming aircraft";
- "Flying Wing" (BWB, HWB, LWB);
- Aircraft with electric or hybrid engines with propellers, "open rotor" configuration;
- "Link & Fly";
- "Flying-V";
- Wing with morphing technology (ACTE, MIT NASA);
- Convertiplane;
- Supersonic commercial aircraft;
- "Progress Eagle" concept.

A brief analysis of the main aspects for assessing the level of implementation or dissemination of the concept is given in Table 18. 9.

Table 18. 9. Basic concepts of aircraft radical design

Key aspects of concept evaluation	Concept name								
	"Transformer aircraft"	"Flying wing" (BWB, HWB)	Aircraft with electric or hybrid engines with propellers, "open rotor"	"Link&Fly"	"Flying-V"	Wing with morphing technology (ACTE, MIT NASA)	Convertiplane	Supersonic commercial aircraft	AWWAQG "Progress Eagle"
Potential CO_2 savings and timeframe	Potential CO_2 savings will not be substantial, as the main problem will be to increase the mass of the structure due to additional mechanisms for aircraft transformation	Potential CO_2 savings are substantial because it is used as a "flying wing" configuration and economical hybrid engines with minimal harmful emissions.	Potential CO_2 savings are substantial because efficient hybrid engines with minimal emissions or electric motors are used.	Potential CO_2 savings will be advantageous because three types of clean energy are claimed	CO_2 savings will be substantial with the use of "flying wing" configuration and economical engines of leading engine manufacturers	Potential CO_2 savings will be substantial as the "flying wing" configuration with morphing technology and fuel-efficient engines are used.	Potential CO_2 savings are substantial because efficient hybrid engines with minimal emissions or electric motors are used.	Potential CO_2 savings are not foreseen due to engines with augmented cycle	CO_2 savings are substantial because they use an efficient aerodynamic design of the aircraft bearing surface with nanotechnology and electric motors
Economic implications	The economic gain will not be substantial, since these designs will first be used on military equipment.	The cost per passenger-kilometre is significantly reduced due to a large number of passengers on board.	Economic gains will be substantial as operating costs are reduced.	The economic gain will be substantial, as operating costs are reduced and the time spent by a passenger at the airport is significantly reduced.	The economic gain from the use of such a concept will be substantial since the new design of the aircraft provides increased comfort for passengers on board.	The economic gain from the use of such a concept will be significant.	The economic gain will be substantial as operating costs are significantly reduced	No economic gain expected	Cost per passenger-kilometre is significantly reduced.

Economic implications	An assessment of the economic impact on civilian technology has not been carried out	The economic impact assessment was not carried out due to the small amount of information about the concept.		The economic impact assessment was not carried out due to the small amount of information about the concept	The economic impact assessment was not carried out due to the small amount of information about the concept	Large passenger capacity onboard, respectively, reducing the cost per passenger-kilometre. Assessment of the economic impact was not carried out due to the small amount of information about			The economic impact assessment was not carried out due to the small amount of information about the concept.
Maturity, feasibility and time to market	Maturity of technical solutions has a second level, feasibility, and time of entrance to the market is expected after 2035	Maturity of technical solutions has a second level, feasibility, and time of entrance to the market is expected after 2040	Maturity of technical solutions has the fourth level, feasibility, and time of entrance to the market is expected after 2025	Maturity of technical solutions has the first level, feasibility, and time of entrance to the market is expected after 2035	Maturity of technical solutions has a second level, feasibility, and time of entrance to the market is expected after 2040	Maturity of technical solutions has a second level, feasibility, and time of entrance to the market is expected after 2040	Maturity of technical solutions has the eighth level, feasibility, and time of entrance to the market is expected after 2025	Maturity of technical solutions has the fourth level, feasibility, and time of entrance to the market is expected after	Maturity of technical solutions has the first level, feasibility, and time of entrance to the market is expected after 2040
Cross impact with other industries and mode of transport.	Cross impact of technical solutions can be with objects type "flying car"	Not applicable	Cross impact of technical solutions can be with objects of marine applications	It is possible with objects of railway and automobile transport	Not applicable	Not applicable	Cross impact of technical solutions can be with objects type	It is possible with objects of space applications	Not applicable

Prerequisites or constrains.	The use of universal components of aviation technology, which leads to a reduction in operating costs. A limitation may be the reliability of design during operation.	Existing military aviation objects of the type F-117 or B-2 (USA) are the background for the creation of such equipment. Future speed issues may be a limitation, as flight time will play a significant role.	The use of universal components of aviation technology, which leads to a reduction in operating costs. Noise level of propellers may be a limitation.	The use of universal components of aviation technology, which leads to a reduction in operating costs. Limitations may include flight safety and structural reliability in the ground and air applications.	The use of universal components of aviation technology, which leads to a reduction in operating costs. Future speed issues may be a limitation, as flight time will play a significant role.	New design. A limitation may be related to ensuring the specified aerodynamic and technological characteristics since the claimed materials were not studied at high flight speeds.	The use of universal components of aviation technology, which leads to lower operating costs. Noise level of propellers may be a limitation.	Modern business requires operational air transportati on. Limitations on certification requirement s for aircraft of this type (sound impact, flight path, emission of	The use of universal components of aviation technology, which leads to lower operating costs. A limitation may be the provision of specified aerodynamic and technological characteristics, since the
Prerequisites or constrains.									claimed materials and flight principles were studied only by theoretical methods
Possible transition cost	Not investigated	Not investigated	Not investigated	Not investigated	Not investigated	Not investigated	Not investigated	Not investigated	Not investigated

Achievements and lessons learned in the past from similar previous	Such developments were partially carried out and implemented on military aircraft in the USA and the USSR in the 1980s. In the USSR there were developed variable-sweep aircraft like MiG-23, Su-17, Su-24, Tu-	No previous similar experience or developments	There is a high level of continuity in the development of propellers in the world. Nowadays, the technologies of design of the propeller engines are almost similar all over the world.	No previous similar experience or developments	No previous similar experience or development s	No previous similar experience or developments	There is a sufficient level of continuity in the development of VTOL aircraft, for example, V-22 Osprey, Bell V-280 Valour and others.	There is development experience in the field of military and civil aviation for example, Tu-144, Concord.	No previous similar experience or developments
Achievements and lessons learned in the past from similar previous experiences	In the USA there were created variable-sweep aircraft like B-1, F-111, F-14, Tornado. Other in-flight variable parts of aircraft have not been implemented. Tu- 144 had the fuselage nose section which deflected electrically during the take-off and landing		A new method for improving the propeller effectiveness in the air is required.						
The potential market for such a solution.	The potential market for variable shape aircraft exists, but much of it is for aircraft with MTOW of about 4 to 5 tons.	Mainly for intercontinental routes	For regional routes	For regional routes, especially in very large airports	For intercontinental and regional routes	For intercontinental and regional routes	For regional routes and urban use	For intercontinen tal routes	For intercontinenta l routes

The potential market for such a solution.	When MTOW exceeds this range, the weight of electric drives increases significantly.								
Synergies with other solutions.	Not investigated	Not investigated. The new configuration of fuselage implements high lift characteristics of the fuselage together with the wing. Integral fuselage actively contributes to the increase in aircraft lift and produces lower drag	Investigations are carried out on the propeller - air intake, and propeller - aircraft fuselage elements integration properties.	Not investigated	Not investigated. The new configuration proposed implements the synergy of fuselage and wing. The fuselage actively contributes to the increase in aircraft lift and produces lower drag	Not investigated. The new configuration proposed implements the synergy of fuselage and wing. The fuselage actively contributes to the increase in aircraft lift and produces lower drag	Investigations are carried out on propeller - aircraft fuselage elements integration properties	Investigations are carried out on airframe-power plant integration properties at high flight speeds.	Not investigated. The new configuration of fuselage implements high lift properties together with the wing. The fuselage actively contributes to the increase in aircraft lift and produces lower drag.

Potential for accelerate or early delivery of results.	Not expected	The potential is possible in the acceleration of study on the properties and aerodynamics of flying wing lifting surface. This is because other companies use similar solutions.	The potential is possible in the acceleration of study on the properties and aerodynamics of new types of BoxProp propellers.	Not expected because of poor project implementation arrangement	The potential is possible in the acceleration of study on the properties and aerodynamics of flying wing lifting surface. This is because other companies use similar solutions.	The potential is possible in the acceleration of study on the properties and aerodynamics of flying wing lifting surface. This is because other companies use similar solutions.	The potential is possible in the acceleration of study on the properties and aerodynamics of new types of propellers.	Not expected because of complicated engine cycle and process on the aircraft lifting surface at supersonic flight	The potential is possible in the study of the properties of new materials. This is because of the necessity to meet the aircraft certification requirements.
Uncertainties.	The error is not known as this theme is nowhere addressed explicitly in the public information	The error is not known as this theme is nowhere addressed explicitly in the public information	The error of technical and economic solutions was not investigated before.	The error is not known as this theme is nowhere addressed explicitly in the public information	The error is not known as this theme is nowhere addressed explicitly in the public information	The error is not known as this theme is nowhere addressed explicitly in the public information	The error of technical and economic solutions was not investigated before.	The error of technical and economic solutions was not investigated before.	The error of technical and economic solutions is not known as this theme is nowhere addressed explicitly in the public information

Restrictions or constraints derived from such a solution impacts with other industries or modes of transport.	Non-existent	Non-existent	Non-existent	The influence of restrictions on other means of transportation does exist as the integration into road transport or railway infrastructure is required. The issue has not been investigated.	Non-existent	Non- existent	Non-existent	The influence of restrictions on the development of spaceplanes	Non-existent
Failure severity and risks, that is derived serious consequences for the sector in case of partial or total failure to achieve that solution.	Serious consequences are not expected	There will be serious consequences for the aircraft sector in case of complete or partial failure to implement the solution. The main task of the project is to use the new configuration of aircraft to ensure better operating performance. This should lead to a significant reduction in operating expenses for this type of aircraft.	There will be serious consequences for the aircraft sector in case of complete or partial failure to implement the solution. The main task of the project is to use the new configuration of aircraft to ensure better operating performance.	Serious consequences are not expected	There will be serious consequences for the aircraft sector in case of complete or partial failure to implement the solution.	Serious consequences are not expected	Serious consequences are not expected	Serious consequences are not expected	Serious consequences are not expected

Failure severity and risks, that is derived serious consequences for the sector in case of partial or total failure to achieve that solution.		If it is not the case, there is a possibility of losing the project development cost and switching to different types of aircraft that are developed by other manufacturers.	If it is not the case, there is a possibility of losing the project development cost and switching to different types of aircraft that are developed by other manufacturers.						
Technology readiness level	2	2	5	1	1	3	8	5	1

9

18.6.4.3 Electrical aircraft

A very important alternative to achieve aviation environmental targets is the electrification of airplanes with electrochemical power sources (batteries, fuel cells).

It is, however, to mention that the production of electrochemical power sources is environmentally harmful. In a comparison of greenhouse gas emissions summarized via the total flown mileages of the aircrafts the electrical airplanes stating with an environmental handicap. This handicap will be neutralized only after a certain time, which depends on the sources of electricity. If there is a higher renewable part in the electricity mix then the neutralization time is shorter.

For the time being the flying range of electrical aircraft is limited by the specific energy of batteries and fuel cells. For today batteries with a specific energy in the region of about 200 Wh/kg, and planes with an L/D relation of 10 and an $m_{batt}/m_{airplane}$ relation of 0.4 the flight range amounted to ≈ 250 km. By changing the aircraft design by larger wingspans, which leads to an L/D relation of 20, the range is increasing to 500 km.

This relatively low specific energy of the battery limits flights with passenger aircrafts over long distances. Even if the specific battery energy is increased by a factor of 2…2.5, as foreseen at ≥ 2030, long-range flights will be not possible with medium size airplanes (≥ 100 passengers). Besides the range also the power of the electric motor (plus turbines in case of hybrids) is an important parameter, which is related to the weight of the airplane.

But for flights with smaller region and planes and/or low payload the batteries specific energy is sufficient. Vertical take-off and landing (VTOL) taxis, general aviation & recreational aircrafts, and regional & business aircrafts, and drones fit the general limitations in weight and range. So, with a market introduction of these applications can be expected by in this decade.

Larger ranges with > 100 passenger aircrafts have only a change as battery/turbine hybrid, i.e. with the help of a conventional turbine.

Based on the power of the electric motor/ turbine the following is expected[i]

- *Power Range 100 kW, market introduction by 2025* UAVs, helicopters with hybrid turbo shaft engine
- *Power Range 500 kW, market introduction by 2025+* VTOL aircraft, commuters with 10 passengers
- *Power Range 1 MW, market introduction by 2030+* Hybrid electric propulsion (turbofan electrically assisted) for short/medium range regional aircraft for 40 passengers.
- *Power Range 10 MW, market introduction beyond 2040…2050* Distributed propulsion on aircraft with 100 Pax

General, also fuel cells are driven with hydrogen are a solution for larger airplanes and larger ranges, because the stored hydrogen volume determines their range, and an increase of the stored hydrogen volume leads only to a relatively low increase of the mass. First developments of FC aircrafts exist but in general, the activities are on a low level. A commercial introduction of FC airplanes will be not before 2035.

A business case of electrical airplanes will be only developed if the costs and the environmental advantages are > 20 % of the conventional planes. Government restrictions as CO_2 emission limits as for cars could be political support the development of electrical airplanes.

18.7 Tax Scenario: Detailed analysis of Climate Change Levy (CCL) schemes.

Climate change levies had been introduced and discussed in section 18.6.1.2, where the potential of taxes to reduce aviation CO2 emissions has been outlined based on recent studies and papers. Although studies agreed on the general principle that taxes lower demand and has economic and environmental impacts, there are still some questions that need clarification regarding the potential and consequences of this MBI. This chapter goes further into the details of this MBI and develops a model to address part of the topics still open.

Aviation may be subject to different types of taxes, being the most common i) Ticket taxes, ii) Value added tax, iii) Taxation on aircraft fuel, iv) Environmental taxes and v) 5. Taxes for air cargo.

The recent study by CE Delft for the European Commission provides the more updated and comprehensive inventory of taxes applied in aviation [73]. Although in many countries' aviation is exempted from all taxes, a significant number of countries levy taxes on certain aviation activities. For example in the European Union, VAT or taxes on domestic flights are the most prevalent and applied in at least 17 states [73]. Six EU states applied some kind of taxes on international aviation, normally in the form of passenger's ticket taxes departing from airports in the country. Outside the EU, the study counted 13 countries (including Australia, Canada, USA, Hong Kong, Brazil and Japan) tax aviation activities, in most of the cases in the form of ticket or departure taxes, normally a fixed amount per passenger, depending on the destination or travel class. A small number of countries applies VAT or sales taxes (a levy proportional to the value of the ticket), for example, Japan, Mexico, USA, and Canada. Additionally, commercial air transport, both passengers and cargo operation, is subject to various charges that are not seen as taxes, as these are levied to cover the costs of provided services.

However, aviation is currently under-charged from an environmental perspective. This low charge regime is even more important for international aviation.

When it comes to the taxation of aircraft fuel different schemes are applied. Fuel on domestic flights is sometimes taxed (e.g. in the USA or France that charges air freight with a tax of € 1.33 per ton of freight). In contrast, the fuel used on international flights is generally exempt from fuel taxes due to international convention. Unlike domestic transportation fuels, they are subject to no excise tax to reflect environmental damages in fuel prices.

ICAO recommends not to tax the intake of jet fuel based on reciprocity, a practice that is followed by most countries and generally mentioned in bilateral Transport Agreements. In Europe, aircraft fuel for commercial air transport operations is exempt from excise duty [74]; although States may abolish this exemption for intra-Community and domestic flights. The Energy Tax Directive establishes a minimum excise duty rate for kerosene of € 330/1,000 L, a value that is normally taken as a reference to quantify the magnitude of the jet fuel tax exemption.

ICAO (policy doc 8632), and also IATA, recommends, that "international air transport is [to apply a] zero [VAT] rate", to guarantee an equitable treatment for international aviation throughout the many jurisdictions into which it operates. However, domestic air transport is often subject to VAT. States may also impose VAT on fuel, or charges such as airport charges, air navigation charges or service fees. At European level [75], States may exempt passenger transport from VAT or apply a zero VAT rate, and add some activities for commercial air traffic on international routes should be exempt from VAT (such as the supply of goods for the fuelling and provisioning of aircraft and other activities).

The ICAO Council considers that any environmental levies on air transport should be in the form of charges rather than taxes, with these directly related to the costs of the resulting damage to the environment. Besides, they argue that any funds collected should be used to mitigate the environmental impact of aircraft emissions

Market-Based Instruments for aviation international fuels are considered not only an environmental improvement measure but also since they would correct an unpriced distortion rather than exacerbating those from pre-existing taxes, a much more cost-effective way to raise finance for climate (or other) purposes than are broader fiscal instruments.

Furthermore, national governments do not have an obvious claim to the tax base for these fuels, given their use for international activities. While there is in principle no reason why any funds raised by such a charge should not be used for other purposes, the concern here is with their potential as a source of climate finance.

At [24] pricing aviation fuel is proposed as a highly cost-effective source of revenue compared with broader fiscal instruments, in the absence of comprehensive, upstream pricing across all fossil fuel products and countries. It is also observed that the difficulty of taxing the final consumption of international aviation services could point to a carbon charge above that called for by climate considerations. A fully appropriate tax structure would levy both a fuel tax to address environmental concerns and a tax on the final consumption of aviation services. In the absence of such explicit sales taxation, a fuel tax also acquires a role in correcting the potential over-consumption of aviation services and enhancing revenue. This can plausibly call for larger fuel taxes.

[24] Also studied the case of a distance-based (non-creditable) ticket tax and conclude that, while inferior to a fuel tax, could also have merit. The air ticket levy in the U.K. is of broadly this form, being chargeable in an amount that varies with distance (within and outside of EU) and by travel class. The weaknesses of such a tax—most notably that it discourages emissions only by discouraging travel—are stressed in AGF [26]. The force of these is diminished, however, by the recognition that the absence of sales taxation means that such a tax would at least serve to correct current tax distortions that likely lead to excessive international aviation transport.

Another interesting environmental taxation option called out lately is the introduction of a Frequent Flyer Levy (FFL), which would vary depending on the number of previous flights taken by an individual. At [76] the authors analyse what such a tax regime for the UK should look like in order to achieve four goals:

- prevent passenger demand from increasing more than 60% by 2050, as recommended by the Committee on Climate Change;
- be revenue neutral to the exchequer;
- obviate the need for new runway capacity; and
- reduce greenhouse gas emissions in line with a low probability of > 2°C warming.

It is found that a progressive tax on frequent flying could play a significant role in restraining demand for flights, while at the same time tending to distribute those flights more equally across the income spectrum.

Despite the inaction at a global level, several states have implemented fiscal measures to combat aircraft emissions. [77] In Europe, the Netherlands, Norway and Sweden have each introduced different forms of environmental charging mechanisms on air transport.

Norway was the first European country to address environmental concerns about aircraft emissions when it introduced in 1994 a passenger tax on domestic flights between Oslo and the four largest regional cities (Bergen, Kristiansand, Stavanger, and Trondheim). The environmental justification for the tax was that there was an alternative mode of public transport available on these routes, namely the train. In 1998, the passenger tax was replaced by a tax based on the number of seats on each aircraft. This tax covered both international and domestic flights, the rates per seat being NOK130 for the former and NOK65 for the latter.

The Government was of the view that the new tax would encourage airlines to increase load factors and so reduce the environmental impact per passenger. The following year, a tax on aviation fuel for domestic flights of NOK0.24 per litre referred to above was introduced. Although originally intended to cover international flights as well, this had had to be abandoned because it violated the terms of bilateral air services agreements that Norway had established with other countries. On the introduction of the fuel tax, the seat tax was reduced to NOK106 for international flights and NOK53 for domestic services.

Norway had introduced a general CO2 taxation system in 1991, but aviation had been made exempt. One of the main proposals of the Norwegian Government in 1998 was that almost all end-users of fossil fuels should pay a minimum CO2 tax of 100 NOK per tonne. With the aviation fuel tax and the seat tax, the CO2 rates for aviation were about half the rates for most other users of oil products.

In 2001, as part of the EEA agreement it became necessary to charge the same tax for domestic and international flights28, but the following year the passenger tax was removed. Over time, the fuel tax has been subject to moderate increases and currently, the tax on CO2 emissions from domestic air transport is NOK0.65 29 per litre, which is expected to generate NOK270 million in revenue annually. Setting the environmental tax at this amount equates to a price per tonne of CO2 of around NOK234 (around €30 at the current exchange rate). There is also a tax on NOx emissions below 3,000 ft. of NOK5.39 per kilogram on domestic flights, which was introduced in 2007 and this is expected to generate around NOK20 million per year.

An environmental tax based solely on distance flown was introduced by the Netherlands in 2008. The tax is fixed at €11.25 per passenger for flights within the EEA (including Turkey) or within a range of 2.500 km. Passengers flying more than 2.500 km pay €45 in tax for the outbound flight. Passengers departing from the Netherlands on journeys of more than 2,500 km and make a transfer at one of Europe's other hub airports are also levied with a €45 tax. Passengers transferring flights at Schiphol do not pay the tax. Turkey was originally separated into two tax zones, with flights from Eindhoven saving each passenger €34.75 compared to travelling from Schiphol. Turkish carriers diverted to Eindhoven or other countries until the Netherlands government decided to include all of Turkey in the €11.25 tax zone. The tax has stimulated some Dutch travellers to make use of airports situated in Belgium and Germany to avoid the tax, resulting in more CO2 emitted by ground transport. The tax is not transparent, and the revenues gained are not reinvested in the industry and so it is not compatible with ICAO's cited objectives in respect of emissions charging mechanisms.

Sweden introduced an emissions-related charge at its airports in 1998, which was modified in 2004. The emissions element of the take-off charge at Swedish airports is currently SEK50 per kg of NOx. For aircraft, over 5.7 tonnes the charge is based on certified emissions values of NOx and HC in the LTO-cycle.

At the European level, ECAC has endorsed recommendation 27-4 agreed in Paris in 2003, which provides a common classification scheme for NOx emissions from aircraft below 8,618 kg MTOW with engines listed in the ICAO Engine Emission Database and the FOI Turboprop Engine Database. For aircraft below this MTOW, Sweden and Switzerland have developed a simple matrix that covers engine emissions for this size of equipment.

Several airports in Europe have introduced aircraft engine emissions charges to improve local air quality. Zurich was the first to introduce such a charging mechanism in 1997 in an attempt to reduce NOx emissions that then exceeded the legal standard set in Switzerland by 30%. The emission charge is set is expressed as a percentage of the landing fee. Five levels of engine emissions are included that are determined on many criteria, including available technologies, clean air incentives and existing and forecast fleet mix. Aircraft with the lowest level of engine emissions (Class 5) are free, while Class 1 aircraft with the highest level of emissions pay 40% of the landing charge. Landing fees were reduced by 5% on implementation of the scheme to make the impact of emission charge overall cost neutral.

Revenue derived from the emissions charges is used to finance environmentally friendly projects aimed at facilitating expansion at the airport. The emissions scheme was extended to include the airports at Geneva in 1998, Bern in 2001, Basel in 2003 and Lugano in 2007.

An emissions charging scheme based on the model used at Swiss airports was introduced at Basel in 2003, while in the UK a scheme based on the ECAC recommendation and the Swedish/Swiss matrix for smaller aircraft was introduced at Heathrow in 2004, Gatwick in 2005 and Manchester in 2007.

18.7.1 Modelling the impacts of Aviation Taxes and generating CCL marginal curves.

One of the key elements in this study is the development of a model to calculate CCL marginal curves. This is an easy to use and generally applicable model that could be employed to assess the effects of the introduction, change or abolition of aviation taxes or aviation-specific tax exemptions.

The model described in this chapter has been programmed in Excel, so it could be easily used and exploited by third parties for further calculations. The model is free and fully accessible to those that would like to reproduce the study calculations or made their own study cases.

Basic rationally behind the model is that because the various CCL schemes (taxes) affects the price of flying, the first impact is on the aviation demand. The extent to which the demand is changed is given by the price elasticity of demand. The change in demand results in a change of supply, i.e. the number of flights and the RPK changes. This also has an impact on fuel consumption and emissions. The change in demand also causes a change in the output of the aviation sector which has an impact on the cost of flying, fiscal revenue, direct and indirect jobs and value-added, and ultimately in GDP. These impacts are calculated by input-output analysis.

Hence, the following impacts can be modelled and projected up to 2050:

- CCL schemes and derived impact on the cost/price of flying.
- Passenger demand.
- Change in RPK and number of flights.
- Change in fuel consumption
- Change in C02 emissions.
- Increase in the flight cost and Fiscal revenue from the aviation sector.
- Impact in jobs (direct and indirect) and GDP.

The model allows to essay different scenarios and hypothesis, and to project the derived impacts up to 2050. Reference yearly growth rates are taken Boeing and Airbus forecasts.

The granularity of the model goes down to flight modelling. Each flight is modelled considering its origin and destination, airline, aircraft model, aircraft model fuel consumption, aircraft passenger's capacity, occupation factor and average ticket price for each flight.

The model applies the hypotheses and variations in parameters down to the level of the flight and allows further aggregation of results by route, country, or region, so impacts of taxes can be studied at the level required by the user. Additionally, the model allows projecting the demand, traffic and impacts up to 2050.

The model allows defining three different CCL schemes: taxes on fuel, on VAT and ticket prices. It allows modelling average airport charges departure and flight range, (e.g. different departure airport charges can be modelled at an airport for short, medium, and long-range flight). It also accounts for the specific VAT of any country in the world and allows to define specify VAT tax for each country. Any value of the fuel tax could be modelled. Exceptions to the taxes could be modelled also to certain extend. The model will allow making different assumptions on fuel consumption and economic impact of the taxes for different companies if necessary.

Concerning the price elasticity of demand, the model is based on Intervistas [1] study, where several elasticities are provided. These are applied to each flight.

Reference year for traffic, demand in RPKs and CO2 calculations of the model was 2018. CO2 calculation has been calibrated by comparing with the actual values of fuel consumption and CO2 emissions in Europe and worldwide for the year 2018. Additionally, results have been found coherent in magnitude to previous studies by ICAO and other sources:

CO2 impacts are considered for each flight taken into account the distance of the route and the specific aircraft model fuel consumption. Improvements in fuel efficiency can be incorporated for each flight or a set of flights, allowing to model improvements in fuel consumption technology, removal of a fleet or the introduction of a new and more efficient aircraft model.

It could be easily extended to consider simplified estimations of other aviation environmental emissions and noise.

The model is well suited to provide a first estimate of the most important impacts of the introduction or abolishment of an environmental aviation tax. It combines clearness and mathematical detail, and the results are easily traceable to the inputs. The model building block is presented in Figure 18. 4. Main blocks, hypothesis and model capabilities are described in the following sections. Finally, Figure 18. 5 illustrates how the model can be used for forwarding or backward analysis.

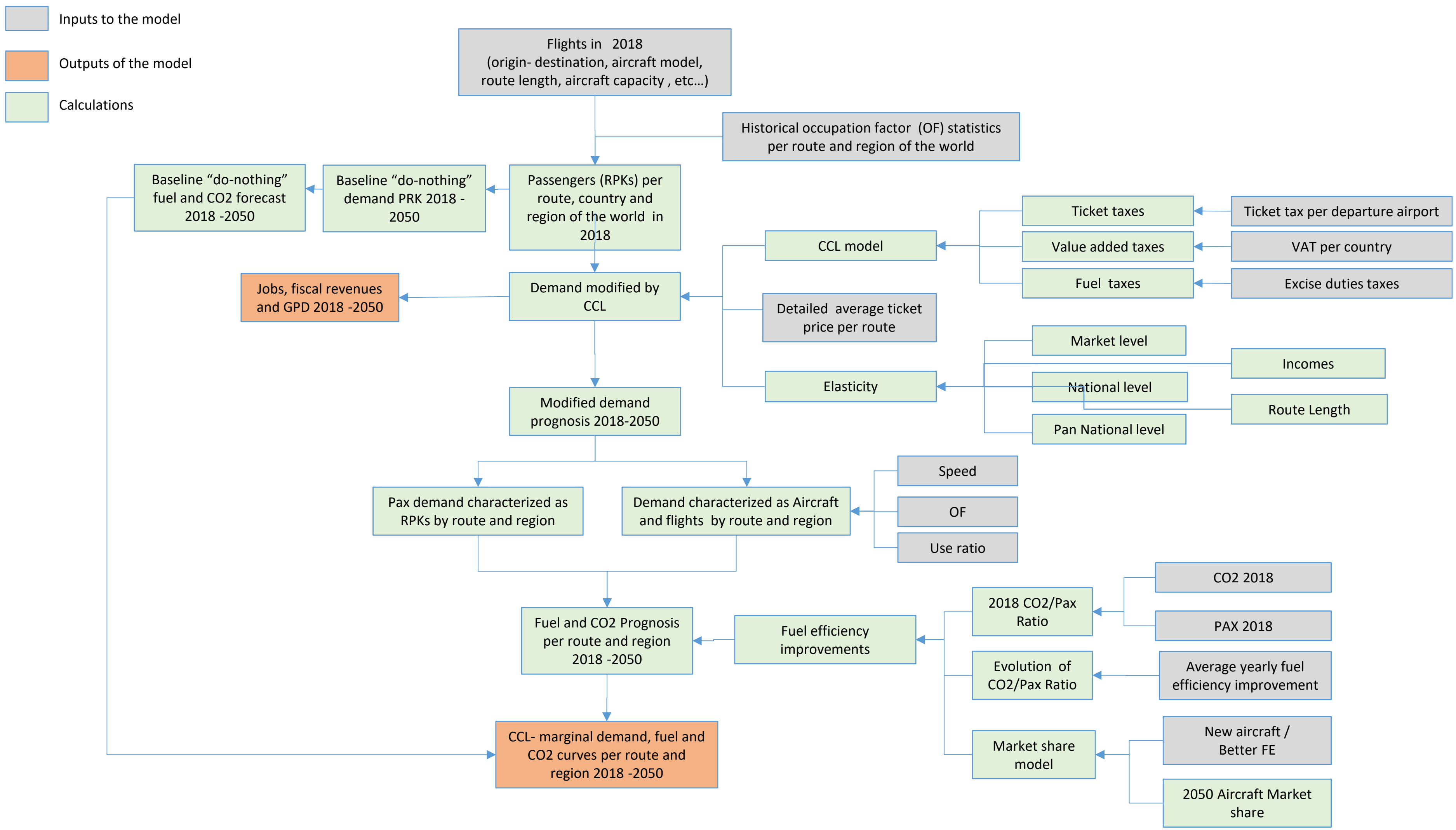


Figure 18. 4. CCL impacts model building blocks.

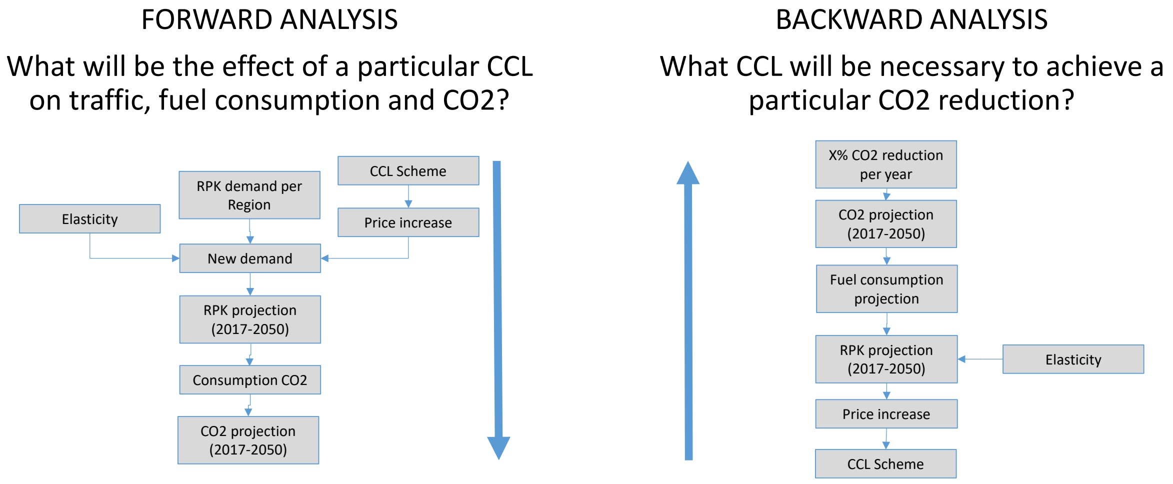


Figure 18. 5. Forward and backwards uses of the CCL impacts model.

18.7.1.1 Definition of the most probable CCL scheme for aviation.

Different approaches can be taken to define and model a CCL. Each one will have different implications on how the levy is calculated, applied and transfer to the passengers, and consequently on how it will affect passengers demand, and the number of funds raised.

The most relevant alternatives are described hereafter:

- Ticket taxes
  - Only levied in the country of departure.
  - Also, apply to inbound passengers which pay the ticket tax on their return leg.
- Value-added taxes
  - Ad-valorem tax on the purchase of a ticket for national or international flights.
  - Levied over the final average ticket price. 100% pass to passengers.
  - Charged on the entire value of the ticket in the country where the ticket is sold.

Legislation on VAT is complex and very particular to the States. For example in Europe VAT is currently levied where the transport takes place and it should be proportionate to the distances covered [78]. This differences in VAT regimes may introduce competitive distortions, which will require detailed and specific analysis [79], beyond the scope of this study. For the sake of the study a simpler and homogenous hypothesis is considered under the assumptions that regulatory changes will be locally adapted as necessary, provided a caveat that the impacts on the number of passengers, GDP and emissions might be overestimated when relatively many international transfer passengers use the airports in a country as a hub.

- Taxes on fuel

- Aircraft fuel is currently exempt from excise duties. Removal of the exemption or the imposition of a standard rate will be a direct way of taxing fuel consumption. [17]
- A default value could be a rate of € 330 per 1,000 litres, which is the minimum rate in the EU Energy Taxation Directive 2003/96/EC for kerosene used in other sectors than aviation.
- It will affect departing, arriving and transfer passengers, but only for one leg of their journey, viz. the leg that departs from the state which levies the excise duty.

Additionally, some hypothesis needs to be done regarding the treatment of fiscal revenues. As this study is focused on aviation decarbonisation, the proposed CCL is assumed to be revenue-neutral tax reform. That means that simultaneous with the change in aviation taxes other taxes are modified and the total fiscal revenue does not change. As a consequence the more rational modelling decision for GDP impacts is to considerer them as a net-zero impulse, -the change in public spending will change the output of economic sectors and thus value added [80]. This approach is supported by most of the studies on environmental tax reform generally assume that environmental taxes are recycled (e.g. [81] [82] [83]). Additionally, studies assuming taxes are rebated or lead to higher government revenues, generally conclude that the impacts of aviation taxes on employment and the environment are limited. Although some authors defend that GDP and welfare impacts may depend on how the revenues are recycled [84] [80], these very detailed models are beyond the scope of the report.

Although in principle all the previous options are possible, implementing globally coordinated charges on international aviation will be easier if the taxes are applied to the fuel than to VAT or tickets, due to the wide variability of VAT and ticket taxes among different countries worldwide. To illustrate this point, the results of a survey on VAT and ticket taxes around the world are presented in Table 18. 10 and Table 18. 11.

The VAT applicable at each country and Ticket taxes at the departure airport have been obtained from macro-economic data provided by Deloitte, Uscib, Expansion and Trading Economics[18]. As can be seen, the VAT regime is extremely different in each country, with types ranging from % 0 up to 25%. Table 18. 11 illustrates the variety of Ticket taxes in the origin airport according to the range of the flight (short, medium, and long haul).

Additionally, the current aviation fuel tax exemptions are built into multilateral agreements within the ICAO framework and bilateral air service agreements, which operate on a basis of reciprocity. Although this framework will required modifications that might present certain challenges, such as amending the Chicago Convention and associated resolutions would remove these obstacles, the EU experience on intra-union charging seems to suggest the possibility of overcoming them without doing so. However, there's no mechanism that will serve as the basis for a global agreement either on VAT or ticket' taxes.

---

[17] A caveat of overestimation should be considered if the impact on ticket prices is calculated on the basis of the price of tickets sold in a country.

[18] This data can be consulted at https://datosmacro.expansion.com/impuestos/iva; https://www.uscib.org/value-added-tax-rates-vat-by-country/; https://www2.deloitte.com/content/dam/Deloitte/cn/Documents/international-business-support/deloitte-cn-ibs-turkmenistan-int-tax-en-2017.pdf; and https://es.tradingeconomics.com/central-african-republic/sales-tax-rate

Country	VAT	Country	VAT	Country	VAT	Country	VAT	Country	VAT	Country	VAT	Country	VAT
Afghanistan	0	Brazil	18	Eritrea	5	Iraq	0	Madagascar	20	Palau	7.5	Sudan	15
Albania	20	Brunei	0	Slovakia	20	Ireland	23	Malaysia	6	Panama	7	South Africa	15
Germany	19	Bulgaria	20	Slovenia	22	Iceland	24	Malawi	16.5	Papua New Guinea	10	South Sudan	15
Algeria	19	Burkina Faso	18	Spain	21	Caiman Islands	0	Maldives	10	Paraguay	10	Sweden	25
Angola	10	Burundi	18	Estonia	20	Cook Islands	15	Mali	18	Peru	18	Switzerland	8
Anguilla	0	Cabo Verde	15	Ethiopia	15	Faeroe Islands	18	Malta	18	French Polynesia	0	Surinam	10
Antigua and Barbuda	15	Cambodia	10	Fiji	9	Marshall Islands	2	Morocco	20	Poland	23	Thailand	7
Saudi Arabia	5	Cameroon	19.25	Filipinas	12	Seychelles Islands	15	Mauricio	15	Portugal	23	Tanzania	18
Argelia	19	Canada	5	Finland	24	Solomon Islands	10	Mauritania	5	Puerto Rico	10.5	Tajikistan	18
Argentina	21	Chad	18	France	20	Turks and Caicos Islands	0	Mexico	16	Qatar	0	Togo	18
Armenia	20	Chile	19	Gabon	18	Israel	17	Micronesia	5	Czech Republic	21	Trinidad and Tobago	12.5
Aruba	2	China	17	Gambia	15	Italy	22	Moldova	20	Rep. Dem. Congo	18	Tunisia	18
Australia	10	Cyprus	19	Georgia	18	Jamaica	17	Mongolia	10	Rep. Central African	19	Turkey	18
Austria	20	Colombia	19	Ghana	12.5	Japan	8	Montenegro	19	Rep. Dominican	18	Turkmenistan	15
Azerbaijan	18	Comoros	10	Greece	24	Jordan	16	Mozambique	17	Ruanda	18	Ukraine	20
Bahamas	7.5	South Korea	10	Guam	2	Kazajistán	12	Myanmar	15.71	Rumania	20	Uganda	18
Bangladesh	15	Ivory Coast	18	Guatemala	12	Kenia	16	Namibia	15	Russia	18	Uruguay	22
Barbados	17.5	Costa Rica	13	Guinea	18	Kirghizstan	12	Nauru	20	San Cristobal and Nieves	17	UK	20

Bahrein	0	Croatia	25	Equatorial Guinea	15	Kosovo	16.69	Nepal	13	Santa Lucía	15	USA	0
Belgium	21	Cuba	20	Guyana	14	Kuwait	0	Nicaragua	15	Santo Tomé y Principe	15	Uzbekistan	4
Belize	20	Curacao	6	Haiti	10	Laos	10	Niger	18.71	Senegal	18	Vanuatu	15
Benin	18	Denmark	25	Holland	21	Lebanon	10	Nigeria	5	Syria	0	Venezuela	12
Bhutan	50	Dominican	15	Honduras	15	Liberia	7	Norway	25	Singapore	7	Vietnam	10
Belarus	20	Ecuador	12	Hungary	27	Lithuania	21	New Caledonia	0	Serbia	20	Yibuti	10
Bolivia	13	Egypt	14	India	18	Luxemburg	17	New Zealand	15	Sierra Leone	15	Zambia	16
Bosnia and Herzegovina	17	El Salvador	13	Indonesia	10	Libya	0	Oman	0	Somalia	10	Zimbabwe	15
Botswana	12	United Arab Emirates	5	Iran	8	North Macedonia	18	Pakistan	17	Sri Lanka	15		

Table 18. 10. VAT applicable to each country

Country	Ticket taxes in the departure airport		
	Short haul	Medium haul	Long haul
Germany	7.47	23.31	41.99
Australia	40.28	40.28	40.28
Austria	8	15	35
Bahamas	69.92	127.4	127.4
Bahrein	15.71	15.71	
Belgium	10	10	50
Brazil	7.99	30.7	30.7
China	6.36	11.44	11.44
United Arab Emirates	7.96	7.96	7.96
Fiji	73	97	97
France	5.61	12.57	12.57
Greece	13	13	11113
Holland	11	45	45
Italy	23.64	119.76	125.21
Jamaica	20	20	20
Kuwait	6.27	6.27	6.27
Mexico	16.25	37.53	37.53
Norway	8.77	8.77	8.77
Qatar	9.26	9.26	9.26
Rep. Dominican	76.36	76.36	
Russia	47.84	250.24	250.24
Sweden	6.26	26.06	41.7
Thailand	0.76	0.76	0.76
UK	28.85	173.1	
USA	15.04	15.04	15.04

Table 18. 11. Ticket taxes in the departure airport for some relevant countries

As discussed in section 18.6.1.2, a common point in almost all studies is that a carbon tax would only be effective in reducing demand if it is common and equal among countries to avoid that airlines could change their operational behaviour to remain competitive. When considering a worldwide implementation, a fuel tax will be the only CCL scheme feasible, due to the difficulties in a consensus among States regarding VAT or ticket taxes. If the CCL is to be implemented at a lower geographical scale, either a country or a region, the two others will be equally convenient. However, CCL will only be effective as emission reduction measurement if apply globally. The local application would prompt disequilibrium and lower environmental performances.

There are also some additional considerations when comparing these 3 CCL schemes. In order to achieve similar CO2 savings to the ones achieved by a tax on fuel, VAT or ticket taxes should be increased in a big percentage, with the consequent social negative impact and opposition. Additionally, taxes on fuel have a direct correlation with the negative effect being taxed: the higher the fuel consumption, the higher the emissions and consequently the higher the tax. Socially this correlation is easily understood and might be straightforwardly accepted. However, a tax related to the price of the good, either a direct increase in the price or and indirect one (VAT), will not necessarily have a proportional relation with the pollution-generated, as it could be charging flexibility and comfortability associated with premium and higher fares.

To illustrate this effect we have simulated CO_2 savings for the three CCL schemes, considering reference values of tax in each case.

- Taxes on fuel: A default value could be a rate of € 330 per 1,000 litres, which is the minimum rate in the EU Energy Taxation Directive 2003/96/EC for kerosene used in other sectors than aviation. A fuel excise duty is chosen as a reference to illustrate the results because it could have the same rate in all countries, viz. the minimum rate for kerosene from the Energy Taxation Directive (which exempts kerosene used in international aviation). Additionally, this number has become a standard reference for most CCL studies that allows for comparison and cross-reference.
- Added Value Tax: considering that the maximum VAT applied by a country is 25%, and the medium is around 14%, an increase of 2% (10% of the maximum VAT) of the VAT of each ticket is used in the simulation as a reference value. It has to be taken into account that an increase in 2 points of VAT is an increase of 10% of the VAT for the countries with higher fiscal pressure, what is perceived as a big increase.
- Ticket tax: for the sake of the simulation ticket tax is express also as an increase in % if the ticket price. For this case, we took also a 2% for each ticket.

The results show that CO_2 emission by 2050 will be much lower, a 25% lower, in the first case with a reference value of the fuel tax, versus a reference 2% value of the tax on VAT or ticket prices. The only way for the added value tax and the ticket tax to get to a similar reduction in CO_2 than the fuel tax is to increase them in a high amount, making it unrealistic.

	2050
CO2 Fuel tax [Bill Kg]	50203.80
CO2 Added Value tax [Bill Kg]	66621.19
CO2 Airport Tax [Bill Kg]	66621.19

Table 18. 12. Comparison between taxes

18.7.1.2 Prices elasticity of air transport demand

Price elasticity is an indicator that reflects consumers' sensitivity to changes in the price of a good or service. It is defined as:

$$Price\ Elasticity = \frac{\%\ Change\ in\ Quantity\ Demanded}{\%\ Change\ in\ price}$$

Price elasticity of -0.6; implies that a 10% increase in the price of a good or service will result in a 6% drop in the demand of that good. A product with an elasticity less than one (in absolute value) is referred to as inelastic or price-insensitive demand. For this product variations in demand will be lower than price variation, and the lost relatively small decrease in quantity will be less than the revenue gained from the higher price. A product with an elasticity greater than one (in absolute value) is referred to as elastic or price-sensitive demand. For this product, the change in demand will be greater than the proportional change in price. Other elasticities particular relevant for this study are the cross-price elasticity and the income elasticity.

The cross-price elasticity measures the sensitivity of demand for a particular good to changes in the price of another good.

$$Cross\ Price\ Elasticity = \frac{\%\ Change\ in\ Quantity\ of\ Good\ A\ Demanded}{\%\ Change\ in\ price\ of\ Good\ B}$$

The income elasticity measures the sensitivity of the demand for a good to change in the income of the buyer.

$$Income\ Elasticity = \frac{\%\ Change\ in\ Quantity\ Demanded}{\%\ Change\ in\ income}$$

According to it, a good can be classified as:

- "Normal" goods if income elasticity is between 0 and +1: the demand increases with the income of the buyer, at the same or a lesser rate.
- "Inferior" goods if income elasticity is negative: the demand decreases when a person's income increases, as he buys less of that good and substitutes with it with better quality goods.
- "Luxury" goods if income elasticity above unity (one).

The literature review shows that airfares elasticity varies depending on a number of factors such as geography, distance and level of aggregation. The right elasticity value to use depends on the type of problem to be analysed. To ensure that air transport policies are effective, reliable estimates for demand elasticities are essential. Analysing the impact of a fare increase on a given route requires a different elasticity than analysing the impact of a CCL fare across all routes in a country or region.

The Intervista [1] analysis for IATA shown that the narrower the applicability of a price change, the more elastic the response. The more general the applicability of a price change (perhaps due to higher costs or taxes) the less elastic the response. As a price increase is extended to ever-larger groups of competing airlines or competing destinations, then the overall demand for air travel is revealed to be somewhat inelastic. At this work authors infer a full set of elasticities, covering characteristics that are relevant for our study, particularly level of aggregation, length of haul and geographic aviation market. In particular, 5 different levels of aggregation, representing five different contexts area identify and quantify:

i) Fare class level – the most disaggregated level- passengers easily chose between different fare classes on a particular airline (first class, business, full economy,). At this level, elasticities are highest.

ii) Carrier level – the level of aggregation represents various airlines competing on a given route-.

iii) Route/Market level- the level of aggregation represents competing airports in the same city when passengers have to face a fare increase on all carries serving a route-, e.g. passenger options are reduced by still can choose an alternative route, e.g. Heathrow–Paris CDG or London-Paris, use another mode of transport or not fly.

iv) National level- the level of aggregation represents a tax imposed at the national level, that passenger can only avoid by using another mode of transport-.

v) Pan-National level- represents the higher level of aggregation, for example, the European Union imposing an aviation tax on all its member states.

Elasticities have been proven to be lower as the level of aggregation increases because the passenger's options for avoiding the fare are reduced as the aggregation and the geographical context increase. For the sake of our study, only the last three are relevant as fares will be considered either at the market, national or supranational level.

Regarding the length of haul, fare elasticities on short-haul routes are generally higher than on long-haul routes, which reflects the opportunity for inter-modal substitution on short-haul routes.

Regarding the type of passenger, business travellers are less sensitive to travel price changes (less elastic) than leisure travellers, as business travellers generally have less flexibility to postpone or cancel their travel than leisure travellers.

The characteristics of a market or region also affect the fare elasticity, due to several factors such as economic development, aviation market structure, government regulation (e.g., regulated vs liberalised), demographic factors, historical factors, etc. In this model for the following major geographic markets are considered, although any specific model could be easily considered just by aggregation of single flight per route:

- Africa
- Central America
- South America
- North America
- Europe
- China
- South Asia
- Southeast Asia
- Northeast Asia
- Middle East
- Oceania

Income is traditionally the most important explanatory variable of air travel demand. Income Elasticities have been consequently broadly studied and found positive in all cases, generally between +1 and +2, as would be expected- air travel increases as incomes increase-. This indicates air travel increases at a higher rate than income growth. This indicates that as the income level of individual's increases and they become more prosperous, they generally dedicate an increasing part of their income to discretionary spendings, such as air travel. This has important implications for policies seeking to manage air travel demand by raising the price of travel. In this study, income elasticity is considered to isolate the effects of a shift along the demand curve (caused by a change in air travel price) from the effect of a shift of the whole demand curve (caused by a change in incomes or GDP).

It might be necessary to consider the case when the passenger flow of concern is inbound or outbound, not the total or average impact. This is relevant for example when considering the diversion of inbound passengers and consequent reduction of effectiveness of a national or regional environmental tax. However, their sensitivity to travel prices including taxes will differ for inbound and outbound traffic. Faced by a passenger or environmental tax the outbound passenger must either pay or not travel. However, the inbound overseas passenger can choose to travel to a different destination or transit by another hub and avoid the tax. This is particularly the case for holiday travel or transfer and transit passengers, which are much more price-sensitive than travel for business or visiting friends and relatives. Inbound travel originating from overseas will be more price-sensitive i.e. will have a larger price elasticity in absolute terms, than outbound travel.

18.7.1.2.1 Air transport demand elasticity model.

The Intervista analysis (2007) condensate all this information into a model of elasticity composed of three base elasticities reflecting the levels of aggregation (route, national and pan-national level); plus some multiplicative factors to reflect specific markets and conditions.

1. Base Elasticities depending upon the level of aggregation considered.

Three base elasticities are considered:

- Route/Market Level: -1.4.

  This elasticity estimate applies to a situation where the price of individual route changes (e.g. higher airport charges at Paris CDG raising the price of travel from London and diverting leisure traffic to another destination, such as Frankfurt) The literature review found that elasticities at the route or market level in the range of -1.2 to -1.5.
- National Level: - 0.8.

  The econometric analysis of all three datasets found that without the route substitution term, the analysis produced elasticities in the region of -0.8. This elasticity is essentially a combination of the route own price elasticity with cross-price elasticities when all national routes have prices which vary identically. Thus, the less elastic result is consistent with observations that part of the so-called price elasticity observed from LCCs at secondary airports involves diversion from primary airports in the catchment area or diversion from trips on other routes. When this is controlled for, LCCs have a lower level of market stimulation, consistent with less elastic national elasticities.
- Pan-National Level: -0.6.

  As the number of routes covered expands, the number of choices for passengers to avoid any travel price increase diminishes. There is less opportunity for traffic to be diverted.

The route elasticity applies to a situation where the price of individual route changes, for example, the fare on Warsaw-Coventry increases with the price of routes from Warsaw to the other UK and other European points remain unchanged. The national elasticity applies to a situation such as all Warsaw-UK prices changing identically, but the price from Warsaw to other European points being unchanged. Pan national changes apply where prices from Warsaw to all points in Europe change identically.

2. Multiplicative factor considering the length of the route.

The literature review consistently found that the fare elasticities on short-haul routes were generally higher than on long-haul routes. In part, this reflects the opportunity for inter-modal substitution on short-haul routes (e.g., travellers can switch to rail or car in response to airfare increases). While the geographic breakdowns capture some variation by the length of haul, there is still considerable variation within each market. In particular, very short-haul flights (approximately less than 1-hour flight time) are subject to greater competition from other modes. On this basis, the following short-haul multiplicative adjustors can be applied to the analysis of short-haul routes:

- Short haul: 1.1 (+10%).

This adjustor does not apply to the analysis of the trans-Atlantic and trans-Pacific market, which are considered entirely long haul, with virtually no opportunity for modal substitution.

3. Multiplicative factor considering the geographic aviation market.

Based on the econometric analysis of the IATA PaxIS, Intervista (2007) analysis found considerable differences between aviation markets and proposed the following multipliers.

Geographic Market	Elasticity Multiplier	Comment
Intra North America	1.00	Reference point. The market is well established with relatively high levels of capacity and traffic. Air travel prices tend to be low, while distances are short to medium-haul
Intra Europe	1.40	Shorter average distances observed use of very low fares resulting in great market stimulation. The significantly low fares in Europe (relative to North America) are consistent with higher elasticities in Europe.

		Traditionally the European market had high charter carrier share, which today is merely being converted to very low fare LCCs.
Intra Asia	0.95	The LCC phenomena is emerging in Asia, but the modest-sized middle class in many markets suggests somewhat less elastic than in North America
Intra Sub-Sahara Africa	0.60	These economies have limited middle class, resulting in high weight on higher-income individuals who are less elastic
Intra South America	1.25	There is an emerging middle class which makes the market more elastic than sub-Saraha Africa, and LCCs are emerging in Brazil, Chile, and Mexico.
Trans Atlantic (North America – Europe)	1.20	This market is often observed to have fares only slightly higher than domestic U.S. fares, consistent with high price elasticity. The market has been well developed by charter carriers, consistent with high price elasticity. Price is likely more important than the frequency in this
Geographic Market Elasticity Multiplier Comment market than in the domestic U.S.		
Trans-Pacific (North America – Asia)	0.60	TransPacific has had no charter services and continues to have major markets (Japan, China) with less liberal pricing provisions. Some emergence of long haul LCCs (e.g., Oasis) but at present, this market seems to be less elastic than the domestic US and then the well-developed trans-Atlantic which serves a substantial middle class
Europe – Asia	0.90	This market has marginally lower elasticities than the U.S. domestic market.

Table 18. 13. Multiplicative factor considering the geographic aviation market

Elasticities for different situations can be developed by selecting the relevant base elasticity and applying the relevant multipliers. The full range of possible elasticities considering multipliers relevant short-haul and geographic elasticity multipliers is presented in Table 18. 14. The route level elasticities range from -0.84 to -1.96 depending on the geographic market and length of haul. The national-level elasticities range from -0.48 to -1.23, while the pan-national elasticities range from -0.36 to -0.92.

	Route/Market Level		National Level		Pan-National Level	
	Short-haul	Long- haul	Short-haul	Long- haul	Short-haul	Long- haul
Intra North America	-1.54	-1.40	-0.88	-0.80	-0.66	-0.60
Intra Europe	-1.96*	-1.96	-1.23	-1.12	-0.92	-0.84
Intra Asia	-1.46	-1.33	-0.84	-0.76	-0.63	-0.57
Intra Sub-Sahara Africa	-0.92	-0.84	-0.53	-0.48	-0.40	-0.36
Intra South America	-1.93	-1.75	-1.10	-1.00	-0.83	-0.75

Trans-Atlantic (North America – Europe)	-1.85	-1.68	-1.06	-0.96	-0.79	-0.72
Trans Pacific (North America – Asia)	-0.92	-0.84	-0.53	-0.48	-0.40	-0.36
Europe-Asia	-1.39	-1.26	-0.79	-0.72	-0.59	-0.54

Table 18. 14. Estimated Price Elasticities of Passenger Demand

Additionally, income elasticity and inbound/outbound model effects can also be considered as indicated below.

4. Multiplicative factor considering the inbound/outbound nature of the traffic flow.

As proposed by IATA/Intervista study, a reasonable rule-of-thumb multiplier to adjust the price elasticities in Table 3 is as follows:

- Inbound travel by overseas residents = -1.3/-1.0 = 1.3 * Table 18. 14 price elasticity
- Outbound travel by domestic residents = -0.8/-1.0 = 0.8 * Table 18. 14 price elasticity

5. Multiplicative factor considering the income/GDP.

Income elasticities, generally in the range +1.0 to +2.0. That is, air travel is generally found to be income elastic. This is supported by a more casual analysis which plots air travel per capita against income per capita across a wide range of nations and finds a strong, positive relationship between the two. That is as income per capita grows, air travel per capita grows, and the growth in air travel is faster than the income growth. These types of two-dimensional analysis typically show some taper among the nations with the highest per capita incomes. That is, the income elasticity appears to decline somewhat at higher incomes, although staying elastic above 1.0. Intervistas study recommends the following values for different markets at the route and national level.

Route/market level	Short-haul	Medium-haul	Long-haul	Very long-haul
US	1.8	1.9	2.0	2.2
Developed economies	1.5	1.6	1.7	2.4
Developing economies	2.0	2.0	2.2	2.7
National level	Short-haul	Medium-haul	Long-haul	Very long-haul
US	1.6	1.7	1.8	2.0
Developed economies	1.3	1.4	1.5	2.2
Developing economies	1.8	1.8	2.0	2.5

Table 18. 15. Estimated income elasticities of passenger demand

The growth of incomes, often proxy by GDP, is the fundamental driver of the demand for air travel. During the past twenty years, global passenger traffic has expanded at an average annual growth rate of 5.1%, while global GDP grew by an average annual rate of 3.7% over the same period. That implies an average income elasticity of 1.4, similar to the average estimated above for developed economies.

Example of application.

By way of illustration, elasticities for different situations can be developed by selecting the relevant base elasticity and applying the relevant multipliers.

- To examine the impact of an EU-wide aviation tax on ▪ short-haul markets, the elasticity would be developed as follows:

  - Base multiplier: -0.6 (supra-national)

  - Geographic market: 1.4 (Intra Europe)

  - Short-haul adjustor: 1.1

The price elasticity would then be calculated as: -0.6 x 1.4 x 1.1 = -0.92

- To examine the impact of a UK tax on aviation on Trans-Atlantic traffic, the elasticity should be developed as follows:

  - Base multiplier: -0.8 (national)

  - Geographic market: 1.2 (Trans-Atlantic)

The price elasticity would then be calculated as -0.8 x 1.2 = -0.96

- To examine the impact of the same tax on overseas visitors and tourism:

- Overseas resident adjustor: 1.3

The price elasticity would then be calculated as: -0.96 x 1.3 = -1.25

- To examine the impact of an increase in airport landing fees on a particular short-haul route in Asia, the elasticity should be developed as follows:

- Base multiplier: -1.4 (route)

- Geographic market: 0.95 (Intra Asia)

- Short-haul adjustor: 1.1

The price elasticity would then be calculated as: -1.4 x 0.95 x 1.1 = -1.46.

18.7.1.2.2 Detailed elasticities for the Pan-national case

This study is built upon the hypotheses that taxes are coordinated and implemented worldwide, therefore Pan-National elasticities have been taking into consideration. The following table summarised these detailed figures.

	Pan-National		
	Short	Medium	Long
Intra North America	-0.66	-0.63	-0.6
Intra Europe	-0.92	-0.88	-0.84
Intra Asia	-0.63	-0.6	-0.57
Intra Sub-Sahara Africa	-0.4	-0.38	-0.36
Intra South America	-0.83	-0.79	-0.75
North America- Europe	-0.79	-0.755	-0.72
North America- Asia	-0.4	-0.38	-0.36
Europe- Asia	-0.59	-0.565	-0.54
North America-South America	-0.745	-0.71	-0.675
South America-Europe	-0.875	-0.835	-0.795
Africa-Europe	-0.66	-0.63	-0.6
Africa-Asia	-0.515	-0.49	-0.465

Table 18. 16. Estimate Price Elasticity used in our model for Passenger Demand.

18.7.1.3 Demand forecast.

There is different information and points of view when it comes to commercial aircraft market forecast. This industry is growing geometrically every year so that its analysis becomes more and more difficult due to the different factors influencing the trends and the changing nature of its dynamics. Many companies and authors divide and explore different sublayers of the market, such as Bombardier in [40], where focuses on the regional jet market. Other authors divide the market according to aircraft seat capacities, like Airbus [19] or Boeing [20].

For our assessment, two different prognoses will be necessary. The first one will correspond to a “do-nothing” scenario that will serve as a base to determine demand, flights, fuel consumption and CO2 emissions up to 2050 in the case no environmental reduction measurements will be taken by aviation. Although this is in certain extend an unrealistic scenario because it does not consider emission reduction measurements already in place, it is used to establish a reference for comparison towards which the effect of each specific CO2 reduction measure could be compared.

The second type of forecasts will correspond to the demand as a result of the application of a particular CCL measure. By comparing these two forecasts the beneficial effect of the CCL can be quantified.

It is to notice that the impact of COVID in air transport is not considered in the forecasts of the project.

18.7.1.3.1 Input traffic data

The data-set used for this analysis has been extracted from the open-source OpenFlights.org [22] database, which recovers data from airlines, airports, aircraft and scheduled air routes from commercial carriers with:

- Over 33,000 international and domestic air routes updated up to December 2018.
- Around 5,800 air carriers.
- Over 10,000 airports.
- More than 130 commercial aircraft models.

Figure 18. 6. Open Flights routes over the world's map. [22]

Although the database does not directly provide traffic volumes (RPKs), the analysis of this data gives valuable information about the busiest flows between regions, represented by the number of routes connecting a certain pair of countries. If two regions hold a big number of routes between their cities, it means that there is an important passenger flow between those two regions and, consequently, a big number of flights and required aircraft to connect these areas. The same argument can be used to discuss the aircraft share of the market. If an aircraft holds a big number of air routes, it can be translated to a big market share percentage of that aircraft, within the considered market segment. RPKs are directly calculated from the field in the database, by considering that capacity of each aircraft, and historical occupation for each route.

To account for some missing routes in 2018 concerning 2020 situation (prior COVID) a corrected calibration of the PRK derived from the data based has been performed. Derived RPKs distribution by distance and region is compared to the one provided by UACs market report [30], and a corrective factor is derived where differences are encountered.

18.7.1.3.2 Demand forecast in the "do nothing" reference scenario

Forecasting the number of airplanes demanded by airlines and passengers in the future is a complex problem affected by important uncertainties. Although a number of approaches and methodologies have been developed by the academia and the industry, the accuracy of any fleet demand forecast relays very much on a deep knowledge of the industry and on reliable data about the evolution of the various markets and segments. In this section, the baseline forecast corresponding to the "Do-nothing" scenario, and the ranges established for the calculations is discussed. The mathematical forecasting model is also described. Based upon these considerations the model generates two forecasts:

1. Demand forecast: Future demand up to 2050 is calculated based on the data provided by the Boeing Global Market Forecast [28] dataset and the RPKs distribution by distance and region provided by the UACs market forecast report [30]. Using these data and the annual growth by region percentage

estimated by Boeing (for the baseline forecast) the MoM traffic demand is projected over the period 2018-2050.

2. Fleet forecast: using the traffic prognosis calculated in the previous step, the fleet size is estimated using airline performance data provided by the Airline Monitor market forecast report [73]. The fleet is calculated yearly over the projected air traffic demand. An insight over the calculations in this step is provided in section 18.7.1.3.2.2. Additionally, the retirements of each traffic sector (short, medium, and long-range) are estimated using the Airline Monitor retirements forecast, which details forecast retirements by model for the period 2018-2050. The total fleet in 2050 will be composed of those aircraft that stay in service from nowadays' fleet, and new deliveries. Equally, new deliveries will be destined to either replace older aircraft from the actual fleet or to expand the fleet.

18.7.1.3.2.1 MAIN FORECAST REFERENCE STUDIES

A selected group of companies, including manufactures, consultancies and governmental agencies, produce regular updates of short, medium- and long-term forecast that are considered a reference for any market study in aviation. The aim of this study is not to build an additional forecast, but to integrate the best publicly available long-term forecasts, as well as hypotheses and trends highlighted by reference reports about credible expected evolution of airplane fleets demand, production, retirement, and delivery. All these inputs about the expected long-term evolution of the global world fleet market will be used to dimension the possible size of the Middle of the Market fleet demand that concerns this study. In that way, the current study will benefit from the best knowledge in the market and will integrate the most optimist and also conservative approaches and hypotheses about the global commercial aircraft market. This will allow us to estimate a range of values for the expected long-term passengers and fleet demand in the Middle of the Market segment.

In this chapter, we manage five worldwide studies covering a forecast period of 20 years and global passenger fleet:

i) Boeing Commercial Market Outlook 2018-2037 Co;
ii) Airbus Global Market Forecast 2018-2037;
iii) JADC Worldwide Market Forecast 2018-2017,
iv) United Aircraft Corporation (UAC) Market Outlook 2017-2036, and
v) The Airline Monitor Commercial Aircraft Market Forecast 2017 – 2040.

Boeing and Airbus both release each year a twenty-five-year market forecast for aircraft demand which provides some insight into the qualitative nature of the market demand and how the two major producers expect demand to evolve over the coming two decades. As it has been discussed in each of the manufacturers make their own segmentation of the market, with blurred boundaries between types of planes.

The JADC (Japan Aircraft Development Corporation) continuously collect and analyse data relating to the world commercial aircraft market, being its "Worldwide Market Forecast" the long term forecast for air passenger and air cargo demand, as well as airplanes demand for turboprops, passenger jets, jet freighters and aero engines over the 20 years covering 2018-to 2037.

The UAC issue of Market Outlook 2017–2036 reflects the vision of United Aircraft Corporation, in modern Russia, on the air transportation development prospects and the formation of demand for new commercial aircraft, and it also takes into account significant market factors in the modernization of Russia's aviation infrastructure.

The Airline Monitor is a leading source of data and forecasts for world's airlines and commercial aircraft, which are published six times a year, bi-monthly from February to December, and they are available in both printed and electronic form.

Although the overall methodology in all these studies is similar, the main differences among them will be highlighted, and alternative hypotheses and differences in values will be used to build up a set of scenarios, including reference and extreme (optimist and pessimist) value forecast. We do not pretend to qualify one forecast against others but to use them all to predict the most acceptable range of values for our "do-.nothing" scenario.

Table 18. 17 summarises main hypotheses and results of every of the market forecasts discussed above are represented in a chart form, to highlight the main differences and assumptions that will serve to the do-nothing prognosis. The following chart lists the main hypotheses used, aircraft deliveries and retirements forecast by region by the kind of segmentation used, and air traffic average yearly growth rate by region.

Publisher	*Air Traffic Growth p.a.*	*Fleet count 2018*	*Fleet 2037 Forecast*	*Deliveries*	*Main hypothesis and considerations*
Airbus	4.5%	19,803	46,121 *(x 2.3)*	37,419	• Wealth effect. Middle class growth stimulates traffic growth. • Low-cost business models are the main drivers of the future market
Boeing	4.7%	24,400	48,540 *(x 1.9)*	42,730	• GDP growth leads to more consumer spending that involves air travel • New liberalized policies (open skies agreements) will stimulate air travel • Airport congestion • Arise of low-cost long-haul business models
UAC	4.6%	26,500	52,400[19] *(x2.0)*	43,659	• China and Asia-Pacific region as the main drivers of the sector
JADC	4.5%	26,463	48,900 *(x1.8)*	33,530	• Slight increment on crude oil prices • Increase of the worldwide middle-class and tourism • GDP growing lead by China
AM	5.1%	26,042	52,578 *(x2.0)*	46,190	• Air transport growth directly linked to GDP growth (with elasticity of 2.5 approx.)

Table 18. 17. Forecasts' results and hypothesis summary

Since the aircraft considered for the forecast and the hypotheses used to differ one from another, it is necessary to take these discrepancies into account to integrate them into our study prognosis.

The fleet considered for the forecast differs from each author. For example, Airbus considers only western-built aircraft, with a total fleet of 19,800 airplanes by beginning 2018. The rest of the authors, on the other hand, use different fleet considerations that are not specified on their reports. To make proper comparisons between results, nominal values are used between brackets.

[19] Value not specified in UAC's report. Estimated value using the UAC's assumptions on fleet remaining [30].

Regarding the hypotheses used, Boeing highlights the existence of increasingly airport congestion in the future, which will constrain airlines to improve fleet efficiency and to manage a better use of airport slots. From the published data, it can be concluded that Boeing believes in an increase of the average aircraft size in the future. This assumption is presented on the forecast's results since, despite predicting more optimistically the air traffic growth per year (4.7%) than Airbus (4.5%), the future fleet is forecast to be 1.9 times the actual one, as opposed to the 2.3 times multiplier of Airbus' forecast. This shows that Airbus believes in a dominance of the single-aisle segment as it has been occurring the previous years, representing more than half of the deliveries worldwide. On the other hand, Boeing believes in an increase of the wide-body aircraft demand, motivated by the infrastructural constraints and airport saturation.

18.7.1.3.2.2 DEMAND FORECAST CALCULATIONS METHODOLOGY

This section provides an insight over the methodology used for calculating the forecasted aircraft demand. The approach used in this method is based on the air traffic demand forecast, so that the necessary fleet to satisfy this demand is estimated based on the following airline performance parameters:

- Load factor (LF): The fraction of seats occupied on the aircraft per flight as a percentage of the total.
- Utilization time (UT): Hours per day in which the aircraft is on service (also called block hours).
- Block mean speed (V): Mean speed of flight per block hour.
- Average of seats offered per aircraft (s).

Using the traffic volume forecast values of Revenue Passenger Miles (RPM) and taking the estimated annual traffic growth TG_k, it is possible to calculate the traffic volume for the next year. Thus, for each year, say k, it yields:

$$RPM_k = (TG_k + 1) \cdot RPM_{k-1}.$$

To transform the passenger volumes to required capacity, (ASM –Available Seats per Mile), the estimated load factor for every year is required, so that:

$$ASM_k = \frac{RPM_k}{LF_k},$$

And the required daily capacity is

$$ASM_{k,day} = \frac{ASM_k}{365}.$$

Once the capacity has been estimated, the number of aircraft (n) composing the fleet of the year k can be calculated as:

$$n_k = \frac{ASM_{k,day}}{V_k \cdot UT_k \cdot s_k}.$$

Note that the block mean speed, utilization time and number of seats are parameters that are assumed to change over the time. The Airline Monitor [182] estimates the evolution of these parameters based on historical values available in its database.

18.7.1.3.3 Demand forecast with CCL.

As introduced in previous sections, the main impact of a CCL tax will be an increase in the price of the flight tickets, and consequently due to consumers' sensitivity to changes or price elasticity of air transport a decrease in the demand.

To properly calculate this decrease of demand after the imposition of a tax we need to consider to magnitudes: the elasticity (already studied in section 18.7.1.2.1) and the increase in flight prices due to the tax.

Rise in prices due to taxation are calculated for each flight and aggregated by routes and countries. Average reference prices have been calculated for each flight using historic public fares published on the internet, excluding 2020 information to avoid distortion introduced by Covid-19. Based upon this information an average flight price is considered at any route from 2021. The study considers that the CCL schemes are applied in 2021, although a sensitivity analysed is done to evaluate the effect of applying the scheme on posterior years.

The ticket price varies very much depending upon the length of the route, the regions of the world, the nature of the airlines (low cost and regular airlines). In Europe, due to the increase of last year's low-cost airlines, tickets prices are cheaper than other regions such as the Middle East or Southeast Asia. The most expensive tickets prices were all in long haul distances, where the consumption and CO2 emissions were higher too. That is why the tax reverberated the most on this kind of flights.

The % of flight price increase depends upon the CCL scheme considerer. It the case of VAT tax or Price tax the increase has been pretty straightforward expressed as a % increase. As explained in section 18.7.1.1, VAT has been surveyed for each country, and ticket taxes have been also surveyed for departing aircraft and market segment (short, medium and long haul).

In the case of a fuel tax increase in prices is not direct and need some calculations. These calculations take into account the length of the route, the aircraft model and its fuel efficiency, to estimate the fuel consumed by each flight. The total increase of price due to the fuel tax is calculated for each flight multiplying the fuel consumed by each flight per the fuel tax. Finally, the increase in each flight ticket is obtained dividing the last figure flight by the number of passengers per flight. The number of passengers per flight is obtained correcting the available aircraft capacity with the historical occupation factor statistics for each route.

For the sake of clarity and comparison with previous studies, although the model allows introducing any monetary value for the fuel tax, in the following studies a fuel excise duty is chosen as an example to illustrate the results, because it could have the same rate in all countries, viz. the minimum rate for kerosene from the Energy Taxation Directive (which exempts kerosene used In international aviation): 0.33€ per litre of fuel.

The variation in demand due to the imposition of a CCL in 2021 is calculated based on the previous data and projected to 2050. Demand is expressed in terms of RPKs.

Although some authors claim that an additional side effect could be that once in place, presumably the fuel charges would increase gradually over time to promote more aggressive emissions mitigation [85], this effect is not considered here. Therefore, the drop in demand will have a point incidence concentrated at the year of application of the CCL. The demand rate of growth will step down the year CCL is imposed and will return to the reference rates of growth in the following years. This effect is perceived in the prognosis as a displacement in the demand curves, which evolve with the same profile but displaced to lower starting values.

18.7.1.4 Fuel consumption and CO2 and forecast

The model calculates the fuel consumed by each flight taken into account fuel efficiency data provided by each manufacturer and the length of the flight. Total fuel consumption of commercial airlines worldwide in 2018[20] is used for validation of the data obtained.

The CO2 levels are calculated for each flight using a conversion factor of 3.15 g CO2 per g fuel.

A ratio of CO2/ RPK can be obtained from the data in 2018. This ratio can also be applied to the RPK forecast as a quicker estimator of CO2 emissions.

18.7.2 Application of the model.

Although the possible applications of the model are broader, in this study it has been used to try to answer some questions about CCL implementation not broadly tackled in the previous work available in the literature. All the following cases are illustrated for a tax on fuel CCL scheme equivalent to the current fuel excise duty of 0.33 € per litre of fuel (equivalent to 0.4€ per Kg of fuel[21]), that will apply in 2021. This value of tax has been selected to easy comparison with the most recent and relevant studies. Note that for the sake of the calculations COVID effect is not considered and traffic in 2021 is calculated as a projection of industrial figures in 2018. Issues analysed include:

- The overall impact of the tax over demand, fuel, and CO2.
- Impact of the tax over the different short, medium and long-range markets.
- Impact on different geographical markets.
- Impact of CCL on fuel efficiency technology improvement/ acceleration.
- Assessment of the cost / fiscal revenues of the CCL scheme.
- Impact of the application year.
- A sensitivity analysis of the value of the tax and generation of marginal curves for different values of the tax.

Additionally, implementation issues are also discussed

18.7.2.1 Overall results: demand, fuel, CO2 and fiscal revenue

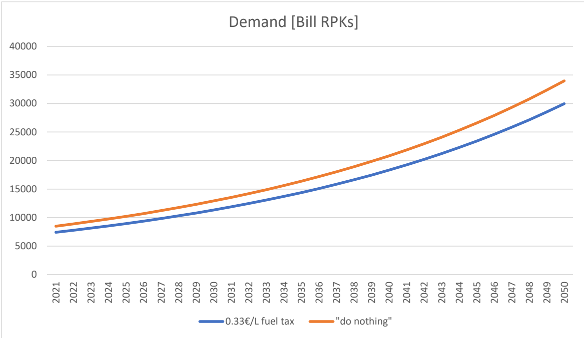
As a starting point, Figure 18. 7 presents the overall results of applying the mentioned fuel tax in terms of demand, fuel consumed and CO2. These results correspond to a worldwide application projected up to 2050.

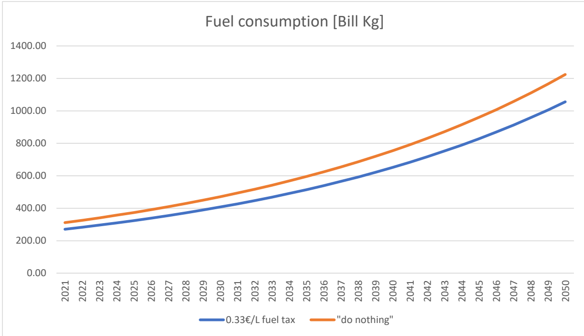
As can be seen for the whole period 2021-2050 the application of the tax implies a global 12% reduction of demand, as well as a reduction on 13% tone of fuel and CO2 produced concerning the, do-nothing scenario. Additionally, the overall fiscal revenue obtained from the tax application is estimated to be 108 Bill € in 2021 and increases progressively up to 422 Bill€ in 2050. Detailed figures for each year are provided in the table below. This figures and values obtained are coherent with other previous studies. Delft study considers a fuel tax of 0.333€/l but applied only to European International flights, with a 10% increase in the average ticket price, 11% decline in passenger demand and 27 Billion € for the year of application.

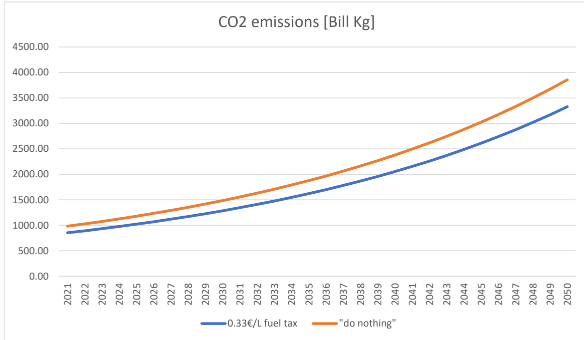
.

[20] Obtained at https://www.statista.com/statistics/655057/fuel-consumption-of-airlines-worldwide/

[21] Density of aviation fuel considered as 0.825 Kg/L. Density is normally in the range of 0,775 – 0,840 kg/l [210]







	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Demand [Bill PRKS] "do nothing"	8490.88225	8890.70919	9310.62861	9751.69971	10215.0394	10701.8256	11213.3004	11750.7738	12315.6277	12909.3194
Demand [Bill PRKS] 0.33€/L Fuel Tax	7426.93597	7779.0633	8148.98646	8537.64759	8946.04027	9375.21249	9826.26957	10300.3775	10798.7661	11322.733
Fuel consumption [Bill KG] "do nothing"	311.69	326.19	341.40	357.36	374.12	391.72	410.20	429.60	449.97	471.37
Fuel consumption [Bill KG] 0.33€/L Fuel Tax	270.75	283.19	296.24	309.95	324.34	339.45	355.31	371.98	389.49	407.88
CO2 emissions [Bill KG] "do nothing"	981.84	1027.49	1075.41	1125.70	1178.49	1233.92	1292.12	1353.23	1417.41	1484.82
CO2 emissions [Bill KG] 0.33€/L	852.88	892.05	933.17	976.33	1021.66	1069.26	1119.24	1171.74	1226.88	1284.81

	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
Demand [Bill PRKS] "do nothing"	13533.3864	14189.4505	14879.2225	15604.5075	16367.2098	17169.3389	18013.0149	18900.4752	19834.0806	20816.3229
Demand [Bill PRKS] 0.33€/L Fuel Tax	11873.6469	12452.9521	13062.1723	13702.9152	14376.8774	15085.8491	15831.7196	16616.4828	17442.2428	18311.2206
Fuel consumption [Bill KG] "do nothing"	493.85	517.47	542.28	568.35	595.74	624.53	654.80	686.60	720.05	755.20
Fuel consumption [Bill KG] 0.33€/L Fuel Tax	427.20	447.50	468.84	491.26	514.82	539.59	565.64	593.01	621.80	652.07
CO2 emissions [Bill KG] "do nothing"	1555.63	1630.02	1708.17	1790.29	1876.59	1967.28	2062.60	2162.81	2268.14	2378.89
CO2 emissions [Bill KG] 0.33€/L	1345.68	1409.63	1476.83	1547.46	1621.69	1699.72	1781.75	1868.00	1958.68	2054.03

	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Demand [Bill PRKS] "do nothing"	21849.8314	22937.3814	24081.9022	25286.4853	26554.3945	27889.0747	29294.1626	30773.4975	32331.1326	33971.3472
Demand [Bill PRKS] 0.33€/L Fuel Tax	19225.7606	20188.3369	21201.5616	22268.1919	23391.1386	24573.4744	25818.4437	27129.4718	28510.1752	29964.3724
Fuel consumption [Bill KG] "do nothing"	792.17	831.04	871.92	914.92	960.15	1007.72	1057.77	1110.43	1165.84	1224.14
Fuel consumption [Bill KG] 0.33€/L Fuel Tax	683.91	717.39	752.61	789.66	828.64	869.64	912.79	958.20	1005.99	1056.28
CO2 emissions [Bill KG] "do nothing"	2495.34	2617.79	2746.56	2882.00	3024.46	3174.32	3331.98	3497.86	3672.39	3856.06
CO2 emissions [Bill KG] 0.33€/L	2154.32	2259.79	2370.73	2487.43	2610.21	2739.38	2875.30	3018.33	3168.85	3327.28

Figure 18. 7. Overall results of a 0.33€/L fuel tax.

18.7.2.2 Impact on operational cost and in the air transport industry activity.

The model does not specifically stimulate the breakdown of the operational cost of the airlines, but although this specific magnitude is not simulated in the study, it is possible to extract some conclusions about the impacts of a 0.33€/L tax fuel policy in the operational cost of the airlines by observing what has been the effect of effective fuel cost increase for the air transport in past periods.

Figure 18. 8 presents the fuel costs of airlines worldwide from 2011 to 2020, as a percentage of expenditure. As can be seen, fuel costs are a significant but highly variable expense for airlines worldwide, constituting 23.5 percent of total expenditure in 2019 [86]. This figure decreased from 32.3 percent in 2012 and is expected to further drop to 15 percent of expenditure in 2020 due to the COVID-19 crisis.

The cost of airline fuel tracks the overall price of crude oil. However, it is common for airlines to hedge fuel purchases, meaning a constant price is agreed in advance for a set period of time. This practice can be used to create a partial buffer between the price of oil and its effect on airlines' expenditure. Despite the practice of hedging, the cost of airline fuel greatly affects the profitability of airlines. For example, a clear correlation can be seen in 2015 between the sharp drop in oil prices and the significant increase in airline profits. Other variable operating expenses affecting airlines' profitability include labour, aircraft maintenance, and airport usage fees.

A tax of fuel of 0.33 per litre (0.4€ per kg) is indeed a big increase in the price of fuel. As of January 2020, the price of Jet A1 was approximately $650 per metric tonne. This equates to about $0.65 per KG or €0.55 per kg [87] [88][22]. The 0.4€ per kg will imply a high 72% increase in the price of fuel respect to the prices in 2019.

Considering that global fuel consumption by commercial airlines reached an all-time high of 96 billion gallons[23] (294 billion of Kg[24]) in 2019 [89] at a 0.55€/kg means a 161.5 Billion € of fuel cost. Being fuel the 23.5% of the airline total expenditure, the operational cost of airlines for the same year is estimated at 687.5 billion of euros. The application of the proposed tax might imply an increase in the percentage of fuel in the total expenditure of the airlines higher than the levels in 2012 (rough calculation lead to 40%). That could mean a decline in air transport activity to levels much worse than those of 2012/2013. This calculation, although approximate, illustrates that although 0.33€/L has been proposed at European level as fuel tax for European aviation (and used in this study for comparative purposes), this tax will not be sustainable worldwide. Additionally if implemented only in Europe it could be too detrimental for European aviation and imply a significant loss of competitiveness against other regions of the world.

---

[22] Due to collapse in oil price bought about by the Covid-19 pandemic, as of May 2020, Jet A1 was approximately $200 per metric tonne which equates to around $0.20 per KG.

[23] https://www.statista.com/statistics/655057/fuel-consumption-of-airlines-worldwide/

[24] 1 Gallon of kerosine A-1 or jet fue is 3.06Kg

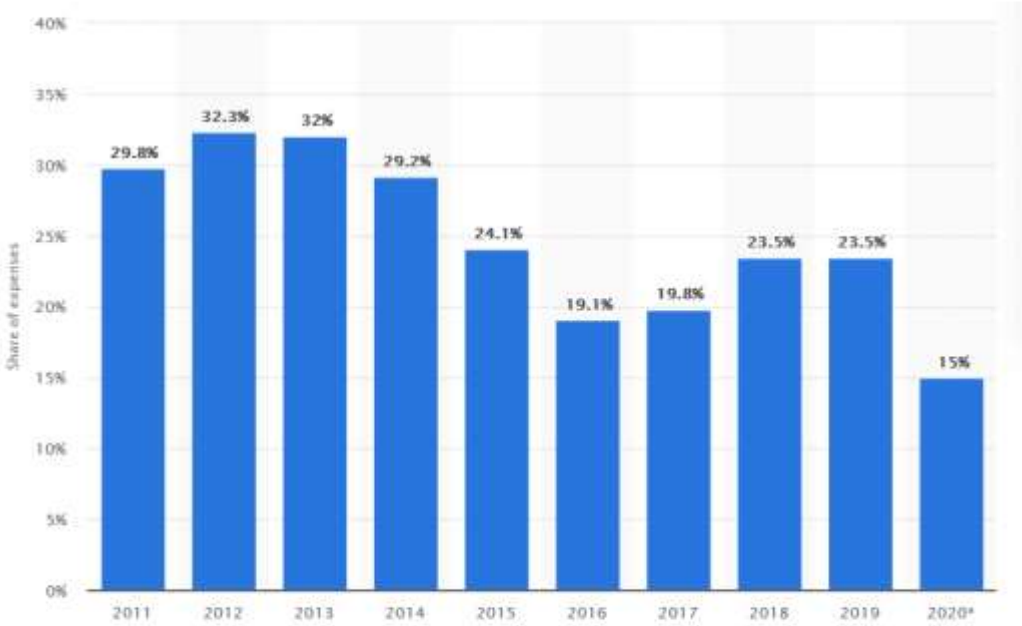


Figure 18. 8. Fuel costs of airlines worldwide from 2011 to 2020, as a percentage of expenditure.

18.7.2.3 Regional contribution and cooperation.

As stated by most authors the effectiveness of a fuel tax will depend very much on the homogeneity of its application. It is expected then that this tax could be applied globally worldwide. Figure 18. 9 and Figure 18. 10 illustrate how the different regions in the world would be affected by the tax.

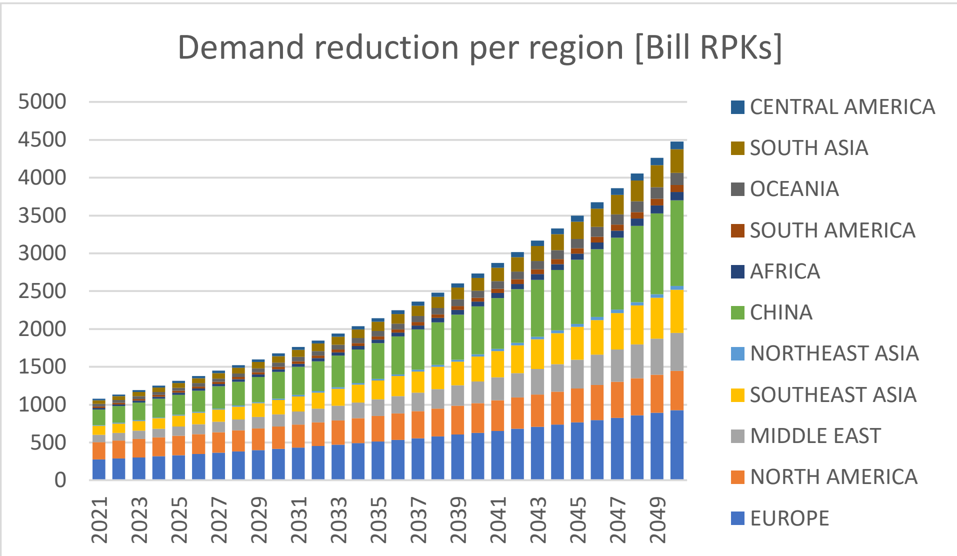


Figure 18. 9. Impact on demand of a 0.33€/L fuel tax worldwide

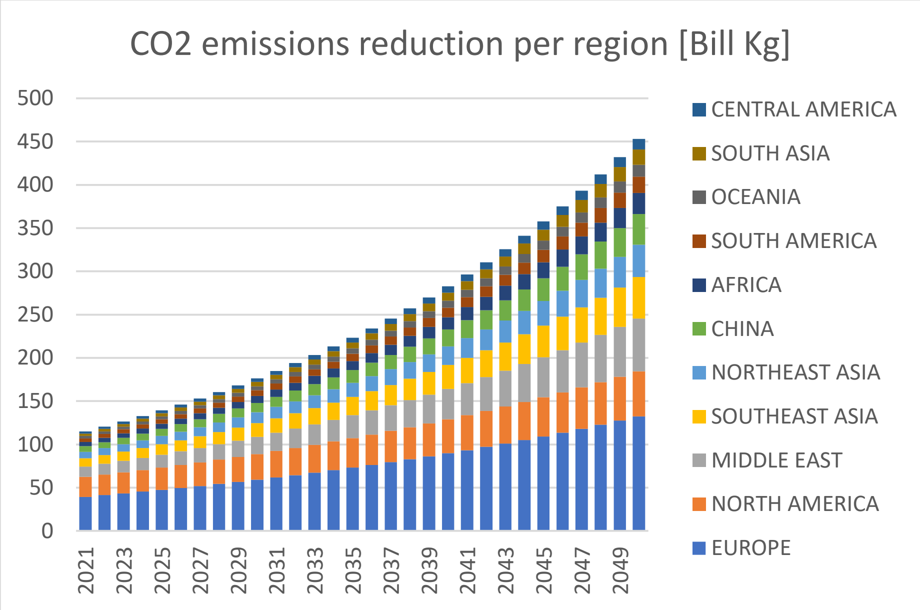


Figure 18. 10. Impact on CO2 emissions of a 0.33€/L fuel tax worldwide

Both figures illustrate that the regions that can contribute most to a reduction in demand and CO2 by the application of the tax are those with the higher traffic. Figure 18. 11 illustrates how 70% of the reduction in CO2 emissions will be produced by aviation with origin just 4 regions: Europe, North America, Middle East and Southeast Asia. By applying the 80/20 Pareto's law, which states that for many phenomena 80% of the result comes from 20% of the effort, it would be necessary that at least these regions would agree on the implementation of the tax in order to obtain a significant CO2 saving. A worldwide agreement less than that could lead to an insignificant CO2 saving and at the same time produce a negative counter effect of the economy, air transport t and tourism for those regions.

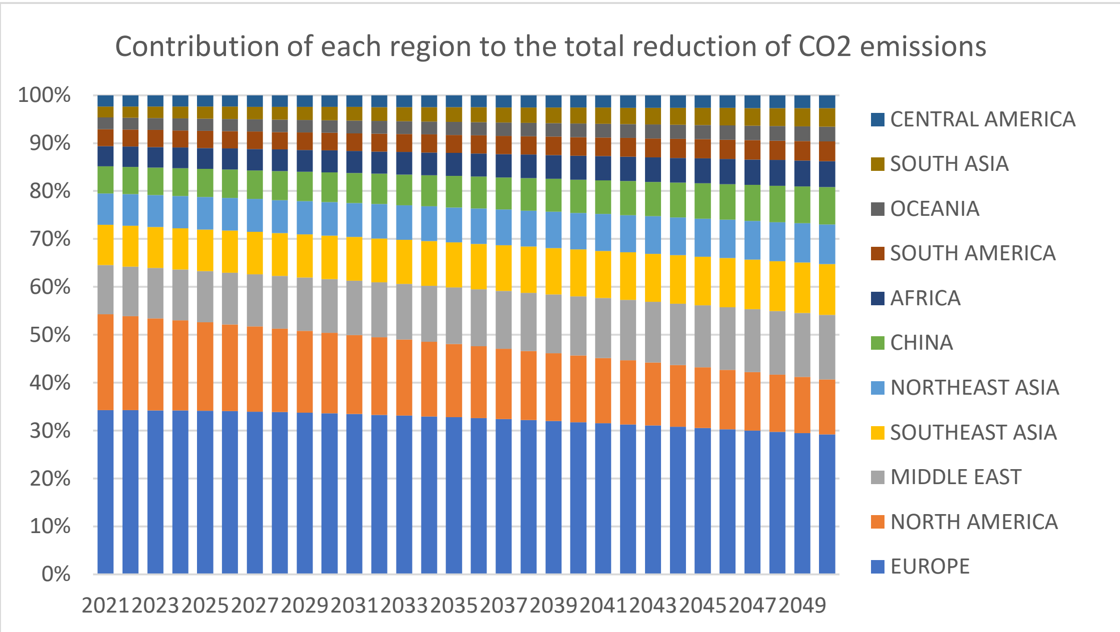


Figure 18. 11. Contribution (in %) of Regions to the reduction in CO2.

Extensive cooperation is therefore required in designing and implementing international transportation fuel charges would be needed to avoid revenue erosion and distortions.

There is an underlying fear that unilateral taxation would harm local tourism, trade and domestic carriers, increase import prices, decrease the demand for exports, and besides leading fuelling to take place in countries without similar policy measures.

If governments set emission charges unilaterally or do not subscribe to an overall agreement, they will be pressured to establish lower rates, to protect their domestic industries and revenues. Because of those reason international coordination is needed. However, it has been defended that for international aviation, an agreement with substantially less than universal coverage - for example, one that exempted some vulnerable developing countries—could still have a significant effect on global emissions and considerable revenue potential, given the relatively limited possibilities for carriers to simply re-fuel wherever taxes are lowest.

18.7.2.4 Compensating developing countries.

Global implementation of the tax is expected to consider also the possible negative effects for developing countries. One of the concerns of implementing carbon charges for aviation is that developing countries are made no worse off by the global adaption of such charges, and up to what extent this could be avoided through reasonably practicable compensation rules. Compensating developing countries for the economic harm they might suffer from such charges—ensuring that they bear "no net incidence"—is widely recognized as critical to their acceptability

ICAO and the international aviation industry is firmly committed to principles of uniform treatment of carriers and nations. A globally applied charge would be consistent with this and could be reconciled with the UNFCCC principle of common but differentiated responsibilities and respective capabilities by a system of compensatory transfers.

A few years ago the Internationally Monetary Fund explored the potential for raising climate finance from charges on fuel for international aviation, with a particular focus on minimizing the negative impact on low-income countries and implementation issues through a system of compensations [24]. The IMF study found that combining a global charge with targeted compensation provides an effective way to pursue both efficiency and equity objectives. However, although a strategy combining globally imposed charges with compensation to adversely affected developing countries would be consistent with both industry standards and UNFCCC principles, it will withdraw a significant part of the potential CO2 savings.

Such compensation seems to require—at most—40 percent of global revenues. With a gross estimation by 2020, a globally implemented carbon charge of $25 per tonne of CO2 on international aviation fuel could have raised in 2020 with no COVID 19 incidence around $12 billion. 40% of this amount would leave about $7 billion for compensating developing economies and will therefore withdraw from climate finance. Moreover, developing countries might use this compensations funds to subside local aviation, jeopardizing the CO2 reductions provided by the tax itself. As it can be seen there is an important trade-off here: the more extensive is compensation, the less public revenue will remain for climate finance or other productive purposes.

18.7.2.5 Impact on Oil prices - Partial pass-through of charges to fuel prices

A critical issue is when setting a CCL scheme is how far charges on jet would be passed on to purchasers? This is key to the first factor identified above: to the extent that the impact is not passed forward, so that aviation fuel prices rise by less than the full amount of the charge, so its impact on and through the sectors will be muted.

Jet fuel prices might not rise by the full amount of any new charge on their use. Some portion of the real burden is likely to be passed back to oil refiners and oil producers. However, if refiners can shift production from these fuels to other oil products fairly easily (which seems plausible), this pass back is likely to be modest. According to [24], a charge of 10 cents per litre on fuels used in both sectors might then increase the price to operators by about 9.5 cents per litre.

Part of the impact would then be felt by suppliers of crude oil—including a number of low-income countries that are new oil producers. The determinants of the degree of a pass forward into fuel prices are complex—one key issue being the degree to which refiners can substitute between the productions of taxed and untaxed fuels.

The following formula considers the likely impact of a charge when such substitution is completely costless. The degree of a pass forward is then likely to be high since producers can readily escape the tax by instead producing other fuels. As a rough order of magnitude, on average over 90 percent of a charge imposed on jet fuel might be passed on.

Suppose first that oil is a homogenous product and consider a specific charge of T levied on its use in only one activity (aviation). In this case, assuming the relevant industries are reasonably competitive and that the elasticity of demand is the same (E) for both taxed and untaxed uses, the impact on the pre-tax oil price P is approximate.

$$\Delta P = \alpha \left(\frac{E}{E + \eta} \right) T$$

Where α is the proportion of all oil consumed in the taxed sector and η the elasticity of oil supply. The impact is thus smaller (i.e. less of the charge passed back to oil producers):

(1) The smaller the amount of aviation/maritime fuel produced from the average barrel of crude oil input;

(2) The smaller the share of global aviation/maritime fuel production that is covered by the charge (i.e., the greater the extent of developing country exemptions); and

(3) The less elastic is the demand for these fuels and the more elastic is the supply of crude oil.

Broadly speaking, the impact is the same as that of a tax on all oil uses but scaled down by the share of oil covered by the tax in all oil production. The empirical evidence suggests that the elasticities of demand for and supply of oil are of broadly the same magnitude: according to [90], the magnitude of oil demand and supply elasticities are both around 0.05 to 0.1 in the short run, though both are larger over the longer run.

This suggests that the bracketed term in the previous equation is around 0.5. Supposing that the share of aviation in global oil demands is 11 percent1 and international fuel taxes are implemented globally (i.e., = 0.11), then a fuel tax of 10 cents per litre imposed on all aviation and maritime fuel demand would reduce the world oil price by around 0.55 cents and, conversely, increase the price to fuel purchasers by around 9.4 cents per litre.

This simple analysis also highlights that taxing the use of oil in some particular use results in a fall in its prices in other uses. Thus, low-income oil-importing countries, for instance, would derive some benefit to the extent that prices of fuels in other uses fall. This effect also means that total emissions fall by less than do those in the affected sector since the reduced price in other sectors leads there to higher emissions.

Total emissions will fall (so long as the supply curve is upward sloping), but the fall will be smaller the more elastic is the demand for oil in untaxed uses.

All this assumes oil in distinct uses to be perfect substitutes. Even allowing for possible difficulties of re-configuring refineries to alter the portions of different fuel products produced from crude oil, pass-back to oil producers is likely to be modest. In effect, costs of reconfiguration mean that the supply of taxed fuel is more inelastic, so that producers bear more of the burden of the tax. Nonetheless, even allowing for somewhat more limited substitution possibilities, simulations in Table 18. 18 suggest that the pass back into lower oil prices is still modest—again at about 6 cents per litre for a $1 per litre fuel charge.36 It is noticeable, nonetheless, that the amount of the tax passed forward is far from complete: A $1 tax increase leads to an increase in the tax-inclusive price of only 65–84 cents per litre. The reason is that the price impacts for the untaxed fuels are in many cases sizable, in the order of 10 percent—implying a benefit to users of these fuels that need to be weighed against any loss from the impact on the taxed fuel.

Elasticity substitution	1			∞		
Elasticity of fuel demands and oil supply	0.1	0.5	0.1	0.5	0.1	0.5
Price change (in cents) of						
Taxed fuel	+0.86	+0.65	+0.93	+0.86	+0.94	+0.94
Untaxed fuel	-0.08	-0.1	-0.06	-0.07	-0.06	-0.06
Crude oil	-0.06	-0.06	-0.06	-0.06	-0.06	-0.06

Table 18. 18. Impact on fuel and oil prices of $1 charge on a subset of fuels.

18.7.2.6 Fuel efficiency improvement.

It is also claimed that emissions pricing would induce other mitigation options beyond this demand reduction. These include more efficient operations (e.g., optimizing flight paths and reducing airport congestion, reducing average time spent idling on runways or circulating airports through advanced communication, navigation, and air traffic management) and improved efficiency of new planes (e.g., improving aerodynamics to reduce drag, more efficient engines, incorporation of lighter materials into the airframe).

It is difficult to estimate the future development and deployment costs of many of these strategies, and hence the extent to which they would be incentivized by higher fuel prices over the longer run. [91]. For cars and light trucks (at least in the United States), it seems reasonable to assume that a 1 percent increase in fuel prices will ultimately increase fuel economy by something in the order of about 0.2 percent [92]. For airlines, the responsiveness might be lower, given already strong incentives to economize on fuel (which is expensive to carry) and ongoing efforts by ICAO to promote better fuel economy.

Simply by way of illustration, suppose the fuel economy response is 0.1 percent (per 1 percent increase in the fuel price). Combining this with the assumed reduction in travel demand implies an overall fuel (and emissions) reduction in response to an 8 percent increase in fuel price of 3–5 percent. Given that developing countries account for 35 percent of fuel use (see above), their exemption from the agreement might limit the global emissions reduction to about 2–3 percent. A similar level of emissions reductions might occur if all countries participated, but for $15 per tonne rather than $25. On the other hand, the emissions reduction might be around 5–8 percent under a CO2 price of $40 per tonne, encompassing all countries.

Based upon historical data some authors have quantified jet aircraft fuel efficiency historical improvement at a rate of 1.2-2.2% per year on a seat/km basis [45], [46], [46]. International aviation community aspire to a 2% annual fuel efficiency improvement and a carbon-neutral growth from 2020.

To comparatively assess the effect of CCL against this effect a simulation has been run under the different hypothesis of fuel efficiency improvement, in addition to de do nothing and 0.33€/L fuel tax scenarios:

- 2% yearly fuel efficiency improvement
- 3% yearly fuel efficiency improvement
- 4% yearly fuel efficiency improvement

As can be seen in Figure 18. 12, there is not a significant improvement related to CO2 emissions. Therefore, a fuel tax is more important than this kind of aircraft efficiency to reduce CO2 emissions. The aircraft efficiency is really important; however, the improvement must be done to obtain similar results as the fuel tax.

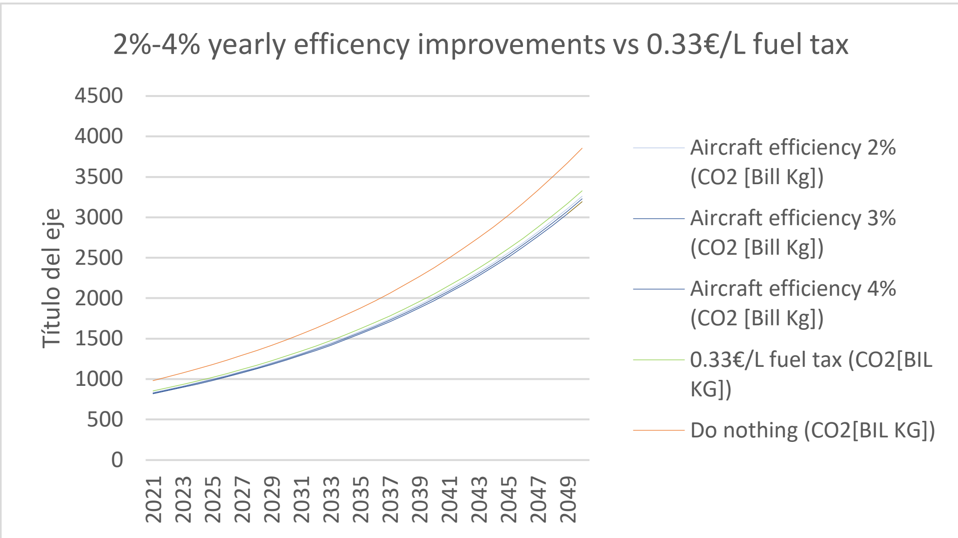


Figure 18. 12. 2%-4% yearly efficiency improvements vs 0.33€/L fuel tax

18.7.2.7 Implementation

Some key challenges need to be considered for implementing globally coordinated charges in international aviation. These range from fundamental issues of sovereignty and governance through to practical issues regarding the administration and legal frameworks.

- New frameworks would be needed to govern the use of funds raised to
  - (1) determine how and when charges (or emissions levels) are set and changed,
  - (2) to provide appropriate verification of tax paid or permits held, and
  - (3) to monitor and implement any compensation arrangements.

While the EU experience indicates that taxation agreements can be reached, it also shows how sensitive are the sovereignty issues at stake.

One possibility is to link an emissions charge on international transportation to the average carbon price of the largest economy-wide emission reduction scheme, for instance, so limiting the need for a separate decision process.

The various detailed proposals being considered to suggest that practical issues can be resolved. There could indeed be some role for ICAO, with its unparalleled technical expertise in these sectors, in implementing these charges, though there are other possibilities.

- Implementation costs. The familiarity of operators and national authorities with fuel excises suggests that implementation costs would be lower with a tax-based approach than with an ETS. [24]

  Collecting fuel taxes is a staple of almost all tax administrations, and very familiar to business; implementing trading schemes is not.

  Ideally, taxes would be levied to minimize the number of points to control—which, broadly, means as upstream in the production process as possible. If taxation at the refinery level is not possible, the tax could be collected as fuel is disbursed from depots at airports and ports, or directly from aircraft and ship operators.

  Implementation would be simplest—and environmental efficiency greatest—if no distinction were made between fuels in domestic and international use. Indeed, eliminating the differentiation imposed at present should in itself be a simplification.

- Administration model. Policies could be administered nationally, through international coordination or in some combination of the two—with the appropriate institutions for monitoring and verification depending on the approach taken.

  For example, national governments might be responsible for implementing aviation fuel charges or trading schemes on companies distributing fuel to airlines, with some of the receipts transferred to a climate finance fund.

  Flexibility may well be needed to accommodate various national circumstances by, for example, allowing certain countries to opt for a national collection that is linked to an international approach.

- Multilateral agreements: The current aviation fuel tax exemptions are built into multilateral agreements within the ICAO framework and bilateral air service agreements, which operate on a basis of reciprocity.

  Though consideration of the challenges this presents is needed, amending the Chicago Convention and associated resolutions would remove these obstacles, although the EU experience on intra-union charging seems to suggest the possibility of overcoming them without doing so.

  An alternative approach would be to use an ETS in this sector, although the consistency of this with international aviation agreements is currently the subject of litigation. For marine fuels, there are no formal agreements prohibiting excise taxes, so there appear to be no legal obstacles to fuel charges in this sector.

Although on a much smaller scale, experience with the air ticket solidarity levy and the International Oil Pollution Compensation (IOPC) Funds suggest a cooperative approach to pricing emissions from international transportation can be aspired to.

While implementation details need further study, especially in terms of governance, it is clear that feasible operational proposals for pricing international aviation and maritime emissions can be developed.

Previous work has stressed the potentially significant distortions that could follow from applying any charge differentially, whether by country, carrier, vessel, or route. This is also stressed in our study.

Because the established principles of the international aviation industry attach considerable importance to non-discrimination and equality of treatment, rather than revisit these issues, it is assumed here, that charges are applied uniformly to all fuels used in international aviation.

18.7.2.8 Impact on different markets.

The fuel tax may affect differently the short, medium and long-range markets. In this regard two key questions need to be evaluated: which market results more affected in terms of demand and which market might contribute the most to the CO2 emissions reduction. Following analysis bring some light into these topics.

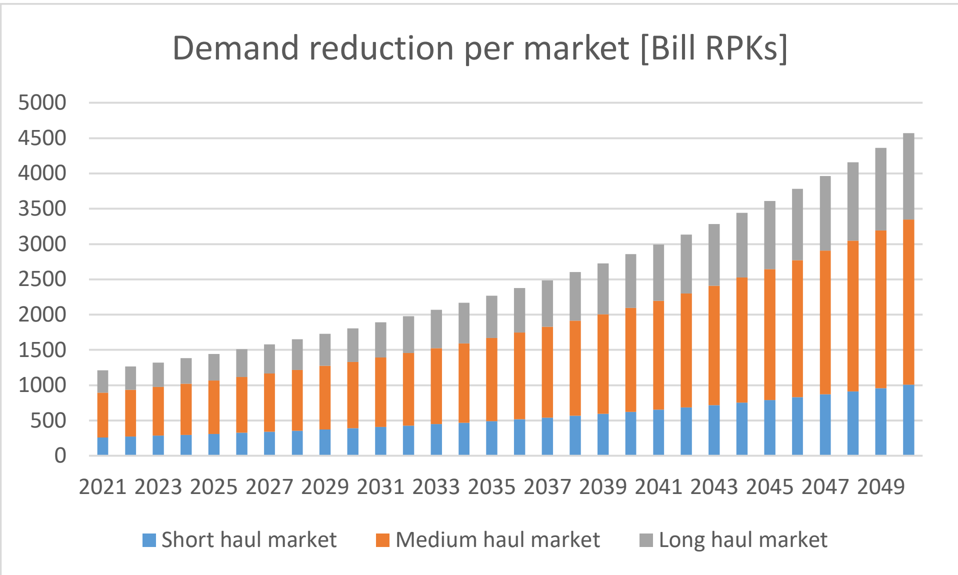


Figure 18. 13. Reduction in demand for short, medium and long haul market

Figure 18. 13 illustrated how the demand is reduced in each of the markets in terms of RPKs. It can be appreciated how the biggest reduction takes place in the medium-haul market with an initial reduction of around 634 Bill RPKS in 2021 and a final of 2340 Bill RPKs by 20250. For the short-haul market the initial reduction by 2021 is around 260 Bill RPKS and by 2050 is around 1007 Bill RPKs. For the long-haul market, the reduction is of 316 Bill RPKs by 2021 and 1225 Bill RPKs by 2050. In average it means an 11% yearly reduction for the short-haul market, a 16% yearly reduction for the medium-haul market and a 14% yearly reduction for the long-haul market.

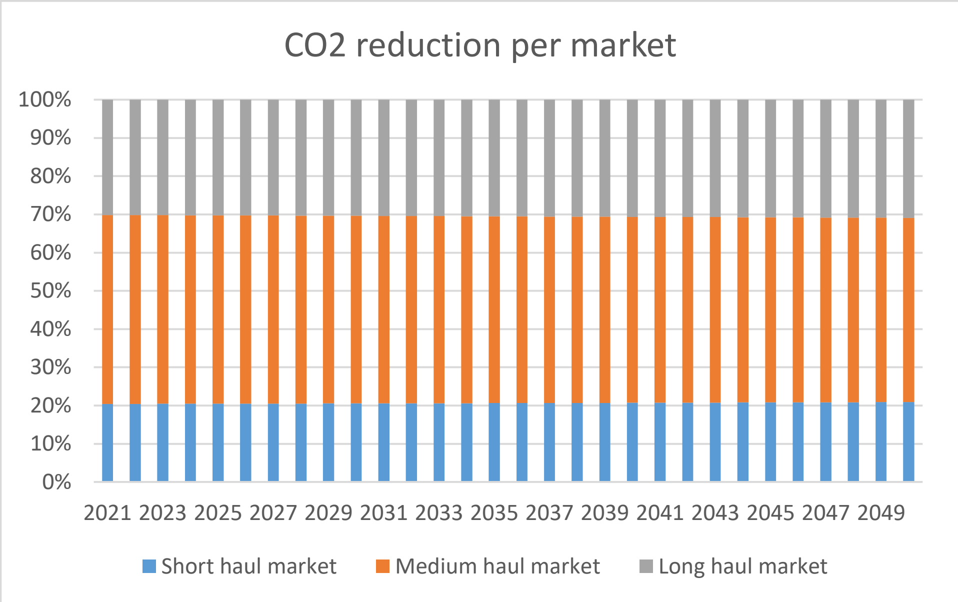


Figure 18. 14. Contribution of each market in % to the global CO2 reduction

Figure 18. 14 shows how each market contributes to the global reduction of CO2. It can be observed that the biggest reduction of CO2 is expected in the medium-haul market, which will account for 49.5% of the total reduction with 68 Bill Kg CO2 by 2021 and 252 Bill Kg CO2 by 2050. The short-haul market accounts for 20.5% of the global reduction with 28 Bill Kg CO2 by 2021 and 109 Bill Kg CO2 by 2050. The short-haul markets account for 30% of the global reduction with 41 Bill Kg CO2 by 2021 and 161 Bill Kg CO2 by 2050.

18.7.2.9 Implementation year.

The next analysis shows the effect of implementing the tax in 2021 or delaying its application up to 2025 or even 2030. Table 18. 19 and Figure 18. 15 presents the accumulated CO2 emissions between 2021 and 2050 in Bill Kg for the three different implementation dates in contrast with the accumulated CO2 emission for the do-nothing scenario.

Implementation of the fuel tax in 2030 instead of 2021 would imply the emission of 3304 Bill Kg more of CO2, whereas implementing the tax in 2025 instead of 2021 would imply the emission of 950 Bill Kg more of CO2. Therefore, the most significant reduction is applying the tax in 2021.

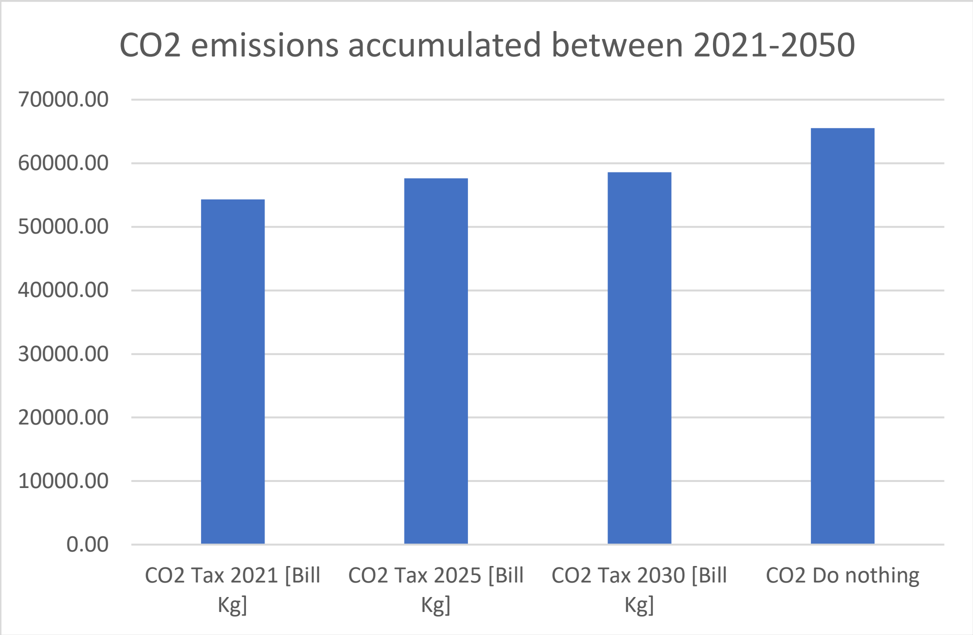


Figure 18. 15. CO2 emissions by 2050.

	Acumulated between 2021-2050
CO2 Tax 2021 [Bill Kg]	54323.11
CO2 Tax 2025 [Bill Kg]	57627.13
CO2 Tax 2030 [Bill Kg]	58578.03
CO2 Do nothing	65562.16

Table 18. 19. CO2 emissions by 2050.

Therefore, as can be seen in Table 18. 19 and Figure 18. 15, the most significant reduction is applying the tax in 2021.

18.7.3 Generation of the marginal CCL curves.

As discussed in the previous sections a fuel tax of 0.33€/L applied worldwide will imply a very high increase in the price of fuel. At the same time, there is no yet an agreement among the different sources and studies of what might be the optimum value for such a tax, these figures varying depending on the study consulted. Those studies are not always easy to compare as they do not reproduce the same scenarios or considerer a local/ regional application of the tax.

To help to solve these problems we construct in this analysis marginal curves that represent the effect in demand and CO2 for different values of a global fuel tax, ranging from 0 to 500€/Ton of fuel in intervals of 25€/Ton. Being the value of 400€ /Ton (333€/KL) the tax equivalent to the exceed of duty study that has served for comparison in the previous analysis.

Figure 18. 16 presents the worldwide yearly demand for the period 2021 to 2050, expressed in Billions of RPKs, corresponding to the application of different values of the fuel tax. Numeric values can be consulted in Table 18. 21. Figure 18. 17 represents the accumulative worldwide demand during the period 2021-2050, expressed in Billions of RPKs for different values of the fuel tax; and the table below provides the numeric

values. It can accumulatively be worldwide demand will be reduced for the whole period up to 545747.445 Bill RPKS for a tax of 25€/Ton up to 477871.025 for a tax of 400~/ton.

Accumulative worldwide demand during the period 2021-2050			
Fuel tax scenario	Bill RPK	Fuel tax scenario	Bill RPK
do nothing	552348.381	Fuel tax 275€/Ton	495939.829
Fuel tax 25€/Ton	545747.445	Fuel tax 300€/Ton	492059.32
Fuel tax 50€/Ton	539546.364	Fuel tax 325€/Ton	488321.101
Fuel tax 75€/Ton	533696.188	Fuel tax 350€/Ton	484715.808
Fuel tax 100€/Ton	528157.629	Fuel tax 375€/Ton	481234.996
Fuel tax 125€/Ton	522898.398	Fuel tax 400€/Ton	477871.025
Fuel tax 150€/Ton	517891.476	Fuel tax 425€/Ton	474616.955
Fuel tax 175€/Ton	513113.927	Fuel tax 450€/Ton	471466.456
Fuel tax 200€/Ton	508546.05	Fuel tax 475€/Ton	468413.739
Fuel tax 225€/Ton	504170.752	Fuel tax 500€/Ton	465453.496
Fuel tax 250€/Ton	499973.073		

Table 18. 20. Accumulative demand during the period 2021-2050 in Billions of RPKs for different values of the fuel tax.

By expressing the previous information in accumulative percentages, we obtain the marginal CCL curve in Figure 18. 18. . This figure gives straightforward the % of reduction for the worldwide demand in the period 2021- to 2050 for any given tax. This marginal curve can be used as criteria for design. Similar abacus can be constructed for each region in the world o for each market segment (Short, medium, long haul). Similar abacus is provided for fuel conception and CO2 emissions in the following figures and tables.

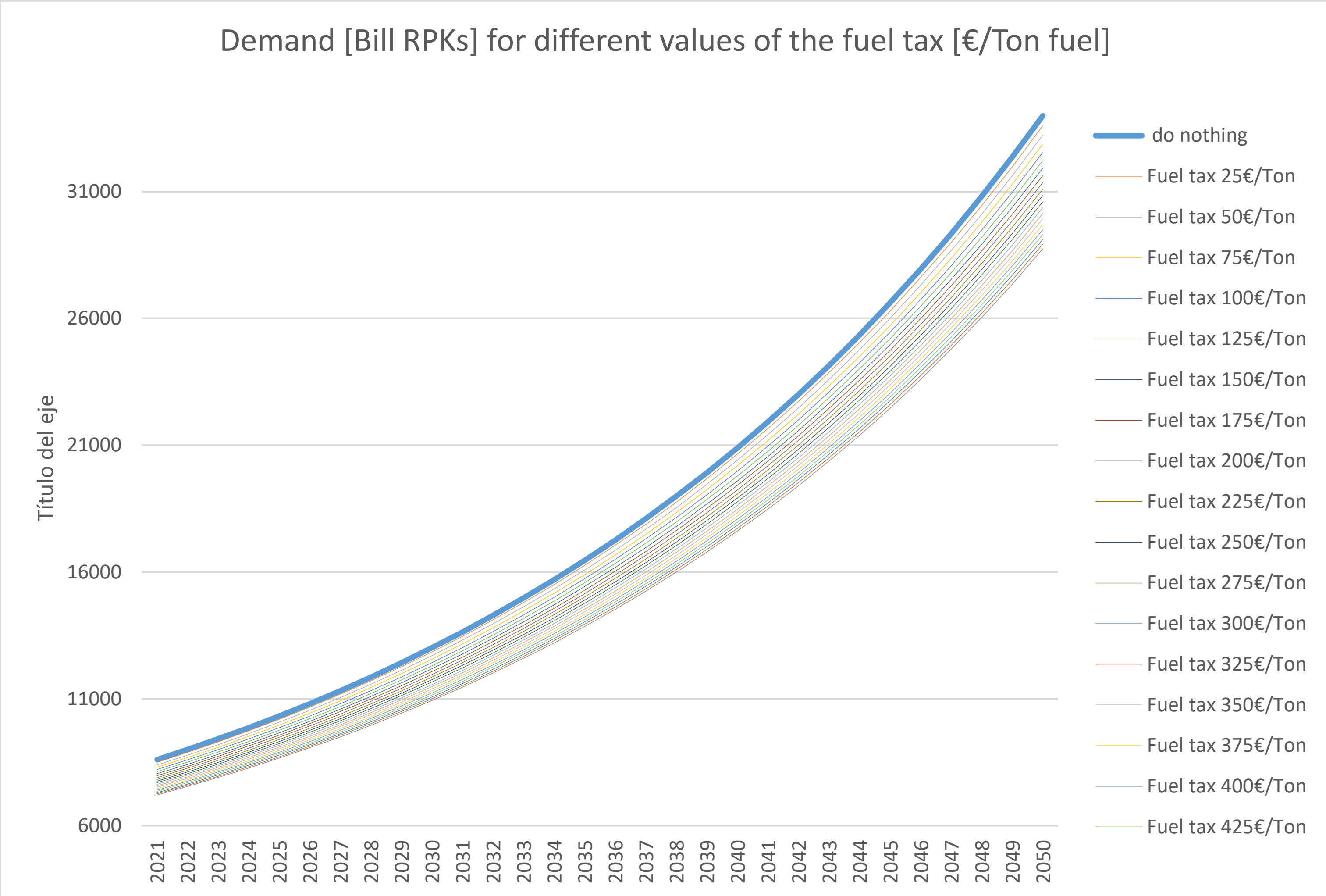


Figure 18. 16. Yearly demand in Billions of RPKs for different values of the fuel tax.

	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
do nothing	7402.16698	7746.05733	8107.04591	8606.19798	9005.32952	9424.46267	9864.64986	10327.0008	10812.6857	11322.9386	11859.0609
Fuel tax 25€/Ton	7402.16698	7746.05733	8107.04591	8499.39973	8893.79661	9307.96965	9742.95987	10199.865	10679.8426	11184.1135	11713.9649
Fuel tax 50€/Ton	7402.16698	7746.05733	8107.04591	8399.25504	8789.20184	9198.7124	9628.817	10080.602	10555.2131	11053.8585	11577.8122
Fuel tax 75€/Ton	7402.16698	7746.05733	8107.04591	8304.92952	8690.6762	9095.78576	9521.27828	9968.22944	10437.7736	10931.1069	11449.4911
Fuel tax 100€/Ton	7402.16698	7746.05733	8107.04591	8215.75624	8597.52493	8998.46588	9419.58953	9861.96135	10326.7049	10815.0052	11328.1119
Fuel tax 125€/Ton	7402.16698	7746.05733	8107.04591	8131.18917	8509.1791	8906.15996	9323.13295	9761.15383	10221.336	10704.8535	11212.9448
Fuel tax 150€/Ton	7402.16698	7746.05733	8107.04591	8050.773	8425.16425	8818.37349	9231.39311	9665.26959	10121.1065	10600.0678	11103.3809
Fuel tax 175€/Ton	7402.16698	7746.05733	8107.04591	7974.12246	8345.07883	8734.68791	9143.93365	9573.85366	10025.5422	10500.1532	10998.904
Fuel tax 200€/Ton	7402.16698	7746.05733	8107.04591	7900.90756	8268.57886	8654.74459	9060.38065	9486.51614	9934.23632	10404.6858	10899.0718
Fuel tax 225€/Ton	7402.16698	7746.05733	8107.04591	7830.84272	8195.3666	8578.23313	8980.41042	9402.91942	9846.8368	10313.2981	10803.5009
Fuel tax 250€/Ton	7402.16698	7746.05733	8107.04591	7763.67865	8125.18215	8504.88246	8903.74027	9322.76866	9763.03603	10225.6692	10711.8566
Fuel tax 275€/Ton	7402.16698	7746.05733	8107.04591	7699.19608	8057.79682	8434.45411	8830.12145	9245.80436	9682.56328	10141.5166	10623.8441
Fuel tax 300€/Ton	7402.16698	7746.05733	8107.04591	7637.2008	7993.0081	8366.73684	8759.3336	9171.79663	9605.17869	10060.5901	10539.202
Fuel tax 325€/Ton	7402.16698	7746.05733	8107.04591	7577.51983	7930.63556	8301.54245	8691.1804	9100.54062	9530.66848	9982.6665	10457.6976
Fuel tax 350€/Ton	7402.16698	7746.05733	8107.04591	7519.99827	7870.51763	8238.70237	8625.48595	9031.8528	9458.84111	9907.54589	10379.1221
Fuel tax 375€/Ton	7402.16698	7746.05733	8107.04591	7464.49673	7812.50889	8178.0649	8562.09198	8965.56798	9389.52419	9835.0483	10303.2876
Fuel tax 400€/Ton	7402.16698	7746.05733	8107.04591	7410.88925	7756.47796	8119.49294	8500.8554	8901.53684	9322.56183	9765.01104	10230.0243
Fuel tax 425€/Ton	7402.16698	7746.05733	8107.04591	7359.06157	7702.30559	8062.86207	8441.64639	8839.62386	9257.81259	9697.28642	10159.178
Fuel tax 450€/Ton	7402.16698	7746.05733	8107.04591	7308.90963	7649.88323	8008.05902	8384.3467	8779.70563	9195.14764	9631.73991	10090.6081
Fuel tax 475€/Ton	7402.16698	7746.05733	8107.04591	7260.33842	7599.11172	7954.98029	8328.84832	8721.66939	9134.44922	9568.24858	10024.1864
Fuel tax 500€/Ton	7402.16698	7746.05733	8107.04591	7213.26083	7549.90018	7903.53104	8275.05225	8665.41179	9075.60945	9506.69977	9959.79504

	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039
do nothing	12422.4251	13014.4789	13636.7493	14290.8471	14978.4715	15701.415	16461.5689	17260.9285	18101.5993	18985.8028	19915.8831
Fuel tax 25€/Ton	12270.7547	12855.915	13470.9565	14117.4727	14797.1446	15511.7456	16263.1469	17053.3224	17884.3553	18758.4434	19677.9062
Fuel tax 50€/Ton	12128.4182	12707.0939	13315.3345	13954.7172	14626.906	15333.6561	16076.8196	16858.3505	17680.3105	18544.8755	19454.3411
Fuel tax 75€/Ton	11994.2569	12566.8077	13168.6241	13801.268	14466.3868	15165.7188	15901.098	16674.4593	17487.8446	18343.4082	19243.4237
Fuel tax 100€/Ton	11867.3431	12434.0892	13029.8168	13656.0729	14314.4898	15006.7893	15734.7882	16500.4034	17305.6576	18152.685	19043.7382
Fuel tax 125€/Ton	11746.9161	12308.145	12898.085	13518.269	14170.3146	14855.9281	15576.9099	16335.1596	17132.6817	17971.5914	18854.1209
Fuel tax 150€/Ton	11632.3405	12188.3125	12772.7375	13387.1351	14033.1087	14712.3499	15426.6434	16177.8723	16968.0238	17799.1948	18673.598
Fuel tax 175€/Ton	11523.0782	12074.0302	12653.1883	13262.0596	13902.2339	14575.3886	15283.2934	16027.8157	16810.9261	17634.7037	18501.343
Fuel tax 200€/Ton	11418.6676	11964.8163	12538.935	13142.5182	13777.1429	14444.4728	15146.2633	15884.3668	16660.7376	17477.4384	18336.6458
Fuel tax 225€/Ton	11318.7086	11860.2537	12429.5418	13028.056	13657.3608	14319.1067	15015.0355	15746.9849	16516.894	17326.8093	18178.8903
Fuel tax 250€/Ton	11222.8519	11759.9775	12324.6282	12918.2758	13542.4727	14198.8572	14889.1575	15615.1974	16378.9015	17182.3004	18027.5376
Fuel tax 275€/Ton	11130.7899	11663.6666	12223.8588	12812.8273	13432.1132	14083.3424	14768.2305	15488.5879	16246.3248	17043.4571	17882.1123
Fuel tax 300€/Ton	11042.2497	11571.0363	12126.9365	12711.4003	13325.958	13972.2237	14651.9008	15366.7866	16118.7778	16909.8757	17742.1927
Fuel tax 325€/Ton	10956.9884	11481.8329	12033.596	12613.718	13223.718	13865.1992	14539.853	15249.4641	15995.9161	16781.1964	17607.4026
Fuel tax 350€/Ton	10874.788	11395.8287	11943.6	12519.5321	13125.1341	13761.9981	14431.804	15136.3246	15877.4306	16657.096	17477.4042
Fuel tax 375€/Ton	10795.4523	11312.819	11856.7344	12428.6193	13029.9728	13662.3764	14327.4991	15027.1018	15763.043	16537.2835	17351.8933
Fuel tax 400€/Ton	10718.804	11232.6184	11772.8057	12340.7774	12938.0228	13566.1136	14226.7076	14921.5547	15652.5012	16421.4957	17230.5945
Fuel tax 425€/Ton	10644.682	11155.0589	11691.6383	12255.8228	12849.0926	13473.0091	14129.2201	14819.4644	15545.5766	16309.4931	17113.2576
Fuel tax 450€/Ton	10572.9397	11079.9871	11613.072	12173.5884	12763.0072	13382.8805	14034.8458	14720.6312	15442.0604	16201.0578	16999.6544
Fuel tax 475€/Ton	10503.4428	11007.2631	11536.9606	12093.9212	12679.6069	13295.5606	13943.41	14624.8728	15341.7618	16095.9901	16889.5765
Fuel tax 500€/Ton	10436.0686	10936.7583	11463.1699	12016.681	12598.7453	13210.8964	13854.7527	14532.0218	15244.506	15994.1071	16782.8323

	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
do nothing	20894.3142	21923.7067	23006.8161	24146.5502	25345.9786	26608.3409	27937.0572	29335.7374	30808.1926	32358.4462	33990.7457
Fuel tax 25€/Ton	20645.1911	21662.8813	22733.703	23860.5334	25046.4097	26294.5373	27608.3002	28991.2705	30447.2191	31980.1271	33594.1977
Fuel tax 50€/Ton	20411.1302	21417.7998	22477.0485	23591.7245	24764.8343	25999.5512	27299.225	28667.3918	30107.7849	31624.3452	33221.2338
Fuel tax 75€/Ton	20190.2905	21186.5407	22234.8468	23338.0296	24499.0664	25721.0999	27007.4476	28361.6116	29787.2891	31288.3833	32869.0153
Fuel tax 100€/Ton	19981.194	20967.5611	22005.487	23097.7665	24247.349	25457.3483	26731.0511	28071.9272	29483.6394	30970.0549	32535.2568
Fuel tax 125€/Ton	19782.6257	20759.5921	21787.6441	22869.5511	24008.2365	25206.7861	26468.4574	27796.6892	29195.1119	30667.5583	32218.075
Fuel tax 150€/Ton	19593.5688	20561.5718	21580.2084	22652.2243	23780.5176	24968.1476	26218.3437	27534.5153	28920.2615	30379.3823	31915.8897
Fuel tax 175€/Ton	19413.1597	20372.5981	21382.2377	22444.8014	23563.1633	24740.3572	25979.5857	27284.2299	28657.8591	30104.2418	31627.3567
Fuel tax 200€/Ton	19240.6568	20191.8959	21192.922	22246.436	23355.2888	24522.4899	25751.2163	27044.8217	28406.8471	29841.0305	31351.3191
Fuel tax 225€/Ton	19075.4163	20018.7926	21011.5582	22056.3931	23156.1258	24313.7425	25532.3954	26815.4124	28166.3066	29588.7875	31086.7713
Fuel tax 250€/Ton	18916.8748	19852.6993	20837.5309	21874.0292	22965.0015	24113.4115	25322.3874	26595.2322	27935.4327	29346.6702	30832.8317
Fuel tax 275€/Ton	18764.5356	19693.0969	20670.2972	21698.7768	22781.3225	23920.876	25120.543	26383.6021	27713.5146	29113.9351	30588.7222
Fuel tax 300€/Ton	18617.958	19539.5244	20509.3754	21530.1321	22604.5617	23735.585	24926.2855	26179.9186	27499.9211	28889.9216	30353.7513
Fuel tax 325€/Ton	18476.7485	19391.5706	20354.3351	21367.6451	22434.2486	23557.0461	24739.0999	25983.6429	27294.0882	28674.0393	30127.3012
Fuel tax 350€/Ton	18340.554	19248.8663	20204.7905	21210.9122	22269.9608	23384.8175	24558.5239	25794.2912	27095.5096	28465.7583	29908.8169
Fuel tax 375€/Ton	18209.0565	19111.0787	20060.3934	21059.5692	22111.3176	23218.5008	24384.1406	25611.4271	26903.7283	28264.6004	29697.7978
Fuel tax 400€/Ton	18081.9679	18977.9068	19920.829	20913.2867	21957.974	23057.735	24215.5722	25434.6552	26718.3308	28070.1322	29493.7903
Fuel tax 425€/Ton	17959.0266	18849.0768	19785.8108	20771.765	21809.6167	22902.1923	24052.4755	25263.6164	26538.9408	27881.9601	29296.382
Fuel tax 450€/Ton	17839.994	18724.3391	19655.0778	20634.731	21665.9598	22751.5734	23894.5374	25097.9827	26365.215	27699.7245	29105.1964
Fuel tax 475€/Ton	17724.6519	18603.4655	19528.3912	20501.9349	21526.7419	22605.6046	23741.4713	24937.4542	26196.8395	27523.0966	28919.889
Fuel tax 500€/Ton	17612.8001	18486.2465	19405.5317	20373.1472	21391.7227	22464.0347	23593.0142	24781.7555	26033.5257	27351.7744	28740.1436

Table 18. 21. Yearly demand in Billions of RPKs for different values of the fuel tax.

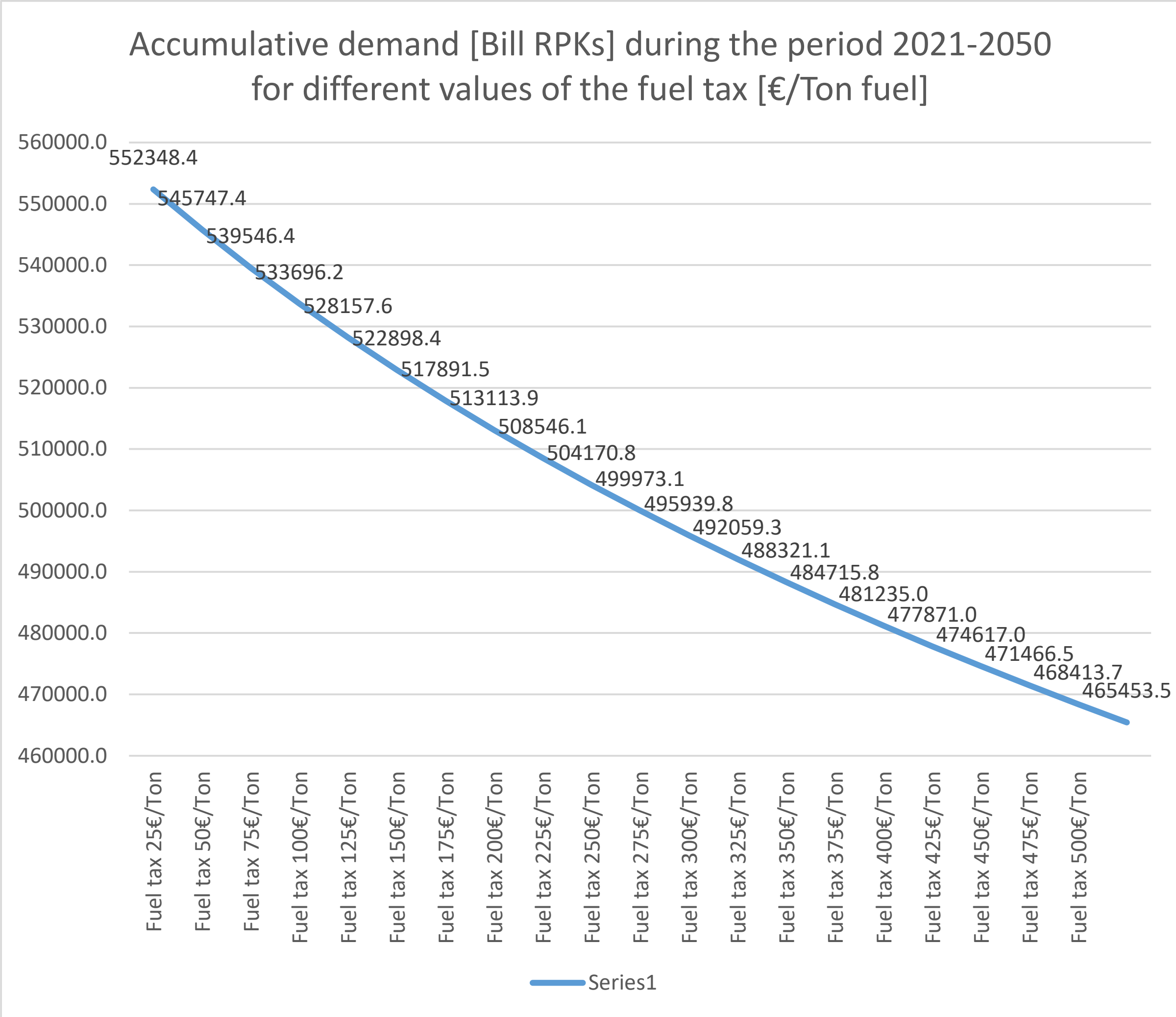
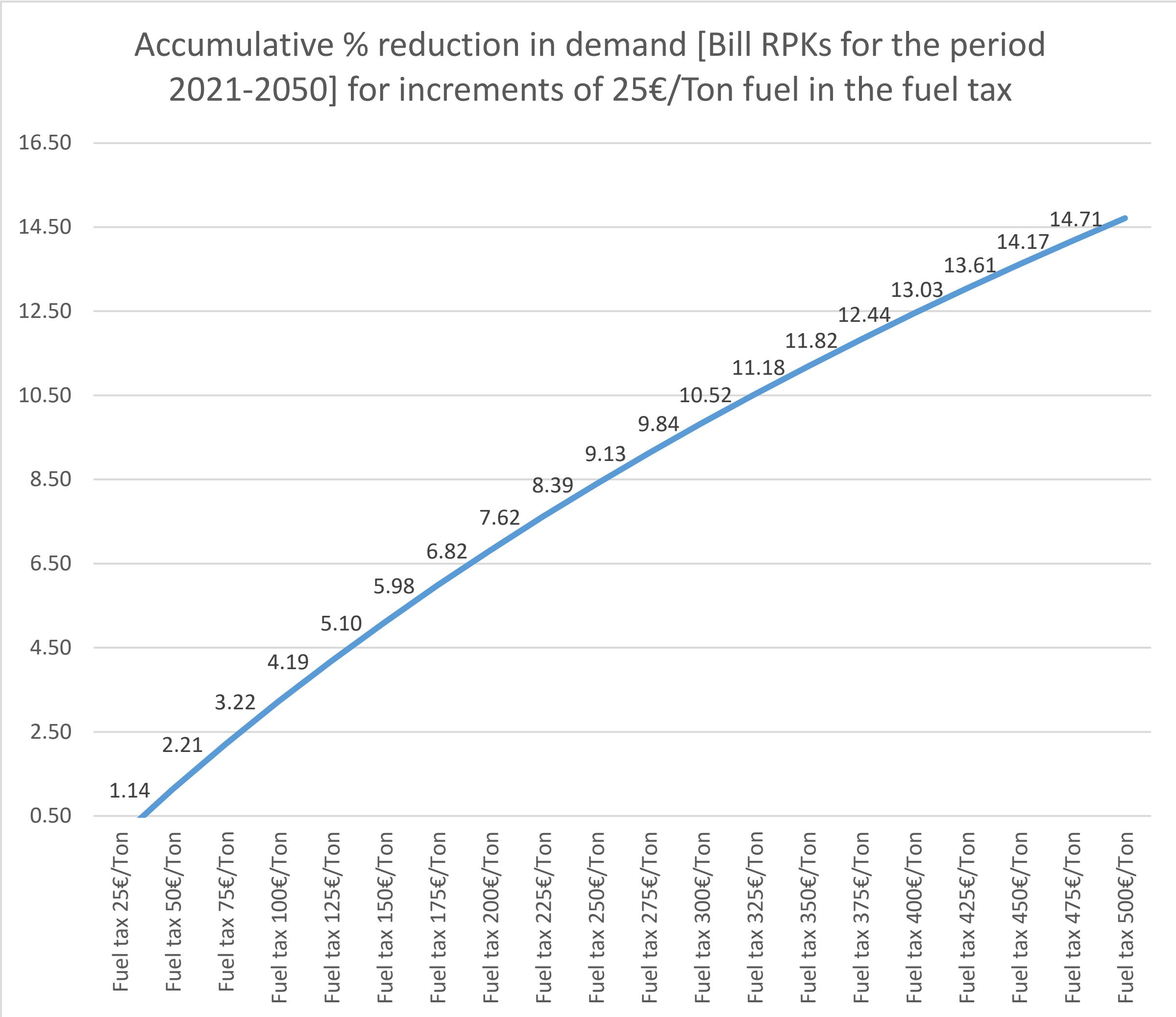


Figure 18. 17. Accumulative demand during the period 2021-2050 in Billions of RPKs for different values of the fuel tax.



Accumulative % reduction in demand [Bill RPKs for the period 2021-2050] for increments of 25€/Ton fuel in the fuel tax
16.50
14.50
12.50
10.50
8.50
6.50
4.50
2.50
0.50
1.14
2.21
3.22
4.19
5.10
5.98
6.82
7.62
8.39
9.13
9.84
10.52
11.18
11.82
12.44
13.03
13.61
14.17
14.71
Fuel tax 25€/Ton
Fuel tax 50€/Ton
Fuel tax 75€/Ton
Fuel tax 100€/Ton
Fuel tax 125€/Ton
Fuel tax 150€/Ton
Fuel tax 175€/Ton
Fuel tax 200€/Ton
Fuel tax 225€/Ton
Fuel tax 250€/Ton
Fuel tax 275€/Ton
Fuel tax 300€/Ton
Fuel tax 325€/Ton
Fuel tax 350€/Ton
Fuel tax 375€/Ton
Fuel tax 400€/Ton
Fuel tax 425€/Ton
Fuel tax 450€/Ton
Fuel tax 475€/Ton
Fuel tax 500€/Ton

Figure 18. 18. Fuel tax marginal curve: accumulative % reduction in demand for the period 2021-2050 expressed in Billions of RPKs for increments of 25€/Ton in the fuel tax.

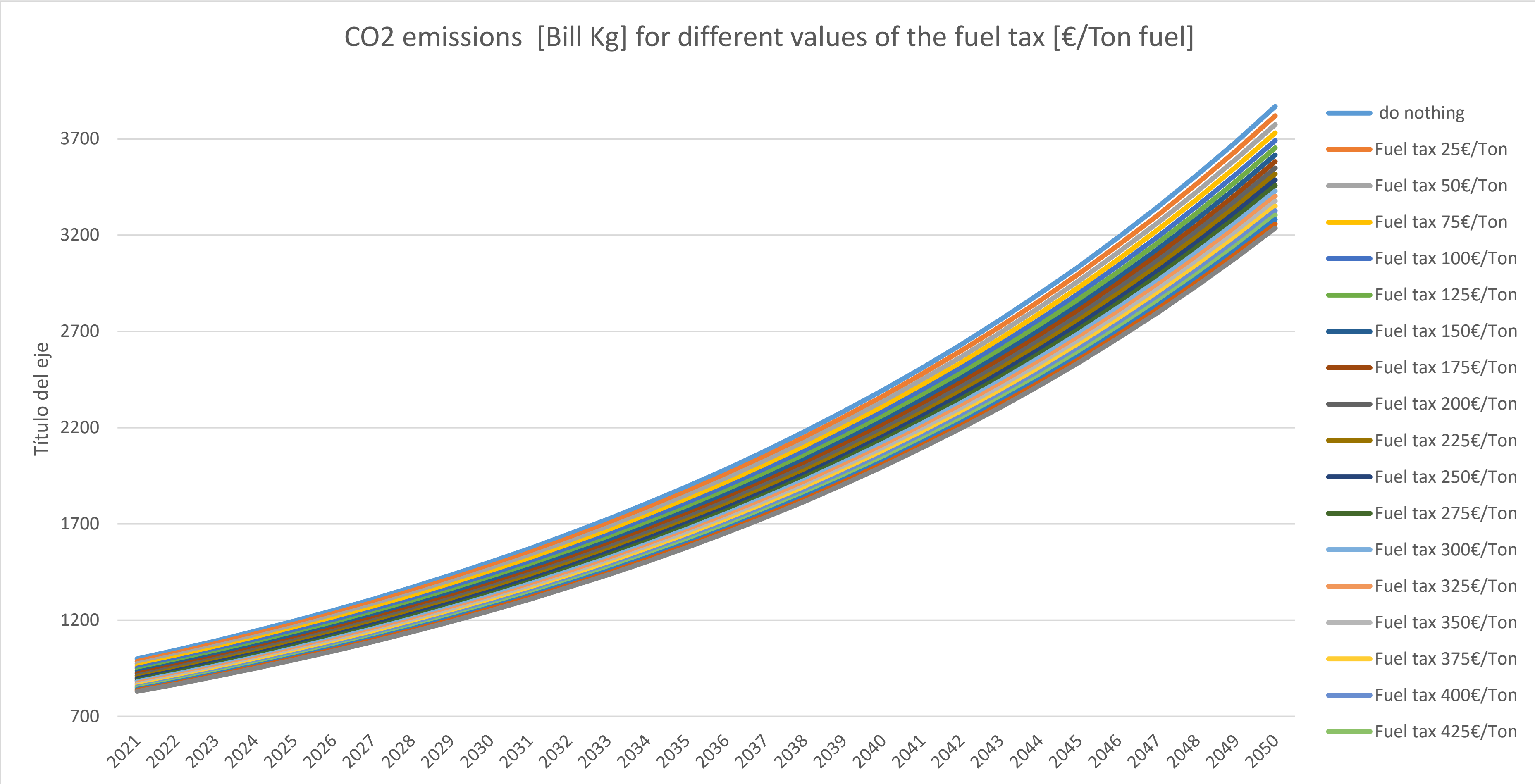


Figure 18. 19. Yearly Fuel consumption in Billions of Kg for different values of the fuel tax.

	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
do nothing	857.357355	896.739876	938.053373	998.556812	1044.2099	1092.1194	1142.40243	1195.18244	1250.5895	1308.76072	1369.84059
Fuel tax 25€/Ton	857.357355	896.739876	938.053373	985.400706	1030.47387	1077.77612	1127.42323	1179.5372	1234.2466	1291.68694	1352.00106
Fuel tax 50€/Ton	857.357355	896.739876	938.053373	973.09385	1017.62333	1064.35623	1113.40703	1164.89639	1218.95146	1275.70626	1335.30203
Fuel tax 75€/Ton	857.357355	896.739876	938.053373	961.526625	1005.54412	1051.7408	1100.22996	1151.13097	1204.56964	1260.67857	1319.59752
Fuel tax 100€/Ton	857.36	896.74	938.05	950.61	994.15	1039.84	1087.79	1138.14	1190.99	1246.49	1304.77
Fuel tax 125€/Ton	857.357355	896.739876	938.053373	940.278493	983.353214	1028.56242	1076.01715	1125.83442	1178.13755	1233.05653	1290.72838
Fuel tax 150€/Ton	857.357355	896.739876	938.053373	930.467579	973.106063	1017.8583	1064.83429	1114.14995	1165.92745	1220.29556	1277.39001
Fuel tax 175€/Ton	857.357355	896.739876	938.053373	921.1294	963.352154	1007.66888	1054.18859	1103.02614	1154.3026	1208.14559	1264.68961
Fuel tax 200€/Ton	857.357355	896.739876	938.053373	912.221528	954.047262	997.94806	1044.03197	1092.41286	1143.21074	1196.55211	1252.57032
Fuel tax 225€/Ton	857.357355	896.739876	938.053373	903.707366	945.153232	988.656052	1034.32296	1082.26685	1132.60675	1185.46807	1240.98304
Fuel tax 250€/Ton	857.357355	896.739876	938.053373	895.555055	936.63685	979.758223	1025.02543	1072.55045	1122.45133	1174.85247	1229.88501
Fuel tax 275€/Ton	857.357355	896.739876	938.053373	887.736647	928.468971	971.22418	1016.10769	1063.23059	1112.70999	1164.66932	1219.23867
Fuel tax 300€/Ton	857.357355	896.739876	938.053373	880.22745	920.623846	963.02707	1007.54172	1054.27805	1103.35225	1154.8868	1209.01082
Fuel tax 325€/Ton	857.357355	896.739876	938.053373	873.005518	913.078588	955.143018	999.302629	1045.66684	1094.35099	1145.47663	1199.17194
Fuel tax 350€/Ton	857.357355	896.739876	938.053373	866.05124	905.81274	947.550686	991.368143	1037.37374	1085.68197	1136.41352	1189.69562
Fuel tax 375€/Ton	857.357355	896.739876	938.053373	859.347002	898.807931	940.230907	983.718267	1029.37787	1077.32341	1127.67472	1180.55813
Fuel tax 400€/Ton	857.357355	896.739876	938.053373	852.876916	892.047584	933.166388	976.33496	1021.66042	1069.25567	1119.23974	1171.73807
Fuel tax 425€/Ton	857.357355	896.739876	938.053373	846.626593	885.51669	926.341467	969.201875	1014.20431	1061.46094	1111.08997	1163.21603
Fuel tax 450€/Ton	857.357355	896.739876	938.053373	840.582952	879.2016	919.741902	962.304151	1006.99405	1053.92303	1103.20853	1154.97436
Fuel tax 475€/Ton	857.357355	896.739876	938.053373	834.734062	873.089864	913.354703	955.628231	1000.01548	1046.62716	1095.57998	1146.99696
Fuel tax 500€/Ton	857.357355	896.739876	938.053373	829.069005	867.170093	907.167983	949.161706	993.255643	1039.55982	1088.19021	1139.26908

	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039
do nothing	1433.98143	1501.34377	1572.09688	1646.41917	1724.49877	1806.53401	1892.73404	1983.31938	2078.52259	2178.58893	2283.77705
Fuel tax 25€/Ton	1415.3395	1481.86096	1551.73274	1625.13121	1702.24234	1783.26218	1868.39749	1957.86627	2051.89843	2150.73641	2254.63593
Fuel tax 50€/Ton	1397.88768	1463.62016	1532.66493	1605.19643	1681.3986	1761.46534	1845.60115	1934.02166	2026.95427	2124.63879	2227.32817
Fuel tax 75€/Ton	1381.47383	1446.4628	1514.72816	1586.44252	1661.78789	1740.95615	1824.14966	1911.5818	2003.47761	2100.07441	2201.6225
Fuel tax 100€/Ton	1365.98	1430.26	1497.79	1568.73	1643.27	1721.59	1803.89	1890.38	1981.30	2076.87	2177.33
Fuel tax 125€/Ton	1351.29752	1414.9162	1481.74495	1551.95298	1625.71875	1703.23039	1784.6863	1870.29571	1960.27926	2054.86965	2154.31233
Fuel tax 150€/Ton	1337.35389	1400.33804	1466.50147	1536.01184	1609.04593	1685.79015	1766.44106	1851.20594	1940.30339	2033.96399	2132.43089
Fuel tax 175€/Ton	1324.07647	1386.45564	1451.98471	1520.82985	1593.16625	1669.17865	1749.06185	1833.02129	1921.27362	2014.04736	2111.58352
Fuel tax 200€/Ton	1311.40593	1373.20712	1438.13012	1506.33965	1578.00939	1653.32249	1732.47206	1815.66178	1903.10643	1995.03257	2091.67912
Fuel tax 225€/Ton	1299.29105	1360.53903	1424.8819	1492.48301	1563.51459	1638.15824	1716.60547	1799.05826	1885.72962	1976.84419	2072.63893
Fuel tax 250€/Ton	1287.68721	1348.40481	1412.19147	1479.20922	1549.62888	1623.6306	1701.40434	1783.15044	1869.08019	1959.41643	2054.39422
Fuel tax 275€/Ton	1276.55521	1336.76354	1400.01612	1466.47368	1536.30573	1609.69098	1686.81791	1767.88531	1853.10279	1942.69147	2036.88456
Fuel tax 300€/Ton	1265.86041	1325.57907	1388.3181	1454.237	1523.50397	1596.2964	1672.80131	1753.21598	1837.74844	1926.61812	2020.05648
Fuel tax 325€/Ton	1255.57199	1314.81923	1377.06381	1442.46408	1511.18699	1583.4086	1659.31457	1739.1007	1822.97351	1911.15082	2003.86236
Fuel tax 350€/Ton	1245.66239	1304.45522	1366.22322	1431.12356	1499.32201	1570.99336	1646.32193	1725.50214	1808.739	1896.24877	1988.25955
Fuel tax 375€/Ton	1236.10683	1294.4612	1355.76931	1420.18724	1487.87958	1559.01991	1633.79126	1712.38668	1795.00978	1881.87529	1973.20973
Fuel tax 400€/Ton	1226.88295	1284.81382	1345.67771	1409.62965	1476.8331	1547.46046	1621.69352	1699.72401	1781.75416	1867.99725	1958.67826
Fuel tax 425€/Ton	1217.97051	1275.49192	1335.92632	1399.42771	1466.15846	1536.28982	1610.00239	1687.48662	1768.94339	1854.58459	1944.63372
Fuel tax 450€/Ton	1209.35107	1266.47626	1326.49505	1389.56042	1455.83372	1525.48507	1598.69391	1675.64946	1756.55132	1841.60998	1931.04751
Fuel tax 475€/Ton	1201.00781	1257.74927	1317.36553	1380.00862	1445.83886	1515.0253	1587.74623	1664.1897	1744.55404	1829.04843	1917.89353
Fuel tax 500€/Ton	1192.92534	1249.29488	1308.52099	1370.75477	1436.15554	1504.89133	1577.13932	1653.0864	1732.92968	1816.87707	1905.14787

	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
do nothing	2394.35976	2510.62482	2632.87574	2761.43269	2896.63345	3038.83432	3188.41126	3345.76089	3511.30173	3685.47536	3868.74775
Fuel tax 25€/Ton	2363.8667	2478.71319	2599.47548	2726.47012	2860.03103	3000.51052	3148.28028	3303.73245	3467.28084	3639.36206	3820.43684
Fuel tax 50€/Ton	2335.28917	2448.8032	2568.16708	2693.69394	2825.7141	2964.57606	3110.6475	3264.31636	3425.99198	3596.10628	3775.11506
Fuel tax 75€/Ton	2308.3859	2420.64308	2538.6878	2662.82994	2793.39641	2930.73213	3075.20097	3227.18688	3387.09499	3555.35278	3732.41137
Fuel tax 100€/Ton	2282.96	2394.03	2510.83	2633.66	2762.85	2898.74	3041.69	3192.08	3350.32	3516.82	3692.03
Fuel tax 125€/Ton	2258.86618	2368.80426	2484.41466	2606.00124	2733.8846	2868.40299	3009.91325	3158.79195	3315.43639	3480.26584	3653.72273
Fuel tax 150€/Ton	2235.96061	2344.82371	2459.30559	2579.70735	2706.34665	2839.55862	2979.69686	3127.13447	3282.26513	3445.50429	3617.29033
Fuel tax 175€/Ton	2214.13631	2321.9739	2435.37917	2554.65055	2680.10288	2812.06833	2950.89738	3096.95984	3250.64592	3412.36739	3582.5588
Fuel tax 200€/Ton	2193.29814	2300.15547	2412.53158	2530.72235	2655.03993	2785.81364	2923.39099	3068.13861	3220.4434	3380.71363	3549.38015
Fuel tax 225€/Ton	2173.36379	2279.28244	2390.67299	2507.82888	2631.05968	2760.692	2897.07046	3040.55868	3191.54037	3350.42044	3517.62619
Fuel tax 250€/Ton	2154.26149	2259.27977	2369.72498	2485.88819	2608.07648	2736.61385	2871.84217	3014.12216	3163.83446	3321.38074	3487.18491
Fuel tax 275€/Ton	2135.92807	2240.0815	2349.6186	2464.82818	2586.01496	2713.5004	2847.62373	2988.74287	3137.23552	3293.50024	3457.95767
Fuel tax 300€/Ton	2118.30766	2221.62919	2330.29277	2444.58503	2564.80837	2691.28185	2824.34214	2964.34447	3111.6637	3266.69541	3429.85706
Fuel tax 325€/Ton	2101.35048	2203.87083	2311.69312	2425.10186	2544.39726	2669.89603	2801.93238	2940.85894	3087.04784	3240.89177	3402.80516
Fuel tax 350€/Ton	2085.01197	2186.75984	2293.77094	2406.32776	2524.72837	2649.28723	2780.33616	2918.22531	3063.32415	3216.0226	3376.73213
Fuel tax 375€/Ton	2069.25205	2170.25431	2276.48241	2388.2169	2505.75377	2629.40532	2759.50107	2896.38873	3040.43524	3192.02781	3351.57509
Fuel tax 400€/Ton	2054.03452	2154.31637	2259.78795	2370.72788	2487.43017	2610.20501	2739.37969	2875.2996	3018.3292	3168.8531	3327.2772
Fuel tax 425€/Ton	2039.32651	2138.91169	2243.65163	2353.82313	2469.71827	2591.64518	2719.92903	2854.91292	2996.95893	3146.44915	3303.78683
Fuel tax 450€/Ton	2025.09815	2124.009	2228.04076	2337.46846	2452.58227	2573.6884	2701.1099	2835.18769	2976.28152	3124.77107	3281.05699
Fuel tax 475€/Ton	2011.32212	2109.57975	2212.92547	2321.6326	2435.98951	2556.30047	2682.88652	2816.08645	2956.25778	3103.77781	3259.04469
Fuel tax 500€/Ton	1997.97342	2095.59777	2198.2784	2306.28696	2419.91003	2539.45004	2665.22609	2797.57489	2936.85177	3083.43175	3237.71056

Table 18. 22. Yearly Fuel consumption in Billions of Kg for different values of the fuel tax.

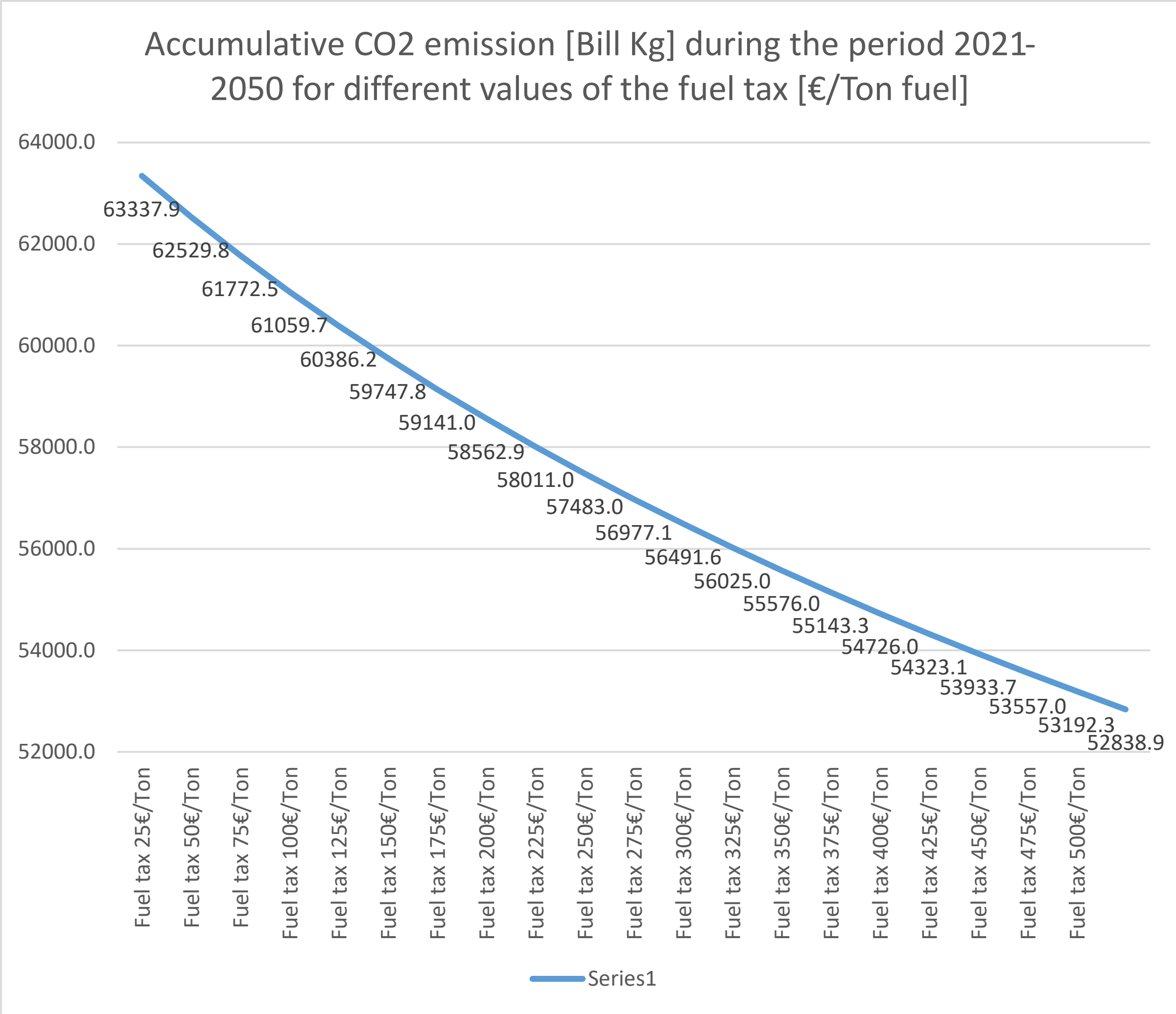
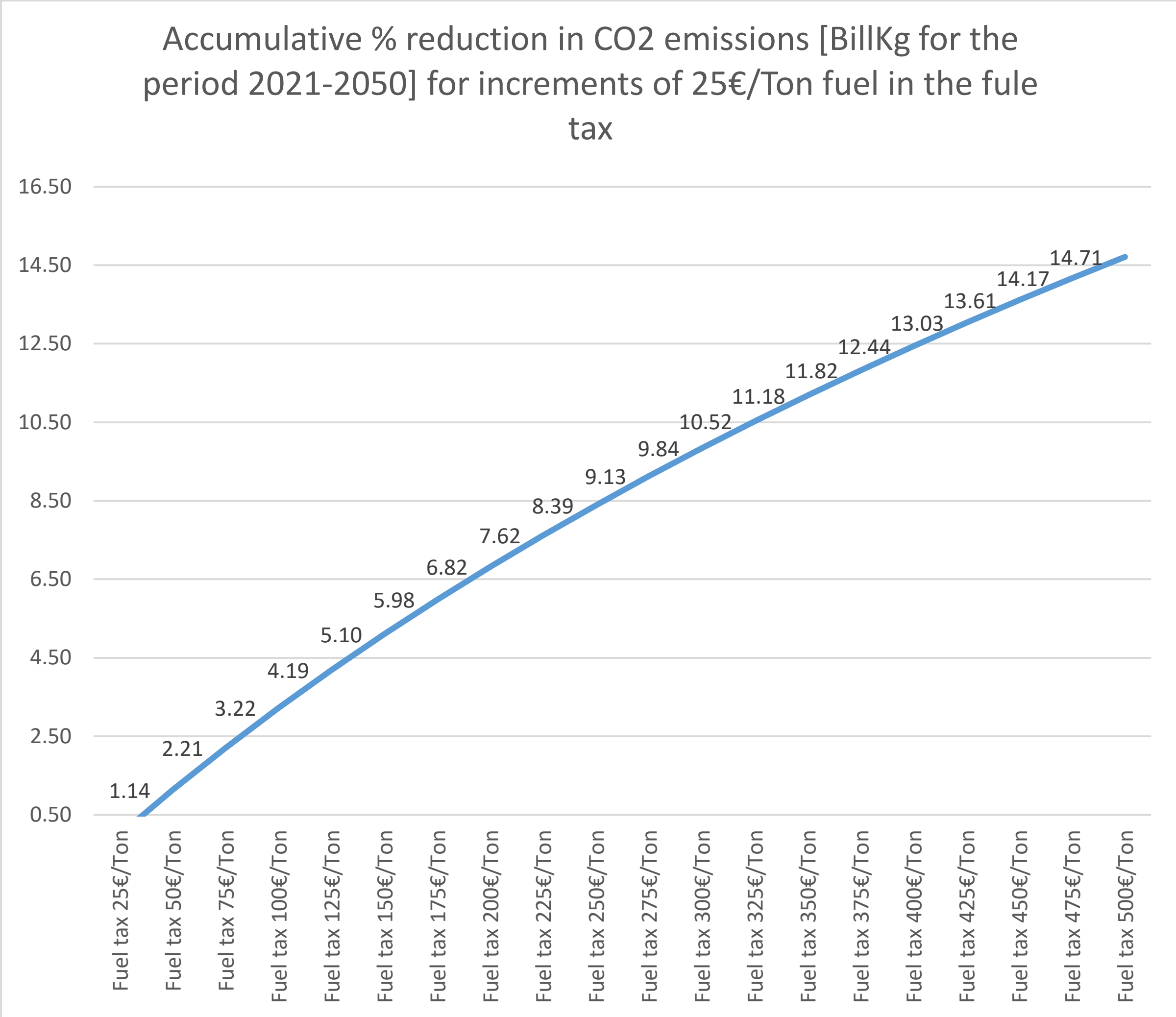


Figure 18. 20. Accumulative fuel consumption during the period 2021-2050 in Billions of Kg for different values of the fuel tax.



Accumulative % reduction in CO2 emissions [BillKg for the period 2021-2050] for increments of 25€/Ton fuel in the fule tax
16.50
14.50
12.50
10.50
8.50
6.50
4.50
2.50
0.50
1.14
2.21
3.22
4.19
5.10
5.98
6.82
7.62
8.39
9.13
9.84
10.52
11.18
11.82
12.44
13.03
13.61
14.17
14.71
Fuel tax 25€/Ton
Fuel tax 50€/Ton
Fuel tax 75€/Ton
Fuel tax 100€/Ton
Fuel tax 125€/Ton
Fuel tax 150€/Ton
Fuel tax 175€/Ton
Fuel tax 200€/Ton
Fuel tax 225€/Ton
Fuel tax 250€/Ton
Fuel tax 275€/Ton
Fuel tax 300€/Ton
Fuel tax 325€/Ton
Fuel tax 350€/Ton
Fuel tax 375€/Ton
Fuel tax 400€/Ton
Fuel tax 425€/Ton
Fuel tax 450€/Ton
Fuel tax 475€/Ton
Fuel tax 500€/Ton

Figure 18. 21. Fuel tax marginal curve: accumulative % reduction in fuel consumption for the period 2021-2050 expressed in Billions of Kg for increments of 25€/Ton in the fuel

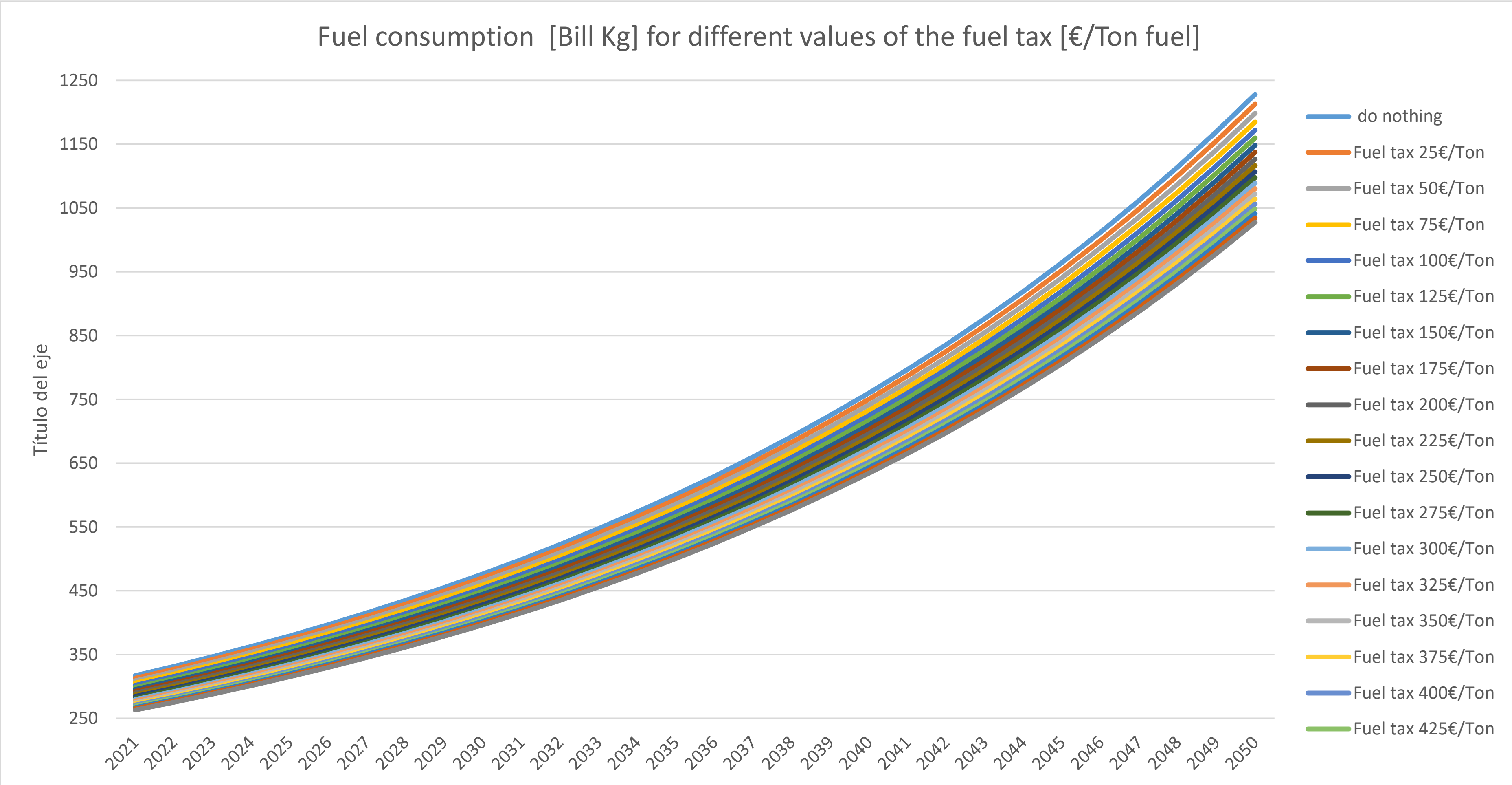


Figure 18. 22. Yearly CO2 emissions consumption in Billions of Kg for different values of the fuel tax.

	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
do nothing	272.176938	284.679326	297.794721	317.002163	331.495208	346.704571	362.667438	379.422996	397.01254	415.479594	434.87003
Fuel tax 25€/Ton	272.176938	284.679326	297.794721	312.825621	327.134562	342.15115	357.912136	374.456253	391.824317	410.059347	429.206686
Fuel tax 50€/Ton	272.176938	284.679326	297.794721	308.918683	323.055026	337.890866	353.462549	369.808377	386.968717	404.986113	423.905407
Fuel tax 75€/Ton	272.176938	284.679326	297.794721	305.246548	319.220355	333.885969	349.279353	365.438403	382.403059	400.215418	418.919849
Fuel tax 100€/Ton	272.176938	284.679326	297.794721	301.78154	315.601719	330.106425	345.331256	361.313724	378.093365	395.71185	414.213099
Fuel tax 125€/Ton	272.176938	284.679326	297.794721	298.501109	312.175623	326.527753	341.592747	357.407752	374.011921	391.446519	409.755041
Fuel tax 150€/Ton	272.176938	284.679326	297.794721	295.386533	308.92256	323.12962	338.042633	353.698397	370.135698	387.395416	405.520639
Fuel tax 175€/Ton	272.176938	284.679326	297.794721	292.422032	305.826081	319.894884	334.663044	350.167028	366.44527	383.538282	401.488766
Fuel tax 200€/Ton	272.176938	284.679326	297.794721	289.594136	302.872147	316.808908	331.43872	346.797732	362.924044	379.857814	397.641372
Fuel tax 225€/Ton	272.176938	284.679326	297.794721	286.891227	300.048645	313.859064	328.356494	343.576779	359.557697	376.33907	393.962871
Fuel tax 250€/Ton	272.176938	284.679326	297.794721	284.303192	297.345032	311.034356	325.404898	340.492208	356.333756	372.969037	390.439686
Fuel tax 275€/Ton	272.176938	284.679326	297.794721	281.821158	294.752054	308.325137	322.573869	337.533522	353.241268	369.73629	387.059895
Fuel tax 300€/Ton	272.176938	284.679326	297.794721	279.437286	292.261539	305.722879	319.854515	334.691444	350.270555	366.630731	383.812958
Fuel tax 325€/Ton	272.176938	284.679326	297.794721	277.144609	289.866219	303.220006	317.23893	331.957727	347.413012	363.643376	380.689504
Fuel tax 350€/Ton	272.176938	284.679326	297.794721	274.936902	287.5596	300.809742	314.720045	329.324996	344.660942	360.766196	377.681148
Fuel tax 375€/Ton	272.176938	284.679326	297.794721	272.808572	285.335851	298.486002	312.291513	326.786626	342.007432	357.991975	374.78036
Fuel tax 400€/Ton	272.176938	284.679326	297.794721	270.754577	283.189709	296.243298	309.947606	324.336641	339.446245	355.314202	371.980341
Fuel tax 425€/Ton	272.176938	284.679326	297.794721	268.770347	281.11641	294.076656	307.683135	321.969624	336.971727	352.726975	369.274931
Fuel tax 450€/Ton	272.176938	284.679326	297.794721	266.851731	279.111619	291.981556	305.493381	319.680652	334.578739	350.224929	366.658528
Fuel tax 475€/Ton	272.176938	284.679326	297.794721	264.99494	277.171386	289.953874	303.374041	317.465231	332.26259	347.803167	364.126019
Fuel tax 500€/Ton	272.176938	284.679326	297.794721	263.19651	275.292093	287.989836	301.321177	315.319252	330.01899	345.457209	361.672725

	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039
do nothing	455.232199	476.617071	499.078374	522.672753	547.459926	573.50286	600.867948	629.625199	659.84844	691.615532	725.008587
Fuel tax 25€/Ton	449.314127	470.432051	492.613568	515.91467	540.394393	566.114979	593.142061	621.544849	651.396326	682.773463	715.757439
Fuel tax 50€/Ton	443.773867	464.641321	486.560295	509.58617	533.777332	559.195346	585.905127	613.97513	643.477545	674.488505	707.088307
Fuel tax 75€/Ton	438.563122	459.194541	480.866083	503.632547	527.55171	552.684491	579.09513	606.851366	636.024639	666.690289	698.927779
Fuel tax 100€/Ton	433.643413	454.051597	475.489107	498.010191	521.672046	546.534981	572.662592	600.121943	628.983757	659.322627	691.217221
Fuel tax 125€/Ton	428.983339	449.179746	470.395221	492.683487	516.101191	540.708061	566.567081	593.74467	622.310876	652.339572	683.908676
Fuel tax 150€/Ton	424.556792	444.551758	465.556021	487.622806	510.808233	535.171477	560.774939	587.684424	615.969331	645.702853	676.962188
Fuel tax 175€/Ton	420.341736	440.144646	460.947527	482.803128	505.767064	529.897984	555.25773	581.91152	609.928135	639.380115	670.343974
Fuel tax 200€/Ton	416.319342	435.938767	456.549243	478.203063	500.955362	524.864282	549.991131	576.400565	604.160773	633.343672	664.025118
Fuel tax 225€/Ton	412.473349	431.917152	452.343462	473.804132	496.353838	520.050234	544.954118	571.129607	598.644323	627.569583	657.980613
Fuel tax 250€/Ton	408.789589	428.065018	448.314753	469.590228	491.945676	515.438285	540.128361	566.079504	593.35879	622.036962	652.188641
Fuel tax 275€/Ton	405.255622	424.369379	444.449562	465.547201	487.716104	511.013009	535.49775	561.233431	588.2866	616.727451	646.63002
Fuel tax 300€/Ton	401.860448	420.818754	440.735904	461.662538	483.652055	506.760761	531.048035	556.5765	583.412202	611.624801	641.287772
Fuel tax 325€/Ton	398.594283	417.402929	437.163115	457.925105	479.741902	502.669396	526.76653	552.095461	578.721751	606.714545	636.14678
Fuel tax 350€/Ton	395.448376	414.112769	433.721657	454.324941	475.975242	498.728051	522.641884	547.778456	574.202856	601.983735	631.193509
Fuel tax 375€/Ton	392.414865	410.940065	430.402956	450.853092	472.342724	494.926955	518.663893	543.614821	569.844374	597.420727	626.415789
Fuel tax 400€/Ton	389.486652	407.877404	427.199274	447.501475	468.835905	491.257288	514.823339	539.594925	565.636241	593.014999	621.802622
Fuel tax 425€/Ton	386.657305	404.918071	424.103595	444.262764	465.447129	487.711054	511.111869	535.710037	561.569331	588.757014	617.344037
Fuel tax 450€/Ton	383.920974	402.055956	421.109539	441.130292	462.169434	484.280975	507.521877	531.952211	557.635338	584.638089	613.030956
Fuel tax 475€/Ton	381.27232	399.285483	418.21128	438.097976	458.996462	480.960411	504.046423	528.314192	553.826679	580.650295	608.85509
Fuel tax 500€/Ton	378.706456	396.601548	415.403488	435.160244	455.922394	477.743278	500.679149	524.789334	550.136408	576.786372	604.808847

	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
do nothing	760.114211	797.023752	835.833567	876.645299	919.566173	964.709309	1012.19405	1062.14632	1114.69896	1169.99218	1228.17389
Fuel tax 25€/Ton	750.433873	786.893077	825.230312	865.546069	907.946359	952.543023	999.454056	1048.80395	1100.72408	1155.35303	1212.83709
Fuel tax 50€/Ton	741.361642	777.397842	815.291137	855.140933	897.052095	941.135256	987.507142	1036.29091	1087.6165	1141.62104	1198.44923
Fuel tax 75€/Ton	732.820921	768.458121	805.932634	845.342837	886.792513	930.391152	976.254276	1024.50377	1075.26825	1128.68342	1184.8925
Fuel tax 100€/Ton	724.750519	760.010047	797.088135	836.082182	877.094944	920.234828	965.616212	1013.35978	1063.59287	1116.44986	1172.07255
Fuel tax 125€/Ton	717.100373	752.001354	788.703066	827.301981	867.899874	910.604123	955.528017	1002.7911	1052.51949	1104.8463	1159.91198
Fuel tax 150€/Ton	709.828766	744.388478	780.731932	818.954715	859.157667	901.447181	945.935512	992.741102	1041.98893	1093.81088	1148.34614
Fuel tax 175€/Ton	702.900416	737.134572	773.136245	811.000175	850.826311	892.720106	936.79282	983.161854	1031.95108	1083.29123	1137.32025
Fuel tax 200€/Ton	696.285122	730.208085	765.883043	803.403922	842.869819	884.385284	928.060631	974.012256	1022.36298	1073.24242	1126.78735
Fuel tax 225€/Ton	689.95676	723.581726	758.943807	796.136154	835.257042	876.41016	919.704908	965.256724	1013.18742	1063.62554	1116.70673
Fuel tax 250€/Ton	683.892535	717.231674	752.293646	789.170854	827.960787	868.766303	911.695928	956.864177	1004.39189	1054.40658	1107.04283
Fuel tax 275€/Ton	678.072404	711.136983	745.910666	782.485138	820.957129	861.428699	904.007533	948.80726	995.947783	1045.55563	1097.76434
Fuel tax 300€/Ton	672.478622	705.279109	739.775484	776.05874	814.224879	854.375192	896.616554	941.061738	987.829747	1037.04616	1088.84351
Fuel tax 325€/Ton	667.09539	699.641535	733.870832	769.873608	807.745161	847.586041	889.502342	933.606012	980.015187	1028.85453	1080.25561
Fuel tax 350€/Ton	661.908562	694.209473	728.18125	763.913576	801.501069	841.043564	882.646401	926.420734	972.483858	1020.95955	1071.97845
Fuel tax 375€/Ton	656.905414	688.969622	722.692829	758.164097	795.477389	834.731848	876.032085	919.488486	965.217537	1013.34216	1063.99209
Fuel tax 400€/Ton	652.074449	683.90996	717.392999	752.612026	789.660372	828.63651	869.644347	912.793525	958.199746	1005.98511	1056.27848
Fuel tax 425€/Ton	647.405242	679.019585	712.270358	747.245439	784.037544	822.744501	863.469532	906.321561	951.415533	998.872746	1048.82122
Fuel tax 450€/Ton	642.888302	674.288572	707.314527	742.053478	778.597547	817.043935	857.495205	900.059583	944.851278	991.990815	1041.60539
Fuel tax 475€/Ton	638.51496	669.707857	702.516023	737.026224	773.330004	811.523957	851.710005	893.995699	938.494535	985.326287	1034.61736
Fuel tax 500€/Ton	634.277275	665.269134	697.86616	732.154589	768.225407	806.174617	846.10352	888.119012	932.333897	978.867221	1027.84462

Table 18. 23. Yearly CO2 emissions consumption in Billions of Kg for different values of the fuel tax.

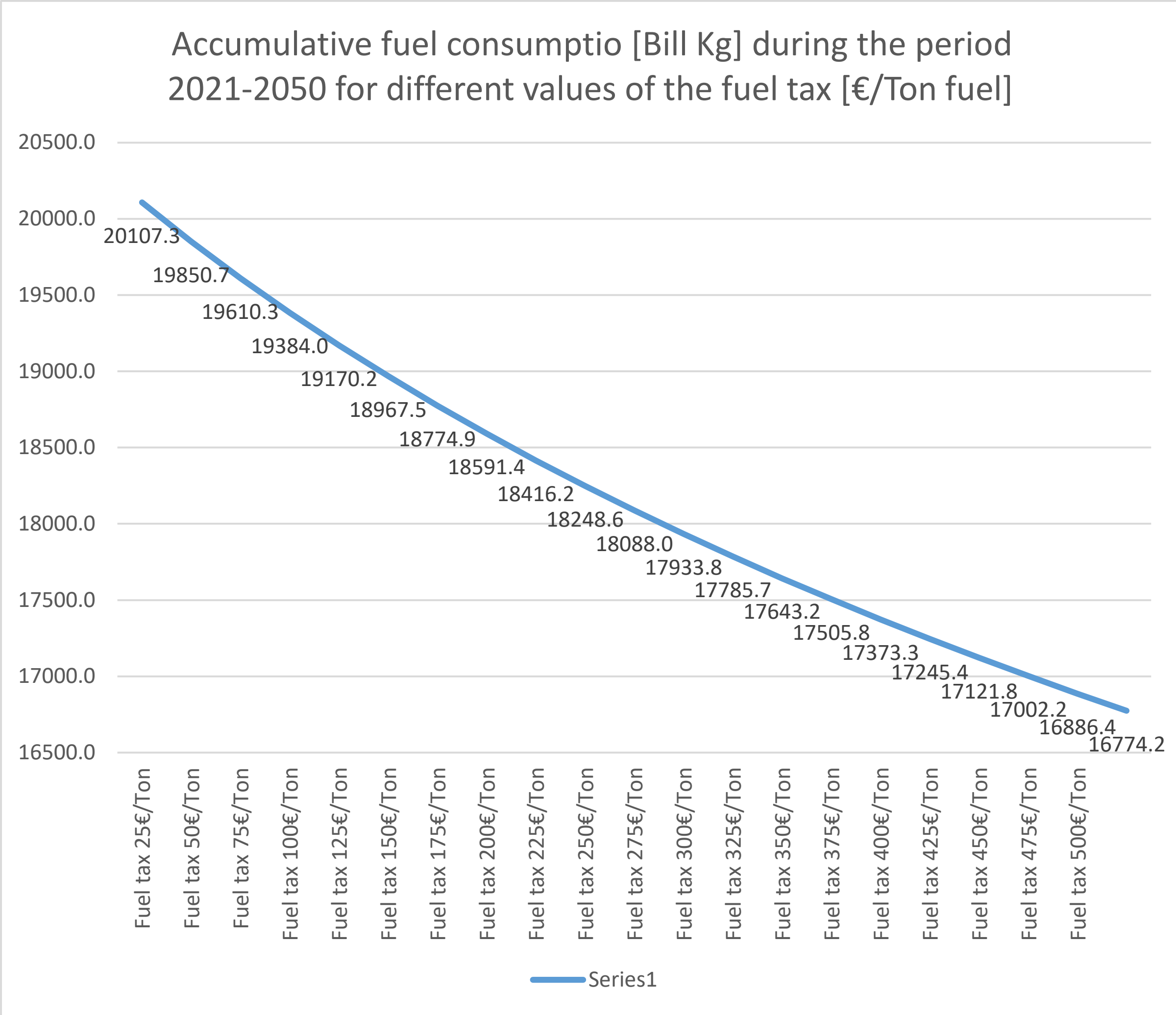


Figure 18. 23. Accumulative CO2 emissions consumption during the period 2021-2050 in Billions of Kg for different values of the fuel tax.

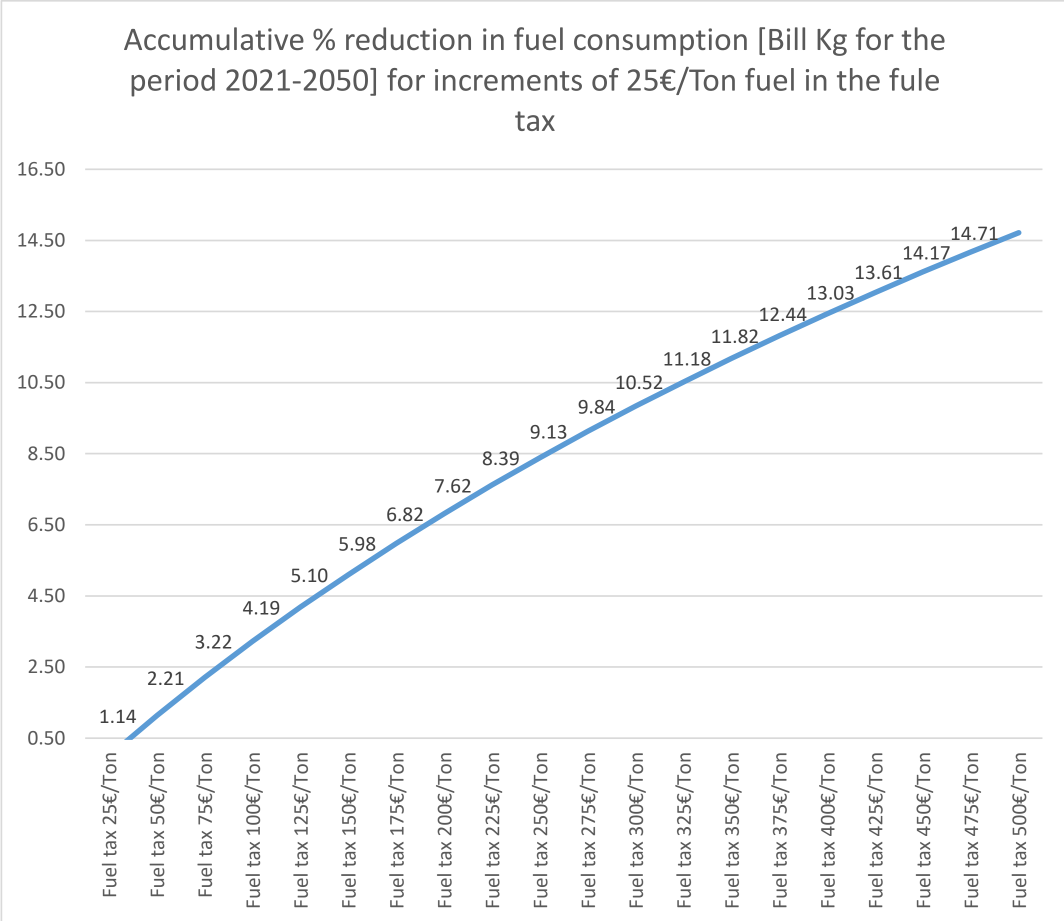


Figure 18. 24. Fuel tax marginal curve: accumulative % reduction in CO2 emissions consumption for the period 2021-2050 expressed in Billions of Kg for increments of 25€/Ton in the fuel

18.8 CO2 emissions and COVID 19[25]

The emergence of COVID-19 was first identified on 30 December 2019 and declared a global pandemic by the World Health Organization on 11 March 2020. Cases rapidly spread, initially mainly in China during January, but quickly expanding to South Korea, Japan, Europe (mainly Italy, France and Spain) and the United States between late January and mid-February, before reaching global proportions by the time the pandemic was declared. Increasingly stringent measures were put in place by world governments in an effort, initially, to isolate cases and stop the transmission of the virus, and later to slow down its rate of spread. The measures imposed were ramped up from the isolation of symptomatic individuals to the ban of mass gatherings, mandatory closure of schools and even mandatory home confinement (Table 18. 24 and Figure 18. 25) the population confinement is leading to drastic changes in energy use, with expected impacts on CO2 emissions.

Government policies during the COVID-19 pandemic have drastically altered patterns of energy demand around the world. Many international borders were closed and populations were confined to their homes, which reduced transport and changed consumption patterns. This chapter compiles government policies and activity data to estimate the decrease in CO_2 emissions during forced confinements.

Daily global CO_2 emissions decreased by –17% (–11 to –25% for ±1σ) by early April 2020 compared with the mean 2019 levels, just under half from changes in surface transport. At their peak, emissions in individual countries decreased by –26% on average. The impact on 2020 annual emissions depends on the duration of the confinement, with a low estimate of –4% (–2 to –7%) if pre-pandemic conditions return by mid-June, and a high estimate of –7% (–3 to –13%) if some restrictions remain worldwide until the end of 2020. Government actions and economic incentives post-crisis will likely influence the global CO_2 emissions path for decades.

Figure 18. 25 shows change in activity by economic sector, including aviation, during confinement level 3 (per cent) [26]. Each data point (filled circles) represents the analysis of a full-time series and shows the changes in activity compared to typical activity levels before COVID-19, corrected for seasonal and weekly biases. The plotted violins represent the kernel density estimate of the probability density function for each sample of data points.

[25] *Coronavirus Airline Schedules Data* (OAG, accessed 7 April 2020); https://www.oag.com/coronavirus-airline-schedules-data

[26] The data includes: for the power sector, temperature-adjusted electricity trends in Europe (https://www.nature.com/articles/s41558-020-0797-x - ref-CR10), India (and the US; for the industry sector, coal use in industry in China and US steel production; for the surface transport sector, city congestion, country mobility, UK (https://www.nature.com/articles/s41558-020-0797-x - ref-CR42) and US state (https://www.nature.com/articles/s41558-020-0797-x - ref-CR43) traffic data; for the residential sector, UK smart meter data (https://www.nature.com/articles/s41558-020-0797-x - ref-CR44); and for aviation, aircraft departures.

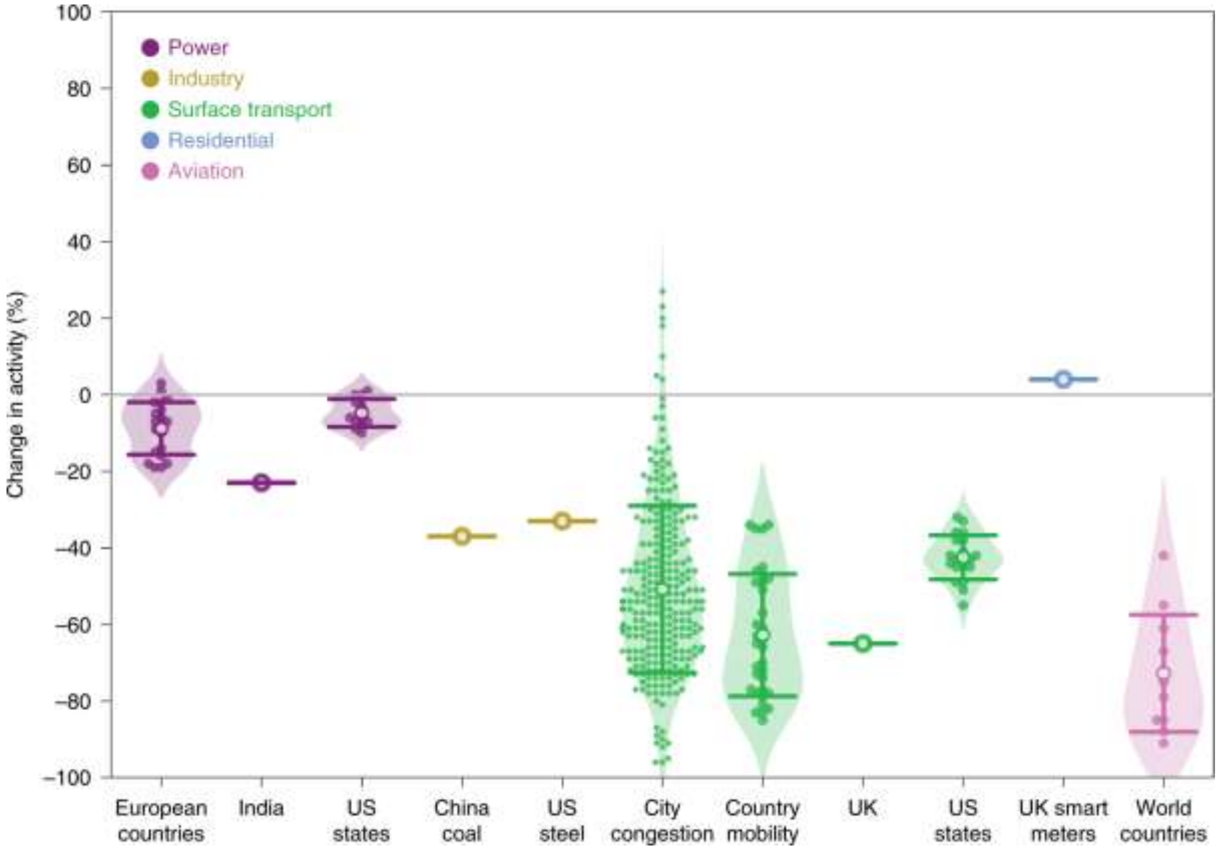


Figure 18. 25. Change in activity by economic sector, including aviation, during confinement level 3 (percent).

Activity data show that the changes in daily activities at the country, state or a provincial level were largest in the aviation sector, with a decrease in the daily activity of –75% (–60 to –90%) during confinement level 3 (Table 18. 24).

	Change in activity as a function of confinement level (equation (1))[a]			Results
	Level 1	Level 2	Level 3	Daily change 7 April 2020
Power	0 (0 to 0)	–5 (0 to –15)	–15 (–5 to –25)	–7.4 (–2.2 to –14)
Industry	–10 (0 to –20)	–15 (0 to –35)	–35 (–25 to –45)	–19 (–10 to –29)
Surface transport	–10 (0 to –20)	–40 (–35 to –45)	–50 (–40 to –65)	–36 (–28 to –46)
Public	–5 (0 to –10)	–22.5 (–5 to –40)	–32.5 (–15 to –50)	–21 (–8.1 to –33)
Residential	0 (0 to 0)	0 (–5 to +5)	+5 (0 to +10)	+2.8 (–1.0 to +6.7)
Aviation	–20 (0 to –50)	–75 (–55 to –95)	–75 (–60 to –90)	–60 (–44 to –76)
Total				–17 (–11 to –25)

Table 18. 24. Changes in daily activities at the country, state or provincial level

CO_2 emissions declined by –60% or –1.7 (–1.3 to –2.2) $MtCO_2\ d^{-1}$ in the aviation sector, which yielded the largest relative anomaly of any sector, and by –21% or –0.9 (–0.3 to –1.4), $MtCO_2\ d^{-1}$ in the public sector. The large relative anomalies in the aviation sector correspond with the disproportionate effect of confinement on air travel (Table 18. 24), although the sector contributed only 10% of the decrease in global CO_2 emissions. Small growth in global emissions occurred in the residential sector, with +2.8% or +0.2 (–0.1 to +0.4) $MtCO_2\ d^{-1}$ and only marginally offsets the decrease in emissions in other sectors.

The aviation sector (2.8%) includes both domestic and international aviation. It is based on the total number of departing flights by aircraft on the ground.

18.8.1 CORSIA and COVID-19

Civil aviation statistics suggest that the growth of basic air traffic doubles every fifteen years, which is much more dynamic than the growth of most other industries. Since 1960, the demand for passenger, luggage, freight, and mail has been steadily increasing. The development of technological progress and related investments are combined and make it possible to multiply the output of the aviation industry by a factor of more than 30. This expansion of air transport is extremely beneficial for the growth of the world economy, primarily for world production (global GDP), when measured in real terms, multiplied more than five times over the same period.

However, a structural analysis of air traffic volumes suggests that the dynamic growth of air traffic is consistently opposed by recession cycles. The aviation industry is an open system that is affected by a wide range of technical, natural, human, and economic threats. For its part, it is a generator of significant threats to the environment. Among the most significant threats to civil aviation in the history of development are the fuel crisis (1973), the Iran-Iraq war (1981), the Gulf War (1991), the Asian crisis (1997-98), and the 9/11 terrorist attack, SARS pandemic (2003), global recession (2008) [93].

The civil aviation industry systematically opposes these negative trends and is itself one of the most effective tools for overcoming them. Figure 18. 26 shows the evolution of global air transport, taking into account external threats and the impact of their negative factors.

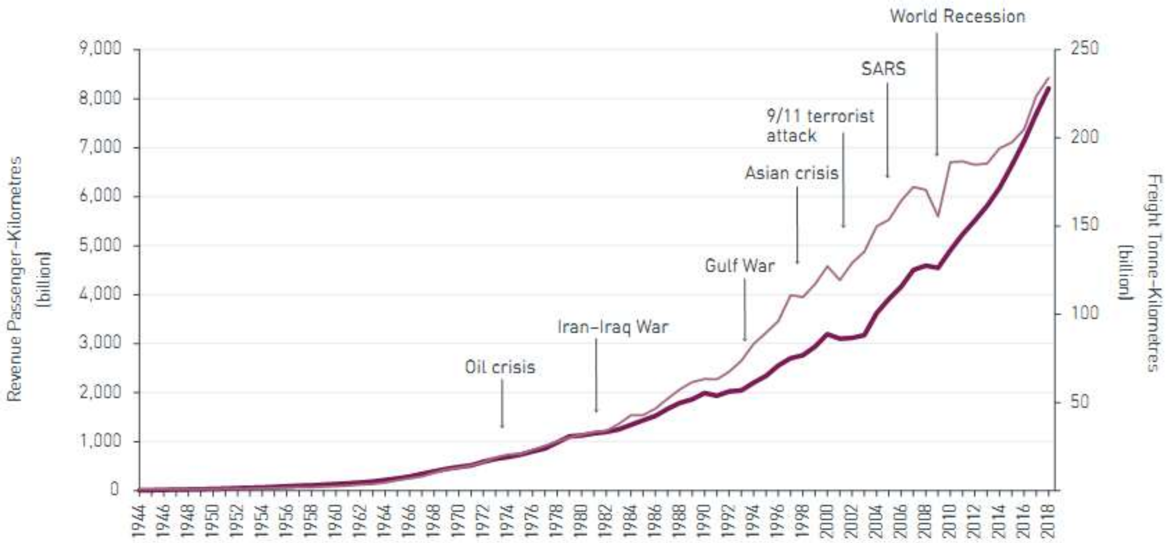


Figure 18. 26. Evolution of the development of world air transportation taking into account the impact of the fuel crisis (1973), the Iran-Iraq war (1981), the Gulf War (1991), the Asian crisis (1997-98), the terrorist attack 9/11 (2001), SARS (2003), the global recession (2008) [93].

In 2019, Airbus Industry specialists prepared an optimistic forecast for further traffic growth, which correlates with ICAO's forecasts and operates with an expected growth of air traffic - 4.3% per year. The results of the Airbus Global Market Forecast (2019 - 2038) are shown in Figure 18. 27 [94].

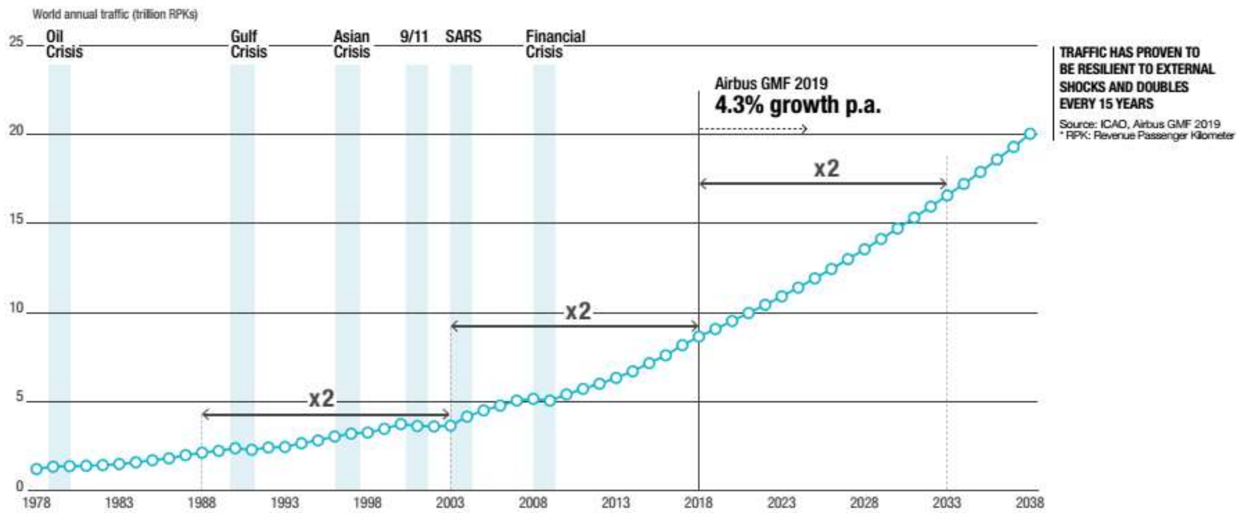


Figure 18. 27. Airbus Global Market Forecast (2019 - 2038) [2].

Until March 2020, these predictions were practically not in doubt among researchers. However, the negative factor of the COVID 19 pandemic, as well as the low level of predictability of the level of its further spread and the effectiveness of the countermeasures, will lead to serious adjustments to the optimistic forecast data.

However, one of the most threatening challenges in the history of aviation is the spread of new deadly coronavirus infection, COVID 19, which effectively leads to a quarantine blockade of entire regions, and a sharp reduction or even ban on air travel. Demand for air travel has declined sharply due to the spread of the coronavirus and flight restrictions in many countries. This creates big problems not only for air carriers but also for aircraft manufacturers and their suppliers.

In response to the Covid-19 pandemic, air traffic has slumped in a manner not seen since the aftermath of the 9/11 attacks on the United States in 2001. Significant reductions in passenger numbers have resulted in planes flying empty between airports and the cancellation of flights. Early March 2020 saw 10% of all flights cancelled, compared to 2019. As the pandemic progressed, 40-60% lower number of flight movements were recorded in late March with international flights affected the most. By April over 80% flight movements were restricted across all geographies, including North America, Europe and Asia and all sectors. Global demand for air travel is down 70% compared to last year and millions of jobs are at risk, according to the IATA, which represents airlines. The world's airlines are even preparing for possible voluntary termination of almost all international and domestic flights due to declining demand. In total, according to preliminary forecasts of the International Air Transport Association (IATA), airlines could lose more than $ 250 billion due to the pandemic. In this case, their revenue will fall by more than 40% in 2020. Sydney consulting company CAPA is even more pessimistic. It predicts that the coronavirus pandemic could lead to the bankruptcy of most airlines around the world if the authorities refuse to agree on steps to avoid such a situation [95].

The COVID-19 pandemic has had a significant impact on the aviation industry due to the resulting travel restrictions as well as a slump in demand among travellers [96].

Understanding planes' impact on the climate is urgent because commercial aviation generates about 2% of global carbon emissions and rising, mainly from burning jet fuel. Taking into account the impact of cloud formation in the upper atmosphere, however, could make the sector's responsibility for human-caused global warming as high as 4% or 5%. "It is welcome that we can have an experiment with the Earth," said Ulrike Burkhardt, of the Institute of Atmospheric Physics at the German Aerospace Centre (DLR) [97]. "But it's not the way we would want to design it. "Researchers will use satellites and measurements by planes to study how clouds form naturally when thousands of flights are grounded and contrast it with data from pre-coronavirus conditions of crowded skies. In the long term, that could help governments set better policies.

"The air traffic system has not been diminished to the current levels since the days following 9/11," said Patrick Minnis of NASA Langley Research Center, who is joining a research effort to study high-altitude clouds [97] . "Flight groundings at the scales initiated in response to the coronavirus pandemic are a significant opportunity to better quantify the impact of air traffic on cloud cover via contrail formation."Minnis and colleagues are trying to determine whether contrails increase the total amount of clouds in the sky, or suck up moisture that might have allowed clouds to form elsewhere. That would help to establish whether contrails and cloudiness linked to aviation had an overall warming or cooling effect on the planet".

Piers Forster, Professor of Physical Climate Change at the University of Leeds, said that the "total historic warming from aviation is roughly twice that from its carbon dioxide emissions alone" [97] . "The total warming effect of aviation is still small: maybe 5% of the warming from all human activity," Forster said, factoring in cloud formation. "But as other emissions will hopefully decline, it is expected that aviation will be the dominant source of emissions within the next few decades…

When assessing the economic impacts on civil aviation, ICAO works with many different scenarios [98] to reflect the very uncertain nature of the current situation and the rapidly changing environment. In order to explore the potential economic implication of the COVID-19 pandemic for the near future (Figure 18. 28), the full report is built around 6 different recovery paths under two indicative scenarios.

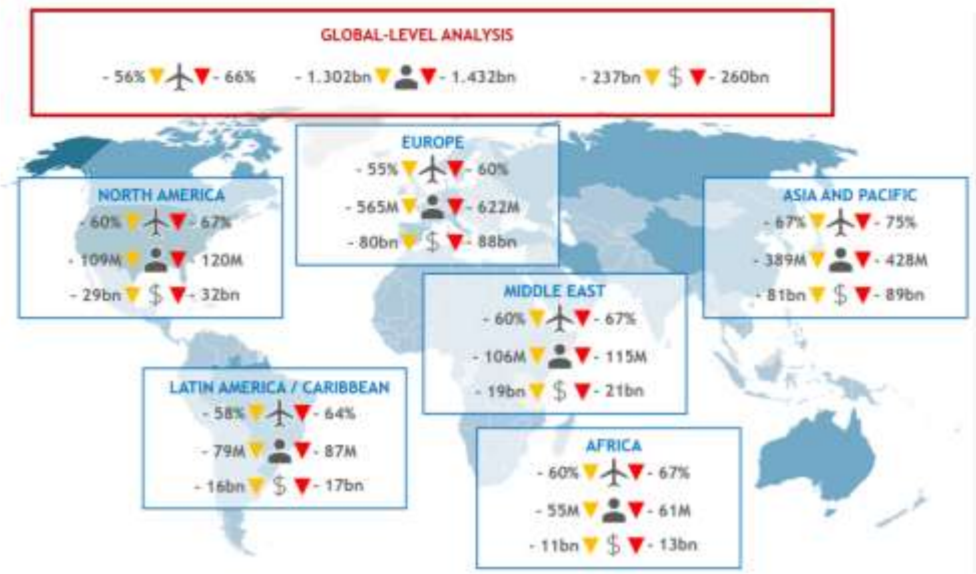


Figure 18. 28. Global-level Analysis [98]

The actual path will eventually depend upon various factors, inter alia, duration and magnitude of the outbreak and containment measures, availability of government assistance, consumers' confidence and economic condition:

1. Baseline: hypothetical situation without COVID-19 outbreak with forecasts as originally planned;
2. Indicative Scenario 1 - "V-Shaped": follows the normal shape for recession where a brief period of contraction is followed by quick/smooth recovery- most optimistic path indicated with a ▼;
3. Indicative Scenario 2 - "U-Shaped": indicates prolonged contraction and muted recovery with a possibility of no return to the trend line of growth (L-shaped)- most pessimistic path indicated with a ▼;

The analytical focus, in the report [98], is on the near-term with monthly profiles from Jan to Dec 2020 and on international traffic only. Scenarios 1 and 2 are not forecasts of what is likely to happen, but merely indicators of possible paths or consequential outcomes out of many. Each scenario considers 3 different paths to take into account differentiated terms of supply (output) and demand (spending).

The latest estimates indicate that the possible COVID-19 impact on scheduled international passenger traffic for the full year 2020, compared to Baseline (counterfactual scenario, in which the COVID-19 pandemic does not occur, so trend line growth from 2019 level, that is, originally-planned or business, as usual, Figure 18. 29, Figure 18. 30), would be:

- *Scenario 1:* V-shaped path (normal shape for a recession, a brief period of contraction followed by quick/smooth recovery the first sign of recovery in late May):
  - Overall reduction ranging from 38% to 55% of seats offered by airlines;
  - Overall reduction of 861 to 1,292 million passengers;
  - Approx. USD 151 to 228 billion potential loss of gross operating revenues of airlines.
- *Scenario 2:* U-shaped path (prolonged contraction and muted recovery, the possibility of not to return to trend line growth (L-shaped) bottom out and pick up in the third quarter or later):
  - Overall reduction ranging from 48% to 71% of seats offered by airlines;
  - Overall reduction of 1,108 to 1,524 million passengers;
  - Approx. USD 194 to 269 billion potential loss of gross operating revenues of airlines.

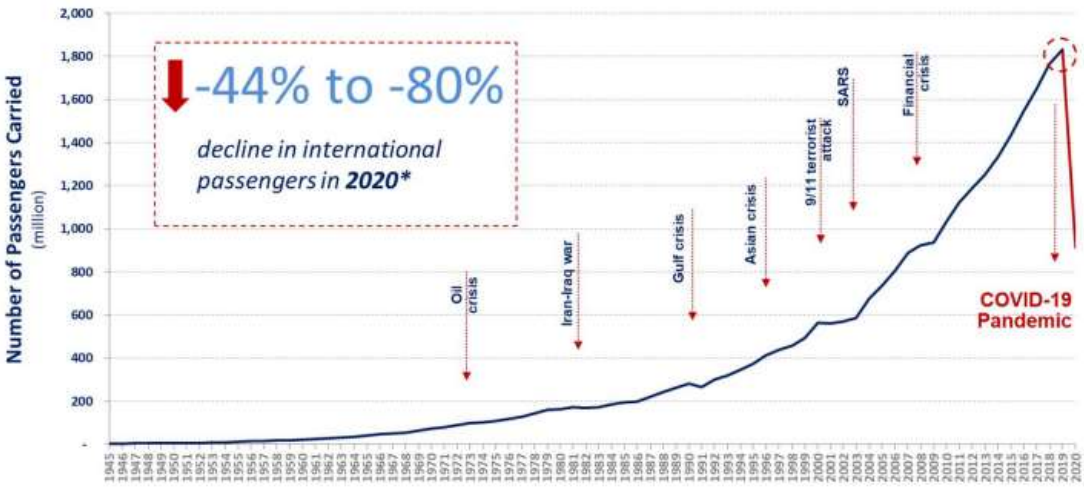


Figure 18. 29. World international passenger traffic evolution 1945 – 2020 [98]

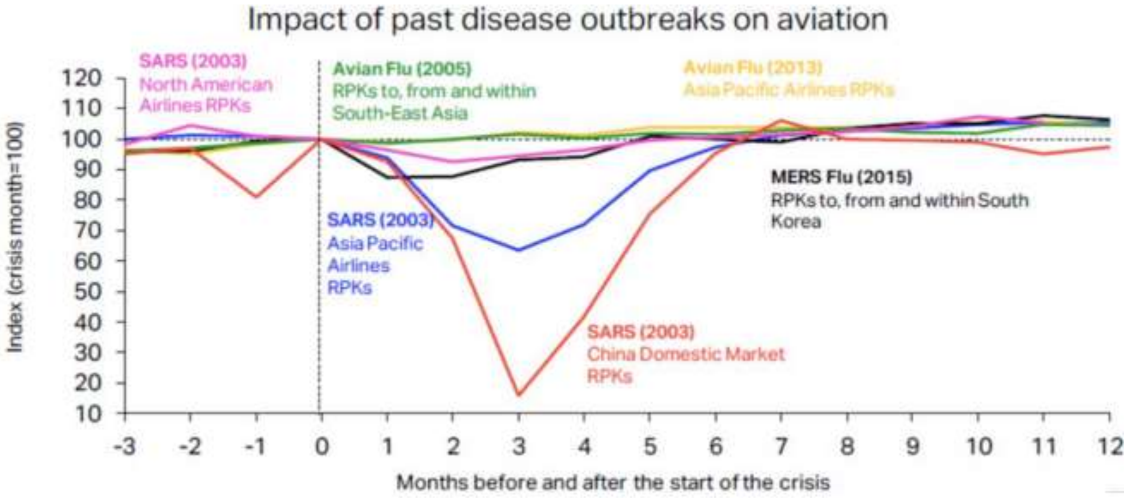


Figure 18. 30. V-shaped and U-shaped paths [98]

The impacts depend on the duration and magnitude of the outbreak and containment measures, the degree of consumer confidence for air travel, and economic conditions (Figure 18. 31), etc. Analytical focus, for the time being, on:

- Near-term, i.e. monthly profile from January to December 2020;
- Scheduled international passenger traffic*.

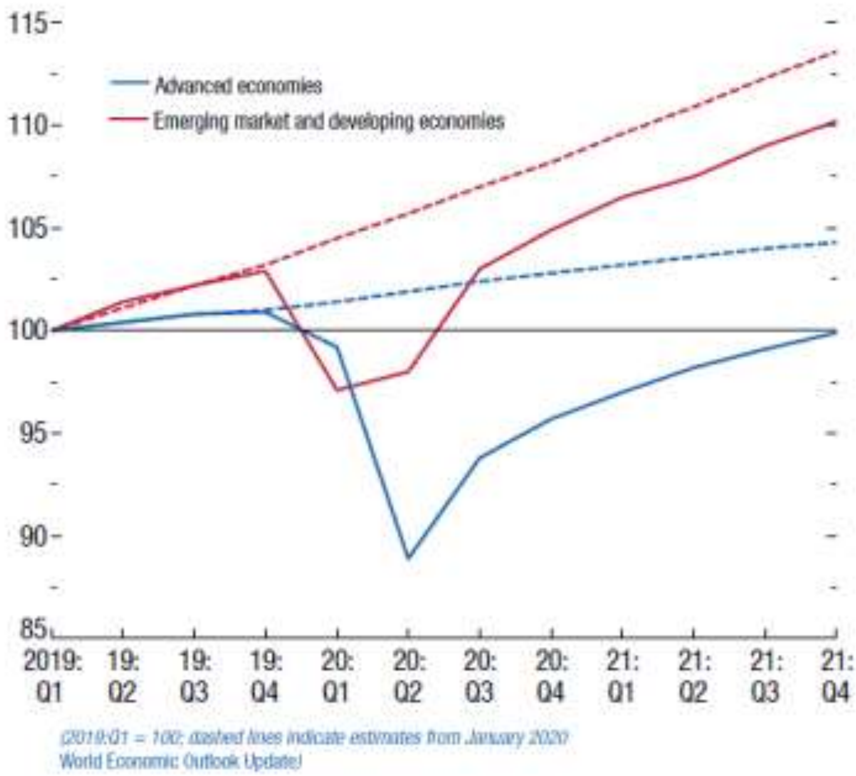


Figure 18. 31. World's GDP Projections (by IMF) [99]

Global impact of COVID-19 on aviation, tourism, trade and economy:

- *International air passenger traffic*: An overall reduction of international passengers ranging from 44% to 80% in 2020 compared to 2019 (by ICAO);
- *Airports*: An estimated loss of over 50% of passenger traffic and 57% or over USD97 billion airport revenues in 2020 compared to business as usual (by ACI);
- *Airlines*: A 48%
- The decline of revenue passenger*kms (RPKs, both international and domestic) in 2020 compared to 2019 (by IATA);
- *Tourism*: Decline in international tourism receipts of between USD 910 to 1,170 billion in 2020, compared to the USD 1.5 trillion generated in 2019, with 96% of worldwide destinations having travel restrictions (by UNWTO);
- Trade: A fall of global merchandise trade volume by between 13 and 32% in 2020 compared to 2019 (by WTO);
- Global economy: A projected -3% contraction in world GDP in2020, far worse than during the 2008–09 financial crisis (by IMF).

Scenarios 1 and 2 are not forecasts of what is most likely to happen. Given a rapidly changing environment, these scenarios are merely indicative of possible paths or consequential outcomes out of many. The exact path (depth, length and shape) will depend upon various factors, interalia, duration and magnitude of the outbreak and containment measures, availability of government assistance, consumer confidence, and economic conditions.

Scenarios 1 and 2 are differentiated in terms of supply (output) and demand (spending) conditions, mainly, a) the timing and scale of airline capacity decline and recovery, and b) the degree of consumer confidence in air travel that can be translated into demand or load factor. The impact of COVID19 has already surpassed the 2003 SARS outbreak which had resulted in a reduction of annual RPKs by 8% and USD 6 billion revenues for Asia/Pacific airlines. The 6-month recovery path of SARS might not apply to today's situation (Figure 18. 32).

Figure 18. 32. Four –quarte rolling passenger volume and operating revenues [98]

Due to extreme uncertainty, 6 different paths up till 4Q 2020 are considered:

- *Baseline (counterfactual, no COVID-19 pandemic):*
  - Originally-planned or business as usual: trend line growth from 2019 level

- *Scenario 1 (V-shaped path, the first sign of recovery in late May):*
  - Path 1: Gradual capacity recovery to 80% of Baseline level by December but weak demand return;
  - Path 1a: A swift capacity rebound to 90% pushed by pent-up demand;
  - Path 1b: Slow progression to recover 60% capacity with downside risk in demand;

- *Scenario 2 (U-shaped path, bottom out and pick up in 3/4Q or even later):*
  - Path 2: Slow progression of capacity recovery to 50% of Baseline with sluggish demand growth;
  - Path 2a: Swift capacity rebound to 90% by December, outpacing demand recovery;
  - Path 2b: Prolonged downturn towards 2021 with marginal seasonal adjustments.

The impact of COVID-19 is still under the development, its recovery path is not understanding completely to today's situation. While more information is needed to accurately quantify the impact of the COVID-19 pandemic on the aviation sector's CO_2 emissions in 2020 and subsequent years, this impact has resulted so far in a sharp decline in aviation activity, with an expected related decrease in the sector's CO_2 emissions in 2020, compared to the forecasted 2020 CO_2 emissions before the pandemic.

CORSIA's sectoral baseline is defined as the average of total CO2 emissions for the years 2019 and 2020 on the routes covered by CORSIA offsetting in a given year from 2021 onwards (Assembly Resolution A40-19, paragraph 11). Therefore, the expected reduction of the 2020 CO2 emissions from international aviation due to the COVID-19 pandemic will lead to a decrease of the CORSIA baseline, compared to the non-COVID-19 scenario [100].

It is important to note that the COVID-19 pandemic is expected to affect not only the global aviation sector's 2020 activity but also that of subsequent years. The impact on the sector's CO2 emissions in years to come is being assessed by the development of possible recovery scenarios from 2021 onwards, which are subject to a high level of uncertainty.

The impact of the COVID-19 pandemic on the CO2 emissions from international aviation in 2020 and subsequent years could affect the following three CORSIA's design features, defined in Assembly Resolution A40-19, as follows:

CORSIA calculates annual offsetting requirements for individual aeroplane operators every year from 2022 based on an annual Sector's Growth Factor (SGF), which represents the CO_2 emissions growth of international aviation in a given year from 2021, compared to CORSIA's sectoral baseline (average of 2019 and 2020). The impact of COVID-19 on a given year's SGF will be reflected through the impact on CORSIA's sectoral baseline; and the impact on the given year's CO_2 emissions from international aviation, which will depend on the aviation sector's recovery pattern from 2021 onwards. All things considered, a given year's SGF could be higher or lower than that year's SGF under a non-COVID-19 scenario. The compounded effect on the year's SGF will determine the magnitude and nature of the impact on the total CORSIA offsetting requirements for that year, as well as the associated costs for the industry [100].

The calculation of an aeroplane operator's annual offsetting requirements during CORSIA's pilot phase (2021 to 2023) requires multiplying the corresponding year's SGF with an emissions value of the operator. For the latter, States can choose, for their attributed operators, between two options: an operator's emissions in a given year (i.e. 2021, 2022 and 2023 emissions); or the operator's 2020 emissions for each of the three years during the pilot phase. Therefore, the impact of COVID-19 on the annual offsetting requirements during CORSIA's pilot phase is not only through the impact on a given year's SGF (as described above), but also through a State's choice of reference emissions.

CORSIA refers to a certain percentage (0.1%) of global CO_2 emissions in 2020 as a threshold for a new entrant operator to be covered by the CORSIA offsetting requirements. Therefore, any impact on the 2020 emissions due to COVID-19 may create the need to review this provision [100].

Considerations on the need and timing to adjust the CORSIA baseline and other design features above, if appropriate, need to be based on proper technical data and assessment. On the matter of timing, for potential adjustments, due consideration has to be given to the timeline for CORSIA implementation, as described in Appendix 1 of Annex 16, Volume IV, and to the related milestones, as follows:

31 October 2022: the SGF value corresponding to the year 2021 CO2 emissions will be provided by ICAO for States to calculate the 2021 offsetting requirements of individual aeroplane operators attributed to them; this will be the first instance in which information on CORSIA's sectoral baseline will be applied.

31 January 2025: deadline for aeroplane operators to cancel eligible emissions units to comply with their total offsetting requirements for CORSIA's pilot phase (2021 to 2023). Annexe 16, Volume IV does not specify any date for the purchase of units by operators

Any adjustment to CORSIA's design features is a matter that requires careful consideration by the relevant ICAO bodies. The ICAO Council, at the 220th Session in June 2020, considered analysis by the Committee on Aviation Environmental Protection (CAEP) on the COVID-19 impact on CORSIA's design features [100].

In addition to the impact assessment, the Council also considered the legal and reputational aspects related to the various options, as well as the importance of maintaining the originally-agreed balance between the scheme's economic impacts and environmental benefits together with its simplicity and practicality, whilst responding to this unprecedented crisis.

The Council agreed that, in order to safeguard against the inappropriate economic burden on aeroplane operators, 2020 emissions should not be used for the three CORSIA design features listed above. In this regard, the Council decided that during the pilot phase, 2019 emissions shall be used for 2020 emissions and published in all relevant ICAO documents referenced in Annex 16, Volume IV. There was no change for the provisions of Annex 16, Volume IV or Assembly Resolution A40-19 text.

In addition to the above, it is important to note that paragraph 17 of Assembly Resolution A40-19 includes a provision that the ICAO Council will conduct a periodic review of the CORSIA every three years from 2022. In this regard, the Council highlighted the importance of undertaking the 2022 periodic review, with technical contribution of the Committee on Aviation Environmental Protection (CAEP), which will offer an opportunity to examine the impact of COVID-19 on CORSIA on various issues, including the impact on the baseline beyond the pilot phase. The Council will consider a structure, process and methodology of the 2022 periodic review, including the work programme of CAEP, at its 222nd Session in March 2021 [100].

18.8.1.1 Latest ICAO Council decisions for CORSIA baseline change

On 1 July 2020, the ICAO Council has voted by a large majority to adopt an industry proposal to change the crucial emissions baseline rule for the CORSIA carbon offsetting scheme for international aviation. The move is aimed at protecting airlines from what ICAO describes as the "inappropriate economic burden" airlines are likely to face from a lower baseline as a result of the collapse of international air traffic this year leading to increased offsetting costs in future years. Instead of the baseline being calculated on the 2019-2020 average CO2 emissions from international flights covered by CORSIA, it will now be based on 2019 emissions only. The Council also voted to remove 2020 emissions from two other design features of the scheme. It plans to consider the effect of the changes during the scheme's first review in 2022. The outcome has been welcomed by IATA although environmental NGOs are highly critical.

IATA had called on ICAO to change the baseline [101], which is set out in CORSIA resolution A40-19 [102] adopted by ICAO's 193 States at their Assembly in 2016 after COVID-19 had largely grounded the global fleet. It argued the original baseline no longer reflected what the States had agreed, which might lead them to reconsider their support for CORSIA. The airline trade body estimates emission levels in 2020 could fall by half in 2020 and lower the original baseline calculation level equivalent to the sector's emissions in 2010. As a result, it said, the baseline would be around 30% lower than expected and result in significantly more offsetting when the sector recovered, even though emission levels may not reach the baseline in the early stages of CORSIA, which starts with the three-year pilot phase in 2021.

An adjusted methodology will still produce a more stringent baseline than would have been the case without the COVID-19 crisis, argues IATA, but would limit the impact on financially struggling airlines. It estimates emissions from international aviation in 2019 totalled around 580 million tonnes.

To allow the verification process to be conducted in accordance with the requirements of Annex 16, volume IV, IATA also calls on ICAO to urge States to extend the deadline for the submission of the verified emissions report and associated verification report for 2019 until at least 31 October 2020 [103].

Elsewhere, some had argued that only the Assembly had the legal power to change a basic design feature that had been agreed in a resolution and called for a delayed decision until the next Assembly in 2022. However, the ICAO Council agreed that paragraph 16 of A40-19 gave it safeguarding powers to ensure the aviation sector was protected against unforeseen circumstances that affected the sustainability of the scheme and imposed an "inappropriate" financial burden on the aviation sector.

An ICAO statement said [104]: "The decision of the ICAO Council acknowledged that making use of the significantly unexpected traffic and emissions results being experienced this year due to Covid-19 will disrespect the originally-agreed intention and objectives of ICAO's the Member States when they adopted CORSIA in 2016."

The Council agreed that 2020 emissions should not also be used for two other CORSIA design features: the selection of the reference year for calculating offsetting requirements in the pilot phase and the emissions threshold for new CORSIA entrants. However, the Council did not remove the requirement for operators to monitor and report their verified 2020 emissions to their national authorities.

It also agreed to consider, following further analysis, amendments to A40-19 to also use only 2019 emissions for the three design features beyond the pilot phase, which would then be presented to the next Assembly in 2022 for a decision. The Council also decided to initiate the process for establishing the 2022 periodic review of the scheme called for in A40-19 and requested the ICAO Secretariat to present it with a review structure, process and methodology for consideration at its 222nd Session in March 2021. The 2022 review would also consider whether it would be necessary to make adjustments to the next phase or compliance cycle and if so, submit recommendations to the Assembly. It would also examine the impact Covid-19 on CORSIA, including a consideration of the baseline beyond the pilot phase, on the different phases of CORSIA implementation, and the growth factors.

The Council's 222nd Session is also expected to consider ongoing analysis by ICAO's environmental committee CAEP on the economic impact of Covid-19, its impact also on international aviation CO2 emissions and the cost implications of CORSIA offsetting requirements. The decision was voted on by the 36-member Council, with 25 in favour, three against (China, Russia and South Africa) and eight abstentions. "The Council States have made a measured assessment and have come to the most reasonable solution available given our current and very extraordinary circumstances," - commented ICAO Council President Salvatore Sciacchitano on the outcome.

Welcoming the agreement, IATA said it provided immediate certainty and a clear path forward for the successful implementation of CORSIA. The baseline would have been "severely skewed" if 2020 had been used for the calculation, it argued.

"Aviation was the first industry sector in the world for which governments agreed to a global carbon offsetting measure. Airlines know that sustainability is its licence to grow. They fully support CORSIA as the single global mechanism for offsetting aviation's international emissions. Even with the financial hardship facing the industry as a result of COVID-19, the world's airlines have not lost sight of their emission reduction goals."

Environmental NGOs, by contrast, expressed big disappointment with the outcome. The International Coalition for Sustainable Aviation (ICSA), which represents civil society and NGOs at ICAO, said the decision further deflated CORSIA's ambitions and was "a slap in the face" to the multi-lateral work in building the scheme. "There is no good reason for the ICAO Council to make this decision now," said ICSA in a statement. "It is unnecessary given the programme's flexibility, and it is illegal unless ratified by the Assembly. CORSIA was already far below what is needed to avoid climate catastrophe. Airlines, in pushing for this change, have undermined their case for international action. "Given ICAO's unwillingness to lead, ICSA urges governments to adopt national measures to support the climate ambition that is needed."

What appears to be a technical change, will, in fact, postpone the start of the scheme by at least three years, until 2024 or later, depending on how fast the sector recovers from the current crisis, and on whether governments decide to extend this change to the subsequent phases, pointed out ICSA member Carbon Market Watch.

Annie Petsonk, International Counsel with the Environmental Defense Fund, another ICSA member which has campaigned against the baseline change since it was first proposed, said: "As airlines scramble to recover from the COVID-19 crisis, they can't afford to ignore the looming global crisis of climate change. Real leadership means setting the aviation sector on a path toward net-zero climate impacts as swiftly as possible. The sooner that the costs of carbon control are included in the costs of doing business, the sooner new technologies will be developed.

"Instead, ICAO's Council decided to backtrack on its commitment to carbon-neutral growth from 2020, so that airlines need only offset emissions above 2019 levels for the first three years of the programme. If emissions do not rise above 2019 levels, airlines are wholly excused from offset obligations. Changing baselines is a bad precedent for the development of carbon markets in other countries and sectors.

Ironically, it means that airlines will lose the first-mover advantage they had sought to secure through CORSIA, as other carbon market actors will beat them to the punch on long-term supply contracts.

With offset obligations likely suspended for the pilot phase, the decision leaves the field wide open for governments – at local, state and national levels – to require airlines to integrate climate action into their economic recovery. That could, in turn, leave the industry with the very patchwork of regulations it fears. "That the Council decided to arrogate to itself the authority to make this rule change, without consulting the full 193 ICAO Member States that adopted CORSIA, to begin with, sets a troubling precedent for the legitimacy of future decision-making by the UN's aviation body."

During the Council session, ICAO officially launched the CORSIA Central Registry (CCR), which is one of the scheme's five 'implementation elements. It obliges States to fulfil their reporting requirements through it and has been implemented as a secure Cloud-hosted application supported by a database. The CCR has been designed to store CORSIA-specific information and data on aeroplane operators, verification bodies, CO2 emissions, CORSIA-eligible fuels claimed and cancelled emissions units. It will retain records from the ICAO States for the duration of the scheme. However, access to the CCR is restricted to authorised users, who are nominated by the States.

"Despite the challenging circumstances, ICAO has been working diligently to put in place all implementation elements of CORSIA to ensure the scheme remains on track, and States have all the tools available to comply with their CORSIA reporting requirements," said ICAO Council President.

June 30 of 2020 was the deadline by which States had to inform ICAO of their participation in the voluntary phases of CORSIA starting in 2021. Late additions to the list of States taking part included Rwanda, Kazakhstan and Afghanistan, bringing the total to 87 States, representing 76.82% of international aviation activity. The BRICS countries – Brazil, Russia, India, China and South Africa – have, however, not agreed to take part from the outset.

18.8.2 18.8.2.4 The Impact of COVID-19 on Emissions and Emission Allowance Prices under the European Union Emissions Trading System (EU ETS)

18.8.2.1 Market functioning trackers

Next to environmental and economic delivery, the performance of the EU ETS in terms of market delivery is critical. The good market function is critical as it leads to a good price discovery, which is the primary function of a market. Good market functioning should show, among other things, liquidity, transparency, and easy to get in and out of the market. Eight KPIs are identified that will help understand how the market is performing over time and should provide a proxy for the basic requirements of a well-functioning market [105]. These indicators are:

- Volumes, allowing market participants to open and close positions at any time with the lowest possible cost.
- Open Interest is an additional KPI that helps us understand trends in liquidity. An open interest indicates the number of outstanding positions in different contracts. Generally, the higher the open interest, the more a particular contract is traded and hence the higher is the level of liquidity.
- Auction participation shows the average number of participants in auctions. This indicator reflects the participation in the primary market, thus the direct demand.

- Auction coverage represents the ratio between total bids in an auction to the number of EUAs available in the auction. It is an indicator that helps assess the actual demand for allowances in the primary market.
- Auction vs Spot shows the difference between the auction and spot prices reveals that is the interaction between the primary market and the financial market. A widespread indicates the possible presence of market power by some players, asymmetry of information, or other factors that highlight a high speculation activity.
- The bid-ask spread shows the difference between the highest price offered and asked in the marketplace.
- The cost of carrying shows the expectations market players have about the future.
- Volatility refers to the amount of uncertainty or risk in a financial product; it indicates how much and how quickly the value of market changes. While volatility is a necessary feature of the market for traders and financial players that can take advantage of price fluctuations to make profits, high volatility can also be a disincentive for industries that need a more stable price signal to predict costs and make investment decisions.

A market is considered to function well if a trade-off is made between ensuring a stable and predictable price trajectory and the guarantee of adequate liquidity provided by traders and financial players.

One important new development is the start of the Market Stability Reserve (MSR) in 2019, which is expected to tackle the historical surplus of allowances on the market and any future shocks to the EU ETS. Besides issues that are generally "on the radar", such as the upcoming EU elections and Brexit, CORSIA and aviation in EU ETS, and review of the MSR, we need to highlight two areas that will require attention in the future: the operationalization of Article 30 of the Directive on reviewing the EU ETS in light of efforts undertaken in light of the Paris Agreement and developments in other major economies, and the need for mechanisms to finance and incentivize the deployment of carbon negative technologies and how, if in any way, they will interact with the EU ETS.

The Market Stability Reserve (MSR) started operating in January 2019, four years after it was adopted. It is meant to provide a long-term solution to the problems created by the historical surplus of EUAs which accumulated in the market during the early years of the EU ETS, as well as to make the EU ETS more resilient to new sources of supply-demand imbalance.

The functioning of the MSR is based on the total number of allowances in circulation (TNAC), defined as:

$$TNAC = Supply – (Demand + allowances\ in\ the\ MSR).$$

The instrument works according to pre-set, volume-based triggers:

- If TNAC > 833mt: Fixed percentage of the TNAC to be subtracted from the auctioning calendar and placed in MSR (24% between 2019-2023, 12% from 2024 onwards).
- If TNAC < 400mt: 100mt to be released from the MSR and added to the auctioning calendar [105].

Furthermore, from 2023 a yearly invalidation of allowances is foreseen, to address part of the surplus held in the MSR: any allowances above the number of allowances auctioned the previous year will be invalidated in the MSR. The combination of 24% intake rate until 2024 and yearly invalidation of allowances is expected to enable the MSR to cope effectively with the current surplus in its first years of operation. With the start of the yearly invalidation of allowances, the MSR is expected to invalidate a number of allowances in the range of 2230 Mt to 2428 Mt in 2023 – including backloaded allowances from 2014-2016 [105] . Notwithstanding these positive effects, however, different models agree that with the current design parameters the MSR will not be able to absorb surpluses from potential new sources of imbalance which might emerge during Phase 4 – e.g. new EU-wide 2030 targets for renewables and energy efficiency; new Member States policies such as coal phase-outs, at least in the absence of voluntary cancellation; new economic shocks; etc. Indeed, Figure 18. 33 shows three projections which indicate that the TNAC will not remain within thresholds in the period 2021-2030, and will go on an upward trajectory after 2024. This implies that the MSR will fall short of fulfilling its long-term goal of making the EU ETS more resilient to future sources of imbalance unless the MSR design parameters are adapted to the new market environment.

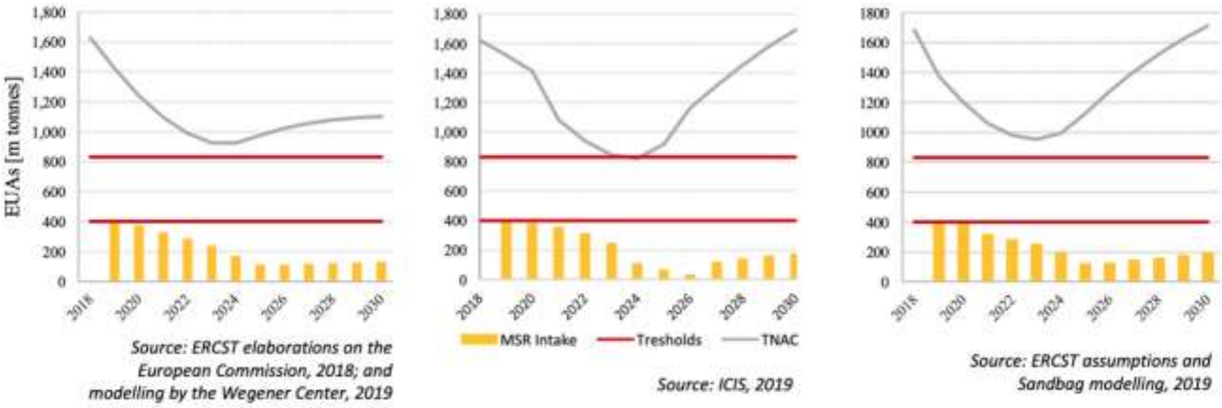


Figure 18. 33: Projections of MSR functioning and intake volumes 2019-2030 [105]

But these forecasts, made last year, have already had to be adjusted to reflect the impact of the coronavirus pandemic. The COVID-19 pandemic brought global economic activity to a sudden halt in the first half of 2020. The result was a substantial fall in energy demand.

The carbon market disruption in 2020 with the Covid-19 crisis is therefore significantly different from the previous crisis in 2008. Nonetheless, it will similarly test the market and will provide an opportunity for examining whether the MSR will be able to deal with the surplus that may arise from a sustained economic depression, or whether alternatives such as a carbon price floor merit reconsideration. A carbon price floor has been implemented nationally in the UK. France has been a long-time supporter and Germany seems to be warming to the idea. A price floor is also a common market design element in North American carbon markets such as the California and Quebec ETS. The ETS surplus increases when emissions stay below the cap. However, the cap as it is currently set largely reflects the policy consensus of 2014. When the European Council adopted the 2030 climate and energy framework, it included a reference to the trajectory of the ETS cap up to 2030 (the 'linear reduction factor' of 2.2%) which was later adopted as part of the ETS revision. Since then, several pivotal climate policy developments have occurred, notably the Paris Agreement, but also the EU long-term climate strategy for 2050 and the European Green Deal. The Green Deal sets out a roadmap to revise the EU's climate and energy policies from June 2021 onwards. The next revision of the ETS can therefore account for the more ambitious climate policies endorsed since 2015, including the climate neutrality target for 2050 and the potentially increased target for 2030. This would increase scarcity in the long run. In the short term, however, the effects on emissions of the Covid-19 downturn will unfold in relation to the existing trajectory of the cap. Figure 18. 34 shows the trajectory of the ETS cap from 2013 (the start of Phase 3) to 2030 (the end of Phase 4) together with emissions up to 2019 (and an estimate for 2020).

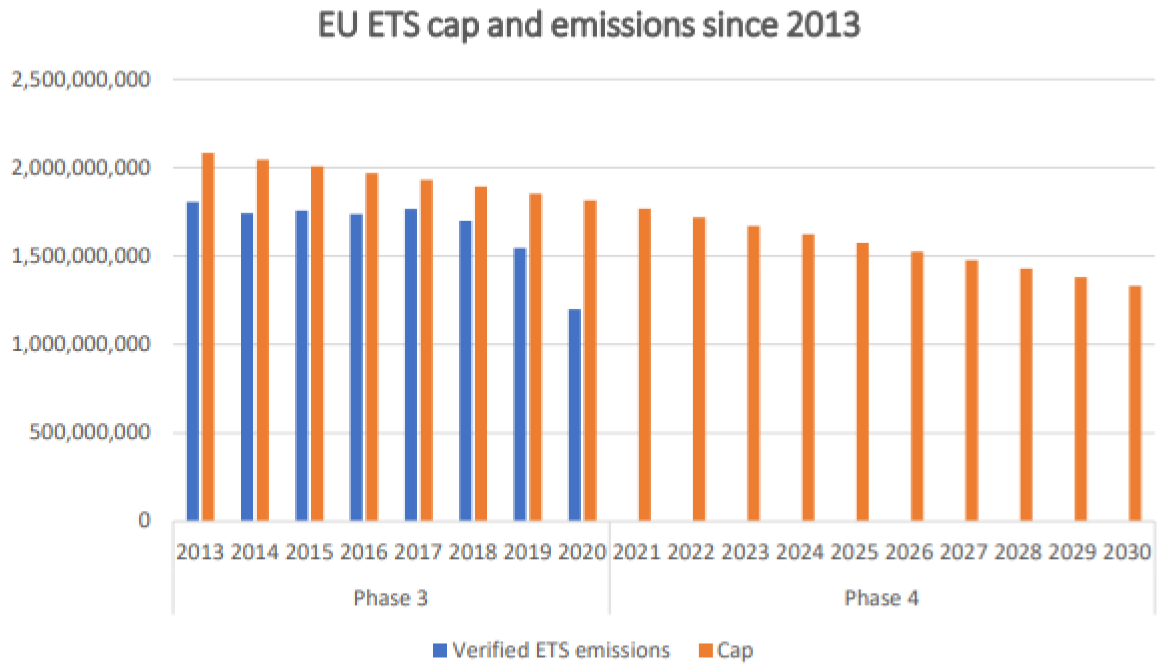


Figure 18. 34. EU ETS cap5 and emissions since the start of Phase 3 [106]

The European Union Emissions Trading Scheme (EU ETS) limits emissions from the electric power sector, the energy-intensive industry and intra-European aviation. This cap-and-trade system covers around 45% of the EU's greenhouse gas emissions, equalling 1749 MtCO2 in 2018 (European Environmental Agency, 2020). To estimate the size of the negative emission allowance demand shock, it is necessary to determine to identify the change in monthly emissions from the three sectors covered by the EU ETS below. First, the change in emissions from electricity generation needs to be estimated, based on the methodology of [107]. We run a regression analysis using more than five years of hourly electricity generation by technology from ENTSO-E (2020). Based on this analysis, we can identify the change in average, hourly output of carbon-emitting electricity generation technologies due to the COVID-19 pandemic. We add month fixed effects and non-linear time trends to control for regular patterns in generation output and for broader time trends impacting output by conventional generation technologies. We run a separate regression for every carbon-emitting generation technology (natural gas, lignite, hard coal and oil) and in each European country of our sample. In this analysis, we consider Belgium, Czech, France, Germany, Great Britain, Netherlands, Portugal and Spain. Together they consist of 65% of EU ETS electricity generation. We find that in our sample, gas generation decreases on average by 9427 MWh/h, lignite by 3152 MWh/h, hard coal by 1519 MWh/h and oil-fired generation by 59 MWh/h (Table 18. 25).

Table 18. 25. Effect of COVID-19 lockdown in different countries on average, hourly output of carbon-emitting electricity generation technologies (MWh/h)

		Gas	Lignite	Hard coal	Oil
Belgium	(MWh/h)	-770***	/	/	0
Czechia	(MWh/h)	-69***	38***	-581***	12***
France	(MWh/h)	-1114***	/	58	16
Germany	(MWh/h)	-2861***	-1873***	-2860***	-91***
Great Britain	(MWh/h)	-1037***	/	-1881***	0
Netherlands	(MWh/h)	-41	/	+568***	/
Portugal	(MWh/h)	-1	/	+85***	/
Spain	(MWh/h)	-3433***	317***	1449***	3
Total	(MWh/h)	-9427	-3152	-1519	-59
Carbon intensity	(tCO_2/MWh)	0.374	0.97	1.04	0.624
Change in carbon emissions	(tCO_2/h)	-3526	-3057	-1580	-37

Note: p<0.05 (*), p<0.01 (**), p<0.001 (***).

Source: [3, p.40]

This is a decrease of respectively 22%, 19%, 13% and 7% compared to the 2019 average (ENTSO-E, 2020). Combined with the assumed carbon intensity for gas, lignite, hard coal and oil listed in Table 1, carbon emissions from electricity generation are estimated to be 8200 tCO2/h lower in our sample. Extrapolating these estimates and correcting for the scope of our sample (65%), every additional month of similar lockdown measures would decrease electricity-related carbon emissions by 9 MtCO2. Second, aviation has decreased by 90% (Statista, 2020), from a pre-COVID 2018 level of 67 MtCO2 per year (European Environmental Agency, 2020). This leads to a decrease of around 5 MtCO2 aviation-related EU ETS emission for every additional month of similar lockdown measures. Last, data for idle industrial production is not yet available for March 2020, but we can make an educated guess of the impact by looking at the business tendency survey of European countries for March 2020 [108]. For example, the March 2020 future production tendency of manufacturing firms in the Euro area dropped to -9.4, down from 4.7 in February 2020, meaning that in one month, the share of optimistic manufacturers decreased with 14.1%. This decrease is even more pronounced in countries like Italy (-23.9), Czech (-20.6) or Germany (-18.2). Similarly, the confidence indicator dropped by 28.6 in China in February 2020. We assume that industrial production activity decreased by 50%, or 24 MtCO2 per month from a pre-COVID 2018 level of 584 MtCO2 per year (European Environmental Agency, 2020). Hence, in what follows, we use a negative demand shock of 40 MtCO2 per month that the lockdown is extended in its current form. Hence, in what follows, we use a negative demand shock of 40 MtCO2 per month that the lockdown is extended in its current form.

As about half of EU's CO2 emissions are regulated by the EU Emission Trading System (EU ETS), demand for emission allowances (EUAs) will likely fall along with lower emissions, and so, one expects, will EUA prices. Indeed, when the 2008 financial crisis hit, the EUA price dropped by more than 50 percent in only a few months.

18.8.2.2 The impact on cumulative emissions & emission allowance prices

Analysis of various studies shows the relationship between CO2 emissions and prices for emissions trading. Article [109] shows the dynamics of demand for EUA (emissions) in the EU ETS (Figure 18. 35).

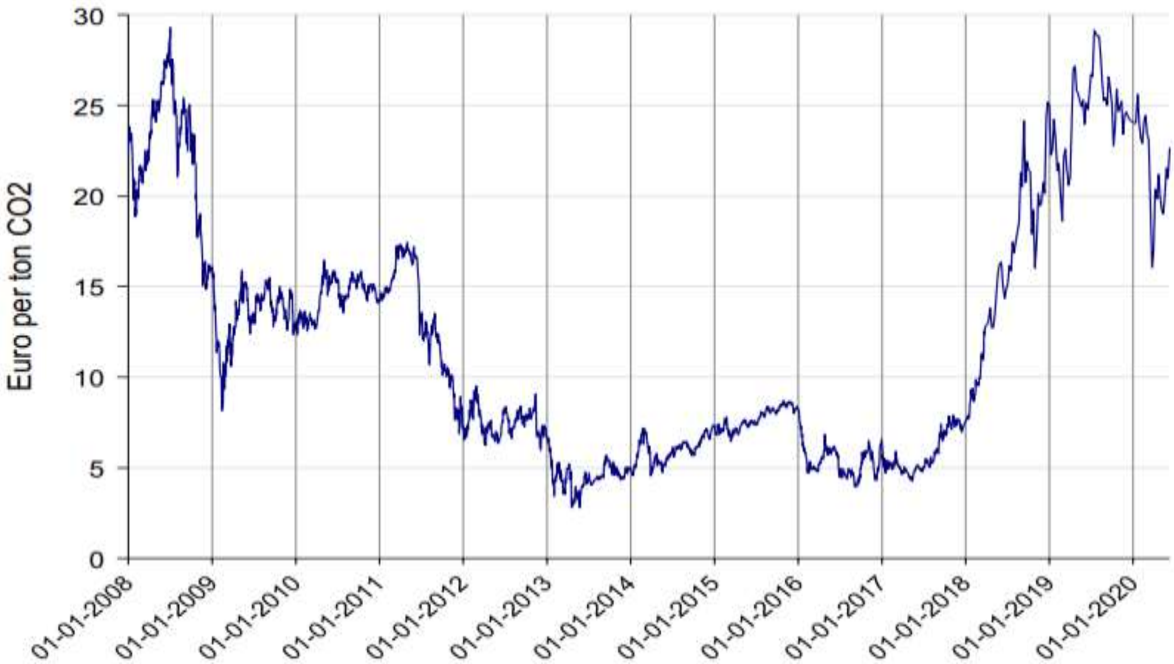


Figure 18. 35. Figure 3. EUA (EU ETS) price 2008–2020 [109]

The EUA price likely decreased as market participants anticipated lower economic activity and hence reduced demand for EUAs (emissions) in EU ETS. When the financial crisis was followed by a recession in many EU countries, the EUA price fell further and stayed below 10 Euro throughout the years 2012–17. When the financial crisis hit the global economy in the middle of 2008, the EUA price responded quickly. It decreased from a high of 25 Euro per ton at the end of August to a low of less than 10 Euro in February 2009, before stabilizing around 13 Euro for the next year.

The article [110] also investigated the impact of this negative demand shock on the emission allowance price and allowed emissions under EU ETS, leveraging our stylized EU-ETS-MSR model (Bruninx et al., 2019). This model is based on the detailed long-term investment model of Bruninx et al. (2020) and assumes rational, price-taking and risk-neutral firms that optimize their abatement and banking actions over the complete EU ETS horizon.

Three scenarios of demand shock were studied, starting from an initial demand shock of 120 MtCO2 (i.e., a three-month lockdown) or 240 MtCO2 (i.e., a six-month lockdown) in 2020:

- A V-shaped demand shock, in which carbon emissions return to a business-as-usual before the end of 2020. The total negative demand shock is, hence, 120 MtCO2 or 240 MtCO2.
- A U-shaped demand shock, which gradually vanishes between 2020 and 2025. In these scenarios, we assume the demand shock linearly decreases from its initial value in 2020 to zero at the end of 2025. The total negative demand shock is, hence, 420 MtCO2 or 840 MtCO2.

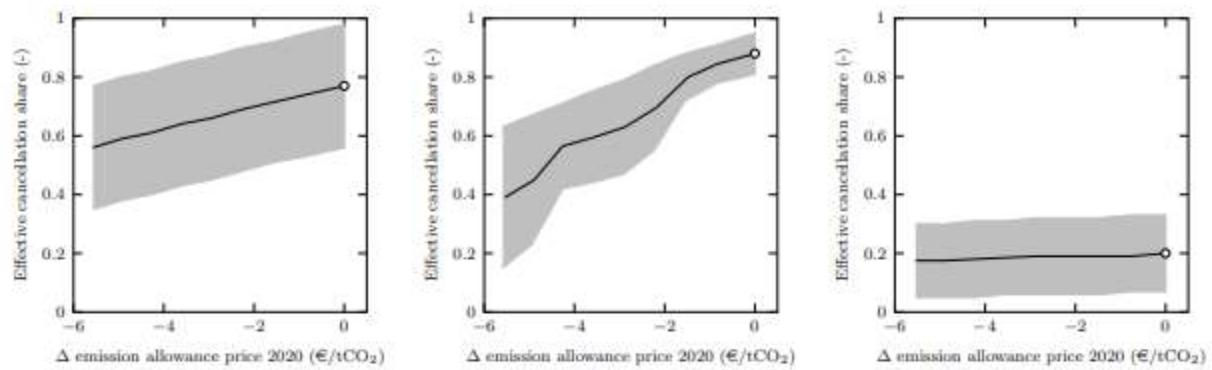
A persistent demand shock, in which 25% of the initial demand shock becomes permanent post2020. The total negative demand shock is, hence, 1470 MtCO2 or 2940 MtCO2.

In each scenario, the state of the EU ETS at the end of 2019 is fixed, based on the records of the surplus in the market, the holdings of the MSR and the emissions up to 2019 [105]. Verified emissions for 2019 are estimated to be 10% lower than emissions in 2018 (Sandbag, 2020).

Since the marginal abatement cost curve, the EU ETS is fundamentally uncertain, we run each demand shock scenario with a linear, quadratic and cubic marginal abatement cost curve, following [111]. Baseline emissions are set to 1900 MTCO2, as in [111]. The discount rate is set to 10% and inflation equals 2% per year. The slope of each abatement cost curve is calibrated to reproduce the average 2019 emission allowance prices (24.7 e/tCO2, based on EEX (Last accessed: April 1, 2020)) without the negative demand shock. If this calibration yields marginal abatement costs at historical emission levels in 2018 below 0.1 e/tCO2, this case is not retained in the results [112].

As a first result, the study found that the MSR and its cancellation mechanism are very effective at stabilizing the emission allowance price in response to negative demand shocks. The allowance price in 2020 decreases by less than 0.1 e/tCO2 and this result holds for different marginal abatement cost curves, magnitudes or shapes of the shock. As a second result, the demand shocks differ in their effect on cumulative emissions. In general, short-lived V- and U-shaped shocks are translated largely into lower cumulative emissions because the MSR absorbs and cancels the increased allowance surplus. On the other hand, persistent demand shocks decrease cumulative emissions much less, as a significant part of the demand shock occurs far away in the future, after the market stability reserve has stopped absorbing and cancelling emission allowances.

In reality, however, the price of EU emission allowances has dropped significantly, by around 6 e/tCO2. Because this does not happen in our model with rational, price-taking, risk-neutral and perfectly optimizing firms, we adapt our model such that we do observe price shocks. This can be done by assuming that firms temporarily change their discount rate by one to eight percentage points during the shock. A temporary change in discount rates makes banking of allowances during the shock less profitable, i.e., it is better to secure the required allowances for future emissions after the shock. This may reflect the situation that many utilities and companies face today: as their financial positions are stressed, they may liquidate assets – such as emission allowances procured to cover future emissions – to improve their cash position. Similarly, they won't have the cash to spare to bank emission allowances for compliance with future emissions. Note that in the persistent demand shock scenarios, these changes in the discount rate are only enforced in 2020, whereas we assume the discount rate to evolve linearly to its original value in the U-shaped demand shock scenarios.



(a) V-shaped negative demand shock (b) U-shaped negative demand shock (c) Permanent negative demand shock

Figure 18. 36. Summary of the results separated according to the type of shock.

Figure 18. 36 summarizes the impact of all three emission allowance scenarios on the emission allowance price (x-axis) and on the cumulative emissions cap (y-axis), represented by the effective cancellation share, which is the fraction of the demand shock that translates into lower emissions. The white-filled marker in Figure 18. 36 presents the average result without any change in discount rates, while the black line shows

how the emission allowances price and the effective cancellation share on the average drop when the future becomes less important (modelled by changing the discount rate). The grey area represents the uncertainty around this average, from the six modelled scenarios (two shocks magnitudes times three curvatures of the marginal abatement cost curve). This figure shows that the emission allowance price does not decrease because of the negative demand shock as such, but because of changes in market participants' importance of the future. Remarkably, we also find that the temporarily decreased emission allowance price leads to a lower effective cancellation share. This happens because emission abatement is temporarily less profitable, such that part of the negative demand shock is offset by lower abatement before the surplus is absorbed and cancelled by the market stability reserve.

18.8.2.3 Model Simulation

To simulate the ETS market with and without the MSR, a stylized, dynamic, and deterministic model is used. The model incorporates key details of the MSR. In our baseline scenario (before the COVID-19 shock), the price begins at 21.0 Euro per ton CO2 in 2019 and increases with the interest rate of 5 percent. Exogenous supply of EUAs declines linearly to zero in 2057, whereas endogenous demand (i.e., emissions) drops to zero in 2067.9 We next construct a version of our model without the MSR but with the lower exogenous supply of EUAs, so that the starting price in 2019 is the same as in the model version with the MSR. Since emissions only depend on the ETS price, this means the (expected) emission paths are the same in both versions of the model and before a shock is implemented. The future effects of COVID-19 on demand for EUAs are uncertain, especially the long-term effects. For this reason, we construct three alternative scenarios that have the same short-run effects (2020–22), but different long-term effects, see Table 18. 26 which shows annual reductions in demand at given ETS prices.

Table 18. 26. Annual and cumulative reductions in demand for allowances

	2020	2021	2022	2023–30 (annual)	2031–66 (Annual)	2020–66 (Cumulative)
Short	260	195	130	0	0	**585**
Long and medium	260	195	130	73	20	**1872**
Long and big	260	195	130	73	50	**2859**

Note: Demand changes at the given baseline equilibrium price, in [$MtCO_2$] Source: [109]

In the "Short" scenario, there are no impacts on-demand after 2022. The difference between "Long and medium" and "Long and big" is the size of demand reductions after 2030. The last column of the table shows cumulative reductions in demand, given the baseline price path. We notice that cumulative demand is almost five times higher in "Long and big" than in "Short". As the model is deterministic, there is perfect foresight within each scenario. Before examining the effects of the MSR, it is constructive to consider how the demand reductions play out in the model without MSR. Since the supply of EUAs is then fixed, the waterbed effect is fully operative and hence cumulative emissions are the same with or without the COVID-19 shock. To bring demand in line with constant supply, the ETS price has to come down; the price reduction, shown in Figure 18. 37, is approximately proportional to the reduction in cumulative demand shown in Table 18. 26.

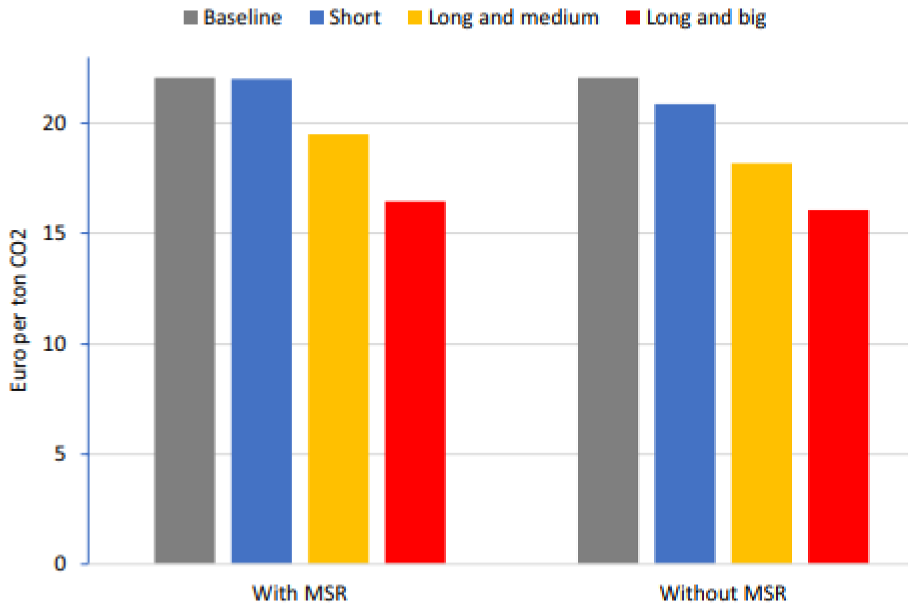


Figure 18. 37. Price in 2020 in different scenarios with and without MSR [109]

In the “Short” scenario, the price drops by 1.2 Euro, while in the “Long and big” scenario it drops by 6.0 Euro. In all scenarios, emissions are higher after 2030 than in the baseline scenario, stimulated by lower ETS prices. Next, we consider the effects of the MSR. In the “Short” scenario, reduced demand for EUAs in 2020-22 leads to more banking of EUAs. By 2024, after three years of 24 per cent intake, 56 percent of these additional banked EUAs have entered the MSR. In the later years, almost all of the additionally banked EUAs eventually enter into the MSR and get cancelled. Cumulative supply of EUAs is reduced almost one-tone with the drop in demand through the MSR; cumulative additional cancelling amounts to 560 Mt (Figure 18. 37, first bar), only slightly below the direct drop shown in Table 2, implying that there is only a 4 percent waterbed effect (Figure 18. 38, right axis). This is why the ETS price hardly changes (Figure 18. 37 seconds vs. first bar).

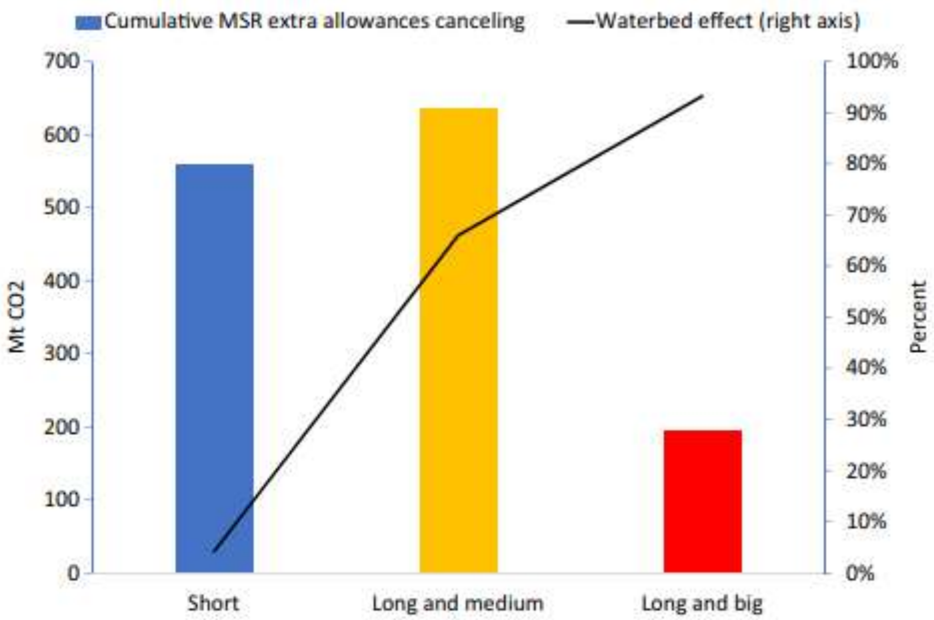


Figure 18. 38. Extra cancelling through MSR and waterbed effect [109]

In the "Long and medium" scenario, the demand reduction is more persistent. Future demand reductions, however, have a lower propensity to flow into the MSR. The extra MSR cancelling is less than 80 Mt (Figure 18. 39, second vs. the first bar), while cumulative demand is decreased by almost 1300 Mt more than in the "Short" scenario (Table 18. 26, second vs the first row). The waterbed effect now amounts to 66 percent (Figure 18. 40, second y-axis). Taken together, the price in 2020 falls by 2.6 Euro, as compared to a drop of 3.9 Euro without the MSR (Fig. 5). In the "Long and big" scenario, the impacts of future demand reductions are even stronger. The reduced future demand reduces banking, and thus the inflow into the MSR, which now works 'in reverse'. Due to lower intake, fewer EUAs get cancelled, from 640 Mt in the "Long and medium" scenario to only 190 Mt in the "Long and big" scenario (Figure 18. 41, third vs the second bar). The waterbed effect is back and almost fully operational at 96 percent (Figure 18. 42, second y-axis). The price in 2020 falls by 5.6 Euro, i.e., almost as much as the 6 Euro drop without the MSR (Figure 18. 37).

18.9 Annexes

18.9.1 Annexe 1: ICAO Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)

ICAO has identified the following areas that can contribute to the attainment of the global aspirational goals. They are commonly referred to as the "***ICAO'S BASKET OF MEASURES***", and includes the following ones:

- Aircraft related technology and standards
- Improved air traffic management and operational improvements
- Development and deployment of sustainable aviation fuel
- The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA).

Figure 1 illustrates the expected contribution of measures for reducing international aviation net CO2 emissions.

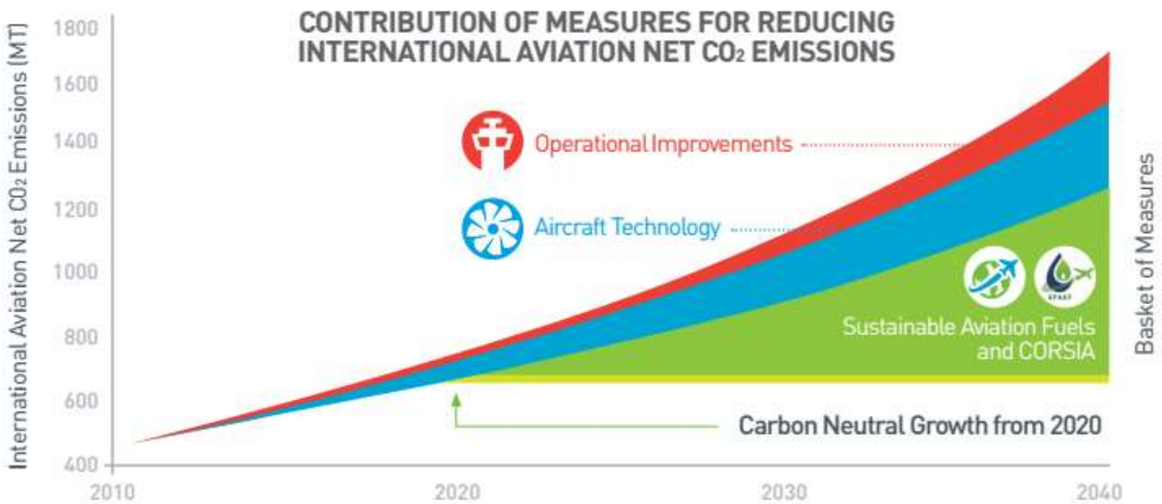


Figure 1. Contribution of measures for reducing international aviation net CO2 emissions [113]

Among ICAO's measures, the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), is the first global market-based measure for any sector. It represents a cooperative approach that moves away from a "patchwork" of national or regional regulatory initiatives through the implementation of a global scheme that has been developed through global consensus among governments, industry, and international organizations. It offers a harmonized way to reduce emissions from international aviation ensuring that there is no market distortion while respecting the special circumstances and respective capabilities of ICAO Member States [114].

18.9.1.1 History of development

The 37th Session of the ICAO Assembly (2010) adopted two aspirational goals:

- to improve energy efficiency by 2 per cent per year until 2050, and
- to achieve carbon-neutral growth from 2020 onwards.

Measures include technological innovations, operational improvements, sustainable aviation fuels, and market-based measures [114] [115].

The 38th Session of the ICAO Assembly (2013) decided to develop a global market-based measure for international aviation, further discussions on its design features and implementation mechanisms were undertaken, including possible means to address special circumstances and respective capabilities of States [114] [116].

The 39th Session of the ICAO Assembly (2016). States finally adopted a global market-based measure scheme for international aviation, in the form of the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), to address the increase in total CO2 emissions from international aviation above the 2020 levels (Assembly Resolution A39-3) [114] [117].

The 40th Session of the ICAO Assembly (2019) acknowledges the progress achieved on all elements of the basket of measures available to address CO2 emissions from international aviation, including aircraft technologies, operational improvements, sustainable aviation fuels and CORSIA. The 40th Session affirms the preference for the use of aircraft technologies, operational improvements and sustainable aviation fuels that provide the environmental benefits within the aviation sector. Marked that the environmental benefits from aircraft technologies, operational improvements and sustainable aviation fuels may not deliver sufficient CO2 emissions reductions to address the growth of international air traffic. Recalls its decision at the 39th Session to implement a GMBM scheme in the form of the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). Determines that the CORSIA is the only global market-based measure applying to CO2 emissions from international aviation to avoid a possible patchwork of duplicative State or regional MBMs [118].

18.9.1.2 Phased implementation for CORSIA

ICAO MEMBER STATES PARTICIPATING IN CORSIA need to ensure that their aeroplane operators comply with the CORSIA offsetting requirements every three years, in addition to annual CO2 MRV [1].

Figure 2. . Phases of CORSIA implementation [113].

The 39th and 40th Session of the ICAO Assembly introduced approach, which based on the use of a phased implementation (Figure 2) for the CORSIA to accommodate the special circumstances and respective capabilities of States, in particular developing States, while minimizing market distortion, as follows:

- Pilot phase applies from 2021 through 2023 to States that have volunteered to participate in the scheme.
- The first phase applies from 2024 through 2026 to States that voluntarily participate in the pilot phase, as well as any other States that volunteer to participate in this phase.
- The second phase applies from 2027 through 2035 to all States that have an individual share of international aviation activities in RTKs in the year 2018 above 0.5 per cent of total RTKs; or those states whose cumulative share in the list of States from the highest to the lowest amount of RTKs reaches 90 per cent of total RTKs, [except Least Developed Countries (LDCs), Small Island Developing

States (SIDS) and Landlocked Developing Countries (LLDCs) unless they volunteer to participate in this phase].

Starting in 2022, the Council will conduct a review of the implementation of the CORSIA every three years, including its impact on the growth of international aviation. This review will serve as an important basis for the Council to consider whether it is necessary to make adjustments to the next phase or compliance cycle and, as appropriate, to recommend such adjustments to the Assembly for its decision [117] [118].

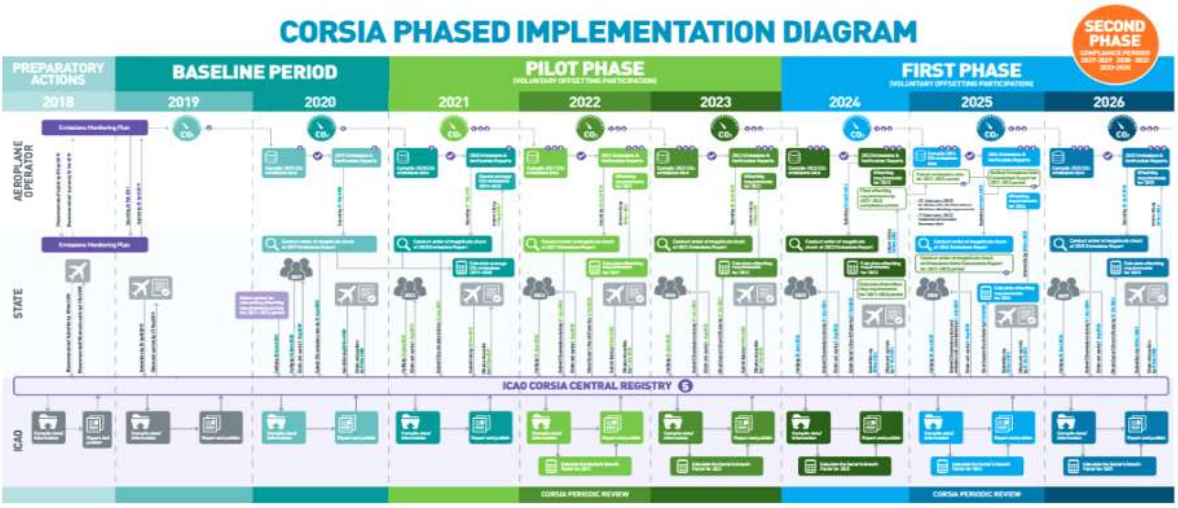


Figure 3. *CORSIA phased implementation diagram* [113]

Figure 4. *CORSIA implementation elements* [113]

18.9.1.3 How to calculate CO2 offsetting requirements

CO2 offsetting requirements are calculated according to the following expression:

Operator's annual emissions X Growth Factor = CO2 offsetting requirements [113]

The Growth Factor changes every year taking into account both the sectoral and the individual operator's emissions growth. The Growth Factor is the per cent increase in the number of emissions from the baseline to a given future year and is calculated by ICAO.

Figure 5. Calculation CO2 offering requirements [113]

After the calculation of the offsetting requirements to be attributed to an aeroplane operator:

- The operator reports the use of CORSIA Eligible Fuels for the compliance period.
- The State deducts the benefits from the use of CORSIA Eligible Fuels and informs the operator's final offsetting requirements for the 3-year compliance period.
- The operator purchases and cancels eligible emissions units equivalent to its final offsetting requirements for the compliance period.
- The operator provides a validated Emissions Units Cancellation Report to the State, who checks the Report and informs ICAO [113].

18.9.1.4 How does an airplane operator monitor CO2 emissions?

An aeroplane operator shall monitor and record its fuel use from international flights in accordance with an eligible monitoring method approved by the State to which it is attributed, and shall use the same eligible monitoring method for the entire 3-year compliance period.

It can choose from five different eligible methods for fuel use monitoring. The methods are equivalent, there is no hierarchy for selecting a method. It may also choose to use the ICAO CORSIA CO2 Estimation and Reporting Tool (CERT), accessible through the ICAO CORSIA website [113].

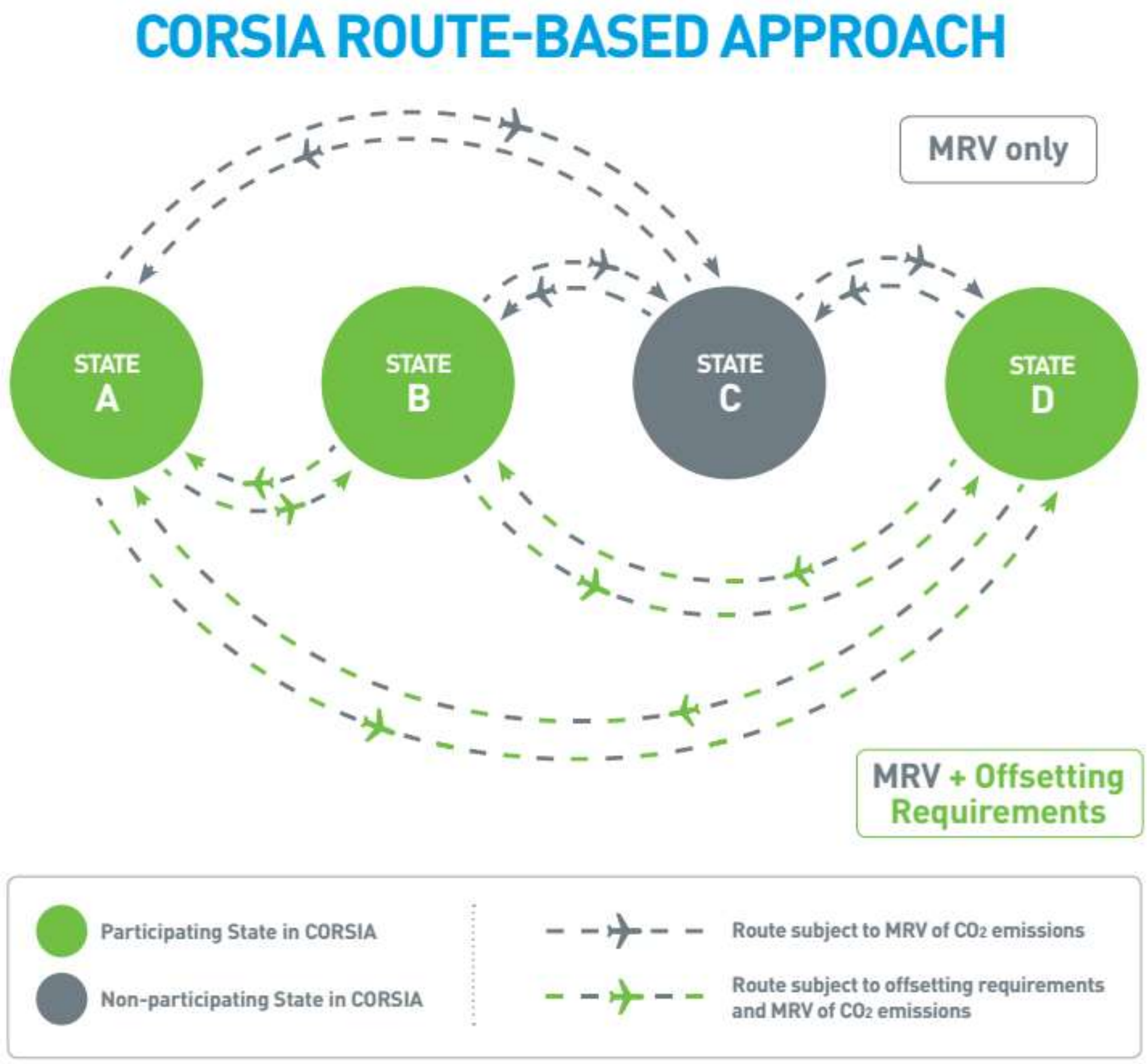


Figure 6. CORSIA route-based approach [113]

18.9.1.5 CORSIA implementation

The success of the implementation of CORSIA relies on the establishment of robust and transparent monitoring, reporting and verification (MRV) system, which includes procedures on how to monitor the fuel use, collect data and calculate CO2 emissions; report CO2 emissions data, and verify CO2 emissions data to ensure accuracy and avoid mistakes [114].

The implementation of CORSIA required a "package" of CORSIA-related SARPs and guidance which comprise of three distinct but interrelated components:

a) Annexe 16, Volume IV, which provides the required actions by States and aeroplane operators (the "what" and "when") to implement CORSIA [114] [50];
b) Environmental Technical Manual (ETM - Doc 9501), Volume IV, which guides the process (the "how") to implement CORSIA [114] [119]; and
c) Five CORSIA Implementation Elements, which are reflected in 14 ICAO documents and are approved by the Council before their publication [114].

These ICAO documents are directly referenced in Annex 16, Volume IV and are essential for the implementation of CORSIA. The Council adopted the First Edition of Annex 16. Volume IV in June 2018. Following its adoption, the First Edition of Annex 16, Volume IV became applicable on 1 January 2019. The First Edition of the Environmental Technical Manual (Doc 9501), Volume IV was issued under the authority of the ICAO Secretary-General in August 2018. This manual will be periodically revised to make the most recent information available to administrating authorities, aeroplane operators, verification bodies and other interested parties in a timely manner, aiming at achieving the highest degree of harmonisation possible.

The Annex 16 Volume IV and ETM Volume IV follow a similar structure to that of the other Annex 16 Volumes (Figure 6). This includes Chapters containing requirements on administration, MRV, CO2 offsetting requirements, Sustainable Aviation Fuels and eligible Emissions Units. Additional detailed processes and information within the Appendices supplement these requirements. The Annex 16 Volume IV also has Attachments that provide supporting information on the implementation of the standard and recommended practices.

The CORSIA also raises various innovative issues, such as;

- the definition of roles and responsibilities of the ICAO Secretariat;
- information required for the implementation of CORSIA and
- information that will need to be updated more often than the typical three-year approval cycle of Annex 16 Volumes. To address these issues, it is proposed to develop and use 'ICAO CORSIA Supporting Information' that is expected to be captured in some form of ICAO documentation (e.g., ICAO Document, Council Decision), managed and approved by an ICAO Body and finally published by ICAO such that it is available to the public. This information is directly referenced in Annex 16 Volume IV and is therefore considered to be an integral part of Standard and Recommend Practices.

The content of the ICAO CORSIA Supporting Information will be built upon the relevant Supporting Documents. The Supporting Documents will include technical information and ICAO processes that will serve as the basis for managing and approving the Supporting Information. Thus the roles of ICAO in the implementation of CORSIA, which cannot be placed directly in Annex 16 Volume IV, can be clearly defined [120].

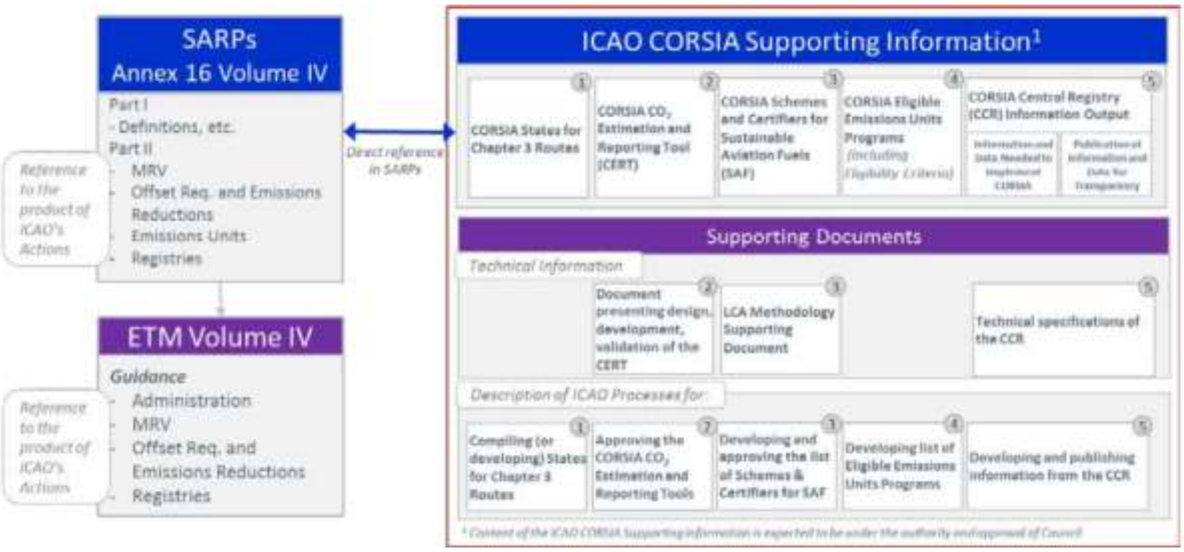


Figure 7. Overview of the CORSIA Package containing various elements including the Annex 16 Volume IV (SARPs), ETM, ICAO CORSIA Supporting Information and Supporting Documents [120].

The ICAO Council has been undertaking work, with the contribution of the CAEP, on the development of the five CORSIA Implementation Elements, namely

- The CORSIA States for Chapter 3 State Pairs is the list of States participating in CORSIA and will be used to define route-based emissions coverage every year from 2021 onwards;
- ICAO CORSIA CO2 Estimation and Reporting Tool (CERT) aims to simplify the estimation and reporting of CO2 emissions from international flights for those operators with low levels of activity to fulfil their monitoring and reporting requirements under CORSIA (for more details, see the dedicated article in this chapter);
- CORSIA Eligible Fuels cover aviation fuels used for CORSIA to reduce the offsetting requirements of aeroplane operators (for more details, see the dedicated article in this chapter);
- CORSIA Eligible Emissions Units are emissions units from the carbon market that can be purchased by aeroplane operators to fulfil the offsetting requirements under CORSIA (for more details, see the dedicated article in this chapter); and
- CORSIA Central Registry (CCR) is an information management system that will allow the input and storage of CORSIA-relevant information reported by States, as well as calculations and reporting by ICAO, in accordance with the CORSIA MRV requirements as contained in Annex 16, Volume IV (for more details, see the dedicated article in this chapter). In June 2018, to ensure that No Country is Left Behind, the Council endorsed the ICAO ACT-CORSIA (Assistance, Capacity-building and Training for the CORSIA) Programme, emphasizing the importance of a coordinated approach under ICAO to harmonize and bring together all relevant actions and promote coherence to capacity building efforts related to CORSIA implementation. By the end of June 2019, CORSIA buddy partnerships under ACT-CORSIA had been established, involving 15 donor States and 98 recipient States [114].

18.9.1.6 CORSIA emissions unit eligibility criteria.

Program Design Elements. At the program level, ICAO should ensure that eligible offset credit programs meet the following design elements:

a) Clear Methodologies and Protocols, and their Development Process.
b) Scope Considerations.
c) Offset Credit Issuance and Retirement Procedures.
d) Identification and Tracking.
e) Legal Nature and Transfer of Units.
f) Validation and Verification procedures.
g) Program Governance.
h) Transparency and Public Participation Provisions.
i) Safeguards System.
j) Sustainable Development Criteria.
k) Avoidance of Double Counting, Issuance and Claiming.

Carbon Offset Credit Integrity Assessment Criteria: There are several generally agreed principles that have been broadly applied across both regulatory and voluntary offset credit programs to address environmental and social integrity.

Eligibility criteria [121] should apply at the program level, as the expertise and resources needed to develop and implement ICAO emissions criteria at a methodology and project level is likely to be considerable. *Eligibility Criterion is:*

- Carbon offset programs must generate units that represent emissions reductions, avoidance, or additional removals.
- Carbon offset credits must be based on a realistic and credible baseline.
- Carbon offset credits must be quantified, monitored, reported and verified.
- Carbon offset credits must have a clear and transparent chain of custody within the offset program.
- Permanence.
- A system must have measures in place to assess and mitigate incidences of material leakage.
- Are only counted once towards a mitigation obligation.
- Carbon offset credits must represent emissions reductions, avoidance, or carbon sequestration from projects that do no net harm [119].

18.9.2 Annexe 2: European Union Emissions Trading System (EU ETS).

The EU Emissions Trading System (EU ETS) is the cornerstone of the European Union's policy to tackle climate change, and a key tool for reducing greenhouse gas emissions cost-effectively, including from the aviation sector. It operates in 31 countries: the 28 EU Member States, Iceland, Liechtenstein and Norway.

The EU ETS is the first and so far the biggest international system capping greenhouse gas emissions; it currently covers half of the EU's CO2 emissions, encompassing those from around 12 000 power stations and industrial plants in 31 countries, and, under its current scope, around 500 commercial and non-commercial aircraft operators that fly between airports in the European Economic Area (EEA). The EU ETS Directive has recently been revised in line with the European Council Conclusions of October 2014 [17] that confirmed that the EU ETS will be the main European instrument to achieve the EU's binding 2030 target of an at least 40% domestic reduction of greenhouse gases compared to 1990 [18].

The EU ETS began operation in 2005; a series of important changes to the way it works took effect in 2013, strengthening the system. The EU ETS works on the "cap and trade" principle. This means there is a "cap", or limit, on the total amount of certain greenhouse gases that can be emitted by the factories, power plants, other installations and aircraft operators in the system. Within this cap, companies can sell to or buy emission allowances from one another. The limit on allowances available provides certainty that the environmental objective is achieved and gives allowances a market value.

The European Directive 2008/101/EC amending directive 2003/87/EC so as to include aviation activities in the scheme for greenhouse gas emission allowance has been applied since 2nd February 2009.

For the aviation sector, there are two distinct periods defined by the Directive:

- 1st period (phase II): 2012
- 2nd period (phase III): 2013-2020

For 2012, the aviation sector allowances' cap has been set at 97% of the historical emissions (the mean between emissions of 2004, 2005 and 2006). For the next period, the cap has been set at 95%.

Airlines continue to receive the large majority of their allowances for free in the period 2013-2020. The annual cap on aviation allowances for phase 3 of the EU ETS (2013-20) was originally 210,349,264 allowances (plus 116,524 allowances from 2014 to account for Croatia's integration) [122].

The total of emission allowances corresponding to this cap is split in this way:

- 85% (in 2012) or 82% (from 2013) of the emission allowances are allocated freely each year, proportionally based on the total activity data (in tonnes-kilometres) reported by each operator in

2010. The Arrêté concerning the allocation of free allowances for aircraft operators has been published in December 2011.

- 15% are put up for auction.
- 3% (from 2013) is placed in a special reserve for "new entrants" or "fast-growing" operators.

For aviation, the cap is calculated based on the average emissions from the years 2004-2006. Aircraft Operators are entitled to free allocation based on an efficiency benchmark, but this might not cover the totality of emissions. The remaining allowances need to be purchased from auctions or the secondary market. The system allows aircraft operators to use aviation allowances or general (stationary installations) allowances to cover their emissions.

By 30th April each year, companies, including aircraft operators, have to surrender allowances to cover their emissions from the previous calendar year. If a company reduces its emissions, it can keep the spare allowances to cover its future needs or sell them to another company that is short of allowances. The flexibility that trading brings ensures that emissions are cut where it costs least to do so. The number of allowances reduces over time so that total emissions fall.

As regards aviation, legislation to include aviation in the EU ETS was adopted in 2008 by the European Parliament and the Council [122]. The 2006 proposal to include aviation in the EU ETS, in line with the resolution of the 2004 ICAO Assembly deciding not to develop a global measure but to favour the inclusion of aviation in open regional systems, was accompanied by a detailed impact assessment [123]. After careful analysis of the different options, it was concluded that this was the most cost-efficient and environmentally effective option for addressing aviation emissions.

In October 2013, the Assembly of the International Civil Aviation Organisation (ICAO) decided to develop a global market-based mechanism (MBM) for international aviation emissions. Following this agreement, the EU decided to limit the scope of the EU ETS to flights between airports located in the European Economic Area (EEA) for the period 2013- 2016 (Regulation 421/2014) and to carry out a new revision in the light of the outcome of the 2016 ICAO Assembly. The temporary limitation follows on from the April 2013 'stop the clock' decision [124] adopted to promote progress on global action at the 2013 ICAO Assembly.

The European Commission assessed the outcome of the 39th ICAO Assembly and, in that light, made a new legislative proposal on the scope of the EU ETS. Following the EU legislative process, this Regulation was adopted in December 2017 [125].

The legislation maintains the scope of the EU ETS for aviation limited to intra-EEA flights. It foresees that once there is clarity on the nature and content of the legal instruments adopted by ICAO for the implementation of CORSIA, as well as about the intentions of other states regarding its implementation, a further assessment should take place and a report be presented to the European Parliament and the Council considering how to implement CORSIA in Union law through a revision of the EU ETS Directive. This should be accompanied, where appropriate, by a proposal to the European Parliament and to the Council to revise the EU ETS Directive that is consistent with the Union economy-wide greenhouse gas emission reduction commitment for 2030 to preserve the environmental integrity and effectiveness of Union climate action.

The Regulation also sets out the basis for the implementation of CORSIA. It provides for European legislation on the monitoring, reporting and verification rules that avoid any distortion of competition to implement CORSIA in European Union law. This will be undertaken through a delegated act under the EU ETS Directive.

The EU ETS has been effectively implemented over recent years on intra-EEA flights and has ensured a level playing field with a very high level of compliance [7]. It will continue to be a central element of the EU policy to address aviation CO2 emissions in the coming years. The complete, consistent, transparent and accurate monitoring, reporting and verification of greenhouse gas emissions remains fundamental for the effective operation of the EU ETS. Aviation operators, verifiers and competent authorities have already gained wide experience with monitoring and reporting; detailed rules are prescribed by Regulations (EU) N°600/2012 [126] and 601/2012 [127].

The EU legislation establishes exemptions and simplifications to avoid excessive administrative burden for the smallest operators of aircraft. Since the EU ETS for aviation took effect in 2012 a deminimis exemption for commercial operators – with either fewer than 243 flights per period for three consecutive four-month periods or flights with total annual emissions lower than 10 000 tonnes CO2 per year applies. This means that many aircraft operators from developing countries are exempted from the EU ETS. Indeed, over 90 States have no commercial aircraft operators included in the scope of the EU ETS. In addition, from 2013 flights by non-commercial aircraft operators with total annual emissions lower than 1000 tonnes CO2 per year are excluded from the EU ETS.

This simplified method allows operators to fill up the monitoring plan more easily, and to use a useful calculation tool provided by Eurocontrol: the ETS Support Facility. This tool can pre-populate the report template of the AO based on Eurocontrol's flights' data (www.eurocontrol.int/ets-support-facility). The ETS Support Facility bases its calculation on a tool which estimates emissions using the flight distance and aircraft type: the Small Emitters' Tool. It is the only tool approved by the Commission for this purpose and can be used independently from the ETS Support Facility, also that involves more work from the operator.

From 2013, 3% of the total of allowances for the aviation sector is set aside in a special reserve for operators :

- who start performing an aviation activity after 2010 ("new entrants"), or
- whose tonne-kilometre data increases by an average of more than18 % annually between 2010 and 2014, amounting to more than 93.88% cumulated from 2010 to 2014 ("fast-growing" operators).

The free allowances "new entrants" can get from this special reserve are proportional to the 2014 tonne-kilometre data they reported. For "fast-growing" operators, only the tonnes-kilometre data reported over the 18% annual growth limit are taken into account to calculate the free allowances they can get from the special reserve.

The aircraft operators who planned to benefit from the special reserve had until June 30, 2015, to submit their applications. The allowances from the special reserve will be distributed from 2017 to 2020.

A further administrative simplification applies to small aircraft operators emitting less than 25 000 tonnes of CO2 per year, who can choose to use the small emitters' tool rather than independent verification of their emissions. In addition, small emitter aircraft operators can use simplified reporting procedures under the existing legislation. The recent amendment to extend the intra-EEA scope after 2016 includes a new simplification, allowing aircraft operators emitting less than 3 000 tCO2 per year on intra-EEA flights to use the small emitters' tool. The EU legislation foresees that, where a third country takes measures to reduce the climate change impact of flights departing from its airports, the EU will consider options available in order to provide for optimal interaction between the EU scheme and that country's measures. In such a case, flights arriving from the third country could be excluded from the scope of the EU ETS. This will be the case between the EU and Switzerland following the agreement to link their respective emissions trading systems, which was signed on 23rd November 2017. The EU, therefore, encourages other countries to adopt measures of their own and is ready to engage in bilateral discussions with any country that has done so. The legislation also makes it clear that if there is agreement on global measures, the EU shall consider whether amendments to the EU legislation regarding aviation under the EU ETS are necessary.

18.9.2.1 Key points

During the fourth phase of the EU ETS (2021-2030), the EU is aiming to cut its emissions by at least 40% by 2030, in line with the 2015 Paris Agreement on climate change. To meet these targets, the EU established a GHG allowance trading system. Each allowance covers the emission of 1 tonne of CO2 or CO2 equivalent over a specific period.

EU countries have amended the original legislation several times as the system has evolved. The most recent changes were agreed in March 2018.

The total number of allowances issued in the EU is reduced annually: by 1.74% between 2013-2020 and by 2.2% from 2021.

Aircraft flying to airports in the EU, Iceland or Norway from elsewhere in the world is exempt from the EU ETS until 31 December 2023.

The allowances may be transferred between installations, airlines and market participants in the EU and to non-EU countries where they are recognised (none so far); they are valid indefinitely if issued from 1 January 2013 onwards, and they are issued from 1 January 2021 onwards cannot be used for phase 3 (2013-2020) compliance.

From 2021, 57% of allowances are to be auctioned. At least half of the EU countries' proceeds must be used for climate-related purposes.

Two new low carbon funding mechanisms will be established:

- The Modernisation Fund will support modernising investment projects in the power sector and wider energy systems in EU countries whose gross domestic product (GDP) per head at market prices in 2013 was below 60% of the EU average; it will comprise 2% of the total number of allowances in 2021-2030;
- The Innovation Fund will support the demonstration of innovative technologies and breakthrough innovation in sectors covered by the EU ETS, including innovative renewables, carbon capture and utilisation, and energy storage; the resources available will correspond to the market value of at least 450 million allowances at the time of their auctioning.

EU countries issue the allowances; ensure recipients of allowances monitor and report their emissions annually; auction, from 2019 onwards, all allowances not allocated free of charge or placed in a market stability reserve; and determine how to use the income from the auctions. Possibilities include measures to:

- develop renewable energy and energy efficiency
- avoid deforestation
- capture and store CO2 safely
- promote low emission public transport
- improve district heating systems
- finance activities to tackle climate change in developing countries;
- submit to the Commission by 30 September 2019 a list and details of the installations covered by the legislation for the 5 years beginning 1 January 2021. This must be repeated at 5-yearly intervals;
- issue annually, by 28 February, the number of allowances to be allocated that year;
- provide the Commission with an annual report on the application of the legislation;
- ensure that allowances can be transferred between installations in the EU and to non-EU countries where the allowances are recognized;

- determine effective penalties for any breaches of the law. Operators without enough allowances to cover their emissions are fined €100 for each tonne of CO2 emitted.

Aviation Sector Cap: The aviation sector cap was originally set at 210 MtCO2e/year. This cap was meant to reflect the initial inclusion of all flights from, to, and within the EEA in the EU ETS. However, following the “stop the clock” temporary suspension until the end of 2016, the number of aviation allowances put into circulation in 2013-2016 was significantly lower than the original cap. In 2017, the intra-EEA scope for aviation was prolonged until 2023. The adjusted approach for determining the annual aviation cap still applies. PHASE 4 (2021-2030): A linear cap reduction factor of 2.2% (48.4 million allowances) annually for both stationary sources and the aviation sector. The linear reduction factor does not have a sunset clause and the cap will continue to decline beyond 2030.

By 2020, global international aviation emissions are projected to be around 70% higher than in 2005 and the International Civil Aviation Organization (ICAO) forecasts that by 2050 they could grow by a further 300-700%. [9]

During the period 2021-2035, and based on expected participation, the scheme is estimated to offset around 80% of the emissions above 2020 levels. This is because participation in the first phases is voluntary for states, and there are exemptions for those with low aviation activity. All EU countries will join the scheme from the start.

18.9.2.2 Auctioning of allowance

Auctioning is the default method of allocating allowances within the EU emissions trading system (EU ETS). This means that businesses have to buy an increasing proportion of allowances through auctions.

In 2013, over 40% of the allowances were auctioned. Over the period 2013-2020, the share auctioned will be higher: it is estimated that up to half of the allowances may be auctioned.

Member States have generated nearly € 15.8 billion from the auctioning of EU ETS allowances over the period 2013-2016. Based on the most recent information available, more than 80% of these revenues has been used or is planned to be used for climate and energy purposes in line with Article 10(3) of the ETS Directive.

In 2017, the average price of emissions of 1 ton of CO2 under the European system of trading in quotas was € 5. At the same time, enterprises that are not part of the quota trading system continue to pay environmental taxes. Their sizes are usually higher: for example, in France - € 31 / t, in the UK - € 21 / t, in Slovenia - € 17 / t.

15.1.1.2 Why ICAO and CORSIA cannot deliver on climate? [128]

As CORSIA is an international agreement which touches on areas of EU competence (climate and aviation), it is ultimately for the EU institutions to determine whether that minimum level of environmental integrity has been reached. This has been codified in the 2017 revision to the EU ETS Directive 2003/87/EC. In line with that legislation, European member states wrote to ICAO at the end of 2018 to state that they were not yet in a position to confirm, either way, whether they will participate in CORSIA. This reflected the EU position that such a decision can only be made once all the CORSIA rules have been decided and following an evaluation by the European Commission of the scheme’s potential environmental effectiveness.

Target the EU’s 2030 economy-wide target commits the bloc to achieve an emissions reduction target of - 40% against 1990 levels. That target is a combination of emission reductions under the bloc’s ETS and targets for each member state for sectors of their economy not covered by ETS under the Climate Action Regulation. In establishing the ETS target, the Council of the EU included outbound aviation emissions i.e. emissions from all flights departing EU airports to any destination either within the EU or beyond the EU, with a target of 111 Mtonnes by 2030 (Council of the EU, 2017). As outbound aviation emissions are currently (2017) estimated to be 174 Mtonnes (UNFCCC), that target is a reduction of over 36% from current emissions. It should be noted that while the initial target includes all emissions from outbound aviation, the scope of aviation's inclusion in EU ETS has been limited to outbound flights within Europe until at least 2024.

By contrast, the CORSIA target has been set to stabilize emissions from international aviation at 2020 levels, allowing airlines to continue growing their emissions. Setting aside how each measure will achieve their respective target (airlines purchasing allowance reductions from other sectors covered by ETS, and airlines purchasing offsets approved by ICAO under CORSIA), the CORSIA target is a weaker target than the EU 2030 target. Therefore, any move to replace the existing ETS target with the CORSIA target would represent a regression in Europe's climate ambition, a move which the Paris Agreement explicitly prohibits.

A further distinction between the EU 2030 targets and the CORSIA scheme is that the former is to be solely achieved through reductions within the EU and therefore does not recognise the use of international credits. In contrast, CORSIA is built explicitly around the use of such international credits.

As a result, implementation of CORSIA into EU law, in a manner which replaces existing EU legislation, risks creating a situation where all sectors of Europe's economy, bar aviation, are legally obliged to achieve emission reductions without offsetting. As the commitment to domestic reductions was stated in Europe's NDC, which explicitly states "No contribution from international credits" backtracking on this for any part of its economy would, like with a weaker target, count as backsliding which the agreement prohibits.

Due to the weaker target and the use of offsets, implementing CORSIA in EU law in a manner which replaces existing legal commitments would weaken Europe's overall climate ambition. According to independent research commissioned by T&E, over the period 2021-2030, Europe's aviation emissions would increase 683.8 Mtonnes CO2 (TAKS, 2019), which is equivalent to the 2017 CO2 emissions of Poland and France combined (Global Carbon Atlas, 2019). [20], [21], [22], [23]

18.9.2.3 Impact on fuel consumption and/or CO2 emissions.

The environmental outcome of an emissions trading system is determined by the emissions cap. Aircraft operators are able to use allowances from outside the aviation sector to cover their emissions. The absolute level of CO2 emissions from the aviation sector itself can exceed the number of allowances allocated to it, as the increase is offset by CO2 emissions reductions in other sectors of the economy covered by the EU ETS.

With the inclusion of intra-European flights in the EU ETS it has delivered around 100 MT of CO2 reductions/offsets between 2012 and 2018. The total amount of annual allowances to be issued will be around 38 million, whilst verified CO2 emissions from aviation activities carried out between aerodromes located in the EEA has fluctuated between 53.5 MT CO2 in 2013 and 61MT in 2016. This means that the EU ETS is now contributing more than 23 MT CO2 of emission reductions annually [19], or around 100 MT CO2 over 2012-2018, partly within the sector (airlines reduce their emissions to avoid paying for additional units) or in other sectors (airlines purchase units from other ETS sectors, which would have to reduce their emissions consistently). While some reductions are likely to be within the aviation sector, encouraged by the EU ETS's economic incentive for limiting emissions or use of aviation biofuels, the majority of reductions are expected to occur in other sectors.

Putting a price on greenhouse gas emissions is important to harness market forces and achieve cost-effective emission reductions. In parallel to providing a carbon price which incentivises emission reductions, the EU ETS also supports the reduction of greenhouse gas emissions through €2.1bn fund for the deployment of innovative renewables and carbon capture and storage. This funding has been raised from the sale of 300 million emission allowances from the New Entrants' Reserve of the third phase of the EU ETS. This includes over €900m for supporting bioenergy projects, including advanced biofuels.

In terms of its contribution towards the ICAO global goals, the states implementing the EU ETS have delivered, in "net" terms, a reduction of around 100 MT of aviation CO2 emissions over 2012-2018 for the scope that is covered, and this reduction will continue to increase in the future under the new legislation. Other emission reduction measures taken, either collectively throughout Europe or by any of the 31 individual states implementing the EU ETS, will also contribute towards the ICAO global goals. Such measures are likely to moderate the anticipated growth in aviation emissions.

18.9.3 Annexe 3: ICAO CO2 emissions standard for new aircraft

Achieving emissions reductions through technical standards is a fundamental element of ICAO's basket of measures to address aviation emissions. The sector remains the last major transport mode without vehicle emission standards, so the intensive CAEP work over the past six years was an important opportunity for ICAO to deliver on its stated climate goals [48].

The development of an aeroplane CO2 Standard was one recommended element within the ICAO Programme of Action on International Aviation and Climate Change, which was subsequently endorsed by the ICAO High-level Meeting of Member States in October 2009. Following the agreement of a draft Annex 16 Volume III certification requirement1 at CAEP/9 in February 2013, the CAEP/10 work programme (2013-2016) for WG3 included work items E.05 on an aeroplane CO2 emissions Standard and E.06 on interdependencies (Appendix A). These items were allocated to the CO2Task Group (CO2TG) [49].

In 2017 the 36-State ICAO Council has adopted a new aircraft CO2 emissions standard which will reduce the impact of aviation greenhouse gas emissions on the global climate. Contained in a new Volume III to Annex 16 of the Chicago Convention (Environmental Protection), the aircraft CO2 emissions measure represents the world's first global design certification standard governing CO2 emissions for any industry sector [49] [48] [50].

The Standard will apply to new aircraft type designs from 2020, and aircraft type designs already in production as of 2023. Those in-production aircraft which by 2028 do not meet the standard will no longer be able to be produced unless their designs are sufficiently modified [48] .

- *Subsonic jet aeroplanes, including their derived versions, of greater than 5 700 kg maximum take-off mass* for which the application for a type certificate was submitted on or after 1 January 2020, except for those aeroplanes of less than or equal to 60 000 kg maximum take-off mass with a maximum passenger seating capacity of 19 seats or less;
- *Subsonic jet aeroplanes, including their derived versions, of greater than 5 700 kg and less than or equal to 60 000 kg maximum take-off mass with a maximum passenger seating capacity of 19 seats or less*, for which the application for a type certificate was submitted on or after 1 January 2023;
- *All propeller-driven aeroplanes, including their derived versions, of greater than 8 618 kg maximum take-off mass,* for which the application for a type certificate was submitted on or after 1 January 2020;
- *Derived versions of non-CO2-certified subsonic jet aeroplanes* of greater than 5 700 kg maximum certificated take-off mass for which the application for certification of the change in type design was submitted on or after 1 January 2023;
- *Derived versions of non-CO2 certified propeller-driven aeroplanes of greater than 8 618 kg maximum certificated takeoff mass* for which the application for certification of the change in type design was submitted on or after 1 January 2023;

- *Individual non-CO2-certified subsonic jet aeroplanes* of greater than 5 700 kg maximum certificated take-off mass for which a certificate of airworthiness was first issued on or after 1 January 2028; and
- *Individual non-CO2-certified propeller-driven aeroplanes* of greater than 8 618 kg maximum certificated take-off mass for which a certificate of airworthiness was first issued on or after 1 January 2028 [50] [48] [129] .

The key points in the CO2 standards for aircraft are:

- Reduces aircraft CO2 emissions by encouraging the integration of fuel-efficient technologies into aircraft design and development.
- Ensures that older aircraft models end production in an appropriate timeframe or that manufacturers invest in technology to improve their efficiency.
- The standard also ensures that new designs go beyond the highest fuel efficiency of today's aircraft. Is a challenging and robust standard that brings CO2 emissions into the formal certification process that new aircraft need to pass in order to enter service.
- Is a significant milestone for the sector: the first such standard for aircraft and is key to the sector's long-term commitment to reduce CO2 emissions from aviation?
- Is part of a basket of measures to deal with industry's climate impact which include improved operations, sustainable alternative fuels, better use of infrastructure and new technology (which the CO2 Standard will support).
- Is complementary to an agreement in September/October this year on a global market-based measure to cap the growth in aviation CO2 emissions from 2020 and meet the industry's mid-term goal.
- Was developed by the ICAO Committee on Aviation Environmental Protection (CAEP) over six years through 26 meetings and some 700 papers and pieces of analysis by 170 aviation experts from governments, industry and environmental groups [129].

CO2 differs fundamentally from ICAO's noise and NOx standards because fuel efficiency has always been a major aircraft design parameter whereas noise and (to a large extent) engine emissions abatement measures, are not in themselves inherent to building aircraft – at least until the regulation was introduced. While those measures simply add costs, every fuel efficiency improving technology has both costs and savings. [51]

Fuel efficiency is central to aviation's business and sustainable growth strategy — as evidenced by the huge gains in fuel efficiency over the decades. The formalisation of a CO2 Standard for aircraft is an important part of the sector's overall basket of measures for climate action and is complementary to the significant work already underway in the sector: new aircraft and alternative fuels technology; optimising operational procedures; and improved infrastructure.

The Standard will ensure that all newly-developed aircraft and engines incorporate the latest commercially-available proven technologies, mindful that no single technology can be applied across the entire range of new aircraft and engine models from small regional and business aircraft to the very large capacity long-range commercial aircraft.

The CO2 emissions of aircraft become part of the certification process, alongside safety compliance and noise measures, among other elements.

The establishment of the first global CO2 standard will allow monitoring and progress in the future towards achieving CO2 emissions reductions in line with research and development targets and technical feasibility [52].

18.9.3.1 How do the CO_2 standards work?

The CO_2 Standard focuses on cruise flight performance because the cruise portion of a flight is typically when the most fuel is consumed, and the majority of CO_2 is emitted.

It takes account of the 'transport capability' of the aircraft — i.e. what is transported and how far it is transported. These two elements, the payload, and the range, are essential in the design of any aircraft. For each aircraft type, depending on its size and weight, the CO_2 Standard defines a maximum metric value (fuel burn per flight kilometre) that may not be exceeded.

For each aircraft type, depending on its size and weight, the CO_2 Standard defines a maximum metric value (fuel burn per flight kilometre) that may not be exceeded [52].

18.9.3.1.1 CO_2 metric system to measure the aeroplane fuel burn

This CO_2 metric system intends to equitably reward advances in aeroplane technologies (e.g. propulsion, aerodynamics and structures) that contribute to reductions in aeroplane CO_2 emissions and differentiate between aeroplanes with different generations of these technologies. As well as accommodating the full range of technologies and designs which manufacturers can employ to reduce CO_2 emissions, the CO_2 metric system has been designed to be common across different aeroplane categories, regardless of aeroplane purpose or capability. An overview of the CO_2 Metric System can be found in Figure 8 [130].

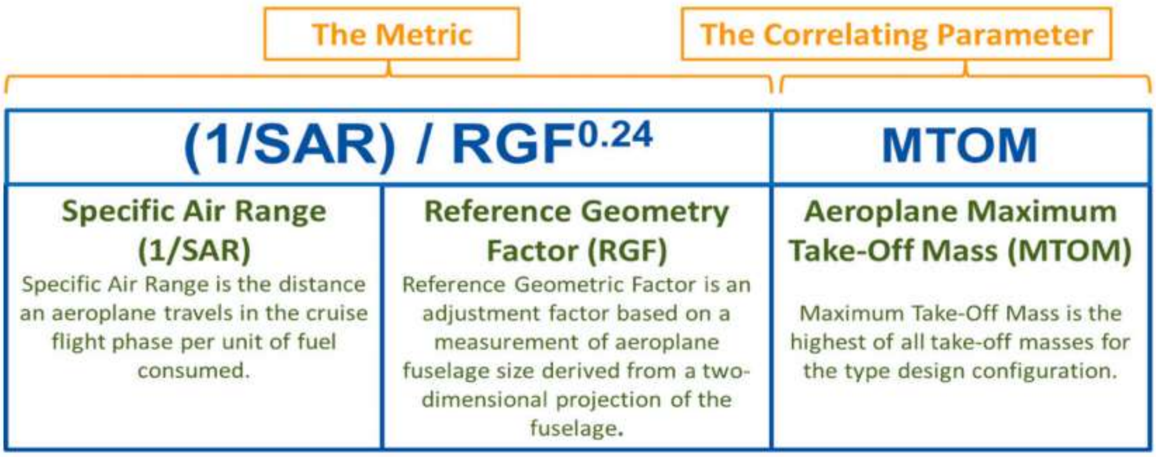


Figure 8. *An overview of the CO_2 Metric System [7].*

To establish the fuel efficiency of the aeroplane, the CO_2 metric system uses multiple test points to represent the fuel burn performance of an aeroplane type during the cruise phase of flight. Specifically, there are three averaged (i.e. equally weighted) points representing aeroplane high, middle, and low gross masses, which are calculated as a function of Maximum Take-Off Mass (MTOM). Each of these represents an aeroplane cruise gross mass seen regularly in service. The objective of using three gross mass cruise points is to evaluate fuel burn performance more relevant to day-to-day aeroplane operations. The metric system is based on the inverse of Specific Air Range (i.e. 1/SAR), where SAR represents the distance an aeroplane travels in the cruise flight phase per unit of fuel consumed. In some aeroplane designs, there are instances where changes in aeroplane size may not reflect changes in aeroplane weight, for example when an aeroplane is a stretched version of an existing aeroplane design [130].

To better account for such instances, not to mention the wide variety of aeroplane types and the technologies they employ, an adjustment factor was used to represent aeroplane size. This is defined as the Reference Geometric Factor (RGF), and it is a measure of aeroplane cabin size based on a two-dimensional projection of the cabin. This improved the performance of the CO2 metric system, making it fairer and better able to account for different aeroplane type designs.

The overall capabilities of the aeroplane design are represented in the CO2 metric system by the certified MTOM. This accounts for the majority of aeroplane design features which allow it to meet market demand. Based on the CO2 metric system, CAEP developed procedures for the certification requirement including, inter alia, the flight test and measurement conditions; the measurement of SAR; corrections to reference conditions; and the definition of the RGF used in the CO2 emissions metric. CAEP utilised manufacturers' existing practices in measuring aeroplane fuel burn to understand how current practices could be used and built upon for the new Standard [130].

18.9.3.1.2 Setting the regulatory limit

ICAO environmental Standards are designed to be environmentally effective, technically feasible, economically reasonable while considering environmental interdependencies.

This involved defining an analytical space within which CAEP would work to investigate the options available. This included the development of options for the regulatory limit line, applicability options and dates, and all the associated assumptions which allowed the CAEP working groups to perform the cost-effectiveness analysis required to make an informed decision on the Standard at the CAEP/10 meeting. The foundation of the CAEP/10 recommendation on the CO2 emissions Standard was supported by this significant data-informed process, involving input from ICAO member states and stakeholders.

The modelling exercise involved several analytical tools, including fleet evolution modelling, environmental benefits, recurring costs, non-recurring costs, costs per metric tonne of CO2 avoided, certification costs, applicability scenarios and various sensitivity studies to inform the decision-making process. This work allowed CAEP to conduct an analysis, with the aim of providing a reasonable assessment of the economic costs and environmental benefits for a potential, CO2 standard in comparison with a "no action" baseline [130].

CHOICES CONSIDERED DURING THE CO2 STANDARD WORK

- Ten Regulatory Limit Lines;
- Treatment of aeroplanes above and below 60 tonnes;
- New Type and In-Production applicability;
- Production cut-off; and
- Applicability dates of 2020, 2023, 2025 and 2028.

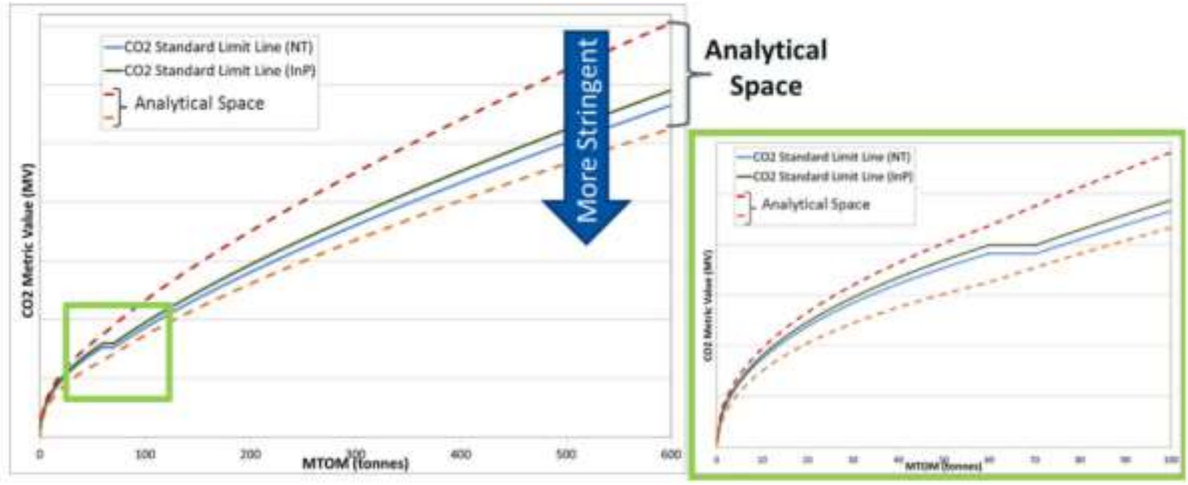


Figure 9. *The CO2 Standard regulatory limits [7].*

18.9.3.1.3 CO2 reduction

Each new generation of aircraft is roughly 15-20% more efficient than the model it replaces. The CO2 Standard mandates that these improvements continue.

However, the continuous development of new aircraft and engine technology, underpinned by the CO2 Standard, is only one part of overall aircraft efficiency improvements.

The aviation industry approach focuses on four pillars of climate action: reducing fuel use (and CO2 emissions) through new technology and alternative fuels; better operations of existing aircraft; and infrastructure improvements. For all emissions that cannot be reduced through these pillars, a global market-based measure will be used to offset the remaining emissions in order to meet the targets set by the industry.

The CO2 Standard will be reviewed as part of the regular cycle of ICAO's Committee on Aviation Environmental Protection (CAEP) [114] [52].

18.9.4 Annexe 4: Current state of aviation in Ukraine

National Aviation Policy Ukraine, with a large power-consuming economy and correspondingly high emissions of greenhouse gases, is committed to the prevention of global climate change. The primary task of the Government of Ukraine is to create and implement a national policy directed to fulfil the obligations of Ukraine within the framework of the international treaties.

The major legislative document of Ukraine in aviation activity is Air Code of Ukraine in force since 19 May 2011 № 3393–VI which regulates among other questions the question of environmental protection. This chapter includes requirements about:

- Maximum acceptable level of aviation noise, air engine emissions established by the Aviation Rules of Ukraine.
- Compensation for damage caused as a result of the aviation activity.
- Limitations and prohibitions for civil aircraft if they exceed noise levels established by the Civil Aviation Authority.

- Limitations and prohibitions taking account taking account of measures aimed at a reduction of noise levels at the airport and in its vicinity including:
- Technical noise reduction at the source.
- Space zoning of the airport adjacent territory and proper zone planning.
- Operational measures to reduce aircraft noise and emissions.
- The cost of the measures aimed at reduction and prevention in noise and emissions shall be funded by airport taxes taking account ICAO recommendations.

Ukraine ratified the United Nations Framework Convention on Climate Change on 29 October 1996 as an Annex I country. One of the commitments of parties to the Convention is to compile national inventories of their emissions sources. For domestic flights, emissions are considered to be part of the national inventory of the country within which the flights occur. For international flights, inventories are also calculated and reported to UNFCCC under the terminology "emissions from international aviation bunker fuels".

Ukraine also adopted the Kyoto Protocol to the United Nations Framework Convention on Climate Change, in 2004. Due to this, the calculation of the Baseline for Ukraine has been based on the available information on National Inventories reported to UNFCCC and provided by the Ministry of Ecology and Natural Resources of Ukraine.

The methodology used for the calculation of those inventories follows the IPCC 2006 Guidelines for National Greenhouse Gas Inventories. As Ukraine has established this systematic way to estimate, report and verify GHG emissions, those procedures will be used to ensure that the estimation, reporting and verification of CO2 emissions in its action plan are undertaken in accordance with the ICAO Guidance on States Action Plans Appendix E recommendations.

For aircraft emissions estimation equipped with jet and turboprop engines, was used method correspond to the Tier 3a of the IPCC sectoral approach. The next tendencies directly affecting the level of aircraft emissions were observed. From 2001 to 2004 there was a dramatic increase in the number of domestic flights, and in 2008- 2009 dramatic fall, caused by a decline in business activity. This led to corresponding changes in the level of CO2 emissions. At the same time, there have been changes in the structure of the fleet, which operates domestic flights. Since 2000, there has been a constant renewal of USSR-produced aircraft (AN-24, AN26, Yak-40, Yak-42) on modern aircraft (Embraer, Boeing, Airbus), which in the 2000 year was made more than 95% of all domestic flights and in 2010 performed about 50% of all domestic flights. In recent years there has been a significant reduction in the basic performance of the aviation industry.

The main factors that led to the demand decline for air travel and caused the consequent breakdown of the current economic situation, in general, are the next: the military-political situation in the state, the annexation of the Crimea, safety recommendations from the international organizations and the EU regarding avoidance of that area of Ukraine using alternative airspace routes. Several national airports not working during the year and many airlines have significantly reduced their route network.

Separation of aircraft emission. Emissions from domestic aviation include all emissions from aircraft flights, departure and arrival airports of which located on the territory of Ukraine. Emissions from international aviation include emissions from the flights where departure airports are located in the territory of Ukraine, and the destination airport - outside Ukraine.

The State Aviation Administration of Ukraine has decided to calculate a Baseline as a suitable element of its action plan, to estimate the levels of fuel consumption, CO2 emissions, and air traffic (expressed in RTK) that can be expected in the time horizons of 2020 and 2025. Such "business as usual" scenario will be used as the reference to estimate the expected results once the measures identified on the Action Plan are implemented and will represent the projected fuel consumption and CO2 emissions willing to reach as results. To calculate the baseline for the evaluation of the Action Plan measures, it has been estimated average yearly growth of air traffic (RTK) of 5,3% from 2010-2020 and 4,5% from 2020 to 2025 taken from the EUROCONTROL forecasts.

Following figures and tables summarise statistics of Ukraine

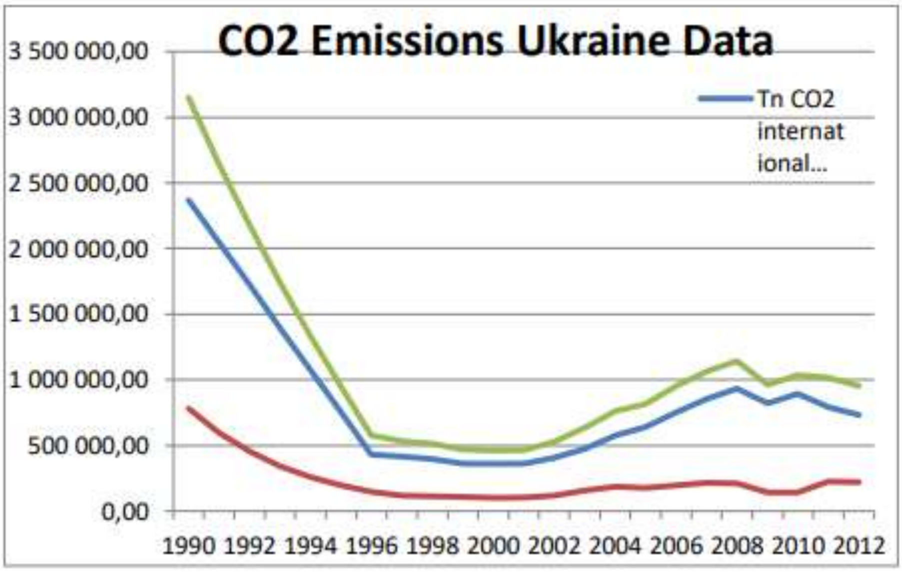


Figure 10. Total CO2 emissions - Ukraine

TRAFFIC FORECAST	TOTAL				
	YEAR	**l Fuel**	**RTK**	**Efficiency factor**	**Kg CO2**
	1990	1.253.570.808,76			3.166.018.435
	1991	1.051.050.179,16			2.654.532.332
	1992	864.639.226,18			2.183.732.830
	1993	691.682.537,23			1.746.913.416
	1994	529.707.437,40			1.337.829.104
	1995	376.684.391,49			951.354.099
	1996	227.934.945,64			575.672.499
	1997	210.781.075,04			532.348.683
	1998	202.749.280,48			512.063.583
	1999	186.582.480,61			471.232.713
	2000	182.631.282,99	184.586.000,00	0,98941	461.253.568
	2001	183.681.857,73	195.209.000,00	0,94095	463.906.900
	2002	208.457.269,78	190.424.000,00	1,09470	526.479.681
	2003	251.053.205,65	288.817.000,00	0,86925	634.059.976
	2004	301.762.175,29	588.180.000,00	0,51304	762.130.550
	2005	322.528.267,45	827.229.360,00	0,38989	814.577.392
	2006	376.429.744,44	935.686.000,00	0,40230	950.710.963
	2007	422.689.385,69	581 105 187,00	0,72739	1.067.544.313
	2008	452.939.714,20	655 000 000,00	0,69151	1.143.944.542
	2009	381.370.433,69	596 000 000,00	0,63988	963.189.167
5,30%	2010	409 338 031,36	***703 000 000,00***	0,58227	1 033 824 132
	2011	401 418 072,97	***992 000 000,00***	0,40466	1 013 821 485
	2012	376 636 412,20	***1 062 000 000,00***	**0,35465**	951 232 923
	2013	272 015 186,59	***767 000 000,00***		687 001 555
	2014	254 637 423,69	***718 000 000,00***		643 112 277
-58,00%	2015	106 947 717,95	***301 560 000,00***		270 107 156
-3,50%	2016	103 204 547,82	***291 005 400,00***		260 653 406
8,00%	2017	111 460 911,65	***314 285 832,00***		281 505 678
8,20%	2018	120 600 706,40	***340 057 270,22***		304 589 144
7,30%	2019	129 404 557,97	***364 881 450,95***		326 824 152
7,20%	2020	138 721 686,15	***391 152 915,42***		350 355 491
6,50%	2021	147 738 595,74	***416 577 854,92***		373 128 597
5,10%	2022	155 273 264,13	***437 823 325,52***		392 158 156
	2023	163 192 200,60	***460 152 315,12***		412 158 222
	2024	171 515 002,83	***483 620 083,19***		433 178 291
	2025	180 262 267,97	***508 284 707,44***		455 270 384

Table 1. Total fuel consumption (l) and emissions (kg CO2)

The State Aviation Administration of Ukraine through the measures included in this Action Plan is willing to contribute to achieving ICAO's climate change goals for international aviation, as stated in Assembly Resolution A37-19:

A global annual average fuel efficiency improvement of 2 per cent until 2020 and an aspirational global fuel efficiency improvement rate of 2 per cent per annum from 2021 to 2050, calculated based on the volume of fuel used per revenue tonne-kilometre performed.

The estimated expected benefits in terms of fuel savings and emissions reductions of the basket of measures included in this plan are the following:

- *AIRCRAFT RELATED TECHNOLOGY DEVELOPMENT:* 2 % annual efficiency improvement (accumulated 16%) till 2020 (including RTK efficiency optimization, through adaptation of aircraft fleets to specific airlines needs)
- *IMPROVED AIR TRAFFIC MANAGEMENT AND INFRASTRUCTURE* USE 5 % accumulated efficiency improvement in 2020
- *BASKET OF POSSIBLE OPERATIONAL OR ADDITIONAL MEASURES TO BE TAKEN IN UKRAINE, ACCORDING TO THE CAPACITY OF NATIONAL KEY AGENTS 6 %* accumulated efficiency improvement in 2020.
- *EXPECTED RESULTS:* The estimated results in terms of fuel and CO2 emissions savings are summarized in the following table:

Year	Tot RTK	Int RTK	Tot Fuel (L) after measures	Int Fuel (L) after measures	Tot CO2 (Kg) after measures	Int CO2 (Kg) after measures
2012	1062000000,00	1002460838,00	376636412,20	289971227,70	951232922,66	732351332,68
2013	767000000,00	705402743,00	266574882,86	203279212,83	673261524,15	505027794,55
2014	718000000,00	692000000,00	244451926,75	198666253,43	617387786,19	485321340,13
2015	301560000,00	290640000,00	100530854,87	83124562,61	253900727,07	199588401,13
2016	291005400,00	280467600,00	94948184,00	79910973,33	239801133,50	188504875,02
2017	314285832,00	302905008,00	100314820,48	85975283,23	253355110,61	199159498,39
2018	340057270,22	327743218,66	106128621,63	92669745,92	268038446,80	210701897,77
2019	364881450,95	351668473,62	111287919,86	99053174,57	281068770,39	220944883,21
2020	391152915,42	376988603,72	116526216,36	105776075,02	294298612,05	231344707,48
2021	416577854,92	401492862,96	121145648,51	112216011,44	305965449,88	240515872,67
2022	437823325,52	421968998,97	124218611,30	117481308,64	313726524,70	246616763,10
2023	460152315,12	443489417,92	127289916,47	122991792,31	321483413,03	252714362,56
2024	483620083,19	466107378,23	130351402,15	128758776,43	329215501,27	258792466,98
2025	508284707,44	489878854,52	133394078,30	134794091,27	336900084,16	264833227,98

Table 2. The estimated results in terms of fuel and CO2 emissions savings

18.9.4.1 Economic information related to the contribution of internal aviation

In recent years there has been a significant reduction in the basic performance of the aviation industry. The main factors that led to the demand decline for air travel and caused the consequent breakdown of the current economic situation, in general, are the next military-political situation in the state, the annexation of the Crimea, safety recommendations from the international organizations and the EU regarding avoidance of that area of Ukraine using alternative airspace routes. Several national airports not working during the year and many airlines have significantly reduced their route network.

During the reporting year, 29 airlines operated on the market of passenger and cargo air transportation, of which 19 carried passenger transport. The number of passengers carried increased by 99.3% compared to the previous year and amounted to 16498.9 thousand pax, which indicates the restoration of the Ukrainian market of passenger air services after the decline of 2014-2015.

According to the results of 2017, 95 per cent of the total passenger traffic was made by 6 leading airlines: Ukraine International Airlines, Azur Air Ukraine, Wind Rose, Yanyeir, Bravo and Atlas Ukraine. Volumes of cargo and mail shipment fell by 29.6 per cent and amounted to 52.3 thousand tons. Transportation of goods and mail carried by 18 domestic airlines, most of the transport - is charter flights to other states within the framework of UN humanitarian and peaceful programs, as well as contracts and agreements with other customers.

Commercial flights of domestic and foreign airlines served 19 Ukrainian airports and airfields. It should be noted that today, about 98 per cent of total passenger traffic and mail traffic are concentrated in 7 leading airports - Boryspil, Kyiv (Zhulyany), Odesa, Lviv, Kharkiv, Dnipropetrovsk and Zaporizhzhya.

18.9.4.2 EXPECTED CHANGES IN UKRAINE

Ukraine is preparing to launch a domestic market for greenhouse gas quotas. Government Bill No. 9253 "On the Basics of Monitoring, Reporting and Verification of Greenhouse Gas Emissions" is included in the Verkhovna Rada agenda for February 28. The introduction of a greenhouse gas trading system between industrial enterprises in the country as envisaged by EU Directive 87/2003. Ukraine has been consistently implementing it in accordance with the Association Agreement with the EU.

The document sets out the procedure for monitoring industrial emissions. Its adoption will be the first step towards the introduction of a system of trade quotas between enterprises in the country. If there are no wires with a regulatory base, the system will fully work in about four years. The Ukrainian legislator expects that the system as a whole will give enterprises specific economic incentives to reduce greenhouse gas emissions.

18.9.5 Annexe 5: Renewable Hydrocarbon Biofuels

As illustrated by the chart in Figure 11, the use of biofuels is needed according to accredited forecasts to contribute to the reduction of CO2 emission by 2050.

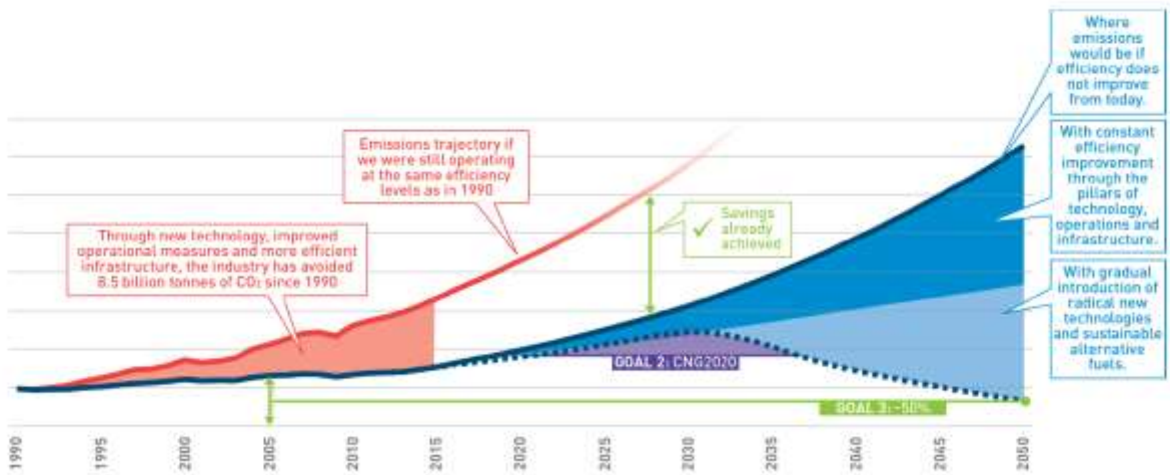


Figure 11. Aviation fuel consumption concerning CO2 emissions. [131], [132]

Renewable hydrocarbon biofuels offer many benefits, including:

- Engine and infrastructure compatibility—Renewable hydrocarbon biofuels are similar to their petroleum counterparts and therefore minimize compatibility issues with existing infrastructure and engines.
- Increased energy security—Renewable hydrocarbon biofuels can be produced domestically from a variety of feedstocks and contribute to job creation.
- Fewer emissions—Carbon dioxide captured by growing feedstocks reduces overall greenhouse gas emissions by balancing carbon dioxide released from burning renewable hydrocarbon biofuels.
- More flexibility—Renewable hydrocarbon biofuels are replacements for conventional jet fuel, and gasoline, allowing for multiple products from various feedstocks and production technologies.

The United States, the European Union, the Netherlands, the United Kingdom and Norway have all recently established policy mechanisms which will support the use of aviation biofuels. To gain the confidence of policymakers and the general public, such support will need to be linked to robust fuel sustainability criteria.

However, sustainable Aviation Fuels (SAF) production capacity requires large industrial investments in a moment when SAF is not yet economically competitive with Conventional Aviation Fuels (CAF). In the EU, two new H2020 projects have been launched: BIO4A [133] and FlexJetFuels [134]. These projects aim at increasing the biojet production capacity in the EU, favouring the market uptake of SAF, also addressing the logistics and distribution, the social, economic and environmental assessment, and the supply of residual lipids. In addition, BIO4A will investigate the sourcing of sustainable lipids from drought-resistant oil crops cultivate in EU MED marginal lands.

Researchers are exploring a variety of methods to produce renewable hydrocarbon biofuels. Production plants may be standalone or co-located at petroleum refineries. Technology pathways explored for the production of renewable hydrocarbon biofuels include:

- Traditional hydrotreating—Used in petroleum refineries, hydrotreating involves reacting the feedstock (lipids) with hydrogen under elevated temperatures and pressures in the presence of a catalyst.
- Biological sugar upgrading—This pathway uses a biochemical deconstruction process, similar to what is used with cellulosic ethanol with the addition of organisms that convert sugars to hydrocarbons.
- Catalytic conversion of sugars—This pathway involves a series of catalytic reactions to convert a carbohydrate stream into hydrocarbon fuels.
- Gasification—During this process, biomass is thermally converted to syngas and catalytically converted to hydrocarbon fuels.
- Pyrolysis—This pathway involves the chemical decomposition of organic materials at elevated temperatures in the absence of oxygen. The process produces a liquid pyrolysis oil that can be upgraded to hydrocarbon fuels, either in a standalone process or as a feedstock for co-feeding with crude oil into a standard petroleum refinery.
- Hydrothermal processing—This process uses high pressure and moderate temperature to initiate chemical decomposition of biomass or wet waste materials to produce an oil that may be catalytically upgraded to hydrocarbon fuels.

Currently, in the United States, commercial-scale production of renewable hydrocarbon biofuels is limited. Instead, commercial facilities are largely focused on renewable diesel production.

A summary of the most relevant process chains to Aviation biofuels is shown in Figure 12.

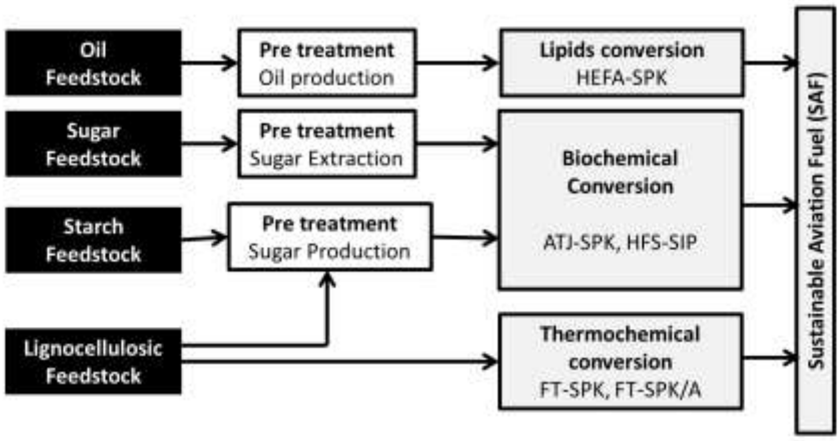


Figure 12. Major Aviation Biofuels process routes [135]

18.9.5.1 Pathway process

Decarbonizing the aviation bringing new fuels in commercial flights requires to go through a long and expensive route encompassing certification, which is governed by the following main norms:

- ASTM D1655 Standard Specification for Aviation Turbine Fuels
- ASTM D7566 Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons
- ASTM D4054 Standard Practice for Qualification and Approval of New Aviation Turbine Fuels and Fuel Additives

To carry out the entire path necessary to certify a new aviation fuel requires significant efforts and resources, as summarized in the ASTM D4054 guideline. There are several obstacles and barriers, both technical and financial, to the goal of introducing a new fuel on the market.

Commercial aviation commonly uses Jet-A1 (also known as kerosene). Due to the high cost of aircraft and the long fleet replacement time, and also to limit infrastructure changes, the aviation sector is likely to rely on liquid fuels similar to kerosene to 2050 and possibly beyond and is currently looking to drop-in sustainable fuels to the conventional, crude based, jet fuel. Renewable jet fuel, also called *biojet* or *aviation biofuel*, is a biomass-derived fuel that can be used interchangeably with petroleum-based aviation fuel. Certain biojet fuels can be blended up to 50% with conventional commercial and military jet (or aviation turbine) fuels by following requirements in the ASTM D7566 specification.

The composition of these new fuels is currently mostly paraffinic, being known as Synthetic Paraffinic Kerosene (SPK) or iso-paraffins. It can be blended in variable amounts up to 50%, depending on the fuel type with conventional commercial and military jet (or aviation turbine) fuel while synthetic kerosene with aromatics (SKA) fuels can be used interchangeably with fossil fuels. Blending is required with SPK fuels because they lack sufficient aromatic hydrocarbons, which are present in conventional jet fuel. While aromatic hydrocarbons are limited in jet fuel to prevent smoke formation during combustion, a minimum aromatic content is needed to cause elastomer swell in aircraft fuel systems and increase fuel density.

There are 5 major fuel routes approved by the ASTM D7566 standard:

- Hydrogenated esters and fatty acids (HEFA) fuels derived from used cooking oil, animal fats, algae, and vegetable oils (e.g., camelina) (HEFA-SPK)
- Fischer-Tropsch (FT) fuels using solid biomass resources (e.g., wood residues) (FT-SKA)
- FT fuels with aromatics using solid biomass resources (e.g., wood residues) (FT-SKA)
- Synthetic iso-paraffin (SIP) from fermented hydro processed sugar, formerly known as direct-sugar-to-hydrocarbon fuels. Blends of up to 10% are permitted for this fuel (SIP-SPK)
- Alcohol-to-jet (ATJ) fuels produced from isobutanol and blended to a maximum level of 30% (ATJ-SPK).

Once blended, SAF has the same characteristics as fossil jet fuel. The blend is then re-certified as Jet A or Jet A-1. It can be handled in exactly the same way as regular jet fuel, so no changes are required in the fueling infrastructure or for an aircraft wanting to use SAF. Any aircraft certified for using the current specification of jet fuel can use SAF [136].

Table 3. Pathway processes approved by ASTM [137]

Pathways Processes	Feedstock	Date of Approval	Blending ratio by Volume	Commercialization Proposals
Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK)	Biomass (forestry residues, grasses, municipal solid waste)	2009	50%	Fulcrum Bioenergy, Red Rock Biofuels, SG Preston, Kaidi, Sasol, Shell, Syntroleum
Hydro processed Esters and Fatty Acids (HEFA-SPK)	Oil-bearing biomass, e.g., algae, jatropha, camelina, carinata	2011	50%	World Energy, Honeywell UOP, Neste Oil, Dynamic Fuels, EERC
Hydro processed Fermented Sugars to Synthetic Isoparaffins (SIP-HFS)	Microbial conversion of sugars to hydrocarbon	2014	10%	Amyris, Total
FT-SPK with aromatics (FT-SPK/A)	Renewable biomass such as municipal solid waste, agricultural wastes and forestry residues, wood and energy crops	2015	50%	Sasol
Alcohol-to-Jet Synthetic Paraffinic Kerosene (ATJ-SPK)	Agricultural wastes products (stover, grasses, forestry slash, crop straws)	2016	50%	Gevo, Cobalt, Honeywell UOP, Lanzatech, Swedish Biofuels, Byogy

Hydro processed Esters and Fatty Acids Plus (HEFA +)	Oil-bearing biomass, e.g., algae, jatropha, camelina, carinata	To be determined.	50%	Boeing
Co-processing	Fats, oils, and, greases (FOG), from petroleum refining	2018	5%	Chevron, Phillips66, BP

There are other 7 routes currently under approval process, plus other 15 waiting to enter the process [54]. Sustainability of those pathways depends upon the feedstock and way of production. Feedstocks considered by the aviation industry[27] are lipids such as waste oils like used cooking oil (UCO), residual animal/vegetable oils from industries, vegetable oils like camelina oil, algae, cellulosic material such as tobacco, jatropha, sugars from sugarcane, lignocellulosic material, lignin residues, municipal solid wastes (MSW), dedicated energy crops. Wastes and residues that do not require land to be produced usually have fewer sustainability concerns. Drop-in fuels could also be produced from electric power (power-to-liquid (PTL) or sunlight (STL)).

18.9.5.2 Current capacities

Beside the assessment of the current technical potential, an appraisal of the maturity level of the various production pathways is summarised in a database, which Joint Research Centre (JRC) updates. In Table 4 a summary of an extract of the data on the current installed capacity of the technologies from the database is reported [138].

Table 4. Current installed capacity (CIC) of the technologies

Current Installed Capacity - CIC

Technologies	Country	Feedstock	2018	2020
			kt y-1	*kt y-1*
FT	Finland	Wood	0	115
HEFA	Italy	oils, fats	0	310
HEFA	Italy	oils, fats	0	530
HEFA	Spain	oils, fats	80	80
HEFA	Italy	oils, fats	360	360
HEFA	Finland	oils, fats	190	190
HEFA	Finland	oils, fats	190	190
HEFA	The Netherland	oils, fats	800	800
HEFA	Sweden	oils, fats	100	100
HEFA	France	oils, fats	500	500
Co-processing	Spain	oils, fats	0	180
Co-processing	Spain	oils, fats	48	60
HEFA	Lapperanta	CTO	100	100
		Total	**2368**	**3515**

Aviation Fuel Share

	CBJ	HBJ
HEFA	15%	60%
FT	32%	32%

Production capacity

kt y-1	CIC	CBJ	HBJ
2018	2368	355	1421
2020	3515	547	2077

[27] The feedstocks types cannot be considered sustainable per se. Sustainability should be demonstrated along the production chain. Those mentioned above have been used in aviation because in particular production chains they have been found as sustainable according to internationally recognized standards like RSB (www.rsb.org) or ISCC (www.iscc-system.org) and the Directive 2009/28/EC.

In Figure 13 are reported, based on publicly available information, airports and airlines involved in ongoing alternative fuel purchase, updated to 2019. Due to the fuel blending procedures at these airports, it is not possible to determine the quantity of alternative fuel being used on any flight that appears on this live feed. Batches of fuel have also been delivered to several other airports [139].

Airline	Traffic Type	Airport
United Airlines KLM to Amsterdam	Departures	Los Angeles International Airport
Lufthansa SAS KLM / KLC	Departures	Oslo Airport
SAS KLM	Departures	Stockholm Arlanda Airport
All Airlines	Departures	Bergen Airport
KLM	Arrivals	Växjö Småland Airport
KLM SAS Finnair	Departures	San Francisco Airport
BRA	Departures	Halmstad City Airport

Figure 13. Airports and airlines involved in ongoing alternative fuel purchase (2019)

According to ICAO, today the situation of distributing blended alternative fuels is as follows [53]:

- 185,000 commercial flights since 2011
- 5 technical SAF pathways certified & 4 more pre-2020
- Growing locations offering daily flights
- 2018 SAF volume = approximately 0.01% of total fuel demand
- A number of major construction announcements in the past 18 months
- Approximately 6 billion SAF liters in a forwarding purchase agreement
- More than 40 airlines have developed experience using SAF

In Table 1 is reported an overview of the first flights and companies that used sustainable fuels.

Table 5. First flights that used sustainable fuels [140]

Carrier	Date of first SAF flight	Details
Air New Zealand	December 2008	The technical test flight on a Boeing 747
Japan Airlines	January 2009	The technical test flight on a Boeing 747

Carrier	Date of first SAF flight	Details
Finnair	July 2011	Series of flights on an Airbus A320-family aircraft between Amsterdam and Helsinki
Interjet	July 2011	Commercial flight on an Airbus A320 between Mexico City and Tuxtla Gutierrez
AeroMexico	August 2011	Commercial flight on a Boeing 777 between Mexico City and Madrid
Iberia	October 2011	Commercial flight on an Airbus A320 between Madrid and Barcelona
Thomson Airways	October 2011	Commercial flight between Birmingham and Arrecife on a Boeing 757
Air France	October 2011	Series of flights on an Airbus A320-family aircraft between Toulouse and Paris
Air China	October 2011	Technical test flight on a Boeing 747
Alaska Airways	November 2011	Series of commercial flights on Bombardier Q400 and Boeing 737 aircraft
Thai Airways	December 2011	Commercial flight on a Boeing 777 between Bangkok and Chiang Mai
Etihad Airways	January 2012	Delivery flight on a Boeing 777 from Seattle to Abu Dhabi
Latam Airways	March 2012	Series of flights in Latin America
Porter Airlines	April 2012	Demonstration flight on a Bombardier Q400 from Toronto to Ottawa
Jetstar Airways	April 2012	Commercial flight between Melbourne and Hobart on an Airbus A320
Air Canada	June 2012	Two commercial flights from Toronto to Mexico City
KLM	May 2014	Commercial flight from Amsterdam to Aruba on Airbus A330-200
GOL Lineas Aéreas	June 2014	Series of flights during the FIFA World Cup
Nextjet	June 2014	Commercial flight from Karlstad to Stockholm
Finnair	September 2014	Commercial flight from Helsinki to New York on Airbus A330
Lufthansa	September 2014	Scheduled flight from Frankfurt to Berlin
Scandinavian Airlines	November 2014	Flights between Stockholm and Ostersund and Trondheim and Oslo on Boeing 737 aircraft
Norwegian Airlines	November 2014	Flight between Bergen and Oslo on a Boeing 737
Hainan Airlines	March 2015	A commercial flight between Shanghai and Beijing on a Boeing 737
Alaska Airlines	June 2016	Two commercial flights from Seattle to San Francisco and Washington D.C.

Carrier	Date of first SAF flight	Details
Alaska Airlines	November 2016	Commercial demonstration flight from Seattle to Washington D.C. on Boeing 737-800
Braathens Regional Airlines	February 2017	Commercial flight from Stockholm to Umeå on ATR 72-600
Air Canada	April 2017	Series of five test flight between Montreal and Toronto
Singapore Airlines	May 2017	Series of trans-Pacific flights between Singapore and San Francisco on Airbus A350 aircraft
Various	November 2017	Commercial flights on 'Fly Green Day' from Chicago by Lufthansa, United Airlines, Etihad, Cathay Pacific Airways, Emirates, Japan Airlines, Korean Air Atlas Air and FedEx
Hainan Airlines	November 2017	Commercial flight from Beijing to Chicago on Boeing 787
China Airlines	December 2017	Delivery flight of A350-900 from Toulouse to Taipei
Qantas	January 2018	Commercial flight from Los Angeles to Melbourne on Boeing 787-9
Air Canada	May 2018	Commercial flight from Edmonton to San Francisco on A320-200
SpiceJet Airlines	August 2018	Demonstration flight on Bombardier Q400 from Dehradun to Delhi
JetBlue Airways	September 2018	Delivery flight of A321 from Mobile, Alabama to New York
Etihad Airways	January 2019	Commercial flight from Abu Dhabi to Amsterdam on Boeing 787
China Southern Airlines	February 2019	Delivery flight of A320NEO from Toulouse to Guangzhou
Braathens Regional Airlines	May 2019	'Perfect Flight' from Halmstad to Stockholm on ATR 72-600
Various	May 2019	21 private aircraft flew to Geneva to the annual European Business Aviation Convention & Exhibition (EBACE)
United Airlines	June 2019	Eco-friendly commercial "Flight For the Planet" from Chicago to Los Angeles
Delta	July 2019	Delivery flight of A321 from Mobile, Alabama to Kansas City (first in series of 20 delivery flights to Delta powered by sustainable fuels)
Egyptair	July 2019	Delivery flight of Boeing 787 from Seattle to Cairo
Finnair	August 2019	First two flights backed by "Push for change" initiative from San Francisco to Helsinki

18.9.5.3 Properties of the advanced biofuels

In Table 6 the properties of fuel categories approved by the ASTM D7566 standard are reported, in comparison with the properties of average conventional kerosene (Jet A-1).

Table 6. Properties synthetic fuels: Boiling Point of neat SIP fuel determined according to ASTM 1120; Flash Point for neat SIP fuel determined according to DIN EN ISO 2719; Thermal stability determined at 325°C

Property	Jet A-1	SIP	HEFA	CTL	CH-kerosene	ATJ-SPK	ATJ-SKA
Acidity, total [mg KOH/g]	0.001	0.002	0.001	0.001	0.014	0.002	0.003
Aromatics [vol%]	18.1	-	-	-	19.7	-	15.8
Distillation [°C]							
IBP (°C) / Boiling Point for SIP (°C; acc. to ASTM 1120)	156.2	247a	148.9	166.0	152.1	174.6	164.8
10 vol% recovered at T [°C]	168.8		162.9	171.5	171.4	178.0	174.8
50 vol% recovered at T [°C]	189.0		210.3	179.5	200.1	180.9	186.7
T50 – T10 [°C]	20.2		47.4	8.0	28.7	2.9	11.9
90 vol% recovered at T [°C]	225.4		270.8	198.7	244.8	220.1	205.6
T90 – T10 [°C]	56.6		107.9	27.2	73.4	42.1	30.8
FBP [°C]	241.7		277.6	215.2	258.5	249.8	249.6
Residue [vol%]	1.1		1.2	1.1	1.5	1.2	1.1
Loss [vol%]	0.9		1.1	1.1	0.9	0.9	1.1
Flash point [°C]	44.5	107.5b	42.0	46.0	42.5	47.5	48.5
Density at 15°C [kg/m3]	795.6	773.1	756.7	761.2	805.2	757.1	785.9
Freezing point [°C]	-57.6	<-80.0	-54.4	-	-41.3	<-80.0	<-80.0
Lubricity [mm]	0.698	0.562	0.906	0.780	0.570	0.839	0.606
Viscosity at -20°C [mm2/s]	3.335	14.13	4.801	3.71	3.977	4.795	3.421
Existent gum [mg/100 mL]	<1	10.0	<1	<1	<1	2	1
Thermal Stability - 2.5 h at 260°C							
Deposit Rating	<1	<1	1c	<1c	<1	<1c	<1
Pres. Drop [mm Hg]	0.0	0.0	0.0c	280.0c	0.0	0.0c	0.0
Net Heat of Combustion [MJ/kg]	43.275	-	44.154	-	43.202	-	43.396
Corrosion Copper Strip. 2 h/100°C	1a	1a	1b	1a	1a	1a	1a
Smoke Point [mm]	23.5	-	-	>45.0	22.5	27.0	23.0
Naphthalene [vol%]	0.13	-	-	-	0.35	-	0.08
Mercaptane Sulphur [wt.%]	0.0014	-	<0.0003	<0.0003	-	<0.0003	-
Sulphur [wt.%]	0.0145	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

The Derived Cetane Numbers (DCNs) of alternative jet fuels are higher than conventional jet fuel because conventional jet fuel contains more than 20% of aromatics. The alternative fuels with higher n-paraffin content will be more reactive, resulting in higher DCNs. The ignition behaviour, which depends strongly on the fuel composition and structure, shows that alternative fuels have shorter ignition delay than conventional jet fuel [141] [28], and the pressure increase due to ignition in the combustion chamber is higher than that of

[28] Kumar, K. and C.-J. Sung (2010). "A comparative experimental study of the autoignition characteristics of alternative and conventional jet fuel/oxidizer mixtures." Fuel 89(10): 2853-2863;

convention jet fuel. The amount of n-paraffins contained in the fuels determines the order of ignition delay [141] [29]. For the laminar flame speed, which is controlled by the heat of combustion, there is no difference between conventional and alternative jet fuels [141].

For the engine performance tests, the Bio-SPK derived from jatropha and algae shows an improvement in the specific fuel consumption and fuel flow compared to Jet-A. The 25% and 50% Bio-SPK blends demonstrate the reduction in fuel flow by 0.7% and 1.2%, respectively. There are no significant differences in engine acceleration response time with these blends. For the emission tests, there is a slight reduction in NOx by 1%-5% due to the differences in ambient conditions and flame characteristics. The emissions of carbon monoxide (CO) and unburned hydrocarbons are increased by 5%-9% and 20%-45%, respectively, because of the reduction of flame temperature, the influence of spray quality and flame location. The smoke emission is reduced by 13%-30% due to the lower aromatic content and higher H/C ratio. In addition, there is no engine degeneration or unusual odours found when testing the biojet fuel in engines. However, the lack of aromatic components could lead to damage to the elastomer materials in the fuel system. Blending the biojet with conventional jet fuels would ensure elastomer swelling [142].

Most production and use of alternative fuels in commercial aviation has been for demonstration and/or R&I purposes. The R&I profile of the use has changed with the blended use of HEFA-SPK at Oslo airport [143] and the start of continuous production of HEFA-SPK by Altair in Los Angeles (CA) for use by United Airlines [144]. The incentive programs available in the USA and in particular in California for advanced biofuels are enabling Altair production and are also driving the building of another facility for FT-SPK based on municipal solid wastes [145]. At European level, the only incentive for airlines using biojet fuel is the EU ETS for intra-European flights but it is negligible compared with the price gap. However, at global level, there is a commitment for development and implementation a global carbon market mechanism (GMBM) from 2020 that could be an incentive for the use of sustainable, low carbon fuels but that, with the current layouts, would be also unlikely covering the price gap for biojet.

18.9.5.4 Main Sustainable Aviation Fuels (SAF)

Commercial aviation commonly uses Jet-A1 (also known as kerosene). Due to the high cost of aircraft and the long fleet replacement time, and also to limit infrastructure changes, the aviation sector is likely to rely on liquid fuels similar to kerosene to 2050 and possibly beyond and is currently looking to drop-in sustainable fuels to the conventional, crude based, jet fuel. The composition of these new fuels is currently mostly paraffinic, being known as Synthetic Paraffinic Kerosene (SPK) or iso-paraffins. There are 5 major fuel routes approved for its use in civil aviation: FT-SPK, HEFA-SPK, HFS-SIP, FT-SPKA/A and ATJ-SPK. There are other seven routes currently under approval process, plus other 15 waiting to enter the process [145] Sustainability of those pathways depends upon the feedstock and way of production. Feedstocks considered by the aviation

---

Kumar, K. and C.-J. Sung (2010). "Flame Propagation and Extinction Characteristics of Neat Surrogate Fuel Components." Energy & Fuels 24(7): 3840-3849;

Wang, H. and M. A. Oehlschlaeger (2012). "Autoignition studies of conventional and Fischer–Tropsch jet fuels." Fuel 98(0): 249-258;

Allen, C., D. Valco, E. Toulson, T. Edwards and T. Lee (2013). "Ignition behavior and surrogate modeling of JP-8 and of camelia and tallow hydrotreaeted renewable jet fuels at low temperatures." Combustion and Flame 160: 232-239.

29

Quintero, S. A. A., M. Ricklick and J. Kapat (2012). Synthetic Jet Fuels and their Impact in Aircraft Performance and Elastomer Materials. 48th AIAA/ASME/SAE/ASEE Join Propulsion Conference & Exhibit, Atlanta, Georgia.

industry[30] are waste oils like used cooking oil (UCO), residual animal/vegetable oils from industries, vegetable oils like camelina oil, tobacco, jatropha, sugars from sugarcane, lignocellulosic material, lignin residues, municipal solid wastes (MSW) or algae. Wastes and residues that don't require land to be produced usually have fewer sustainability concerns. Drop-in fuels could also be produced from electric power (power-to-liquid (PTL) or sunlight (STL)).

The alternative fuels mentioned are used blended with conventional Jet-A1 according to the limits established by the standard ASTM 7566. Once blended, the fuel is considered as Jet-A1 (ASTM 1655 or DEFSTAN 91-91) and can be used in all civil infrastructures and aircraft that use jet fuel, which is a key advantage to avoid duplication of infrastructures or operations [146]. The blend is needed because the synthetic hydrocarbons fuels do not contain some hydrocarbons naturally present in fossil fuels such as aromatics, or other elements such as Sulphur, that are known to play a relevant role for the performance of the aircraft's fuel systems. Overall, these properties make the sustainable fuels cleaner at combustion (clearly for PMs and potentially NOx) and with higher energy content (per weight unit) that translates to some limited energy efficiency gains (due to the reduced weight to be transported and slightly more efficient combustion). However, the role of those compounds and their interaction with other parameters in the jet fuel is not fully understood, and knowledge is based on experience with fossil fuel rather than with these new synthetic alternatives. This means that understanding the optimal properties and limits of blends requires further work. Table 10 provides a summary on the state of the art of alternative fuel use in aviation.

Table 7. State of the art on alternative fuel use in aviation

Jet Engines	SPK (FT, HEFA, FT/A)	SIP	ATJ	HEFA+	LNG
How much is used and why?	Not used in Europe on a large scale, there is a growing interest in developing these fuels as they are considered large contributors for decarbonisation of air transport in the short and medium-term [147]. More than 1600 commercial flights have been done using sustainable fuel blends from 20-50% [148]. Use at the airport as non-segregated fuel has started in January 2016 in Oslo [149] increasing the number of flights, but the volumes needed to keep continuous supply are a challenge. There is no continuous production of drop-in fuels for aviation in Europe. Use outside Europe, mostly in the USA, has been promoted by military contracts and now starting from private companies.	Used at Lab'line demonstration project and some Airbus delivery flights, but not used continuously.	Recently approved, no use reported in Europe.	HEFA+ refers to upgrading from the conventional green diesel (HVO) to the aviation quality standards (cold temperature properties, density...). Not yet approved for commercial aviation, but testing is ongoing.	Not used.
How is it used?	Synthetic paraffinic kerosene, once it has been blended, can be used as drop-in jet fuel. Maximum blend ratios accepted for commercial aviation are: FT-SPK (50%),	It can be used blended with fossil jet fuel up to 10% v/v.	Can be used blended with fossil	HEFA is approved up to 50%. HEFA + could be probably used	It is not drop-in, requires a radical change of airframe and combination

[30] The feedstocks types cannot be considered sustainable per se. Sustainability should be demonstrated along the production chain. Those mentioned above have been used in aviation because in particular production chains they have been found as sustainable according to internationally recognized standards like RSB (www.rsb.org) or ISCC (www.iscc-system.org) and the Directive 2009/28/EC.

	HEFA-SPK (50%) and FT-SPK/A (50%) [146]. Once the fuel has been blended and approved according to the ASTM D7566 standard, it can be used in all civil aircraft and infrastructures using conventional jet fuel without any segregation.		jet fuel up to 30% v/v.	blended with fossil jet fuel up to 10% v/v.	with electricity still not in the market.
Trends	The technology is at an early commercial stage and the production capacity is still limited, which is mainly due to economic reasons. However, HEFA is an industrially mature technology. Recently a production facility in Los Angeles (CA, USA) has started continuous production of HEFA, able to produce about 30,000 t of HEFA-SPK per year. Besides, outside Europe, there are several offtake agreements from airlines or governments, but considering facilities still not running. In Europe, potential production capacity according to the EU Flightpath and the latest updates could reach 15,000 t of sustainable fuel (FT-SPK) per year in France from 2018 [150].	The technology is at an early commercial stage with low availability.	The technology is at an early commercial stage with low availability.	The technology is a commercial-stage with high availability. It could be easily adopted with some 'minor' adaptations. HEFA (Green Diesel) is well developed for ground transport fuels but the extension of HEFA+ is still to be approved.	Possibilities of using LNG as jet fuel are being explored
Challenges & opportunities	There are almost no challenges due to their drop-in characteristics at the defined blend ratios, but to reach pure use is still not possible (but could potentially be). Minimum content in aromatics related to fuel system seals is one of the limitations to unblended use while it has been identified that there the nvPM emissions lower when aromatics are also lower. Different aerosols, nvPM and shoot combustion profiles from SPK suggest different nonCO_2 effects at high altitude that would need better understood to know the real decarbonisation potential. Use of low blend ratios of green diesel (as HEFA+ for aviation) SPK could suddenly increase the production capacity and would increase the uptake but there is still some fuel system testing required.	This is a unique molecule vs the incumbent what is more complex. It has reported that the 10% blend ratio could be difficult to be higher.	Same as SPK, but blend ratio unlikely to be enlarged.	Use of low blend ratios of green diesel (as HEFA+ for aviation) SPK, if approved, could suddenly increase the production capacity and increase the uptake in the short term, but there is still some fuel system testing required to know the limits. It wouldn't be a long term solution due to the low blend ratios.	Non-drop-in is not feasible in the time frame for a real implementation but it could be a solution for the future.

18.9.5.5 Approval Status

A generic approval for FT kerosene as a blendstock with a maximum blend ratio of 50% was given by ASTM in 2009. For this purpose, a new specification ASTM D7566 was created, which is a specification for blends with synthetic kerosene. This specification is referred to in the jet fuel specification, ASTM D1655, to the effect that these blends are jet fuel; hence a blended meeting ASTM D7566 is an ASTM D1655 jet fuel. Although the approval was largely based on coal as a feedstock, the generic approval covers the product from FT processes in general, regardless of feedstock. The FT fuels described above do not contain aromatic compounds. However, a certain percentage of aromatics is required in jet fuel to ensure seal swell and tightness of valves. This is one of the reasons why the fuel may only be used as a blend with conventional kerosene, with a maximum blend ratio of 50%. The specification also states that the blend must have a minimum aromatics content of 8%[31]. Approval has been granted by ASTM in November 2015[32] to a semi-synthetic fuel called IPK/A which is partly synthesised via the Fischer-Tropsch process and partly from the naphtha cut produced from the coal-tar-product of coal gasification [151].

HEFA has been approved by ASTM in July 2011, and is now covered by ASTM D7566. Like normal FT kerosene, it does not contain aromatic compounds and is only certified for use as a blend with a 50% maximum blend ratio[33]. The US company Swift Fuels has proposed producing a blend of HEFA kerosene and aromatics that requires no further blending with conventional kerosene. At the moment they produce the Swift Jet (Mesitylene and High-Performance Aromatics) used by the AFRL in the FAA CLEEN-II Program[34]. A process using essentially the same feedstock as HEFA is currently pursued by the US company Applied Research Associates. For this process, the terminology "HEFA-SKA" is sometimes used, although the technical process is different from that for HEFA. Minimum content in aromatics related to fuel system seals is one of the limitations to unblended use while it has been identified that there the nvPM emissions lower when aromatics are also lower. Different aerosols, nvPM and shoot combustion profiles from SPK suggest different non-CO_2 effects at high altitude that would need better understood to know the real decarbonisation potential.

SIP fuels were approved as a kerosene blendstock in June 2014, and are now covered by Annex 3 of ASTM D7566. Unlike FT- and HEFA fuels, SIP fuels are only approved to a maximum blend ratio of 10%[35]. The lower maximum blend ratio is due to the SIP fuel solely consisting of one single compound, namely farnesane, although all the tests were also performed at 20% incorporation and show no deviation as compared to conventional jet fuel.

Certification work has been performed by Gevo on ATJ-SPK from iso-butanol[36], by Cobalt on ATJ-SPK from butanol, by Swedish Biofuels on ATJ-SPK from ethanol and by UOP on ATJ-SPK from both iso-butanol and various alcohols[37]. A research report on ATJ-SPK was approved by ASTM in November 2014, with some minor corrections to be included as an annexe [152]. Use of ATJ-SPK blends as aviation kerosene was approved in April 2016[38]but was limited to ATJ from iso-butanol (the Gevo pathway). ATJ-SKA is not yet approved by ASTM. Certification work has been mainly performed by Swedish Biofuels and Byogy. Tests have been successfully passed, as have a fuel atomizer spray test, APU combustor test and nozzle flow test.

CH kerosene is not yet approved by ASTM. Certification work is being performed by ARA, based on fuel produced from its 4 barrel per day pilot and 100 barrel per day demonstration plants[39]. Neat CH kerosene is

---

[31] ASTM 7566, issue 14a, Table 1 Part 2. This requirement already existed in the 1999 approval, see Moses, Wilson, Roeds.

[32] ASTM D7566 15c

[33] ASTM D7566, issue 14a, paragraph 6.1.2

[34] http://swiftfuels.com

[35] ASTM D7566 14a, paragraph 6.1.3

[36] Swedish Biofuels communication

[37] Subcommittee J on Aviation Fuels 12. March 2012, p. 23

[38] ASTM D7566 -16

[39] http://www.ara.com/fuels/CH-Technology-Status.html, researched 28. August 2014

very similar in composition and properties to fossil kerosene, including in aromatic content[40]. From its composition, it could in principle be used as a neat fuel without blending, but current tendency at ASTM is for the moment only to approve blends with a maximum 50% blend ratio. Extensive tests have been conducted, including a test flight in 2012[41]. A research report has been finished and submitted for OEM review [153].

HDO-SKA is not yet approved by ASTM. Certification work is being performed by Virent in cooperation with Shell. Neat HDO-SKA consists solely of aromatics, the other components having been removed by distillation. This composition gives the neat fuel poor thermostability and an off-spec smoke point and anyway is way above the maximum permissible aromatics content of 25%. It is therefore unsuitable for use as a neat fuel and is not intended to be used as such. Rather, approval is pursued use as a blend component where appropriate and advantageous. Certification testing of HDO-SKA has so far been limited to lab tests. Specification testing, fit-for-purpose testing and toxicity testing are essentially finished, with no issues identified, but only preliminary materials compatibility tests have been performed. Work on rig and engine tests, including emissions performance, is planned but is still pending. HDO-SKA, therefore, is still some time away from ASTM certification.

HDCJ is not yet approved by ASTM. Most of the certification work has so far been performed by KiOR, based on their production pathway where depolymerisation is performed by a combined thermo catalytic process. Some work has also been done by UOP using pyrolysis for depolymerisation, but this process is still being developed. Neat HDCJ has an aromatic content of some 50%, which is above the permissible maximum for jet fuel of 25%. Therefore, HDCJ will have to be blended with conventional jet kerosene for the aromatic content to be diluted to specification levels. Approval is currently pursuing a maximum blend ratio of 30%.

HDO-SK is not yet approved by ASTM. Certification work is being performed by Virent in cooperation with Shell. Neat HDO-SK has a cycloparaffin content of 80% and only minor aromatics content. HDO-SK will have to be blended with conventional jet kerosene, to achieve the required minimum aromatics content and dilute the cycloparaffins. No blend ratios have as yet been formally proposed but testing of blends has so far concentrated on a 50% blend. Certification testing of HDO-SK has so far been limited to lab tests. Specification testing and fit-for-purpose testing are essentially finished, with no issues identified, but only preliminary materials compatibility tests have been performed. Work on rig and engine tests is still pending. HDO-SK, therefore, is still some time away from ASTM certification.

Liquefied Natural Gas (LNG) is not used. It is not drop-in, requires a radical change of airframe and combination with electricity still not in the market. Possibilities of using LNG as jet fuel are being explored, but non-drop-in is not feasible in the time frame for a real implementation but it could be a solution for the future.

18.9.5.6 Availability and compatibility

FT kerosene is a "drop-in" fuel and can be used in Turbofan powertrain technology. Large-scale production facilities exist for the conversion of coal to liquid fuels (Sasol in South Africa) and the conversion of natural gas (Shell in Qatar)[42]. A novel approach to feedstocks is planned by Fulcrum Inc. with various airlines[43].

---

[40] http://www.ara.com/fuels/Readi-Jet-Diesel-Specs.html, researched 28. August 2014

[41] http://www.ara.com/fuels/CH-Technology-Status.html, researched 28. August 2014

[42] Zennaro, Roberto: Fischer-Tropsch Process Economics, p.155; in: Peter M. Maitlis and Arno de Klerk (eds.): Greener Fischer-Tropsch Processes for Fuels and Feedstocks, Weinheim 2013

[43] Jim Lane: United Airlines invests $30M in Fulcrum BioEnergy; inks $1.5B+ in aviation biofuels contracts; in: Biofuels Digest 30.6.2015

More than 1600 commercial flights have been done using sustainable fuel blends from 20-50% [44]. Use at the airport as non-segregated fuel has started in January 2016 in Oslo [45] increasing the number of flights, but the volumes needed to keep continuous supply are a challenge. It can be produced in large quantities, but there is no continuous production of drop-in fuels for aviation in Europe. The use outside Europe, mostly in the USA, has been promoted by military contracts and now starting from private companies.

HEFA–SPK is a "drop-in" fuel and can be used in Turbofan powertrain technology. The largest operator of HEFA refineries is Neste Oil, with a total annual production capacity of two million tons[46]. The largest HEFA kerosene batch so far has been the 800 tons produced by Neste in 2011 for the Lufthansa burnFAIR in-service evaluation. Some smaller facilities have also been or are producing limited quantities of HEFA kerosene for aviation purposes, particularly the Dynamic Fuels refinery at Geismar, Louisiana, used by SkyNRG to procure fuel for KLM[47]. A recent development has been the start of deliveries of HEFA kerosene to United Airlines at Los Angeles airport. These deliveries are by AltAir Paramount, from a refinery converted to the production of HEFA products, and take place based on a multi-year supply contract between United Airlines and AltAir[48]. HEFA–SPK is anticipated to be the principal aviation biofuel used over the short to medium term. Meeting 2% of annual jet fuel demand from international aviation with SAF could deliver the necessary cost reduction for a self-sustaining aviation biofuel market thereafter. Meeting such a level of demand requires increased HEFA-SPK production capacity. If met entirely by new facilities, approximately 20 refineries would be required. SAF is currently more expensive than jet fuel and this cost premium is a key barrier to their wider use. For HEFA-SPK economies of scale could be realised by refineries designed for continuous production. At current prices and today's fleet average energy efficiency, the additional cost per passenger for a 15% blend of HEFA may not be high in comparison with other elements that influence ticket prices, such as seating class, the time of ticket purchase and taxation. However, due to the competitiveness of the aviation industry customer price sensitivity is a core consideration for airlines[49]. HEFA is an industrially mature technology. In 2016 a production facility in Los Angeles (CA, USA) has started continuous production of HEFA, able to produce about 30,000 t of HEFA-SPK per year[50].

SIP kerosene can be used in Turbofan powertrain technology. It can be used blended with fossil jet fuel up to 10% v/v[51]. The technology is at an early commercial stage with low availability and there is only one producer, which is Total/Amyris. It is still needed integrated, fuel-centric research, investigating the effects of fuel composition on operations and emissions, where fuel is varied for otherwise identical conditions, and the effects identified.

---

[44] Ecofys (2016) "Accounting methods for biojet fuel. Final report". Available at: http://www.ecofys.com/files/files/ecofys-2015-accounting-methods-for-biojet-fuel.pdf

[45] ITAKA project (2016) "Press release. ITAKA provides sustainable fuel for worldwide's first biojet supply via hydrant system at Oslo Airport". http://www.itaka-project.eu/Shared%20Documents/20160122_ITAKA_airportusage_start.pdf

[46] http://2013.nesteoil.com/business/renewable-fuels/

[47] "KLM plans drive-down of jet biofuel price premium as it starts regular series of biofuel transatlantic flights", GreenAir online 18. March 2013

[48] United Airlines Makes History with Launch of Regularly Scheduled Flights Using Sustainable Biofuel; United Airlines press release 11. March 2016

[49] Are aviation biofuels ready for take off? – Analysis – IEA, https://www.iea.org/commentaries/are-aviation-biofuels-ready-for-take-off

[50] Greenaironline (2016) "United begins regular use of commercial-scale volumes of AltAir's renewable jet biofuel on flights from LAX". Available at: http://www.greenaironline.com/news.php?viewStory=2208

[51] ASTM (2016) "ASTM D7566-16, Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons". Available at: http://www.astm.org/Standards/D7566.htm

ATJ-SPK can be used in Turbofan powertrain technology. The EU, under FP7,26, is supporting the development of two demonstration projects. One will produce bio-jet from ethanol using Swedish Biofuels' technology and the other will produce bio-jet from the lignin fraction of a cellulosic ethanol plant using Biochemtex' technology. The former will have a capacity of 10 ML/y. of bio-jet, and the latter will be smaller[52]. The main producer is Gevo[53]. The variation with the addition of aromatics, ATJ-SKA can also be used in Turbofan powertrain technology. Can be used blended with fossil jet fuel up to 30% v/v [54]. The technology is at an early commercial stage with low availability. It has the same opportunities as SPK, but blend ratio unlikely to be enlarged. The main producer is Swedish Biofuels[55].

The only provider of CH kerosene in 2012 was ARA. The only possible provider of HDCJ kerosene is currently KiOR, however, the KiOR plant has been idle since March 2014[56], and no fuel was available. The only producer of HDO-SK and HDO-SKA kerosene is currently Virent[57]. LNG It is not drop-in, volume/weight/energy ratio requires different aircraft, logistics facilities.

18.9.5.7 Cost, maturity, users

The gasification-FT conversion pathway is the second cheapest, particularly for MSW-derived fuels, with a range of €1.34 to €1.87 per litre. The primary costs attributable to the conversion process come from upfront capital expenses. Operating and input costs are low as a result of relatively low facility overhead, feedstock costs, and operating expenses[58]. A harmonized analysis conducted by de Jong (2018)[59] estimated a levelized cost of around €1.80/litre for gasification-FT of wheat straw.

HEFA is not fundamentally different from conventional refining, and the investment required for a HEFA refinery is on the same order of magnitude as that for a conventional refinery. Operating costs per ton of product are currently still somewhat higher than for conventional kerosene but are expected to come down to the same level. However, the price of the feedstock material is typically a good deal 20 higher than the price of crude oil and has typically exceeded even the price of conventional kerosene. The expected capital costs for new renewable diesel and HEFA production facilities are expected to be in the range of several hundred million euros[60]. These fuels cost, on average, €1/liter to produce substantially less than other AJF pathways. However, HEFA production costs are unlikely to decline further in the future because they are dominated by the high cost of feedstock for vegetable and waste oils[61]. A harmonized analysis conducted by

[52] IRENA (2017), Biofuels for aviation: Technology brief, International Renewable Energy Agency, Abu Dhabi

[53] https://gevo.com/

[54] ASTM (2016) "ASTM D7566-16, Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons". Available at: http://www.astm.org/Standards/D7566.htm

[55] http://www.swedishbiofuels.se/

[56] E4tech (UK) Ltd.: Sustainable Aviation Fuels - Potential for the UK industry, July 2014, p.8

[57] https://www.virent.com/

[58] The cost of supporting alternative jet fuels in the European Union, Nikita Pavlenko, Stephanie Searle, and Adam Christensen, ICCT working paper 2019

[59] de Jong, S. (2018). Green Horizons: On the Production Costs, Climate Impact and Future Supply of Renewable Jet Fuels (master's thesis, Utrecht University); http://skynrg.com/ wp-content/uploads/2018/06/dJong.pdf.

[60] (S&T)2 Consultants Inc. (2018). Description and Data Collection on Biofuel Technologies. Prepared for the Danish Energy Agency.

[61] The cost of supporting alternative jet fuels in the European Union, Nikita Pavlenko, Stephanie Searle, and Adam Christensen, ICCT working paper 2019

de Jong (2018)[62] estimated a levelized cost of around €1/liter for used cooking oil (UCO) HEFA. Neste is the largest producer of HEFA, with a production capacity of 2.7 million tons/21.2 million barrels[63].

The expense of SIP production is largely driven by the economics of sugar conversion, in which large amounts of a relatively expensive feedstock are converted into farnesene at low yields. Even at a relatively optimistic rate of 0.3 ton of farnesene per ton of sugar, at a molasses price of €167/ton and sugar content of approximately 55%, more than €1,000 worth of molasses is required to produce 1 ton of jet fuel, which has a substantially lower value[64].

The cost results for ATJ pathways illustrate that lignocellulosic feedstocks are approximately 40% more expensive to convert into fuel. For corn and sugarcane, the upgrading process represents around 50% of the minimum viable price, whereas, for lignocellulosic ATJ conversion, it only accounts for around 80% of the minimum viable price. A substantial portion of the ATJ production cost for food crop–derived fuels is attributable to ongoing feedstock and energy costs, whereas the largest expense for lignocellulosic ATJ pathways is attributable to the upfront CAPEX costs, which account for approximately 40% of the levelized cost. Sugarcane ATJ (with ethanol as an intermediate product) has yields of approximately 0.45 ton per ton of sugar[65]. A harmonized analysis conducted by de Jong (2018)[66] estimated a levelized cost of around €2.50/liter for ATJ from wheat straw, all on greenfield, Nthof-a-kind facilities.

18.9.5.8 Distribution

Fulcrum invested in Fulcrum Bioenergy in 2014, with 375m gallons off-take agreement over 10 years of FT kerosene. Sierra Biorefinery (10m gallons/ year) broke ground May 2018 and the completion is expected in 2020[67]. Neste has cooperation with leading aviation brands (Figure 14) for the distribution of HEFA biofuel[68].

62 de Jong, S. (2018). Green Horizons: On the Production Costs, Climate Impact and Future Supply of Renewable Jet Fuels (master's thesis, Utrecht University); http://skynrg.com/ wp-content/uploads/2018/06/dJong.pdf.

63 Jonas Rorarius, Head of Supply Chain Compliance, Neste, Deployment of Sustainable Aviation Fuels, Sustainable aviation fuels at ISCC meetings and conferences (2019)

64 The cost of supporting alternative jet fuels in the European Union, Nikita Pavlenko, Stephanie Searle, and Adam Christensen, ICCT working paper 2019

65 The cost of supporting alternative jet fuels in the European Union, Nikita Pavlenko, Stephanie Searle, and Adam Christensen, ICCT working paper 2019

66 de Jong, S. (2018). Green Horizons: On the Production Costs, Climate Impact and Future Supply of Renewable Jet Fuels (master's thesis, Utrecht University); http://skynrg.com/ wp-content/uploads/2018/06/dJong.pdf.

67 Yee Chow, Lead Manager Procurement, Cathay Pacific Airways, Implementation of Low Carbon Fuels in International Aviation, in Sustainable aviation fuels at ISCC meetings and conferences (2019)

68 Jonas Rorarius, Head of Supply Chain Compliance, Neste, Deployment of Sustainable Aviation Fuels, Sustainable aviation fuels at ISCC meetings and conferences (2019)

Figure 14. Neste cooperation with leading aviation brands

In Figure 15 is reported the IATA analysis with the estimation of the annual global production potential of SAF, considering the prevision of development of new production facilities and SAF capacity already announced. The bar error is related to the difference between a low take-up of SAF from production facilities (lower numbers) and a high take-up, driven by policy and airline decision making. The top numbers represent the full possible output of SAF production already in operation, under construction or in advance planning and financing.

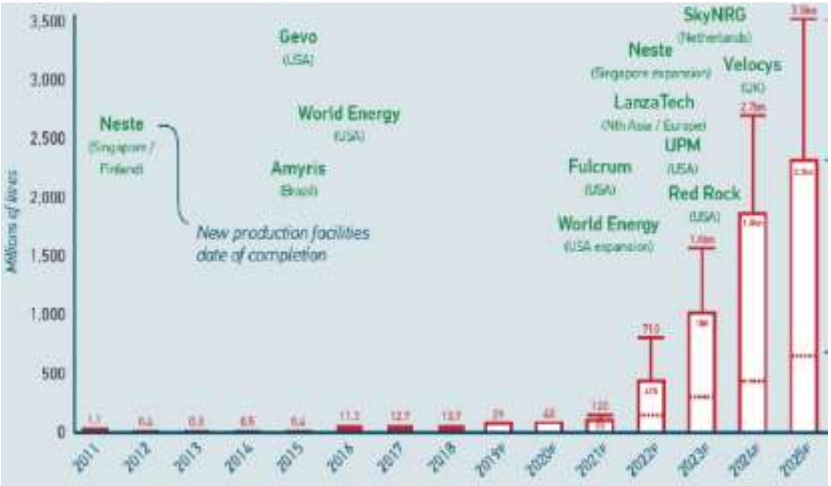


Figure 15. Sustainable aviation fuel ramp-up

18.9.6 Annexe 6: Synthetic fuels, electrofuels, synthetic kerosene.

Electrofuels are those that use renewable energy for fuel synthesis and that is carbon-neutral concerning greenhouse gas emission. Some potential electrofuels respect to the potential application as aviation fuels are n-octane, methanol, methane, hydrogen, and ammonia. The physical and combustion properties significantly differ from jet fuel, except for n-octane. Different electrofuels perform differently for important aspects such as fuel and air mass flow rates.

Electrofuels are produced by combining hydrogen with carbon extracted from CO_2, as schematically depicted in Figure 16. Ideally, the hydrogen would be produced by electrolysis using renewable electricity to obtain it from water, and this would be combined with CO_2 sucked from the atmosphere to make a drop-in fuel. If such a process were implemented on a large scale, it would be effectively carbon neutral, but it with present time technology would cost up to six times more than jet fuel[69].

[69]'Electrofuels' that increase plane ticket price by 60% only way to clean up air travel, report finds, Josh Gabbatiss October 2018, The Indipendent

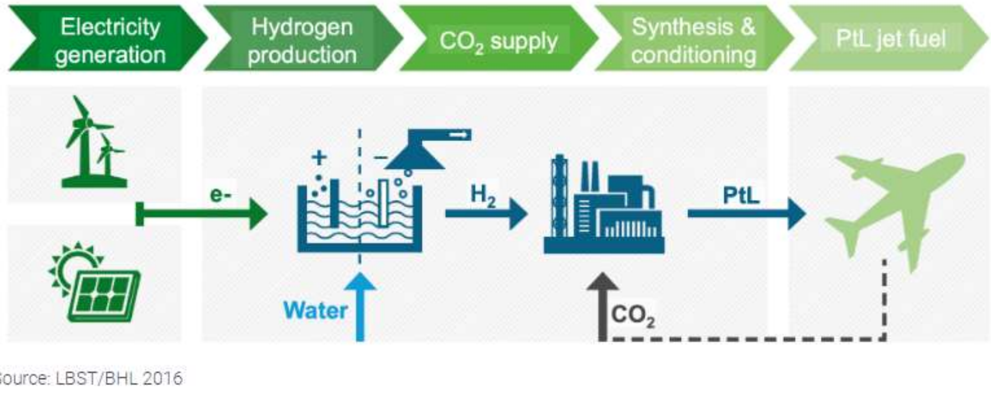


Figure 16. Possible electro fuel pathway[70]

18.9.6.1 Hydrogen from Water Electrolysis

The electrolysis of water to produce hydrogen has been well known since the end of the 18th Century[71]. The energy efficiency of the water electrolysis is already high (70–80%[72]). Hydrogen is an almost ideal electrofuel[73], it possesses the highest gravimetric energy density of all fuels. However, hydrogen has a very low volumetric energy density and a high diffusion coefficient, which makes hydrogen difficult to store. Compression and liquefaction are the main ways to store hydrogen effectively, but hydrogen compression consumes 15.5% of the hydrogen's inner energy content and liquefaction up to 45%[74]. The use of hydrogen in a combustion engine or its oxidation in a fuel cell ("cold combustion") currently yields efficiencies from 40% (combustion) up to 55% (fuel cell).

18.9.6.2 Power-To-X

Due to the obstacles in using hydrogen as a fuel, molecular hydrogen is generally rather used as a chemical intermediate for the production of easily manageable liquid or gaseous fuels, such as methane ("power-to-gas") and longer chained hydrocarbons ("power-to-liquid") from carbon dioxide, or for the production of ammonia from nitrogen ("power-to-ammonia"). All three conventional "power-to-X" technologies (Figure 17) share the combination of the electrolytic hydrogen synthesis and subsequent catalytic conversion of the hydrogen gas with carbon dioxide or nitrogen[75].

---

[70] https://www.flightnook.com/4th-generation-cleaner-fuels-from-carbon-in-the-air

[71] Salem, R.R. The electrolysis of water. J. Electroanal. Chem. 1999, 476, 92–93.

[72] Gülker, F. Production of hydrogen (Herstellung vonWasserstoff). Patent DE446488 (GB), July 1927.

[73] Crabtree, G.W.; Dresselhaus, M.S.; Buchanan, M.V. The Hydrogen Economy. Phys. Today 2004, 57, 39–45.

[74] Sap, K.A.; Demmers, J.A.A.; Nimit Patel, G.R.The energy efficiency of onboard hydrogen storage. Intech 2012, 6, 111–133.

[75] A Study on Electrofuels in Aviation, Andreas Goldmann, Waldemar Sauter, Marcel Oettinger, Tim Kluge, Uwe Schröder, Joerg R. Seume, Jens Friedrichs, Friedrich Dinkelacker, Energies 2018, 10, 392; doi:10.3390/en11020392

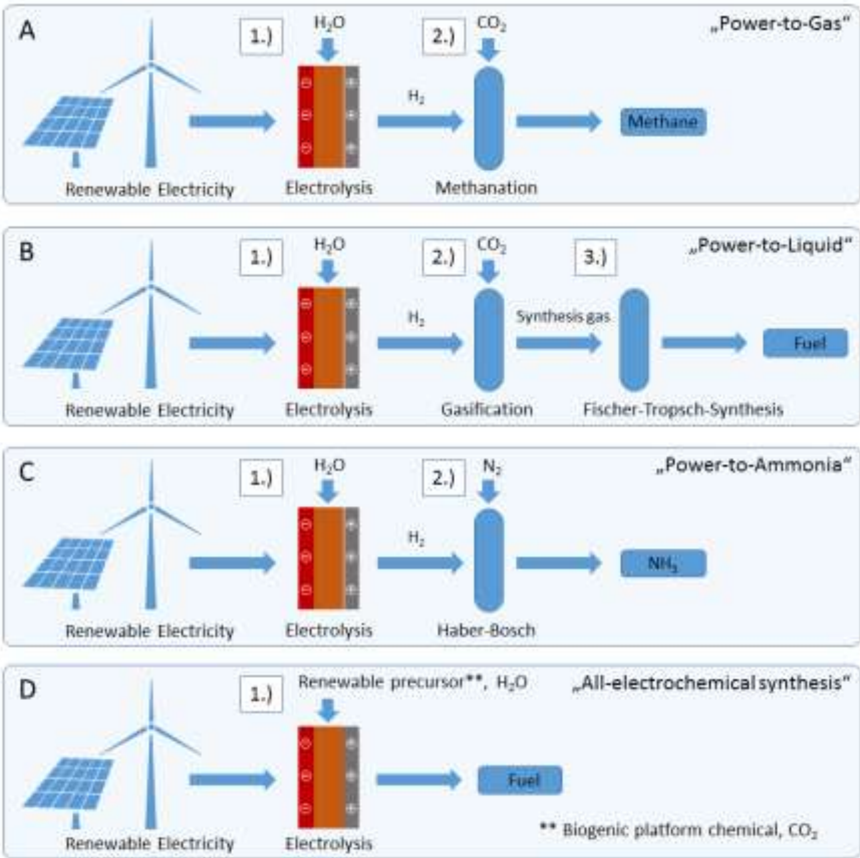


Figure 17. Schematic illustration of the described "power-to-X" technologies: (A) Power-to-Gas; (B) Power-to-Liquid; (C) Power-to-Ammonia; (D) All-electrochemical synthesis[76].

New one-step reactions are needed to bypass the production and the storage of hydrogen to raise energy efficiency further. Electrochemical pathways can be, given the appropriate technology readiness, more efficient than conventional processes and are needed to steer the demand for electricity in a way that new regenerative energies can handle. All electrochemical pathways are, in terms of technology readiness, far behind, but have the potential for the creation of tailor-made emission-free aviation fuels with renewable energies.

18.9.6.3 Comparison of Physico-Chemical Fuel Properties

In Table 8 five representative electrofuels: n-octane, methanol, methane, hydrogen, ammonia are compared with conventional jet fuel (Jet A-1) regarding some selected properties of importance for the utilization as potential sustainable aviation fuels.

Table 8. Comparison of physical and chemical properties of Jet A-1 and different potential electrofuels (L = liquified; * at 15 _C; † at 20 _C; ‡ at boiling point)[77].

[76] A Study on Electrofuels in Aviation, Andreas Goldmann, Waldemar Sauter, Marcel Oettinger, Tim Kluge, Uwe Schröder, Joerg R. Seume, Jens Friedrichs, Friedrich Dinkelacker, Energies 2018, 10, 392; doi:10.3390/en11020392

[77] IFA. Gefahrstoffe—Datenbanken (GESTIS). Available online: http://www.dguv.de/ifa/gestis/index.jsp

Physical Property	Jet A-1	nC_8H_{18}	CH_3OH	LCH_4	LH_2	LNH_3
Flash point (°C)	38	12	11	-	-	-
Autoignition temperature (°C)	210	205	455	595	560	630
Specific energy (MJ kg^{-1})	43.2	44.64	19.9	49	120	18.6
Energy density (MJ L^{-1})	34.9	33.2	15.9	21.2	8.4	13.6
Density (g cm^{-3})	0.808 *	0.70 †	0.796 †	0.58 ‡	0.071 ‡	0.73 ‡
Boiling point (°C)	176	126	65	−162	−252	−33
Melting point (°C)	−47	−57	−98	−182	−260	−77.7
Vapor pressure at 20 °C (hPa)	3	14	129	n/a	n/a	8573
Lower explosive limit (vol %)	0.6	0.8	6.0	5.0	4.0	15.0
Upper explosive limit (vol %)	6.5	6.5	50.0	15.0	77.0	28.0
Mass fraction of hydrogen (-)	n/a	0.16	0.13	0.25	1.00	0.18
Mass fraction of carbon (-)	n/a	0.84	0.38	0.75	0.00	0.00
Mass fraction of oxygen or nitrogen (-)	n/a	0.00	0.49	0.00	0.00	0.82

18.9.6.4 Combustion Characteristics

All investigated electrofuels, except n-octane, differ significantly from jet fuel regarding their combustion properties. The mass flows of air for combustion and cooling the burned hot gases are nearly the same, whereas the mass flow of fuel differs due to the specific energy. Mixture approaches (ammonia/hydrogen mixture) might be of special interest, where more research is needed. The design of combustors has to be adapted to the fuels, requiring basic research on flame stabilization and emission. Although this process will need great effort, it provides the chance to reduce the emission of soot and nitrogen oxide, if the combustion were based on more advanced approaches, like lean premixed or partially premixed combustion.

18.9.6.5 Turbine Performance

Fuel choice influences turbine performance. Higher power output and higher shaft speed are observed, therefore, the alternative electrofuels may be used in current turbine designs without major performance impacts. Concerning the aerothermodynamics of the hot gas path, they can even be used with current designs. About the turbomachinery design, however, the increase in rotor speed changes the mechanical loads and thus requires modifications in the mechanical design. The fuels, therefore, are not drop-in options but appear to be alternatives worth further evaluation concerning the upstream fuel supply chain and, if that turns out promising, with regard to a more detailed component design for the compressor, the combustor and the turbine of the aero engine.

18.9.6.6 Availability and Impacts

We only consider drop-in electrofuel, i.e. electrofuels which can be used by aircraft through combustion in a jet turbine, with minimal or no modifications to the aircraft, engines, or ground refuelling infrastructure. The emission reductions resulting from the use of electrofuels depend mainly on what electricity is used to produce the hydrogen and the choice of the source of CO_2 leads to different impacts. Using CO_2 from a fossil carbon origin, such as the one being emitted in a steel or a power plant, means the fuel is not carbon circular because the CO_2 ends up in the atmosphere anyway. In a 2050 timeframe, the alternative is to use CO_2 captured directly from the atmosphere, that is a more expensive process, but ensures the electrofuels is fully circular. Despite these cost impacts, as fuel efficiency improvements will not decarbonise aviation, and with sustainable advanced biofuels unable to meet all of aviation fuel demand in 2050, if the sector wishes to decarbonise, it must steadily and in a sustainable manner increase electrofuels production to meet the remainder of its fuel demand. At least until more radical technology breakthroughs become available[78].

[78] Roadmap to decarbonizing European aviation, October 2018, Transport & Environment

However, the cost implications of electrofuels will remain substantial. The fact that electrofuels production requires enormous quantities of electricity means that its cost will likely exceed that of untaxed kerosene. It is unlikely that, even with carbon pricing, electrofuels will reach cost parity with kerosene. As a result, policies will need to be put in place to ensure the uptake of electrofuels. Any policy which requires airlines to purchase a more expensive fuel will result in an overall increase in operational costs. At least some of that increase can be expected to be passed onto consumers, increasing the price of tickets, and thereby reducing demand. Electrofuels uptake will have an impact on overall electricity demand: meeting aviation fuel demand with electrofuels will require 912 TWh. This amount is equivalent to 28.2% of Europe's total electricity generation of 3234 TWh in 2015, or 94.4% of the 966 TWh of renewables generation (Figure 18). This electricity used in the production of electrofuels will have to be renewable and additional for the resulting fuel to be considered zero carbon.

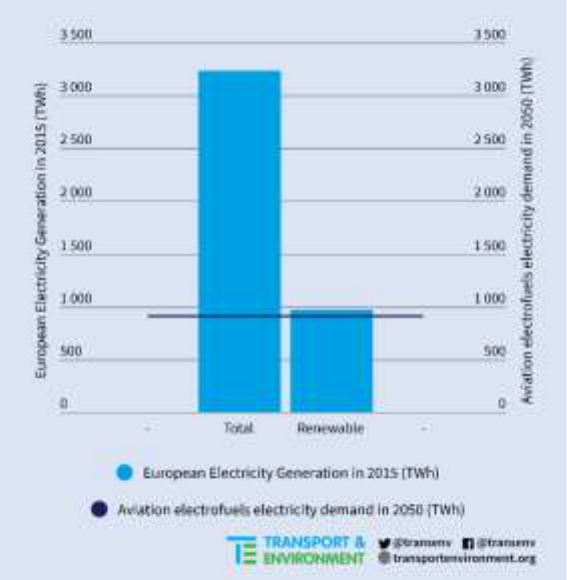


Figure 18. Electricity required to produce electrofuels for EU aviation in 2050

Also, other sectors, such as industry, are expecting to use some types of electrofuels as a way to decarbonise. These competing demands for additional renewable electricity need to be taken into account to assess the realistic amounts of electrofuels which could be used in aviation. In the production of electrofuels, only a portion will be suitable for use in the aviation sector (for example 80%, a very optimistic assessment).

In the proposed scenario electrofuels are produced from 100% additional renewable electricity using direct air capture CO_2. With a cost of 2,100 Euro per ton in 2050, electrofuel uptake will increase ticket prices a further 23% compared to a ticket price with a 150 Euro/ton CO_2 equivalent price, resulting in a 28% reduction in projected passenger demand compared to a business-as-usual scenario. Safeguards are essential to ensure that electrofuels results in actual emission reductions, without negative side effects on other sectors. As discussed above, the two areas of concern are the supply of electricity and the supply of CO_2. Renewable electrofuels have an expanded role in the regulatory framework proposed for the RED II (Renewable Energy – Recast to 2030)[79].

[79] https://ec.europa.eu/jrc/en/jec/renewable-energy-recast-2030-red-ii

18.9.6.7 Cost scenario

In table 5[80] the price of fuel in the Reference Scenario is projected to increase to approximately 930 Euro/ton; the aviation demand has been corrected for this by assuming that the fuel price remains constant at 600 Euro/ton, which results in a 13% cheaper ticket price. Fuels made from hydrogen and CO that is captured from air cost about 5 Euros per litre, but this could drop to around 0.9 Euros per litre longer term. This option is currently not applied on a commercial scale[81].

Table 9. Projection of the price of fuel

Parameter	2020	2050	Description/notes
Kerosene price (Euro/t)	600	600	Assumed constant
Fuel price fraction of ticket price (domestic & intra EU)	25%	25%	Literature[82]
Fuel price fraction of ticket price (extra EU)	20%	20%	
Extra improvement on fleet compared to the BaU	0%	6%	0.2% per year from 2020. This metric includes fuel and operational efficiency
Gen II aircraft	0%	3%	From 2040, 1% per year ingress of 30% more efficient aircraft design
Advanced biofuels (ktoe)	50	7500	In 2020 the amount of 50 kton is assumed to be available, requires 33% year on year growth.
CO2 price Euro/t	30	150	From ETS, VAT, kerosene tax
PtL price Euro/t	5000	2100	Literature[83]
PtL conversion efficiency	38%	50%	Literature[84]

18.9.7 Annexe 7: Developing near term technology solutions

Progress in aviation fuel efficiency, and implicitly in CO2 emissions cut, is exclusively the result of technologies developments in various related fields. As defined by an IATA report [1], two categories of new technologies with impact in aviation environmental sustainability are expected. Some of these technologies, named "*evolutionary*" are strongly considered accessible before 2035, i.e. applicable for the next generation of aircraft. Using NASA's scale of technology maturity, i.e. for Technology Readiness Levels (TRL) [1], (see Figure 19), the evolutionary technologies are supposed to have reached by now at least TRL 3.

---

80 Roadmap to decarbonizing European aviation, October 2018, Transport & Environment

81 Advanced Aviation Biofuels: ready for take-off?, Dolf Gielen, Sakari Oksanen, May 2019, energypost.eu/advanced-aviation-biofuels-ready-for-take-off/

82 UK Aviation Forecasts Moving Britain Ahead. (2017) Department for Transport. assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/674749/uk-aviation-forecasts-2017.pdf

83 Mallins (2017) What role is there for electrofuel carbon future?

84 Schmidt, P., & Weindorf, W. (2016). Power-to-Liquids. Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel. Dessau-Roßlau. Mallins (2017) What role is there for electrofuel technologies in European

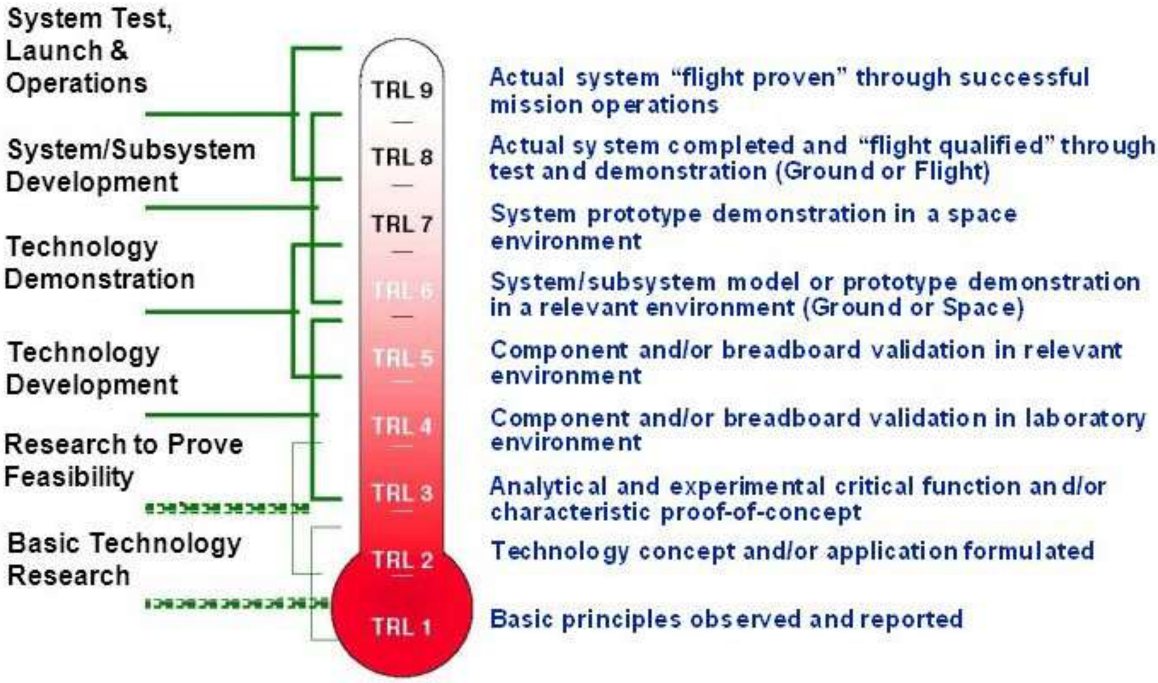


Figure 19. The NASA TRL Meter

IATA believes that other technology solutions, the "*revolutionary*" ones, imply definitely longer and riskier development, probably to be implemented by 2050. The latter category is covering Blended Wing / Body Aircraft, Open Rotor Engine and Hybrid and fully Electric Propulsion. All these will be described in subsequent Chapters of this PARE Report. They are probably somewhere below TRL3.

Of the *evolutionary* technology solutions, some provide marginal gains over the existing performance, gains that can cumulate into non-negligible values. To paraphrase IATA and introducing here two sub-categories, those technologies are "slowly evolutionary". If the current generation of airliners is N, the *slowly evolutionary* solutions had already been introduced on N-1, or N, or are expected to be introduced or refined on N+1.

Other technologies provide rather visible steps, bringing larger measurable generational differences. They will be called "fast evolutionary". This annexe is reviewing such recent improvements and some potentially applicable experimental technologies, promising considerable efficiency to shift together with considerable CO2 reduction. Those technologies might be validated and applicable to generations N+1 or later.

However, due to saturation in exploiting the classical configuration of aircraft, the *evolutionary* technologies are not expected to achieve more than 30-35% reduction in fuel burn compared to 2010 levels, according to IATA [3]

Research in both *evolutionary* and *revolutionary* technologies is encouraged by governments - funded programmes as Clean Sky 1 and 2 in EU [4] and ERA (Environmentally Responsible Aviation) [5] and CLEEN I and II (Continuous Lower Energy Emissions and Noise) [6] in the US.

A few main directions are currently available to improve the fuel efficiency in aviation, as well as its emissions footprint. The technologies used in the design and manufacture the machine can provide the most important source of that improvement. In the case of *evolutionary* technologies, three fields can provide the most promising results: powerplants performance, aircraft aerodynamics and weight reduction.

18.9.7.1 Improving aerodynamics

- High aspect ratio designs

Limitations of the stress in current wing configurations can be overcome either using lightweight structures and stronger materials or introducing new shapes. In the latter kind of solutions, a very thin and long wing will provide less induced drag and consequently less fuel burn and higher speeds. A strut or truss braced wing could offer such advantages. Of course, the strut needs to have very carefully designed aerodynamics to avoid upsetting the gains obtained by the lightweight wing. A Boeing project [7] designated SUGAR (Subsonic Ultra Green Aircraft Research) powered by an advanced turbofan, expects to achieve on a 900 nm mission a 29% fuel economy compared to a Boeing 737-800. Further optimisation may lead to savings of up to 53%. Entry into service (EIS) might be in 2030-35 [1]. The configuration with a parasol wing is also providing a suitable accommodation of a large diameter Ultra High Bypass Rotor or even an Open Rotor engine. Such a solution, however, should deal with the challenge of designing a foldable wing to respond to ICAO airport limitations. Measured on NASA TRL scale SUGAR is probably reaching TRL3-4, other similar designs being considerably behind.

Figure 20. Boeing SUGAR concept

- Boundary layer ingestion

Several concepts exploiting this idea of placing the propulsive fan on the axis of the tail of the fuselage so that thrust is generated using ingested slower boundary layer airflow. The effect is a decrease of the drag and the necessary thrust while the forces are distributed on the main structure and not transmitted via nacelles and wings. Bauhaus Luftfahrt "Claire Liner" [8], NASA's "Fuse-Fan" and "STRAC ABL [9] and MIT "D8" [10] are all different variants of what is called PFC (Propulsive Fuselage Concept) [1]. According to some studies [10],[11] a fuel reduction of 7-12% is estimated when using this solution. The advantage of the configuration is enhanced when turbo-electric propulsion is chosen; in this case, a "distributed propulsion" might be preferable, i.e. one of the three or more electrically driven fans would be placed on the aircraft tail to absorb the boundary layer. However, for the moment, a turbine-driven fan does not look like a viable choice. Currently, the PFC solution is in TRL3.

Figure 21. The Propulsion Fuselage

- Laminar flow control revisited

A technology with proven benefits in reducing the drag consists in controlling the laminar airflow, i.e. eliminating turbulences on the surfaces of the aircraft, and correspondingly reducing drag. Maintaining laminar flow by controlling the pressure distribution on an airfoil is called Natural Laminar Flow (NLF) and has been achieved by sailplane designers and successfully applied 80 years ago in the design of P-51 Mustang fighter [12]. Even if during the following decades there was a substantial amount of research into laminar flow control, lack of cost motivation and difficulties in a compromise between the necessary shape and the mass increase prevented a commercial application. A solution obtained by adding to the wing shaping (NLF) some boundary layer suction on the front part of the wing is called Hybrid Laminar Flow Control (HLFC). The result is the increasing of Reynolds numbers at which turbulent flows appear. Flows can be organised with surface suction through a multitude of very small holes. Some proposals for applying such solutions on large aircraft were submitted during the 60s and 70s the projects were never funded. Eventually extending HLFC effect on the whole surface would create an all laminar aircraft, but this is unlikely to happen before 2050.

A successful NLF Control experiment was achieved by BLADE (Breakthrough Laminar Aircraft Demonstrator in Europe, started in 2017 as part of the Clean Sky Programme. An A340 test aircraft was fitted on the 9 meters with outer wing sections made of carbon fibre composites, having laminar profiles (see Figure 2.1). It is modelling about 2/3 of the span of a single-aisle airliner. The over 60 hrs flight tests revealed a potential of fuel-saving of about 5% by a decrease of the drag by 10% [2], [13]. Other Clean Sky II tests are prepared to demonstrate HLFC on horizontal tail of an Airbus A320. By April 2019, Airbus was testing a hybrid laminar flow control (HLFC) on the leading edge of an A350 prototype vertical stabilizer, with passive suction like the boundary layer control on the Boeing 787-9 tail, but unlike the natural laminar flow on BLADE.

TRL 4-5 can be assumed both for NFL and for HLFC, promising application on the next generation of airliners (N+1).

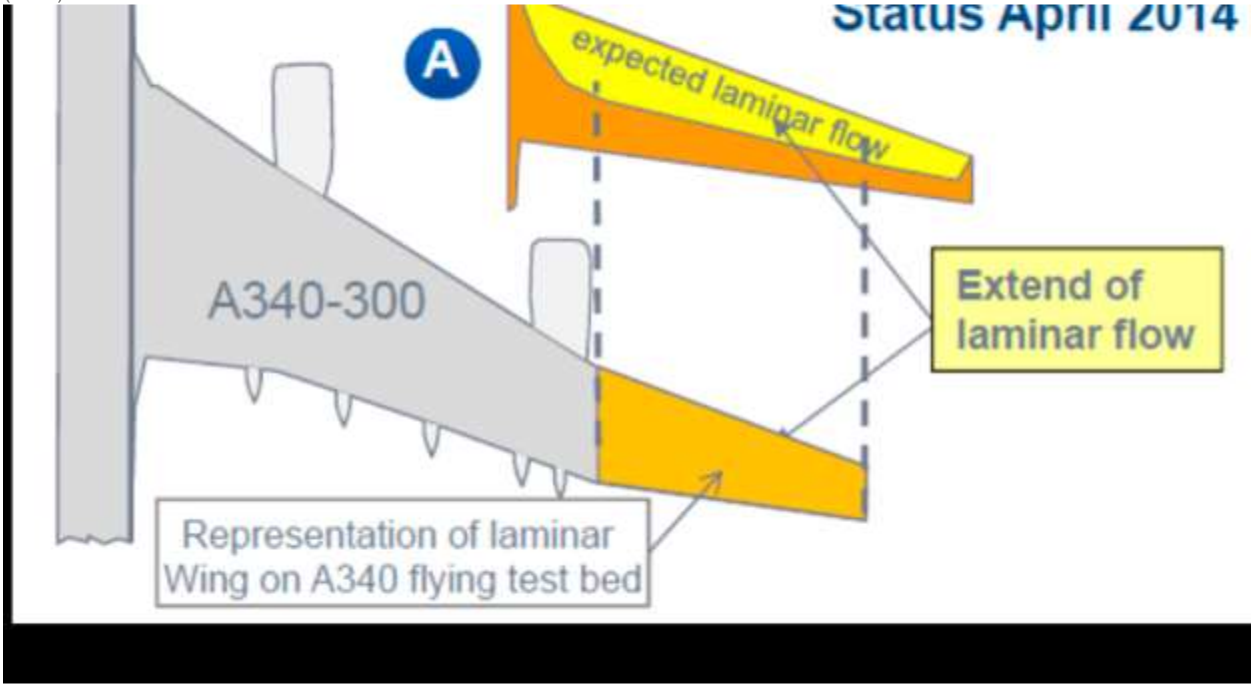


Figure 22. Blade A340 experiment

To obtain a laminar flow wing, a high precision profile and surface properties needs to be achieved and this became less difficult when using composite materials. The suction system involved in the HLFC solution creates an even stronger challenge for engineering. And the solution is not expected to function at speeds over M 0.8 which makes it applicable on short- and medium-range aircraft and less on widebodies. However, great expectations for benefits in fuel economy are already built over LFC.

As John E. Green, Consultant Chief Scientist Aircraft Research Association Ltd. [12] appreciates "overall, the limits set by the laws of physics lead to the conclusion that laminar flow control, in all its respects, is the most promising but also perhaps the most challenging way forward in the quest to reduce fuel burn. All other avenues to higher fuel efficiency have to be pursued in parallel but it is in laminar flow control that the greatest long-term opportunity lies – the all-laminar aircraft, with NLFC and HLFC aircraft as milestones along the road. There are many engineering and operational problems to be addressed but the underlying physics is well understood and there is a substantial body of experience from which to draw encouragement. Looking to the environmental and economic pressures that will confront aviation in the coming decades, we must conclude that it is now time to return in earnest to the challenge of building laminar flow control into our future transport aircraft".

A recent press report [14] is suspecting that some tests with HLFC on an A350 prototype with a system visible on the leading edge of the vertical stabilizer might announce the production application of the technology.

- Active flow control

A complex experimental programme started in 2009 and continued at present at Boeing is designated *ecoDemonstrator*, involving in time several types of aircraft modified to assess the benefits of over 50 innovative technologies aimed to reduce the fuel consumption [15]. One of those technologies is Active Flow Control (AFC) [16].

The size of a twin-engined airliner vertical tail is imposed by the need of providing rudder efficiency in controlling the trajectory in the event of an engine failure which creates asymmetrical forces. This is much oversized in all other circumstances of the operation of the aircraft but needs to be carried on the machine allover its life.

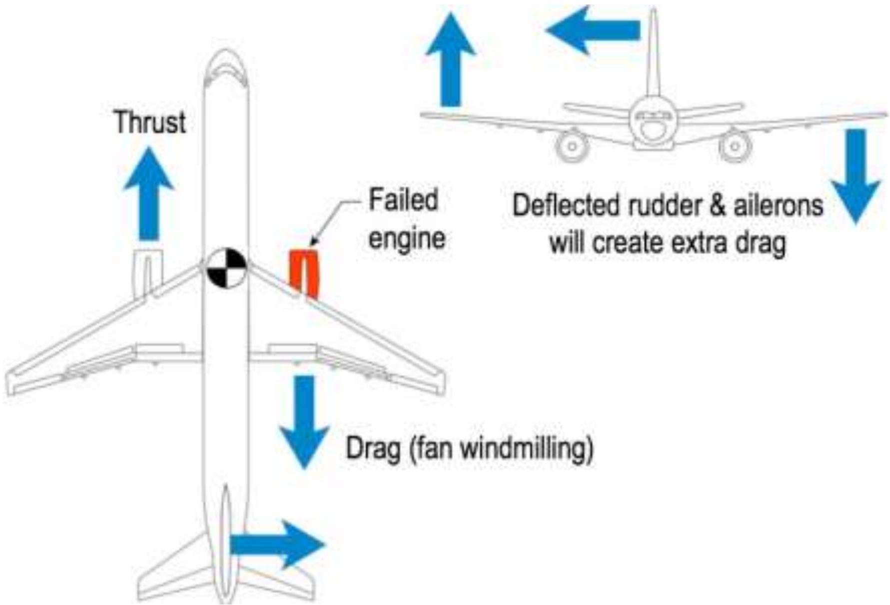


Figure 23. Forces in the situation of one engine failure

Another aspect of the vertical tail oversize is the use of the same tail for all types of a family of airliners. In all cases, the design is satisfying the requirements of the shorter model, while the stretched variants in which the arm of the momentum is longer do not need, even in an engine-out emergency, such a large tail. The conclusion is that in all cases the large tail is a waste in most of the flight situations.

A simple idea was to reduce the size (and consequently the mass and the induced drag) of the tail to the normal operation (non-emergency) necessities. For special requirements, like the situation of failure of one engine, the airflow on the rudder surface can be enhanced by turning on a system blowing some supplementary flow air.

A testing programme was successfully performed by Boeing, first on a scale model, then on a real tail in the wind tunnel and finally, in 2015, in-flight tests on a B757 [16] involved in the ecoDemonstrator project by NASA ERA [5].

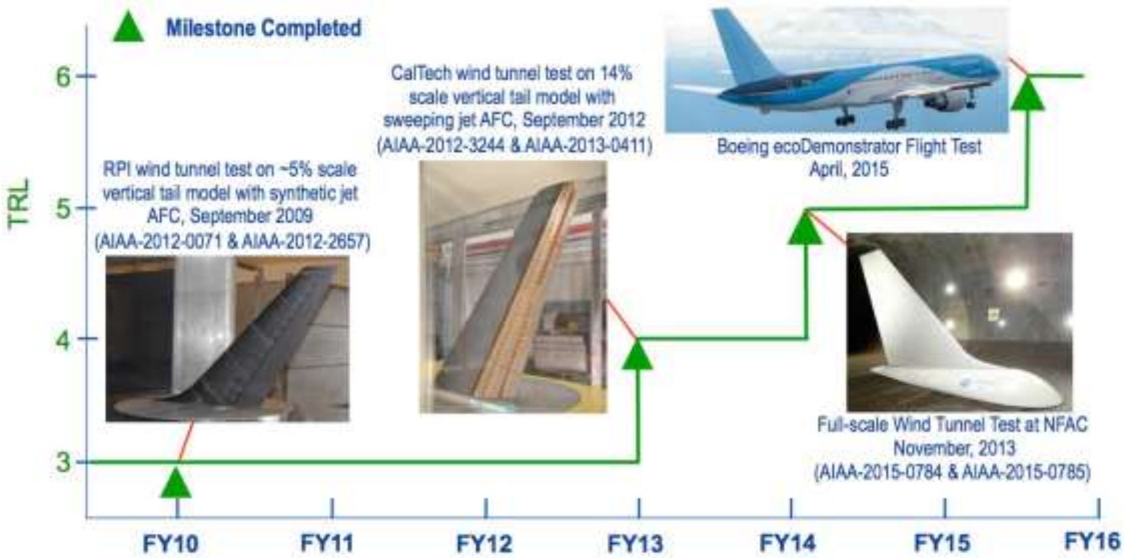


Figure 24. Stages of ecoDemonstrator experiments [18]

When needed, and only then, a flow of pressurised air from the aircraft's APU is sent via a heat exchanger and then via a duct built inside the vertical fin to a set of "actuators" located near the trailing edge of the fin, on a length from the root to about 70% of the span. The test results showed that the aerodynamic effectiveness of the rudder for the testing selected manoeuvres was increased by 14% [17]. That can permit a 17% scaledown of the vertical tail, with reduced mass and drag, which can lead to a half per cent fuel economy [15].

18.9.7.2 Weight reduction

- Advanced Composite Structures

While industrial composite materials are widely produced at reasonable costs and used in a variety of applications worldwide for the second half of the past century, advanced polymer matrix composites are much more expensive, developed starting much later and aviation is one of the few applications that can afford their use. Good mechanical characteristics combined with a very low density (high strength-to-weight ratio) makes them particularly attractive in this field. Initially, major control surfaces were introduced about 40 years ago then gradually larger structural elements as wings, tails and fuselage sections could be manufactured once the technology developed. Precision parts "out of autoclave" are now feasible and cost-effective. Boeing 787 Dreamliner, certified in 2011 was the first aircraft designed with a primary composite structure, estimated by the airframer as about 700kgs lighter than it would have been if made in aluminium. The A350 XWB airframe is made out of 53% composites, carbon fibre reinforced plastic (CFRP) for the outer and centre wing box (covers, stringers, spars), fuselage (skin, frame, keel beam, and rear fuselage) and the empennage (horizontal and vertical tailplanes). This is the most recent in a series of technology developments at Airbus, started modestly in the 80s with the tail fins (5% of the total structure weight) of A310-300 [19].

Figure 25. Composite structures at Airbus [19]

Besides substantial weight savings, other advantages are recognized for the composite materials: accessible aerodynamics profiles – encouraging NLFC, better comfort for passengers due to higher cabin pressure, improved maintainability, the feasibility of smart structures etc. The continual rise in the content of composites is relevant for the maturity of the technology achieved during the last decades, TRL might be considered above 7.

- Smart Intelligent Structures

Substantial progress in the technology of materials, microprocessors, actuators, sensors, signals processing, etc, opened the way for designing adaptive aircraft structures more efficient and safe. Smart structures are considered the systems of Structural Health Monitoring (SHM) already introduced in newer designs, up to the Morphing Structures (MS) which are still in a TRL 2-3 range.

SHM is already used in a rather primitive form on some types of helicopters and aircraft engines. It enables a new approach in maintenance, the condition-based maintenance. For the composite structure, prone to "discrete traumas of random nature" [20], the design can take advantage of its layered configuration and embed low-cost printed sensors able to detect and signal any modification in the material, i.e. a crack which might develop. A lighter structure can be used with benefits in terms of fuel consumption, besides the obvious gains in life cycle cost.

Next step is the currently rather remote perspective of surface morphing, i.e. using smartness to control, optimise and rearrange the shape of the wing to better adapt to different flight conditions. Fixed wings are optimised for a single design point while in the rest of the flight envelope their shapes are less than efficient. Hinged hypersustentation surfaces (e.g. flaps) used in lower speeds manoeuvres are high drag generators due to aerodynamic gaps in the profile. If the shape is changing for different flight conditions such lack of efficiency could be avoided. The solution is gapless and deformable leading and trailing edge devices, made of flexible outer skin moved by inside driving mechanisms. Successful experiments were conducted in a wind tunnel and in-flight on UAVs [21]. DARPA Smart Wing Project was aimed to evaluate a SM wing concept equipped with a hingeless trailing edge control surface and its results were particularly promising. However, this research identified issues to be addressed in future designs: aeroelastic behaviour, the fatigue life of the structure, the need for compact power sources, etc. There is less chance that SM to become production standard during the next several decades.

- Additive manufacturing

Additive manufacturing is the process of creating an object by building it layer over layer. Classical machining is the opposite, in this, the part is obtained by removal of material from a rough piece can be referred to as subtractive manufacturing. Introduced during the 80s for plastics, additive manufacturing was called 3D printing, this name is still used today for any additive processes of various materials. By the early 2000s, additive manufacturing was being used to create functional products including complex metallic parts. The two biggest advantages of additive manufacturing are creating complex geometries and producing small lot sizes. More recently, companies like Boeing, Airbus and especially General Electric have begun using additive manufacturing as integral parts of their business processes. Experts recognise that, at present, the two biggest advantages offered by additive manufacturing are creating complex geometries and producing small lot sizes [22]. Some applications in aviation are the perfect fit with those requirements, inviting the adoption of the process. Parts produced with this method are already beginning to appear on the latest generation of aircraft, producing components that

weigh 30-55% less than traditional metal parts [15]. To produce such parts using subtractive technologies would ask for high costs of processing, tooling, labour, etc. With additive manufacturing, strength is provided where it is needed, with no excess in the material used. Less weight reduces fuel burn and CO2 emissions. 3D Polymer components, such as ramps used to attach electrical harnesses to the aircraft structure, saving 2.4 kilograms per plane, will be equipping the A350XWB [15].

In 2016, General Electric Additive offered a convincing demonstration of the benefits of the technology: a small team of 6 engineers *"started experimenting in secret with printing pieces of an old commercial helicopter engine... Within 18 months, the team was able to print half of the machine, reducing 900 separate components to just 16, including one segment that previously had 300 different parts. The printed parts were also 40 % lighter and 60 % cheaper. To make these parts the ordinary way, you typically need 10 to 15 suppliers, you have tolerances, you have nuts, bolts, welds and braces..." [23].*

Figure 26. Additive manufactured bracket vs. substractive manufactured equivalent [15]

Additive manufacturing has its share of challenges, too. Additive manufacturing machines are expensive, sometimes hundreds of thousands of dollars. One of the biggest challenges, though, is making sure that your final part has good properties. If powders don't quite sinter together, it forms defects that lead to failure. You can get residual stress based on how you process your metal, and there can be some internal strain on the material that can lead to the part wanting to naturally bend [22].

Expected component weight gains will increase once the technology is growing in maturity and the costs of the process will decrease.

18.9.8 Annexe 8: Generating incremental efficiency improvements from current aircraft designs

The current airliner generation (N) is the result of careful design, aimed to substantially reduce fuel consumption and consequently the CO2 emissions compared to the previous one (N-1). However, a more diligent review might reveal new possibilities for improvement. Of those technology solutions, some provide marginal gains over the existing performance, gains that can cumulate into non-negligible values. As mentioned above, those *slowly evolutionary* solutions had already been introduced on N-1, or N, or are expected to be introduced or refined on N+1.

18.9.8.1 Aerodynamics gains

- Wingtip devices

A strong drag generating area is located at each of the aircraft wingtips, where vortices are dissipating a large amount of energy, thus creating unwanted drag. To reduce this drag by recovering some tip vortex energy, a solution was introduced some decades ago and refined subsequently in successive stages: wingtip devices. First introduced on airliners during the 80s by Airbus on A300-310 and Boeing on B747-400, they later took various shapes with various effectiveness. For the initial 747 application, Boeing claimed a 3.5% fuel burn reduction.

Figure 27. Canted winglet 1985, Boeing [Arpingstone, GNU Free Doc License]

Figure 28. Wingtip fence 1985, Airbus [Arpingstone, GNU Free Doc License]

Figure 29. Current models of wingtip devices [15]

Current shapes provide some serious savings in fuel and emissions as well: between 3% and 6% off a single aircraft's CO2 emissions per year [24]. The attractivity of the technology is proved by the fact that retrofits for older types of airliners are available and in large demand, even if a Supplementary Type Certificate (STC) is needed.

"Blended Winglets" (BW) available for several models of B737 are estimated to save 380 -570 tons of fuel per year compared to a 737 without the devices. Savings climb to 1.9 million litres per year on the 767ER. Aside from fuel and CO2 savings, co-benefits include a reduction in aircraft noise and as much as 8% reduction in NOx emissions [25]. The newer model launched in 2014, "Split Scimitars" (SSW), brings down emissions a further 2% compared to the Blended Winglets. Boeing's newest "Advanced Technology" third-generation winglet, a combination of rake tip technology with a dual feather winglet concept is claimed to improve efficiency by up to 5.8% relative to a wing without a winglet, and by more than 1.5%, depending on range, over current designs.

Airbus has also developed the "Sharklet" product for its own A320 aircraft family. These deliver more than 4% fuel saving on longer sectors and are available on new A319, A320 and A321 aircraft, or for retrofit. An A320 equipped with Sharklets can cut between 500 and 1,000 tons of CO2 per year in typical operations [15].

Other aircraft, such as the Bombardier business jet lines, Embraer and some existing Airbus and Boeing aircraft also have wingtip devices in-built, including some that may not appear to be as obvious — like the Boeing 777's "raked wingtip".

More advanced wingtip devices solutions are currently explored and evaluated. Aviation Partners, the makers of BF and SSW claimed they had obtained promising results with Spiroid Winglets and expect to apply the technology on some businesses and commercial aircraft types [25].

Figure 30. Spiroid winglet [25]

Some estimates place the number of wingtip-equipped airliners at over ¼ of the total world fleet. in total, over 20 million tons of jet fuel has been saved, avoiding over 56 million tons of CO_2 emissions since the year 2000 [15].

Like any other improvement wingtip devices have setbacks: weight penalty and the cost. One winglet can have a mass of over 200kgs and a retrofit usually implies a wing box reinforcement modification. The price is also non-negligible: as an example, a BW retrofit kit for B737NG has a list price of $1.7mil per shipset, while that for a B767 is $2.4mil. [24]. However, the fact that so many airlines pay for this equipment means that the business case for wingtip devices is interesting.

- Miscellanea refinements

Manufacturers are continuously at work to introduce performance improvement 'updates' to existing, N-1, even N-2 generation aircraft. Since the total fleet is still rather large, such small gains are cumulating into important fuel burn saves.

A good example [15] is given by the engineers at Embraer found a cost-effective way to re-sculpt an existing aircraft model to achieve its efficiency potential without compromising the original handling.

The E175 fuel burn improvements package project consisted of a combination of aerodynamic improvements that reduced fuel consumption for the commercial aircraft model by 6.4% in a typical flight, cumulating more than a tone in CO_2 emissions per year.

These improvements include new wingtips, systems optimisation and streamlining of aerodynamic surfaces.

The project had two phases [26]. The first phase devised a package of modifications that resulted in:

1. horizontal tail gaps and
2. rain-deflector adjustments;
3. environmental control system and anti-ice optimisation; and
4. wheel fairing and
5. RAM air door development.

Figure 31. E175 fuel burn package [26]

The second phase involved more aerodynamic improvements such as:

6. tail cone inlet modification and
7. red beacon optimisation.

A new 8 wingtip was also a part of this package and turned out to be the main contributor for the fuel burn gains as well as the main challenge for the engineers.

The project had an important premise to follow — the modifications incorporated had to preserve the aircraft handling. This target was accomplished, allowing the changes to be brought in by airlines without any pilot re-training or additional costs [15].

Boeing had also such initiatives: they introduced some performance enhancements to the Next-Generation 737 that reduced fuel consumption and emissions by 2%. up to $120,000 worth of fuel saved per aircraft [15]. The 737 Performance Improvement Package (PIP) comprises technologies designed to both reduce drag and improve propulsion efficiency to reduce fuel use and CO2 emissions. Among other changes, the package [27]:

1. Replaced the upper and lower red manoeuvring light assemblies with a more aerodynamically designed shape to reduce aerodynamic drag. The upper skin was revised, and no electrical interface changes were required to accommodate the new lights;
2. Refined wing control surfaces, such as reducing the thickness, minimising gaps and altering the shape slightly of some of the wing control surfaces;
3. Re-contoured the five rear wheel-well fairing assemblies to smooth the airflow near the main landing gear, reducing aircraft drag;
4. Included changes to the CFM International engines that contributed additional reductions in fuel use and CO2 emissions.

Figure 32. B737NG fuel burn package [15] [26]

More than 1,500 of the performance-improved aircraft have been delivered so far [15]. And the technology isn't just restricted to new 737s straight off the production line: it can be retrofitted to existing aircraft, allowing airlines to improve the environmental performance of their existing fleet.

- Bug avoidance

One factor increasing the turbulence on the wing profile is the insect build-up on the wings. Insect residue especially settled on the leading edge interrupts the laminar flow, creating supplementary drag. To reduce this harmful effect, two methods were tested on Boeing ecoDemonstrator package of experiments mentioned at 9.2.2.4. On the left-wing, Boeing tested a Krueger shield to block insects from hitting the wing's leading edge. The wing has been modified to include a 6.7 m-span glove section supporting a variable-camber Krueger flap which was deployed during landing and which protrudes just ahead of the leading edge. Although Krueger flaps have been tried before as insect-mitigation screens, previous designs caused additional drag; the newer design being tested is variable-camber and designed to retract as seamlessly as possible into the lower wing surface. As shown in 9.2.2.3. above, increasing the use of natural laminar flow (NLF) on an aircraft wing has the potential to improve fuel burn by as much as 15%, but even small contaminants from insect remain will trip the airflow from laminar to turbulent, destroying the performance benefit. [28]

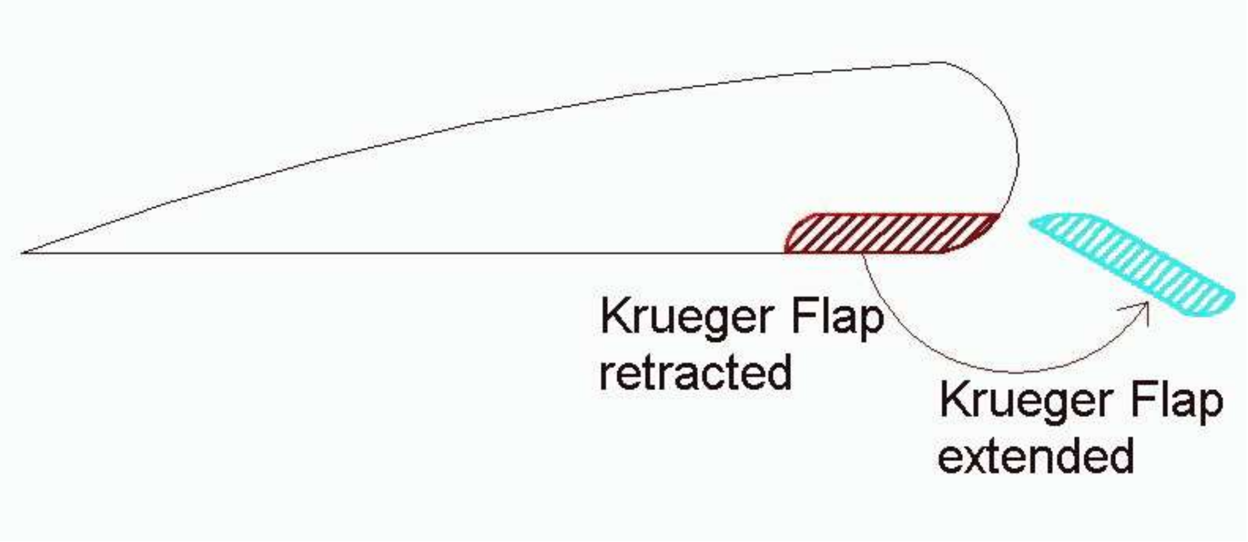


Figure 33. Krueger shield [Stahlkocher, GNU Free Doc

On the right-wing of the ecoDemonstrator test 757, Boeing in collaboration with NASA tested several 'bug-phobic' coatings. NASA reports that the most efficient of the tested coatings reduced bug remnants by as much as 40% [15].

18.9.8.2 Weight saving

- New lightweight aircraft paints

Aircraft's paint is an area where airlines can save weight. The fuselage of a painted Boeing 747-400, for example, typically carries about 250 kgs of paint [15]. Besides making the aircraft look good, it performs an important role in protecting the fuselage, so this is a dead load the aircraft has no choice but to carry. Any reduction of this is a gain in terms of fuel consumption.

KLM's engineering and maintenance department took on the challenge of reducing the weight added by the livery paint and, with the help of German supplier, Mankiewicz, was able to develop a new paint system that reduces the weight of the paint by 15%, through applying more, but thinner layers [29].

The paint developed also has other advantages. It is also chrome-free and the aircraft can be washed by simply using soap and water alone, cutting out the need for the use of additional solvent chemicals, which can have a detrimental effect on the local environment. There are also cost advantages. The gloss and colour last longer with the new paint, so the aircraft doesn't have to be painted as often. Furthermore, because the paint dries quicker, the aircraft don't have to stay on the ground for as long for each paint job. Each layer dries within two hours. It used to take eight for the traditional process of painting [29].

Figure 34. Painting process at KLM

- Removing unnecessary weight

Any extra weight carried on board of an airliner means more fuel used and more CO2 released.

The world's largest airlines are continuously working on programmes of cutting weight across their fleets of aircraft. It is a strategy resulting both in better economics and in environment protection. A careful analysis can identify several areas in which weight optimisation is possible. Small investment might be necessary, but they are offset by the benefits of weight saving actions.

Such a weight analysis carried out by Lufthansa on an A340-300 identified potential reductions of 100 kgs, obtained by removing unnecessary items and replacing other items with lighter alternatives [30].

The same group of airlines, demonstrating a special focus on lightweight solutions, introduced a new model of the seat, BL3520. At just under 11kgs, Lufthansa's new seat is 4.3kg lighter than its predecessor. The nearly 30% weight reduction has been achieved through the replacement of seat padding foam with a polyester mesh, a new armrest and detail optimisations such as an enlarged hole in the seat belt lock, which saves 60g per seat. While the new accommodation will shave off, for example, around 300kg off a Boeing 737's empty weight, the savings across the fleet are to total approximately 131 tones [31].

Figure 35. New Lufthansa lightweight seats [31]

Inside the cabin, almost 30,000 new light-weight catering trolleys have been introduced into service. The new trolley, which is one third lighter than its predecessor, saves around 28,000 tons of CO2 annually.

Lufthansa is also equipping its long-haul fleet with a new in-flight entertainment system. Depending on the type of aircraft, this saves 30% to 40% weight when compared with previous equipment.

Lufthansa Cargo completely replaced its fleet of 5,500 standard freight containers with versions around 15% lighter than their aluminium predecessors. With up to half a million movements per year, the 14-kilogram difference cut overall CO2 by around 7,000 tones. Tomorrow's standard pallets which are developed for the airline are expected to weigh as much as 25% less than the existing ones.

KLM also has managed to make weight savings. As well as the usual lighter seats and trolleys, KLM was the first airline to implement polypropylene trays, which not only reduces weight but also has a less environmental impact during production. In addition, Air France-KLM-Martinair Cargo introduced a range of new lightweight cargo nets made from a fibre called ultra-high-molecular-weight polyethylene which reduces the weight of the nets by 50% [29].

[1]. Mankins, J.C. 2009, *Technology readiness assessments: A retrospective*. Acta Astronautica 65. http://www.onethesis.com/wp-content/uploads/2016/11/1-s2.0-S0094576509002008-main.pdf

[2]. IATA, 2017, Aircraft *Technology Roadmap to 2050* https://www.iata.org/contentassets/8d19e716636a47c184e7221c77563c93/technology20roadmap20to20205020no20foreword.pdf. retrieved Feb 2020]

[3]. IATA, 2019, *Technology Roadmap for Environmental Improvement Fact Sheet,* https://www.iata.org/contentassets/8d19e716636a47c184e7221c77563c93/fact-sheet-technology-roadmap-environment. pdf]

[4]. https://www.cleansky.eu/innovative-technologies-0

[5]. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20140012638.pdf

[6].https://www.faa.gov/about/office_org/headquarters_offices/apl/research/aircraft_technology/cleen/

[7]. Boeing, January 08, 2019, *in Technology, Innovation Lightweight, ultra-thin and more aerodynamic wing concept*, https://www.boeing.com/features/2019/01/spreading-our-wings-01-19.page

[8]. Bauhaus Luftfahrt, 2020, *Concept study "Propulsive Fuselage": Adding an extra engine to reduce emissions* https://www.bauhaus-luftfahrt.net/en/topthema/propulsive-fuselage/

[9]. NASA, 2019, *Boundary-Layer Ingestion Propulsion*, https://www1.grc.nasa.gov/aeronautics/bli/

[10]. Uranga, A. et a., 2014, *Preliminary Experimental Assessment of the Boundary Layer Ingestion Benefit for the D8 Aircraft*, http://web.mit.edu/drela/Public/N+3/Uranga2014_compressed.pdf

[11]. Welstead, J.R., Felder, J.L., 2016, *Conceptual Design of a Single-Aisle Turboelectric Commercial Transport with Fuselage Boundary Layer Ingestion* https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160007674.pdf

[12]. Green, J.E., 2008, *Laminar Flow Control – Back to the Future?* 38th AIAA Fluid Dynamics Conference Seattle June 2008, https://web.archive.org/web/20120916162555/http://adg.stanford.edu/aa241/supplement/Lam-Flow-Control-AIAA-2008-3738.pdf# retrieved Feb 2020.

[13]. Beck N. et al., 2018, *Drag Reduction by Laminar Flow Control*, Energies, 2018, 252, www.mdpi.com/journal/energies

[14] Thierry Dubois, 2019), *Does Airbus A350 Laminar Flow Test Signal Production Possibilities?* 30 April 2019.

[15]. ATAG, 2015, *Aviation Climate Solutions*, https://aviationbenefits.org/media/125796/Aviation-Climate-Solutions_WEB.pdf

[16]. ***2015, *EcoDemo Focusses on Laminar and Active Flow,* Aviation Week & Space Technology, 25 March 2015

[17]. Whalen, Edward A. et a., 2016, *Flight Test of an AFC Enhanced Vertical Tail,* AIAA Aviation Forum 13-17 June 2016, 8th AIAA Flow Control Conference, Washington, D.C.

[18]. Lin, John C. et a., 2016, *An Overview of Active Flow Control Enhanced Vertical Tail Technology Development,* 54th AIAA aerospace conference 4-8 January 2016 https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160007653.pdf

[19]. Hellard, G., 2008, *Composites in Airbus – A Long Story of Innovation and Experiences*, https://web.archive.org/web/20161004204641/https://www.airbusgroup.com/dam/assets/airbusgroup/int/en/investor-relations/documents/2008/presentations/GIF2008/gif2008_workshop_composites_hellard.pdf

[20]. Spekmann, H., Roesner, H. 2006, *Structural Health Monitoring: A Contribution to the Intelligent Aircraft Structure,* 9th European Conference on NDT, Berlin, September 2006

[21]. Dufault, F., Akhras, G, 2008, *Smart Structure Applications in Aircraft,* The Canadian Air Force Journal, summer 2008. https://web.archive.org/web/20130522211717/http://www.airforce.forces.gc.ca/CFAWC/eLibra

ry/Journal/Vol1-2008/Iss2-Summer/Sections/06-Smart_Structure_Applications_in_Aircraft_e.pdf

[22]. Linke, R., 2017, *Additive manufacturing explained*, MIT Journal, December 11, 2017, https://phys.org/news/2017-12-additive.html

[23]. Zelinski, P., 2017, *GE team secretly printed a helicopter engine,* Additive Manufacturing. 31 March 2017 https://www.additivemanufacturing.media/blog/post/ge-team-secretly-printed-a-helicopter-engine-replacing-900-parts-with-16

[24]. ***, 2017, *The benefits of winglets and performance-enhancing kits*, Aircraft Commerce issue no. 109 December 2016 / January 2017

[25]. Aviation Partners, Inc, *Types of Blended Winglets*, https://www.aviationpartners.com/aircraft-winglets/types-blended-winglets/

[26]. ****Cutting edge aerodynamics reduce fuel burn*, https://aviationbenefits.org/case-studies/cutting-edge-aerodynamics-reduce-fuel-burn/

[27]. Tesch, D., 2012, *Next-Generation 737 Fuel Performance Improvement*, Boeing Aero Magazine Q4 12 https://www.boeing.com/commercial/aeromagazine/articles/2012_q4/3/

[28]. *** 2019, *Boeing Takes New Technologies Out of the Lab and Onto ecoDemonstrator Flying Test Bed*, July 1, 2019, PR Newswire, https://boeing.mediaroom.com/2019-07-01-Boeing-takes-new-technologies-out-of-the-lab-and-onto-ecoDemonstrator-flying-test-bed

[29]. ***, 2013, *Friendly, feather-light paint,* KLM Takes Care, https://klmtakescare.com/en/content/friendly-feather-light-paint-

[30]. ***, 2013, *Lufthansa Strips A340 In Weight-saving Experiment,* Aviation Week & Space Technology, 29 March 2013, https://m.atwonline.com/air-transport/safety-ops-regulation/lufthansa-strips-a340-weight-saving-experiment

[31]. Gubisch, M. 2018, *New Lufthansa seat saves nearly 30% in weight,* Flight Global, sourced from Air Transport Intelligence news, https://www.flightglobal.com/new-lufthansa-seat-saves-nearly-30-in-weight/97485.article

18.9.9 Annexe 9: Combination of design and operational efficiency improvements

For more than 20 years, the European Union has been striving to conclude an international agreement within the UN framework to reduce aviation greenhouse gas emissions. The European Union supports activities in this direction within the ICAO framework. The European Parliament, in a separate resolution, called on the EU to present a strategy to achieve climate neutrality as quickly as possible, by 2050 at the latest, for its inclusion in the UN Convention on Climate Change. Deputies also called on the new European Commission President to include the goal of reducing carbon dioxide emissions by 55% by 2030 in the provisions of the so-called European Green Agreement. [154]

To date, ICAO has not been able to achieve any breakthrough on this issue, and the countries represented there have not been able to reach agreement on binding global goals and measures regarding aviation. The resolution on global climate change marks the beginning of a movement to establish action plans on a struggle with climate change, which is to be reported to ICAO. The Resolution points out that states shall take measures to reduce emissions from aviation, and the European Union shall develop a comprehensive system of measures aimed at reducing these emissions.

The EU Emissions Trading Scheme is one element of this system. The EU Emissions Trading System affects energy sector organizations or enterprises. The system allows enterprises to buy and sell greenhouse gas emission quotas to reduce the environmental impact of their organization. The same system works in the field of using aviation equipment. Greenhouse gas emission trading is a market-based tool for regulating greenhouse gas emissions into the atmosphere by which states and companies can sell or buy greenhouse gas emission quotas in the national, regional or international markets. [155] .

It is commonly known that the International Monetary Fund (IMF) favoured the introduction of a greenhouse gas tax in all countries of the world. The rationale for such recommendations points out that to achieve the objectives of the Paris Climate Agreement, carbon dioxide emissions should be reduced by one third by 2030. A proposal was made to tax one ton of industrial CO2 in the amount of $70 or 62 euros. For aircraft, this amount can reach $180 per ton.

According to the leaders of international organizations, namely, taxation is the most efficient tool to reduce the use of fossil fuels and the associated reduction in CO2 emissions. IMF intends to establish a fund for the development of renewable energy for the proceeds of this global tax. As for the analysis conducted by the IMF, if it is possible to tax 70 dollars per ton of industrial CO2 emitted into the atmosphere for all countries included in G20, this will mean receiving from each country from 1% to 2.5% of GDP. This will bring the IMF from $630 billion to $1.58 trillion a year.

Thus, an actual issue for organizations and companies that work in the field of creation and operation of air transport is the reduction of CO2 emissions. Reducing the tax on harmful emissions will allow companies to maintain the dynamics of the development of air transport.

In this case, one of the rational approaches to reducing CO2 emissions is: switching to alternative fuels, if gas turbine engines are used, or using an all-electric power plant on an aeroplane. It is obvious that the development of fundamentally new aircraft for flight operation is becoming exigent for green aviation. For civil aviation, the main requirement is to ensure the high operational efficiency of the aircraft. Therefore, the basis for predicting the development of aircraft is the substantiation of periods and stages of the introduction of technologies to achieve the goals of Flightpath2050.

It is expected that by 2050 the number of civil aviation flights will double. This will lead to oil shortages, increase greenhouse gas emissions and the overall negative impact on the environment. The search for technological solutions in response to these global challenges lies in the plane of increasing the fuel efficiency of aircraft - by reducing the consumption of traditional fuels and reducing greenhouse gas emissions. This implies optimization, in particular, facilitating the design of the aircraft, reducing the weight of the engine, on-board equipment, and improving the means of control and monitoring of aircraft and engine control systems. In this regard, we will analyze the three most promising areas of technological development that can improve the environmental data of air transport, the abandonment of internal combustion engines, the use of nanotechnology, the use of airplanes with variable airframe geometry.

It is known that internal combustion engines are the most common power plants in modern aviation. Due to the large volumes of fuel consumed and greenhouse gases generated they have an extremely negative impact on the environment. The abandonment of such engines will be a milestone on the road to improving the environmental friendliness of aircraft.

Internal combustion engines can be replaced by those of a new type, powered by solar energy or other types of renewable sources. For the commercial introduction of manned aircraft of this type, it is necessary to solve the problem of reducing the take-off weight of an aircraft by reducing the weight of solar panels and its airframe.

The first prototypes of solar-powered equipment have already been created. Due to powerful batteries that charge during daylight hours, such aircraft are capable to fly at night. In the near future, they can become a popular type of transport for shipping goods and passengers by regional and local routes.

Solar-powered airplanes will dramatically reduce the cost of air travel and completely solve the key environmental problems of modern aviation - greenhouse gas emissions and acoustic impact on the environment.

At the initial stage, solar panels will be used along with other sources supplying the electric motor. In 2020 the global market of electric aircraft in civilian and military aviation is expected to reach 22$ billion with an average annual growth rate of 4.6%. By 2030, the market share of solar-powered aircraft will be 50-70% of the market of electric aircraft.

It is obvious that the increase in the cost of aviation fuel and the reduction in the cost of solar energy produced in photovoltaic systems will create favourable conditions for the serial production of solar-powered aircraft, their operation on local and regional routes.

High safety requirements for flights and the resulting "inertia" in the aircraft industry may hamper the implementation of the trend. In the segment of long-distance transportation, the insufficient battery capacity may become an obstacle to the commercial operation of solar-powered aircraft.

Existing advances are the availability of basic knowledge, competencies, infrastructure, which can be used for the accelerated development of relevant research areas.

Consider the use of nanotechnology for the miniaturization of avionics. A significant increase in the environmental sustainability of aviation can be achieved by reducing the size and weight of the basic elements of aircraft avionics - navigation, communication, automatic control systems while enhancing their reliability and increasing energy efficiency.

Reducing the maximum take-off weight of aircraft through the miniaturization of avionics will allow, on the one hand, reducing fuel consumption, and on the other decreasing the number of flights by raising the commercial load of each flight performed.

To realize the trend, a qualitative change in aircraft design will be required, as well as the use of fundamentally new materials for nano sensors built into different parts of the aircraft body.

When implementing such projects, it is expected to reduce the cost of airborne equipment and the general costs of aircraft production, cut off operating costs by reducing the maximum take-off weight of aircraft, and increase the availability of air transportation for the population.

In 2020, the global market for on-board aircraft equipment for civil aircraft can reach 105$ billion, with an average annual growth rate of 10.5%. By 2030, aircraft, partially or fully equipped with miniaturized airborne equipment, can occupy approximately 80% of the civil air transport market.

At the same time, military aviation most stimulates the demand for miniature airborne equipment of aircraft. The labour input and duration of the process of changing the aircraft design as well as the high cost of production of this equipment can inhibit the development of the trend.

Today, the greatest interest is the development of projects of aircraft with variable geometry of the airframe elements (or wing sweep). It is possible to increase the fuel efficiency of an aircraft by optimizing flight dynamics and distributing maximum take-off weight. Developments in the field of variable wing geometry and other airframe elements are aimed at solving these problems.

Adaptation of the wing structure to flight conditions (at high speed, a large wing sweep is effective, at low speed – a small one) allows the aerodynamic quality of the wing to be increased by 15-20%, which contributes to a significant reduction in fuel consumption.

One of the most promising developments in this area is performed by FlexSys Inc, by NASA order. Its transformable wing technology has already passed flight tests based on the Gulfstream III aircraft, showing high efficiency.

The application of this development leads to a decrease in the amount of fuel consumed and greenhouse gas emissions, an increase in aircraft speed, a reduction in the cost of flight hours, an increase in the availability of air shipment and a reduction in travel time.

Currently, the turnover of the civilian segment of the aircraft market with variable wing geometry is estimated at 135$ billion (or 10,000 units of equipment, including business jets). In 2025, the demand for aircraft of this type will be about 14,000 units of equipment, in 2030 - about 23,000 units.

However, the military aviation and space industry will initially generate demand for aircraft with variable wing geometry. The development of the industry of supersonic passenger aircraft new generation will become an incentive for the widespread use of this technology in the civilian sector. The development will be especially demanded in the production of business jets. A limitation is a fact that the adaptive wing is fit for flying at supersonic speeds, therefore, with the modern aircraft design system, the use of variable wing geometry is limited.

Thus, for civil aviation, the main requirement is to ensure high technical and economic efficiency in the operation of aircraft. Operational efficiency is a notion that determines the degree of compliance of performance indices of the aircraft and its systems with the established levels of these indices over a predetermined service life. However, to evaluate efficiency, it is necessary to use appropriate indices and criteria. As it is known, today all operational processes, including flight, are evaluated by economic criteria, subject to specified safety requirements. The objectives of improving operational efficiency are directly related to improving economic performance and increasing the competitiveness of aircraft. At the same time, technical efficiency is determined in aircraft development by optimizing its aerodynamic characteristics, new design solutions, power plant parameters by optimizing flight conditions under given restrictions and operating conditions. If we neglect the issues of aircraft reliability and the associated costs of maintenance, repair and flight delays, the economic efficiency of a transport aircraft will primarily be determined by the available commercial load and the required fuel costs. The payload determines the amount of the airline potential income per flight, and fuel costs are one of the main expense items.

As an index of the aircraft technical and economic efficiency, a certain function is considered, depending on six groups of factors:

- The aggregate of aerodynamic and weight characteristics of the aircraft;
- Set of parameters characterizing the flight condition;
- Set of high-speed and throttle characteristics of engines;
- The aggregate of passenger comfort and safety characteristics;
- An aggregate of operational factors;

- A set of technical and economic parameters.

Due to the growth of passenger and cargo shipment and the increase in consumption of aviation kerosene, it is extremely important to improve the fuel efficiency of aircraft. According to an international group of experts on climate change [156], global annual growth in air shipment within 1990-2015 will make 5%, fuel consumption 3%, and the fuel efficiency of new aircraft entering service will improve by 1% per year.

Raised requirements for reduction of CO2 emissions in the first place can be met with more advanced aircraft. The efficiency of traditional schemes of modern aircraft engines and airframes is approaching its maximum limit. It is impossible to drastically improve their performance and reduce CO2 emissions without developing alternative engine designs and new airframe layouts. The use of new fuels is also a prerequisite. [55] [56]

The effect of alternative fuels on the performance indices of a new or modernized aircraft can be analysed, for example, using a simulation model based on mathematical models of an aircraft and a power plant. The necessity of using the simulation model is led by the clearly expressed multi-disciplinarity of this system and the need to take into account factors depending on the fuel used and affecting the technical concept, flight technical and environmental characteristics of the system. Thus, we can conclude the following:

- Improving the transport efficiency of alternative-fuel aircraft occurs only in those flight missions that require maximum fuelling and maximum payload with maximum take-off weight;
- For a more significant increase in the performance indices of passenger and transport aircraft, it is necessary to design a power plant and aircraft directly for specific alternative fuel.

Moreover, the operational efficiency of airlines can be increased in two directions:

- Improvement of design and engineering technologies to ensure the creation of new, more economical aviation equipment with elements of modification of serial equipment to save fuel and energy resources.
- Reducing the cost of jet fuel in conditions of mass operation of the fleet.

Also known ways and methods of cutting off aviation fuel costs in real operating conditions:

- Reduction of the operating time of aircraft engines on the ground;
- Decrease in take-off weight of the aircraft;
- The optimality of the power ratings and trajectories of aircraft descending.

The operational characteristics of the aircraft are formed at the stages of development and creation of the aircraft and implemented in the course of technical operation. The operational characteristics of the aircraft include:

- Design features of the airframe, engine, functional systems and their products;
- Failure characteristics of the aircraft, its functional systems and products;
- Endurance characteristics (service life of the aircraft and its components);
- Maintainability is a feature of fitness to perform a scope of maintenance and repair works;
- The need for maintenance and repair, regulated by maintenance and repair programs for the airframe, engine, functional systems, taking into account the application of maintenance strategies;
- Characteristics of the flight operation of the aircraft.

The modern automated dialogue design system makes it possible at the preliminary design stage to analyse some options for passenger aircraft schemes and layouts and select the best option that most fully meets customer's specifications with high fuel economy and operational efficiency. The result of the system operation is to obtain geometric data that are used in the system of aerodynamic model automated manufacture.

This requirement is determined by one of the factors of the scientific and technological revolution, which consists in the frequent updating of manufactured types of products, in this case, power equipment, the constant introduction of more and more new design changes that increase their manufacturability and operational efficiency.

Despite the significant cost of resources of the enterprises themselves and government spending on breakthrough projects, in the absence of clear criteria for a "breakthrough" product status, aircraft manufacturers' expectations regarding entry to new markets may not be justified. Moreover, not only breakthrough status but also the belonging of a product to a new generation of aircraft can be disputed. If we are guided in the course of classification by technical features (for example, the use of new structural materials, the availability of intelligent information systems onboard, etc.), the question arises: at what minimum proportion of new structural and technological solutions can a product be attributed to a new generation and how to measure this proportion? The complexity of the separation of aircraft generations is aggravated by the following factors:

- Over several decades, the appearance, general design, and even many consumer properties (for example, speed and flight altitude) of jet passenger airplanes have not undergone significant changes;
- Guided by some economic considerations (reducing risks, ensuring the continuity of the revenue stream, etc.), manufacturers strive to introduce as new not revolutionary solutions, but evolutionary ones, through unit-by-unit modernization of the basic design, as a result, there are generations designated by industry experts as "4+", "4 ++", etc.

In this regard, it is possible to classify new types of aircraft based on economic rather than technical criteria (especially since all new technical solutions in civil aviation are ultimately subordinated to the desire to increase the economic efficiency of equipment and the level of flight safety).

It is suggested that such a product be considered a breakthrough, which, appearing in the market, may cause a voluntary refusal in its favour at least of several operating organizations to use their aircraft, even though the latter has not yet exhausted its service life. This criterion has a logical justification and does not contradict the data on the change of aircraft generations.

As a result, researching methods and means of improving operational efficiency is associated with the forecasting of flight-technical and economic characteristics, taking into account the system of technical operation of the aircraft.

Based on the analysis of the main directions of aircraft development [157] [158], [159], when researching the development trend of aircraft, promising innovative products were identified:

- New types of light and high-strength materials;
- Fuel cells, catalysts for innovative energy carriers;
- Nanostructured composite and ceramic materials and coatings with special thermal properties (heat-conducting, thermoregulating);
- Nanostructured antifriction, adhesive and hydrophobic materials, anticorrosion coatings;
- Composite, ceramic materials and nanofluidic materials with special magnetic properties;

- Nanostructured materials with the effect of "shape memory" and "self-healing materials";
- New generation solar batteries, radiators based on nano heterostructures;
- Transducers and sensors based on nanostructured materials for analysing the composition of various media.

The implementation of these products will permit to achieve a new quality in the operational characteristics of the aircraft.

However, the evaluation of degree or improvement level of the aircraft operational efficiency with the introduction of new measures or developments remains a pressing issue. As you know, the functional properties of an aircraft are determined by its specifications. In some cases, the evaluation of the economic and engineering perfection of an aircraft may be limited to considering individual particular criteria. In other cases, for the uniqueness of evaluation, it is possible to use a complex criterion, which combines the values of individual particular criteria. This is usually the criterion of "cost-effectiveness", which combines the individual values of cost criteria and tactical capabilities of the aircraft.

With the updating of design data on aircraft at various stages of the life cycle, it becomes possible to take into account sufficiently detailed record of all operational features of current and advanced aircraft. First of all, this refers to the comparative evaluation of aircraft using indicators of economic and engineering perfection. For this purpose, the utilization rate of passenger aircraft during two flight missions is considered: distance flight and endurance flight.

For a total evaluation of economic and engineering perfection of the aircraft, it is used an index [160], that includes the flight technical and economic components, such as the characteristic coefficient of the aircraft flight cycle; parameter value or specifications for the base and new aircraft; utilization rate of the aircraft for the life cycle with a certain share distribution of flight tasks; value cost of the life cycle of the base and new aircraft.

In order to conduct studies on coordination the design of the aircraft and improve operational efficiency, groups of aircraft, which are represented by configurations No. 1-6 (Fig. 9.4.1-9.4.6) were formed. Development paths with different options for improving operational efficiency have been identified for the selected aircraft groups. [57], [58] [59], [60]. In this case, the considered control system may consist of:

- Turbofan engine of traditional configuration with direct (m <14) or geared (m> 14) fan drive.
- Turbofan engine ("open" rotor).
- Distributed power plant.
- Engine for supersonic aircraft.
- Hybrid power plant.
- Fully electric motor.

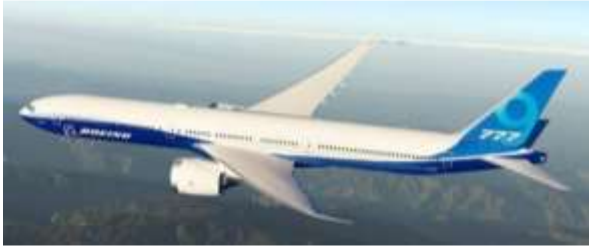


Figure 36. *Boeing 777X and Boeing 787 aircraft family (configuration No.1)*

Figure 37. *Airbus A350 XWB aircraft family (configuration No.2)*

Figure 38. *"Flying wing" type aircraft (configuration No.3)*

Figure 39. *Supersonic commercial aircraft (configuration No.4)*

Figure 40. *Propeller propulsion aircraft (configuration No.5)*

Figure 41. *Aircraft with transformation technologies and morphing technology of airframe elements (configuration No.6)*

The main content of the research is the forecast for aircraft configurations improvements and their control systems over timeframes to track the time history of their characteristics [61], [62]

Configuration No.1. Aircraft that start operation in 2020 and will fly until 2050 are under consideration. The general structural layout of the airframe and power plant won't change until 2050. The power plant consists of turbofan engine of traditional configuration with a direct fan drive, from 2030 configuration with geared fan drive will be used, from 2040 a hybrid power plant will be used. For 2020, all achievable technologies have been introduced. The implementation of innovative products is 2%, from 2030 – will be 10%, from 2040 – will be 30%.

Configuration No.2. The development of aircraft is supposed to be similar to configuration No. 1. The difference in the trend is the number of aircraft released on the world market and the cost of their maintenance.

Configuration No.3. "Flying wing" type aircraft, which will begin operation in 2030, is under consideration. In 2020 the development of new airframe designs type "flying wing" is equal to TRL = 9 (for military aircraft). The development of a new passenger aircraft configuration is TRL = 5. From 2030, the power plant will include a hybrid engine. From 2035, a distributed power plant and a hybrid engine will be used; from 2045 a fully electric motor will be in operation. For 2030, the implementation of innovative products will be 35%, from 2040 – 70%.

Configuration No.4. In 2020 the development of new airframe configuration for supersonic aircraft has a value of TRL = 5. The operation of this type of aircraft is expected from 2030. The power plant includes a turbofan engine or ramjet engine. From 2040, a distributed power plant will be used. In 2030, the implementation of innovative products will be 40%, from 2040 – 70%.

Configuration No.5. Aircraft that start operation in 2020 and will fly until 2050 are under consideration. The general structural layout of an airframe and a power plant changes according to technology readiness. The power plant consists of turboprop of traditional configuration. From 2030, a hybrid engine with propeller will be in operation. From 2040, a power plant with a fully electric motor will be used. In 2030, the implementation of innovative products will be 35%, in 2040 – 80%.

Configuration No.6. Aircraft that will be in operation from 2040 are under consideration. The design layout of the airframe and power plant changes according to technology readiness. In 2020, the development of new airframe designs type "flying wing" with adaptive functions (transformation technologies) for passenger aircraft is TRL = 2. It is expected to have TRL = 6 from 2030. The power plant consists of fully electric motors or engines of non-traditional configuration. In 2030, the introduction of innovative products will be 55%, in 2040 – 90%.

Figure 42 shows the results of the studies. Analysis of the data demonstrates that the development paths of new aircraft are not monotonic. By 2050 the best result can be shown by "flying wing" type aircraft with transformation technologies and morphing technology of airframe elements. Of course, such developments are accompanied by the use of electric motors, the introduction of fully nanostructured materials and other advanced technologies.

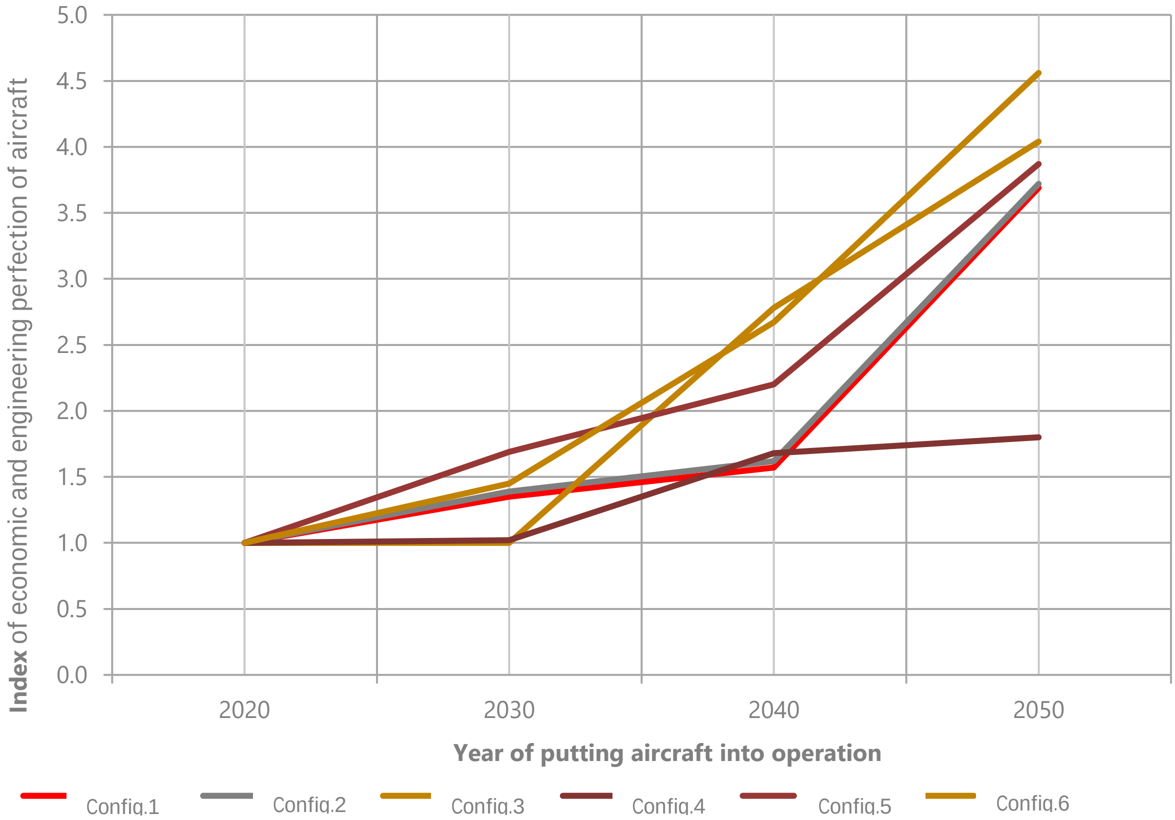


Figure 42. *Dependence by year of economic and engineering perfection index on the implementation of innovative products*

"Flying wing" type aircraft will become more profitable than traditional aircraft, such as the Boeing 777 or Airbus A350. This is due to the best aerodynamic characteristics and improved integration properties of the airframe and power plant of a new aircraft configuration. The rational use of distributed power plant with fully electric motors will significantly improve the operational characteristics of "flying wing" type aircraft.

Supersonic commercial aircraft show the worst result. This is due to the fact that flying at supersonic speeds has negative environmental impacts. Supersonic aircraft still have serious limitations in terms of noise and economy. These problematic issues will persist for a long time. The economic efficiency of such aircraft will not be high due to the small number of passengers and the high price of tickets compared to tickets for other types of aircraft. Besides, flying at a supersonic speed of up to M = 1.8 ... 2.3 can provide an engine with high energy efficiency, which for the coming decades will be with a forced cycle and based on the combustion of liquid fuel (turbofan or hypersonic ramjet engines). It is planned to use new fuels without harmful emissions of CO2 or NOx by 2050.

At the same time, the use of biofuels promises a reduction in carbon dioxide emissions in the range of 36-85%. This greatly depends on the type of soil on which a particular plant will grow. Although the hybrid biofuel-kerosene mixture was certified for use in aviation in 2009, the industry doesn't hurry to introduce a new product. There are certain technical obstacles and difficulties towards increasing biofuel production to commercial scale. But the main factor is the price, that will be compared with traditional kerosene in only a few decades.

Based on the results of research, one can assume CO_2 decrease relative to 2020, and, accordingly, a significant reduction in taxes on greenhouse gas emissions. The introduction of aircraft as per configurations No. 1 and

No. 2 will lead to a reduction in CO_2 by 16% in 2030, by 28% in 2040, by 45% in 2050. Implementation of configuration No. 3 can contribute to a reduction in CO_2 by 45% in 2040 and by 90% in 2050. Implementation of configuration No. 4 can lead to a reduction in CO_2 by 15% in 2040 and by 35% in 2050. The application of configuration No. 5 can contribute to a reduction in CO_2 by 45% in 2030 and by 80% in 2050. The application of configuration No.6 will completely remove CO_2 emissions by 2050 based on the introduction of all innovative products and with the use of electric motors and systems.

18.9.10 Annexe 10: Review of the ways of technical development of radically new aircraft designs

The review of the technical development of the structural and layout schemes of modern and promising passenger and transport aircraft showed that a new generation of aircraft would be created according to a new aerodynamic scheme. Significant reserves to improve the aerodynamic perfection of aircraft are laid in the integration processes and new layout schemes. Modern aircraft, such as Boeing B787 and Airbus A350, will be the last generation to be created by the traditional scheme. The next generation of aircraft will completely exhaust the reserve of improvement of this layout and no matter how much effort is spent, it will be practically impossible to obtain significant results.

In the medium and long term prospect, the main directions of technological improvement of aircraft will be the creation of aircraft with a long duration and flight range based on improving the mass-dimensional characteristics of special and general aircraft equipment, increasing the aerodynamic feature and weight perfection of the airframe design, as well as the use of promising power plants based on electric and hybrid engines.

It is planned that the introduction of such revolutionary innovations will take about 20...25 years. Experts predict the appearance in the operation of radically new aircraft designs at the turn of 2040.

The main task of civil aviation for the period up to 2050 is the transportation of people that determines the improvement of civil aircraft in the direction of upgrading safety, ecology, efficiency, comfort, etc. The practical impact of these factors is expressed in the studies carried out in the following areas:

- Increasing the speed performance of traditionally designed aircraft (supersonic and subsonic aircraft and helicopters).
- Increasing the speed performance of an aircraft by combining traditional design solutions (a combination of the advantages of an airplane and helicopter flight principle, when creating high-speed vertical take-off vehicles).
- Practical mastering of new flight power ratings (hypersonic aircraft).

The main directions in the development of material technology for the implementation of a new aircraft generation are:

- Self-healing materials and coatings.
- Self-organizing regulatory structures and systems.
- Sensor and active elements with improved performance.
- Composites based on polymers, ceramics, adhesives with new properties.
- Graphene-based structures.

The most likely features in creating a new aircraft generation will be:

- Remote control of aircraft elements.

- Use of "smart" structural materials and coatings.
- Possibility of adaptive variations in the geometry of flight vehicle planes.
- Application of engines with a variable cycle and with an integrated electric generator.
- Application of new physical principles in the operation of electronic computing equipment (photonics, fibre optic signal transmission, etc.).

Despite these development directions, all scientific and technical studies of world air companies are reduced to two areas:

- Improving the fuel efficiency of the power plant using new workflow cycles.
- Improving the aerodynamic characteristics of the design of the flight vehicle airframe based on the use of radically new aircraft designs.

These two directions contain a common sense in integrating a flight vehicle airframe and its power plant into a single complex technical system to ensure the specified operational performance of a new aircraft. We review separately these two extensive challenges.

18.9.10.1 Ways to improve the fuel efficiency of the power plant

Despite significant progress in recent decades, the aviation industry still encounters significant tension to reduce fuel consumption, pollutant emissions and costs, especially, when it comes to ambitious goals set by aviation authorities such as Flightpath 2050 in Europe [161] , [162]

In Table 10 it is stated quantitative assessment of the goals for reducing CO2 aviation emissions in the United States and Europe, both in the short and long term.

	Europe (relative to the year 2000 a/c)		US (relative to the year 2005 best-class a/c)	
Programme	Vision 2020	[163]FlightPath 2050	N + 2 (2025)	N + 3 (2030–2035)
Value	50%	75%	50%	60%

Table 10. Objectives of CO2 emission reduction in aviation

To accomplish the aforementioned complicated tasks, researchers and engineers strive to develop new concepts and technologies. According to the IATA Technology Roadmap [63], [64], 24 potential airframes and power plants were determined that may be available for sustainable aviation in 2050 as for the level of technology readiness. As part of NASA's N-plus USA programs, several innovative airframe technologies were determined to reduce emissions [65], [66]

However, IATA and NASA researchers concluded that technology development alone could not achieve the desired goals in emission reduction. New aircraft concepts should be developed to achieve the target performance of the aircraft. Besides, researchers from the University of Cambridge summarized various new aircraft concepts proposed by the aeronautical research communities and concluded that ACARE and NASA emission reduction goals could not be achieved without developing new concepts for the transformation of the aircraft conceptual design [67] . In support of this statement in Figure 43, it is shown the historical development of fuel efficiency for commercial aircraft since 1980. Selected aircraft are commercial airliners from regional aircraft to wide-body long-range aircraft. From this figure, one can observe the difficulty in realizing the goals of reducing emissions, since the rate of reduction in fuel consumption is not high enough.

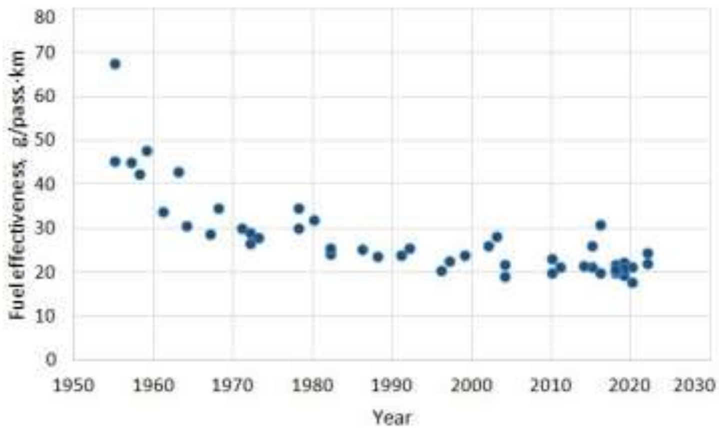


Figure 43. Aircraft fuel efficiency trend

One of the key provisions for creating aircraft engines is the advanced development of critical technologies. [164] [165]. Over a more than 70-year period of development of civil jet aviation, the transition to new engine design, an increase in the parameters of the operating process, the introduction of new structural materials and technical solutions, as well as an improved aerodynamic performance of aircraft made it possible to reduce fuel costs per passenger-kilometre by more than 80%, of which almost 50% reduction was achieved due to the improvement of the engine.

Improving the performance of civilian aircraft engines occurs with constant requirement strengthening for noise levels and emissions of harmful substances. In this regard, in the engines currently being developed, it is necessary to apply such technical solutions and technologies that will satisfy the ICAO requirements they plan to adopt in 2025 ... 2035. Taking into account ICAO recommendations and research results, target indicators have been developed for promising models of aviation equipment that determine the improvement of performance in terms of time. In accordance with these indicators, new passenger aircraft with promising engines should provide in the 2030s:

- Noise reduction of at least 30 EPNdB relatively to the requirements of ICAO Chapter 4;
- Reduction of cruising specific fuel consumption by at least 20% compared to modern engines;
- Reduction of NOx emissions as for takeoff and landing cycle by at least 65% relatively to CAEP/6 ICAO requirements.

Achieving the specified indicators requires solving a number of complicated challenges, developing advanced technologies and can only be realized with an integrated approach by improving the performance of the engine and aircraft, as well as improving the air traffic control system.

Despite the achieved high level of technical excellence of aircraft engines, new solutions are needed to further improve their performance both at the architecture level and at the level of increasing the efficiency of individual units. Possible aerodynamic schemes of promising passenger aircraft and engines for their power plants are shown in Figure 44.

Compared with the fifth-generation engines (PW1000G, LEAP, GEn [68]x, Trent), the maximum reduction in specific fuel consumption with increased flight and thermal efficiency (while increasing cycle parameters and the bypass ratio) can be 25...30 % for a propfan engine or distributed power plant (DPP).

The decrease in specific fuel consumption for a turbofan engine with direct or reduction fan drive or a turbofan engine with a complex thermodynamic cycle (for example, with intermediate cooling) with increasing cycle parameters and the bypass ratio to $m = 14...18$ can be $15...20\ \%$ [69] [70] .

Figure 44. Aerodynamic schemes of promising passenger aircraft and engines for their power plants

Based on a comparison of the efficiency of engines of various structural schemes to achieve the required flight speed (Figure 45), today we discuss the development of technologies for:

- Turbofan engine of the traditional scheme with direct (m<14) or reduction gear (m>14) of a fan.
- Propfan engine ("open" rotor).
- Distributed power plant.
- Engine for supersonic aircraft.
- Hybrid powerplant.
- Fully electric motor.

The main goal of technological achievements is to make the aircraft more environmentally friendly, reliable, safe and economical. These goals can be combined into one main goal, which is to reduce airline operating costs. From the point of view of technologies for creating engines, the main technological trends that will lead to the achievement of these goals are:

7. Increasing the bypass ratio *m*, which increases propulsive efficiency and thereby reduces specific fuel consumption.
8. Increase in turbine inlet temperature (TIT) and overall pressure ratio (OPR), which increases thermal efficiency.
9. Increasing the efficiency of engine elements, that is, the polytropic efficiency of fans, compressor stages and turbines.
10. Reducing the weight of the engine structure based on the use of lightweight materials with increased strength, which will lead to a decrease in specific fuel consumption.

11. The use of built-in electric generators to increase the efficiency of propulsors.
12. Today, the most economical engine option is a turboprop scheme.

The most promising engine in terms of emissions is a fully electric engine. However, the transition to a fully electric motor is a long way, which requires the development of new technologies (Figure 45). Taking this into account, NASA offers a phased approach to creating an electric engine for aircraft of various purposes. [71]

It is planned that for regional aircraft with a capacity of up to 50 people the necessary equipment (electric motors of acceptable weight with a capacity of 1...2 MW) will be available within the next 10 years, for 100-seater aircraft (electric motors with a capacity of 2...5 MW) within 20 years, and B737 / A320 class aircraft (electric motors with a capacity of 5...10 MW) for 30 years [72].

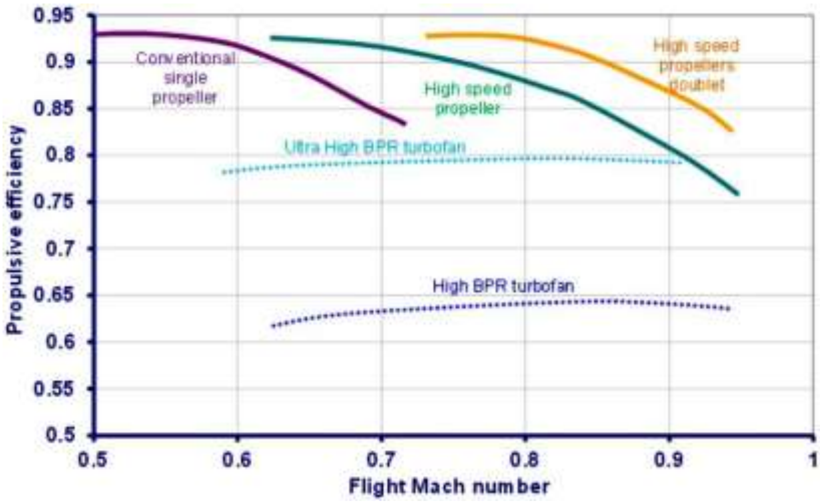


Figure 45. Comparison of the efficiency of engines of various design schemes as for flight speed

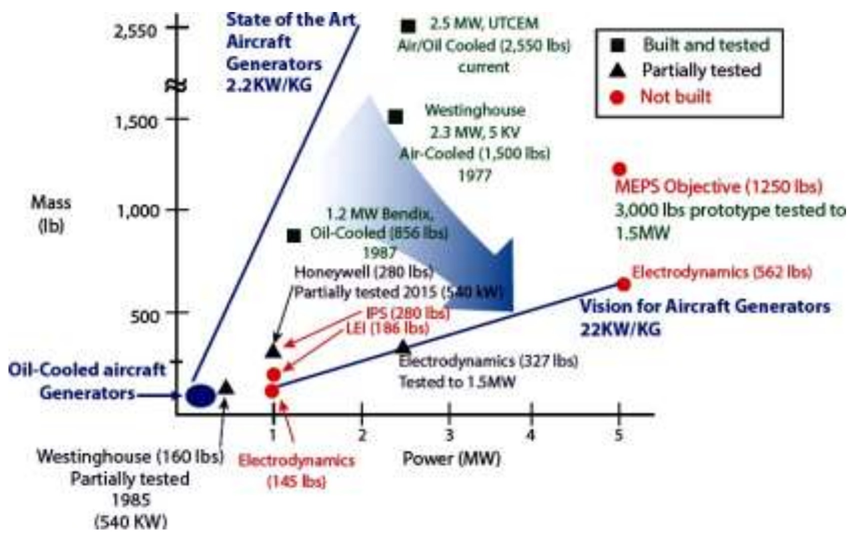


Figure 46. Development of aircraft electrical generators

In addition to electric motors and generators, the development of accumulators and converters of electric energy, as well as on-board electrical networks for high power, is required. In this case, the weight efficiency of all elements of electrical equipment (except for superconducting ones) significantly decreases with the growth of their power. In addition, the storage of energy in the form of fuel is considerably more efficient than any existing electrical energy storage system. Therefore, all-electric light and ultralight aircraft, although they exist, have an extremely limited flight duration.

In Figure 47 there are shown the basic principles of increasing the fuel efficiency of aircraft engines of various world companies, the trends in the application of new technologies for promising engines.

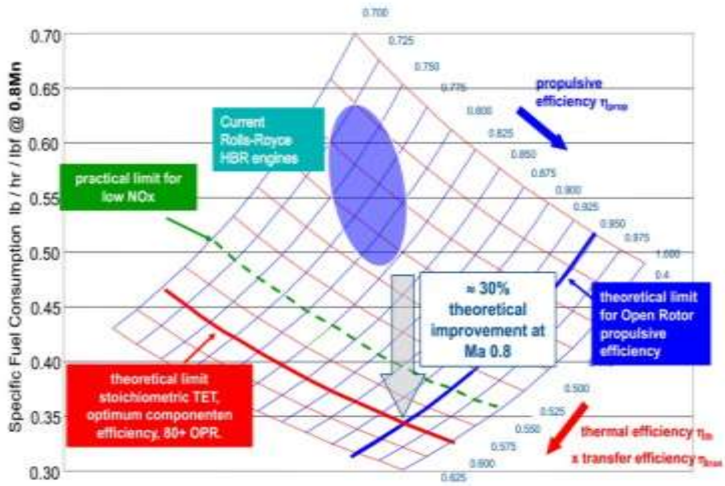


Figure 47. Substantiation of specific fuel consumption for Rolls-Royce engines

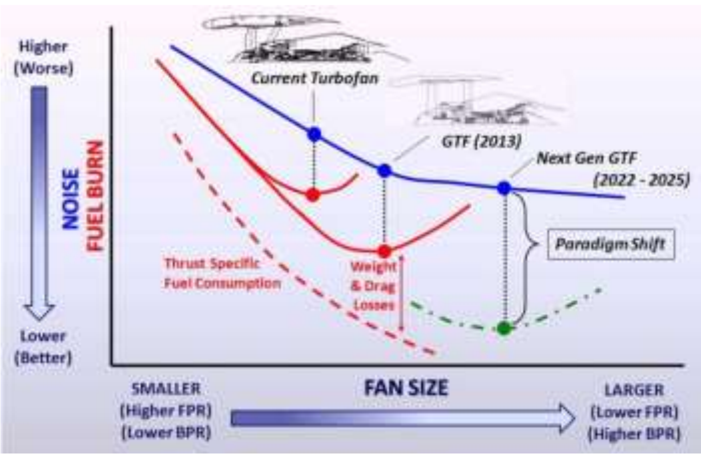


Figure 48. Change in turbofan technology

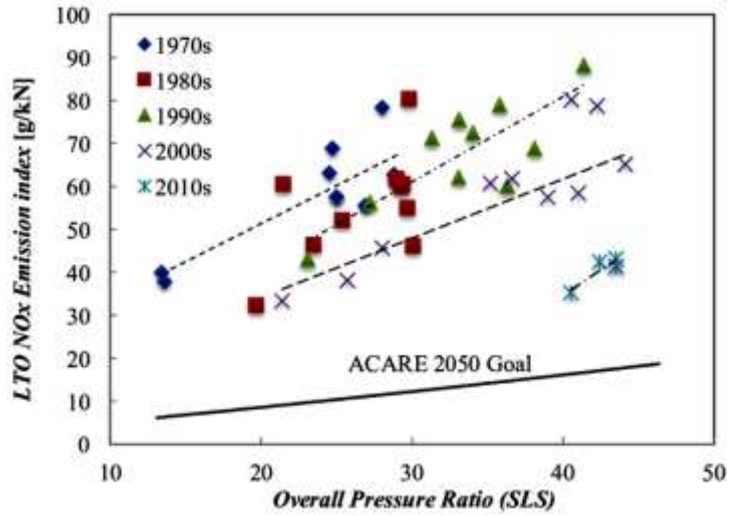


Figure 49. The interdependence of parameters by years

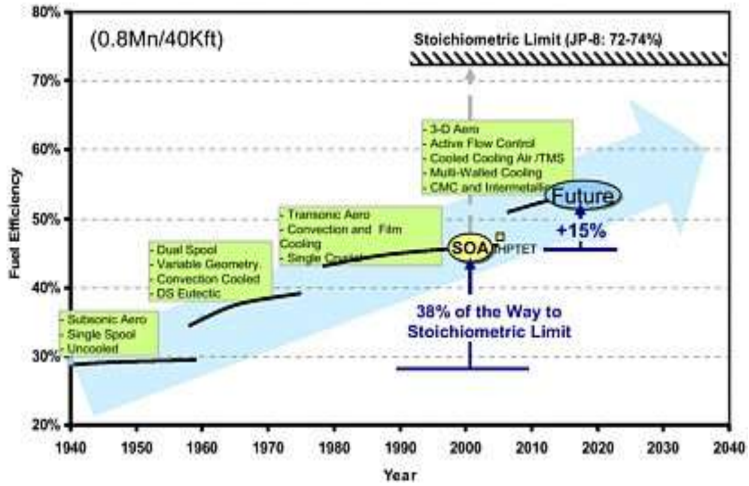


Figure 50.Forecast for Increased Fuel Efficiency

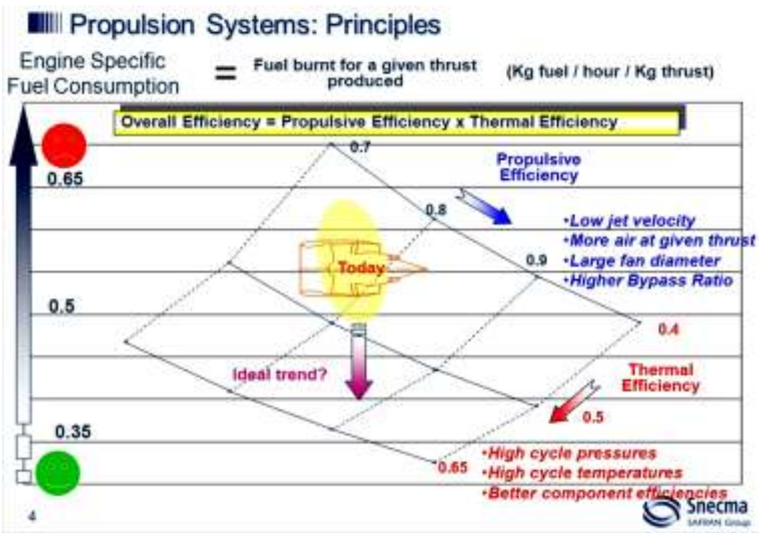


Figure 51. Principles for increasing fuel efficiency of SNECMA engines

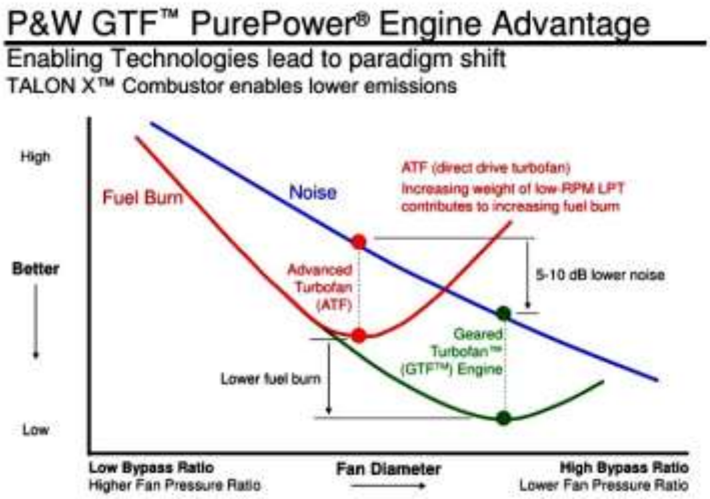


Figure 52. 0 Benefits of P&W's Best Technologies

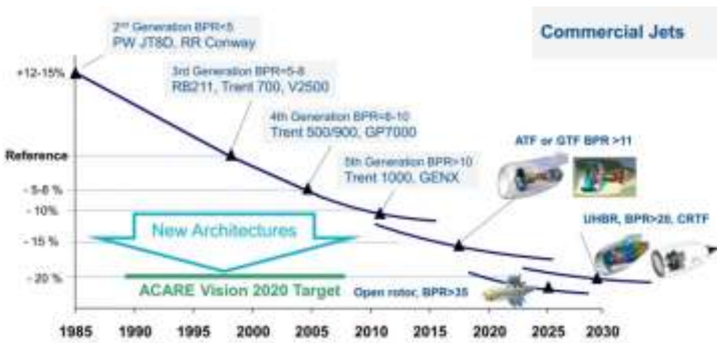


Figure 53. Rolls-Royce forecasts of CO_2 emissions

The hybrid scheme, which assumes the generation of electricity onboard through a heat engine (piston or gas turbine), circumvents this limitation and is at the current stage of development of the most promising for various types of aircraft, including for light aircraft with no more than 12 passengers, and in the near future for regional aviation.

Based on the studies on ways to increase the fuel efficiency of aircraft engines of different world companies, a group of researchers in the work [166] presented a change in the bypass ratio of a turbofan engine for airplanes with a maximum take-off weight of more than 100 tons (Figure 54) and airplanes with one aisle (Figure 73). The actual engine data are shown as circles, and the engine concept data from the literature are shown as triangles. Trend data in both cases were studied with a confidence interval of 85%.

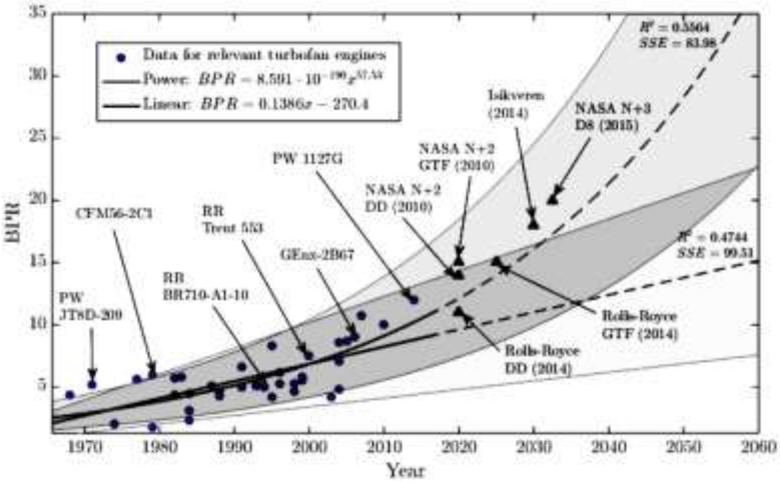


Figure 54. Change in the bypass ratio of turbofan engines for aircraft with a maximum take-off weight of more than 100 tons

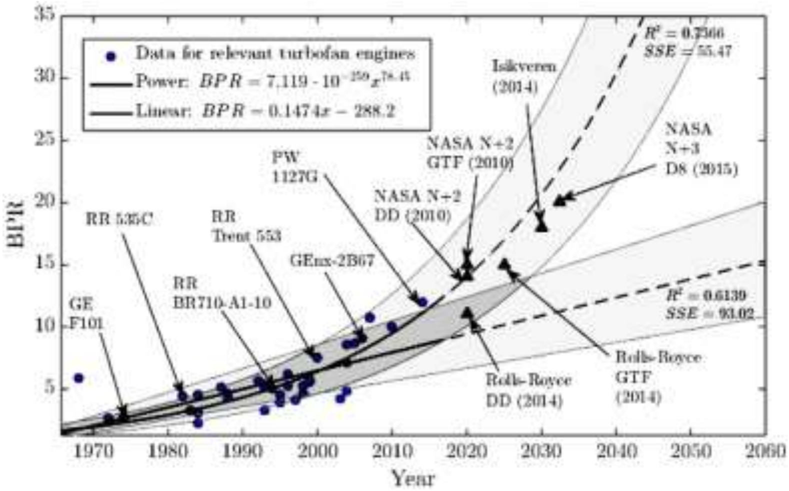


Figure 55. Change in the bypass ratio of turbofan engines for single-aisle aircraft

Analysis of the research results implies that the maximum possible efficiency of the engine elements is practically achieved in those time periods that are being analysed. During this period, advances in production processes and materials science will develop. Possible improvements in the efficiency of engine elements of modern structural schemes do not have great prospects. It is supposed that technology is a more limiting factor for improvement, for example, the use of additive manufacturing to create more complex geometries with more efficient cooling systems.

Analysis of the results of the study of technical concepts shows that the revolution in fuel efficiency that commercial air transport has experienced over the past 60 years is amazing and has helped airlines become interested in acquiring new aircraft with high fuel efficiency. However, development efforts are currently showing diminishing returns, increasing interest in more radical concepts.

Large turbofan engines create thrust with an overall efficiency of about 40%. Significant improvements should still be possible, if the remaining major losses can be influenced by more radical design concepts. [167]

It is commonly known that the main sources of losses in modern gas turbine engines are the irreversibility of the combustion chamber, the heat loss of the exhaust gases of the active area and the kinetic energy of the exhaust gases. Together, they make up more than 80% of the total losses (Figure 56).

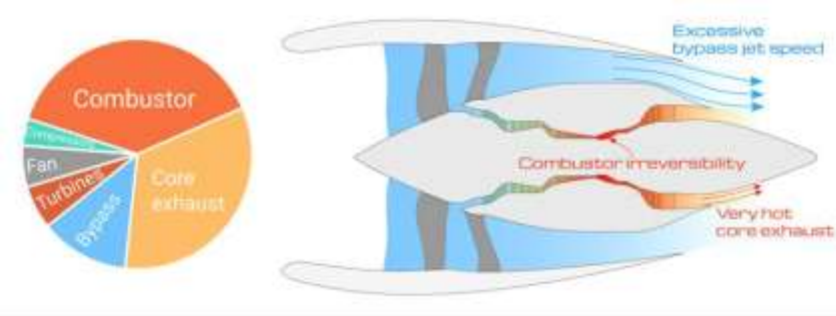


Figure 56. Main losses in modern GTE

Industry is already reducing kinetic energy losses by introducing engines with reduction gears with ultra-high bypass ratios, and concepts with an "open" rotor are being considered.

ACARE's most challenging environmental goals for 2050 are to reduce CO2 emissions by 75% per passenger-kilometre and reduce NOx emissions by 90%. Technologies that currently are at TRL 3-5 level cannot achieve this goal. Around 30% reduction in CO2 is estimated to occur from the radical innovations that are now at a lower TRL level. Due to EU projects: VITAL, NEWAC, DREAM, LEMCOTEC, E-BREAK and ENOVAL, ULTIMATE partners have gained in Europe the most comprehensive experience in the development and evaluation of advanced aircraft engine architectures. Existing tools, knowledge and models will be used for joint optimization and evaluation in accordance with the SRIA goals for the successful improvement of technologies up to TRL 2.

The ULTIMATE project identifies the main sources of losses in modern gas turbine engines for the classification of breakthrough technologies [168]. This classification approach provides a structured way of combining and exploring synergies between technologies in search of ultra-low CO2, NOx and noise. Then, the most promising combinations of radical technologies for Middle Eastern, European and long-distance intercontinental ATW (Advanced Tube and Wing aircraft) will be developed. At the same time, ULTIMATE will help European industry achieve its environmental, social and economic goals by putting into practice synergetic breakthrough technologies for every part of the air transport system (Figure 57).

Forecasts until 2050 without these breakthrough technologies can reduce CO2 emissions by 45% for long-range aircraft with advanced turbojet engines and 59% for short-range aircraft with open rotor engines. These values are compared to operating aircraft in 2000. But ACARE goals require a 75% reduction, with 68% for aircraft, and the rest for operational improvements.

It is supposed that the concept of a new engine (Figure 58) will provide about 12% improvement in fuel combustion compared to conventional 2050 engines. It is shown that the inclusion of intermediate cooling provides more compact combustion systems with a constant volume, reducing the weight of the system and facilitating engine integration.

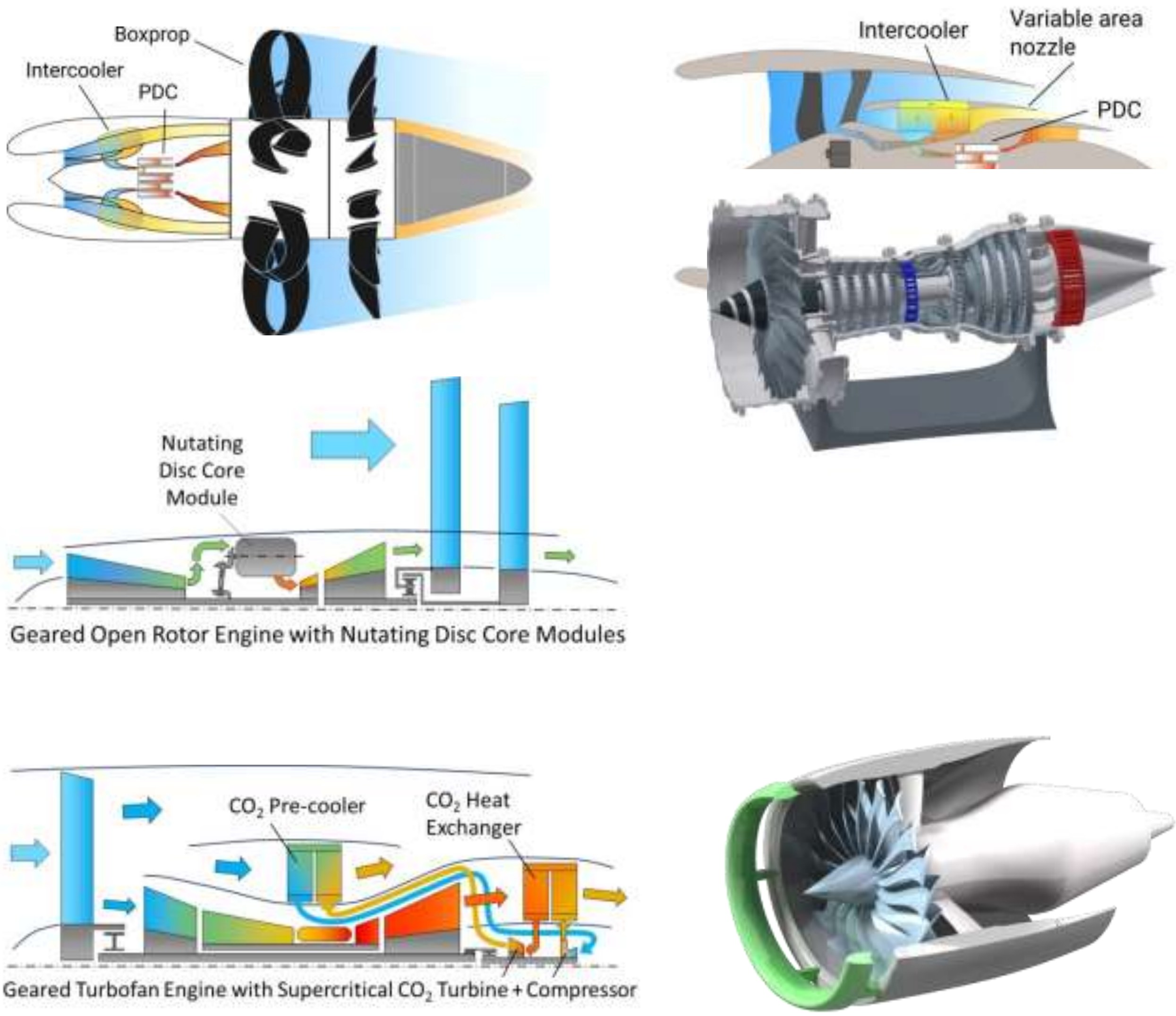


Figure 57. – Technology concepts of project ULTIMATE

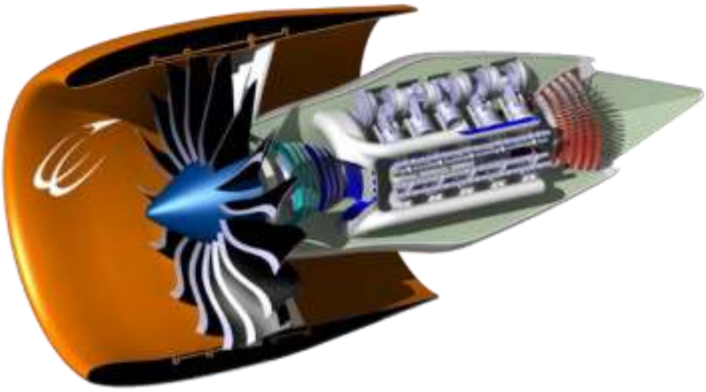


Figure 58. – Concept of combined cycle engine

The combined-cycle engine concept has a supercharged gas generator and two rows of four-stroke V-10 piston engines. Secondary liquid heat exchangers provide more efficient heat recovery of exhaust gases and ensure an additional degree of freedom in the design. Additional ULTIMATE technology with the innovative BOXPROP low-noise propeller will result in a quieter powerplant. The "open rotor" drive is operated by an ultra-compact gas generator with intermediate cooling, which uses pulsed detonation combustion. Significant performance improvements with ULTIMATE technology should help to achieve ACARE goals. However, to achieve the goal of significantly reducing CO2 emissions, it is necessary to use biofuels or more radical aircraft designs.

18.9.10.2 Improving the aerodynamic performance of the aircraft airframe design based on the use of radically new aircraft designs.

In Figure 59 it is shown S-curve of performance of civilian aircraft from the pioneering age of aviation to the present day [169]. It can be seen that a sharp improvement in aircraft performance can only be achieved by introducing new technologies or new aircraft concepts.

An overview of changing technologies includes laminar flow control, active load reduction, technology for new structures and materials, boundary layer ingestion (BLI).

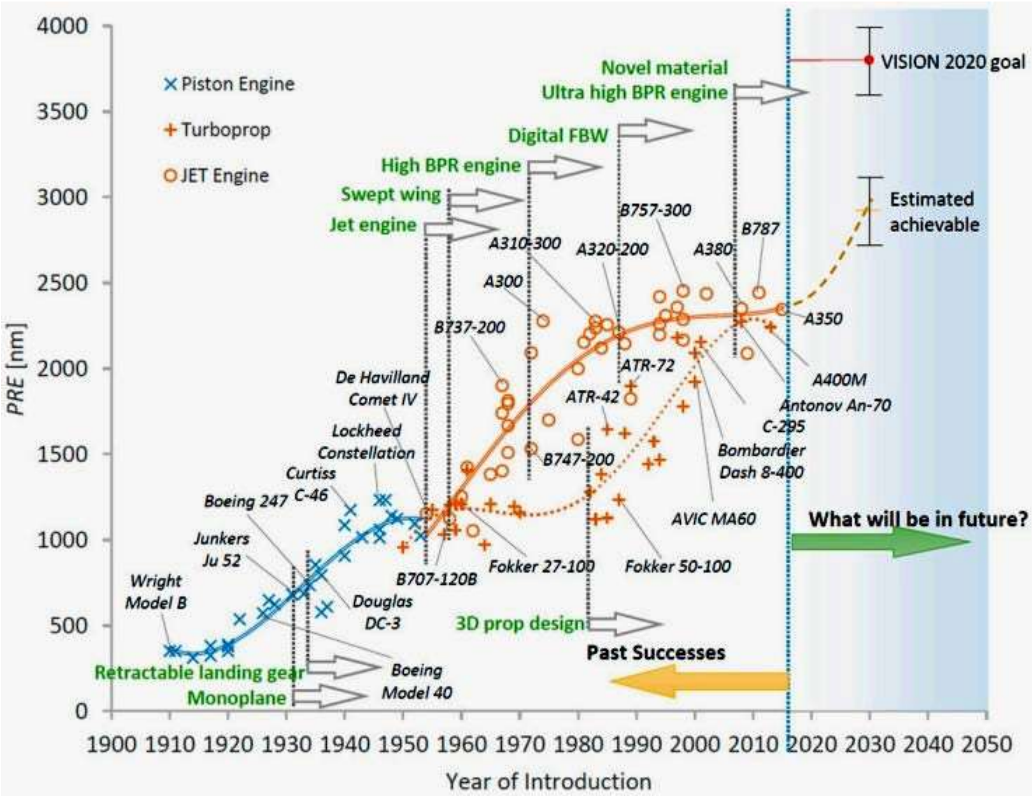


Figure 59. - Change in a flying time of aircraft by years

The global civil aviation market has rather high development prospects in the next 20 years. According to the forecast of Boeing experts, the market value for new civilian aircraft in the stated period will make $2.6 trillion. Growing competition in the market will lead to an increase in air traffic volume. High demand for new civilian aircraft will continue. Reduced fuel consumption and increased flight range will create the ability to connect non-stop routes to airports around the world. It is expected that new liners with reduced noise and emissions will completely change the face of the global fleet (Figure 60). Transcontinental routes will be dominated by wide-body aircraft, capable of implementing a rational frequency and number of non-stop flights. Most of the fleet will be narrow-bodied airliners, which will make it possible for airlines to operate more non-stop flights on domestic routes and short-haul international routes.

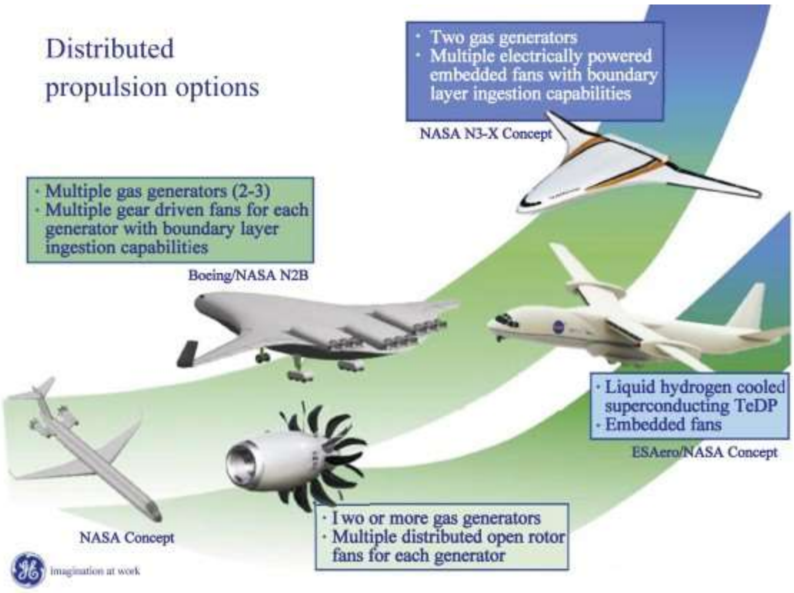


Figure 60 – Trends in the development of passenger aircraft schemes

Air traffic volume growth trends and market demands in the next two decades will be almost entirely provided by narrow- and wide-body aircraft with a capacity of 100 to 400 passengers. The largest market for civil aircraft in the period until 2025 will be the countries of the Asian-Pacific region.

The new generation of aircraft will be characterized by unsurpassed efficiency, excellent flight performance, reduced environmental impact and the highest passenger comfort.

18.9.10.3 Analysis of the development of radically new aircraft designs

In civil aviation at the global level, the four largest companies Boeing, Airbus, Embraer and Bombardier are leading in research and development costs. Namely, they generate the main number of innovations, and determine the parameters of the "aeroplane of the future".

In the future, only fundamentally new technologies can provide a new level of aviation development, since traditional technologies have already exhausted themselves, their further use gives insignificant results at substantial expenses. In this regard, nanotechnology offers virtually countless opportunities for the development of aviation. They will make it possible to move to fundamentally new concepts of aircraft.

The most popular idea in the last 5 years is a transforming aeroplane [170]. If it is possible to develop the appropriate technology to solve this problem, the aircraft will be able to change shape smoothly, continuously maintaining the optimal aerodynamic mode (Figure 61, Figure 62, Figure 63). It will flexibly adapt to external aerodynamics, continuously changing the shape of the wings and control planes, as well as the thrust of its engine. This wing transformation opens up the possibility of using one aircraft for various purposes [171].

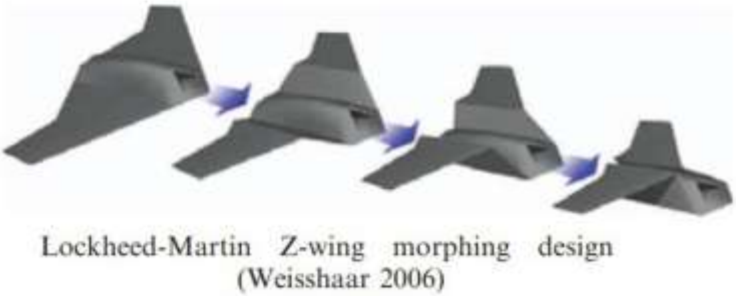


Figure 61. – Z-wing Lockheed-Martin (Weisshaar 2006)

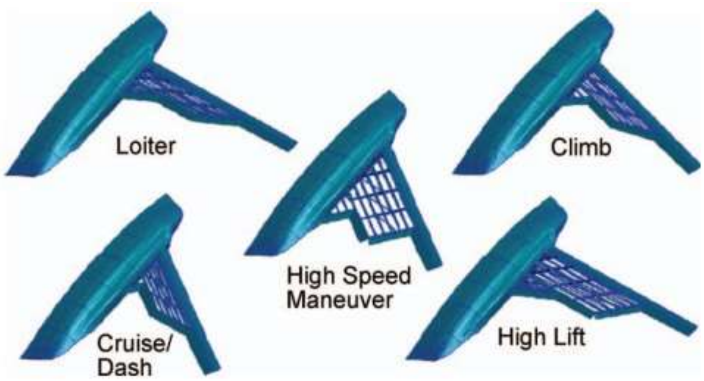


Figure 62. - Changing wing configurations for take off, climb, cruise, braking and manoeuvre (Andersen and Cowan 2007)

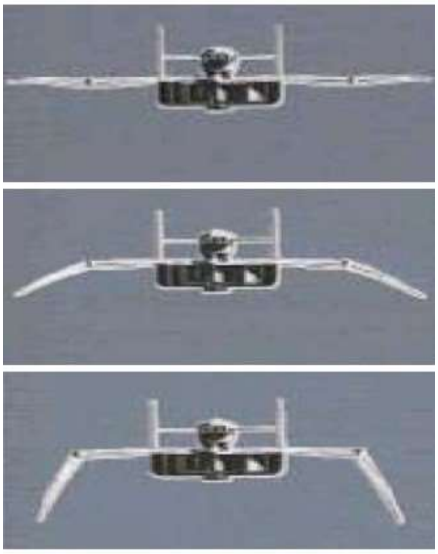


Figure 63. – XB-70 bomber (Weisshaar 2006)

Morphing wing aircraft schemes affect aircraft performance due to a sharp change in aircraft body shape [172], [173], [174]. Such schemes eliminate the need to create several expensive aircraft for specific tasks. Morphing designs include rotation, sliding, and swelling based on shape-changing mechanisms. The current trend in technology development shows that there is room for improvement in terms of aircraft size, flight range and envelope of flight performance. There must be a balance between a change in form and fines in cost, complexity and weight. The ultimate performance of an aircraft with a morphing design is highly dependent on how that balance is achieved.

In defining the concept of passenger aircraft, new aircraft schemes are reviewed that are more efficient than modern designs. The main attention is paid to aeroacoustics as a branch of physical sciences with engineering and operational aspects of aircraft design with low noise [175] .

Company Airbus researches new aircraft concepts in several programs, for instance, NACRE, VITAL, Clean Sky, Clean Sky 2 and others [176] . New Pro-Green concepts have been developed that have enabled the appropriate work on Powered Tails and Advanced Wings. These concepts aim at an immense reduction of environmental noise and CO2 emissions [177]:

- Power plants Contrafan and Open Rotor have been assessed and integrated into the promising aircraft design.
- Advanced Wings, like wings with a low compression ratio, contributed to achieving high fuel efficiency at the aircraft level.

Work on Flying Wing (Figure 64, Figure 65, Figure 66) make it possible to advance in understanding these complex configurations and opened a new path for a promising configuration of the aircraft.

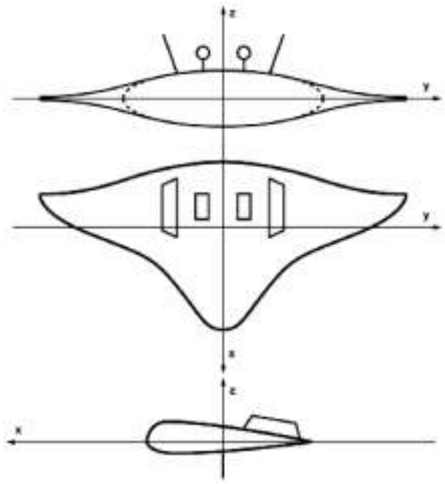


Figure 64. Flying wing: low noise and compromise with efficiency.

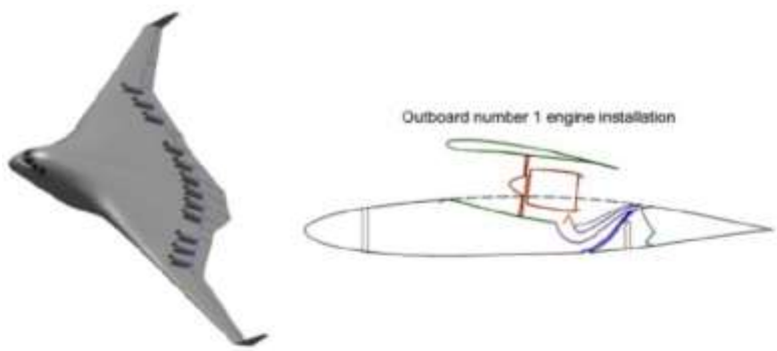


Figure 65. Flying wing with distributed power plant

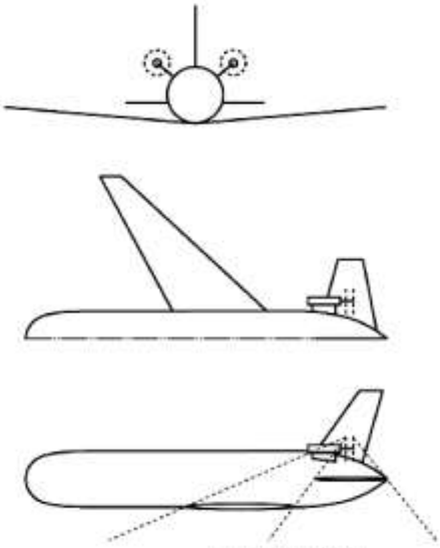
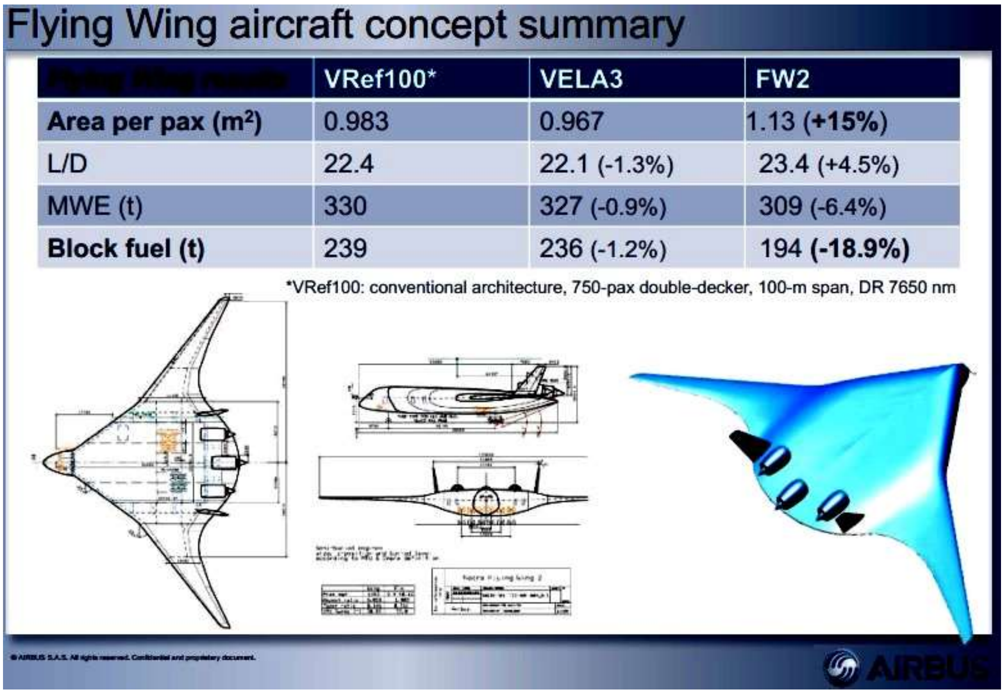


Figure 66. Efficient low-noise open-rotor aircraft configuration

The possibilities of interdisciplinary design of new aircraft and the analysis of their components are being studied (Figure 67):

- Open rotor power plants and their integration with the airframe;
- Analysis of innovative integrated design Powered Tail;
- Design of a wing with laminar flow and forecasting the transition to new technologies;
- Flying Wing configuration design and multidisciplinary flight performance assessment.



Flying Wing results	VRef100*	VELA3	FW2
Area per pax (m^2)	0.983	0.967	1.13 **(+15%)**
L/D	22.4	22.1 (-1.3%)	23.4 (+4.5%)
MWE (t)	330	327 (-0.9%)	309 (-6.4%)
Block fuel (t)	239	236 (-1.2%)	194 **(-18.9%)**

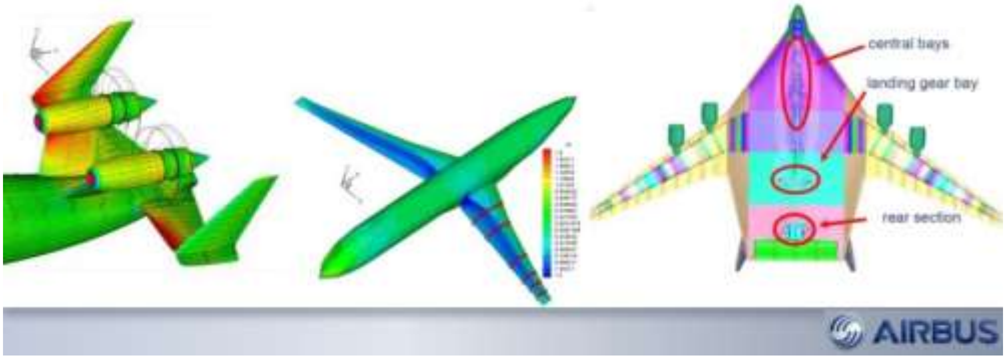


Figure 67. Interdisciplinary design of new aircraft (Airbus)

In works [178] [179] [180] the authors research the potential of ultra-high bypass turbofan engines (UHBR). To assess the potential of engines to replace existing mid-range aircraft, ONERA identified four different NOVA (NextGen Onera Versatile Aircraft) aircraft geometries, shown in Figure 68. Particular attention is paid to the integration of engines in the design of the airframe.

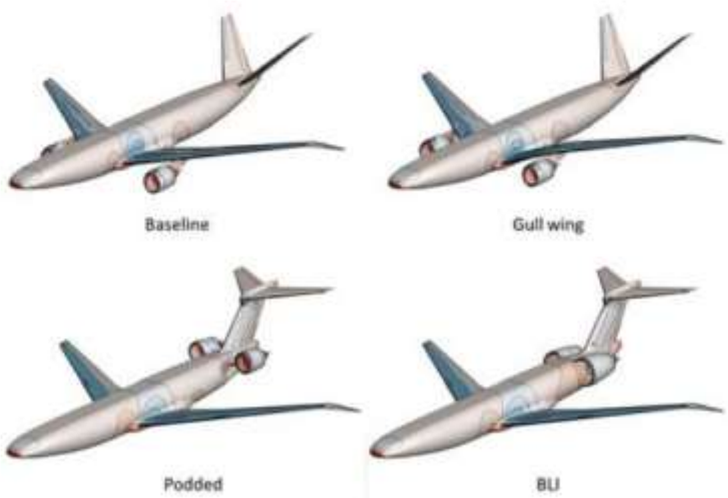


Figure 68. General view of NOVA configurations

In Europe, the Clean Sky 2 program is being implemented [EU, 2018, Clean Sky 2 Joint Undertaking.]. Based on this program, it is planned to develop innovative approaches, advanced technologies for creating wings with better aerodynamic characteristics, more advanced and lighter designs, more efficient engines. It takes into account the emergence of completely new configurations of aircraft and their more stable life cycle, the emergence of areas of hybridization and electrification of aircraft, the improvement of their control system, activation and guidance to the target. The scope of the program includes large regional and suburban aircraft, as well as helicopters.

The program aims to accelerate the introduction of new technologies in the period 2025-2035. By 2050, 75% of the countries of the world will be replaced by airplanes that are in operation (or on order) that can use Clean Sky 2. Direct economic benefits are estimated at 350-400 billion euros and indirect benefits of about 400 billion euros. Clean Sky 2 technologies are expected to bring potential savings of 4 billion tons of CO2 between 2025 and 2050 [181]. Boundary-Layer Ingestion (BLI) technology is a promising idea (Figure 69) that NASA researchers are studying to reduce jet fuel combustion, thereby lowering emissions and operating costs of aircraft [182].

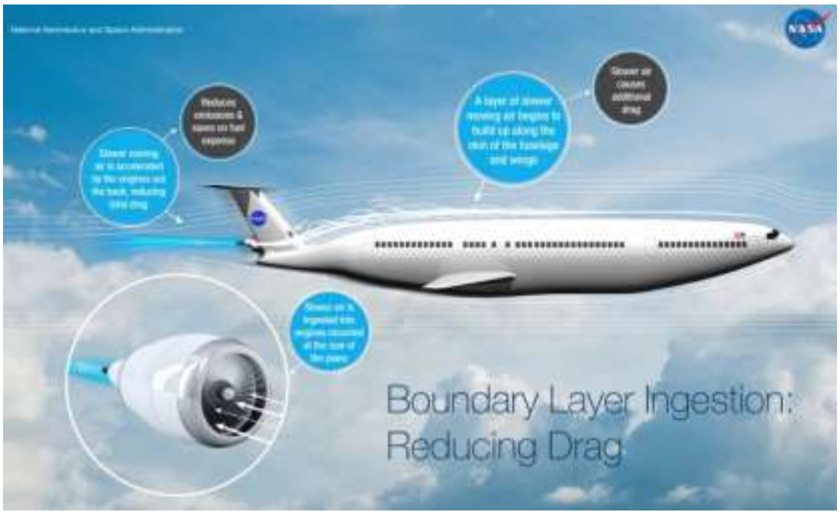


Figure 69. Application of BLI technology (NASA)

One of the innovative design concepts D8 is now a smaller model that is being tested in a wind tunnel at Massachusetts Institute of Technology (Figure 70). The design developed for NASA by the team of this institute has a very wide fuselage to provide additional lift, a low-swing wing to reduce drag and weight, and engines located above the fuselage block some noise.

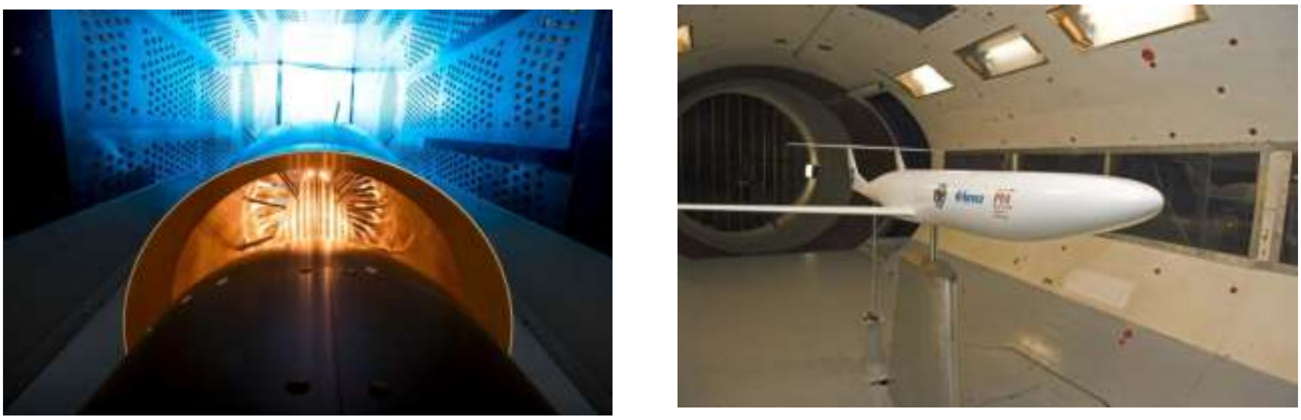


Figure 70. Experimental studies of BLI characteristics

The advantage of this scheme is to reduce the overall drag, which is created by slower air that moves above and behind the entire aircraft body. At the end of the fuselage, part of the slow air again accelerates as it passes through the engines. With lower total aircraft drag, installed engines require less thrust to propel the aircraft forward. This means that less fuel is needed to burn. However, there are difficulties with the arrangement of the working process at the engine inlet. Due to the unevenness and large oscillations of the air inlet flow, the fan blades should safely withstand these additional loads. Therefore, the NASA-led research team is conducting many tests of the BLI engine configuration in a wind tunnel in Glenn.

A new study of the AHEAD project shows that the design of the aircraft may differ from the modern project (Figure 71). On a promising aircraft, hybrid engines can be used, which will become the future of aviation [183]. In the long term, alternative fuels, such as biofuels and hydrogen, are expected to replace traditional jet fuels.

Figure 71. Concept of aircraft AHEAD

The efficiency of BWB aircraft will be greatly enhanced by integrated hybrid engines using the boundary layer ingestion method (BLI). The project is aimed at establishing the feasibility of the proposed hybrid engine configuration and will demonstrate that the concept will significantly reduce engine emissions, power plant resistance and noise.

The hybrid engine proposed by AHEAD is a new propulsion system with a different architecture compared to a conventional turbofan engine. The hybrid engine uses several unique technologies, such as casing counter-rotation fans, exhaust cooling, a dual hybrid combustion system (using hydrogen and biofuels in flameless conditions to reduce CO_2 and NOx emissions. The hybrid engine (Figure 72) offered by AHEAD, will be a step forward in terms of environmental friendliness, it will use an advanced multi-purpose fuel and will make it possible to develop economical configurations of aircraft with Blended Wing Body (BWB).

Figure 72 - Hybrid engine concept for the AHEAD project

The configuration of the BWB aircraft (Figure 73), together with the proposed hybrid engine concept, will bring a much-needed breakthrough in civil aviation [184] . The project will also assess the impact of the

LH2 hydrogen storage facility on its integration with built-in hybrid engines and the environmental benefits achieved.

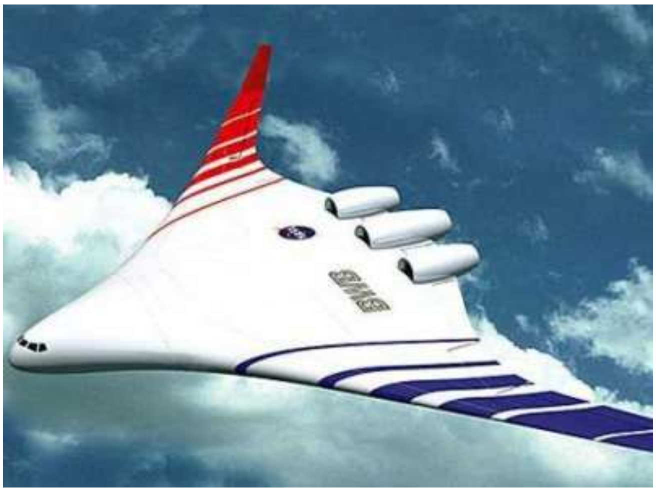


Figure 73. Configuration of aircraft BWB (NASA)

Particular attention will be directed at assessing the environmental impact of H_2O emissions. Another conceptual direction is the HWB concept (hybrid wing body) (Figure 74).

Figure 74. HWB design with engines on the airframe top

NASA and Lockheed Martin studied the fuel consumption of HWB configuration. They concluded that arrangement of the engines above the trailing edge of the wing reduces drag in the plane. HWB airplanes generally have better aerodynamic properties than traditional airplanes, which in turn leads to a significant reduction in fuel consumption and harmful emissions. [185]

NASA estimates that the best HWB configuration will consume much less fuel per flight compared to the Boeing 777 [186], [187], Engine location options are under study (Figure 75)

Figure 75. Configuration of the aircraft type "flying wing" by options for installing hybrid engines

Aircraft manufacturers would like to switch to open rotor engines because they are more efficient and economical. However, their higher noise level is a concern. By switching to an HWB aircraft and introducing noise protection technologies such as chevron nozzles, modified pylons, vertical tail and acoustic liner processing, NASA hopes to achieve its goal 42 dB below the standard FAA stage, even with open rotor engines.

The main limitation of HWB aircraft is strong noise generated by their landing gear during the approach phase. Compared to the traditional aircraft layout, the landing gear on the HWB design produces significantly more noise. This is due to the geometry of the glider and the acceleration of airflow at the location of the landing gear [188].

There are other similar concepts of aircraft type "flying wing" (Figure 76 - Figure 80). Such schemes differ in the types of engines used and their location.

Figure 76. Scheme of aircraft BWB X-48B (NASA)

Figure 77. Scheme of aircraft BWB with turbofan

Figure 78. – Scheme of aircraft BWB (NASA)

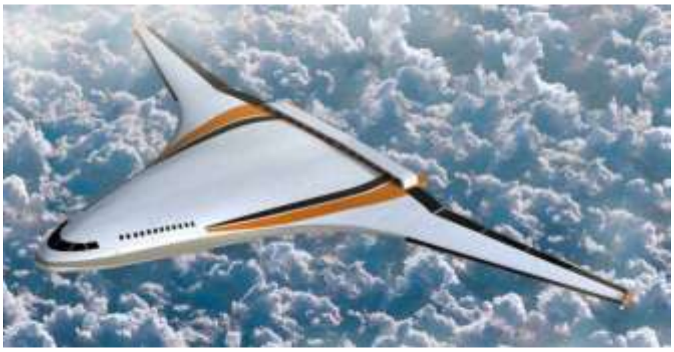


Figure 79. Scheme of aircraft BWB with distributed power plant

Figure 80. Scheme of aircraft BWB K3-X with different types of engines

By 2032, Airbus forecasts expect 6.7 billion passengers compared to 2.9 billion today. Designers and engineers in the aerospace industry are working intensively on new types of aircraft that will make the flight more flexible and therefore more efficient. One of the new concepts is a Stingray type aircraft. [189]. A test aircraft with a wingspan 13 meters has inflatable wings, which make it much lighter than conventional aircraft of the same size (Figure 81).

Figure 81. Scheme of aircraft type Stingray

Besides, the profile of the wings can be changed. As a result, current aircraft steering controls can be replaced with much simpler technology. However, it is not yet clear whether the experimental aircraft will be able to turn into batch production.

In the foreseeable future, the strict separation of cargo and passenger aircraft may disappear. Up to now re-equipping the aircraft has been laborious and expensive. Researchers in Silicon Valley have found a suitable solution for this with the concept of a modular cabin Transpose. The fixed rows of seats in current salons can be changed to functional modules that can be flexibly replaced. Thus, all furniture in the cabin can be replaced within a few hours. For example, if an airplane carries passengers during the night, more sleeping compartments can be installed, and during the day - more seats or even working places. This concept is still being studied.

In work [190] there are described the main directions of aviation development.

1. Electric propulsion. High-tech batteries needed to power aircraft elements are being intensively developed and the risk parameters that they represent are being substantiated.

2. Hypersonic travel. This is the perspective of 2040. The main task for air traffic control. The aircraft will fly at altitudes that are not controlled. NextGen space platform will be able to track the flight profile.

3. Biofuel. FAA and EASA are leaders in the continuous reduction of energy consumption, emissions and noise. The use of biofuels is one of the measures to achieve these requirements.

4. Autonomous flight. We are talking about an autonomous flight on drones and similar vehicles. The issue of more stringent fault tolerance testing and the adoption of certain laws is being investigated.

5. Biometrics. The possibility of monitoring the biometric parameters of a person at a distance is being investigated.

6. Communication and entertainment. Onboard the aircraft, equipment will be installed to connect to ground-based communications. However, the issue of flight safety arises.

In works [191] [192] they study the possibility of Akka Technologies to create a new service for passengers who want to fly on an airplane (Figure 82).

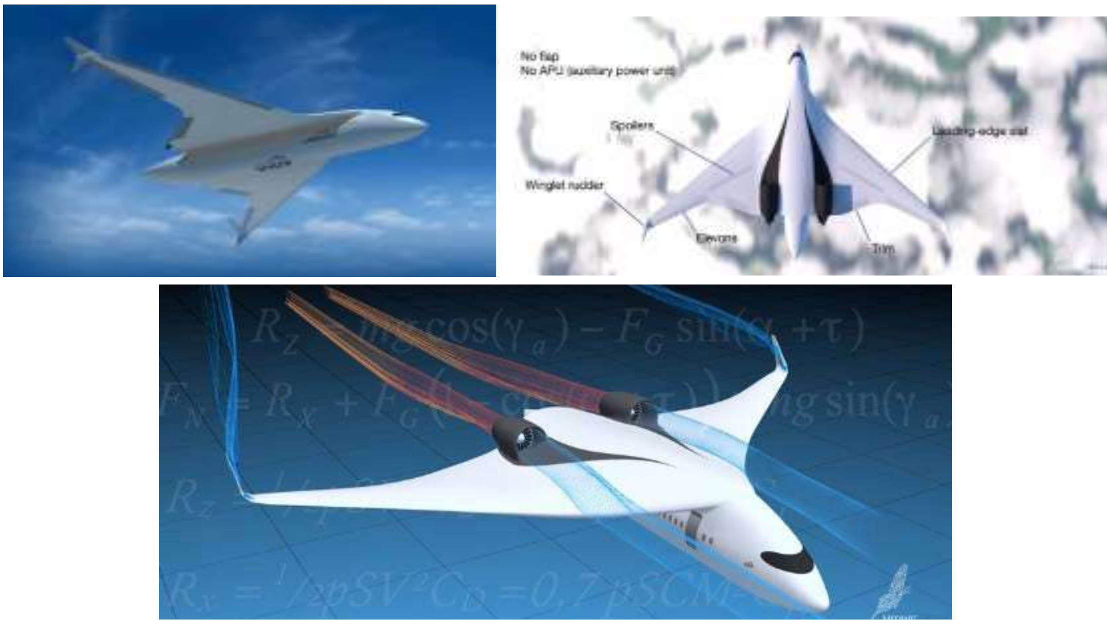


Figure 82. Akka Technologies' concept plane.

"Link & Fly" is Akka Technologies' new flagship aircraft design. The concept involves the reduction in airport-drive and boarding time per passenger. The concept aims to create an airplane mock-up on a scale sufficient to prove the technical feasibility of the airplane. Particular attention is paid hereby to the airfoil and structural integrity of the airplane.

The innovative concept will show the following aspects:

- Alternative use of cleaner energy (photoelectric, kinetic, hydrogen).
- Inductive coupling/superconductivity.
- A futuristic cockpit (human-machine interface management).
- A means of simulating inspections, manufacturing, and training of pilots (Operantis).
- A means for managing and coordinating all operations (model based on systems engineering).
- Digitalization of information.

The modular aircraft will in turn enable a new and innovative concept of infrastructure, which will allow faster turnarounds and reduce saturation in airports. This concept will reduce noise pollution and use alternative energy sources, to protect future generations.

According to the futuristic concept of Link & Fly, passengers aboard a train-like capsule at the nearest station, and along the route to the airport, they are retinal scanned for the reason of safety. Upon arrival at the airport, the capsule with the passengers is attached to the wing for further flight.

For Akka's customers, Boeing is one of the main targets, as it seeks to restrict its dependency on Airbus and Renault in Europe. Akka does not expect to convince the aircraft manufacturer to necessarily create the entire concept of Link&Fly. It puts it hope in the design to attract attention and show the concept.

New business opportunities are offered to aircraft manufacturers and companies around them, especially in China. The Chinese aircraft manufacturer Comac is developing its own fleet and can call on the aerospace ecosystem for technological partners. Similar to Airbus' A320 jet in size and target usage, the Akka Link & Fly carriage for short-range flights carries 162 passengers and the seats can be taken out to move freight instead. With the wings clipped on, and the engines fixed on top, the design has a wingspan of about 49 metres, is 34 metres long and 8 metres high.

Akka generates 75 per cent of its sales in France and Germany and became more dependent on car manufacturing with the takeover of a Daimler engineering unit for about 7 years ago. The Paris-based company hopes its new concept will woo new aeronautics customers in the US.

One of the innovative solutions for aviation is the 'Flying-V' concept. [193]. It is not only about the ways to power aircraft, it is also about a wholly new and radical aircraft design (Figure 83). This technical appearance might lay the foundations for long-range wide-body aircraft. It is KLM Royal Dutch Airlines, the flag carrier of the Netherlands which announced, jointly with the Delft University of Technology (TU Delft), the technical solution on an innovative flight concept known as the 'Flying-V' project.

Figure 83. 'Flying-V' project

The airline and university have signed a new cooperative agreement to work together on making aviation more sustainable. One of the main features of the 'Flying- V' project is already present in the name of the concept. The aircraft is projected to be V-shaped what makes aircraft design to stand out from the ordinary ones with a standard shape of a fuselage. The future aircraft can be compared to Airbus A350.

'Flying-V' will be a bit shorter than the A350 but the wingspan length will be the same. When manufacturing a new aircraft, a lot of operating details are taken into account, including airport features, runway length, hangars where aircraft could be stored and repaired (Figure 84).

Figure 84. Parked 'Flying-V'

The aircraft weigh will be less than the A350. This, in turn, means that the 'Flying-V' will use 20% less fuel than the Airbus A350. The new aircraft will have another fuel storage philosophy so that passengers could enjoy the views of the earth beneath the wings. Also, the airline said in a standard configuration the 'Flying-V' will carry the same number of passengers as the A350.

KLM Royal Dutch Airlines announced in 2019 it will develop and purchase 75,000 tons of sustainable aviation fuel (SAF) a year in 10 years. It is the first airline in the world to invest in sustainable aviation fuel on this scale.

The 'Flying-V' project is propelled by the most fuel-efficient turbofan engines, but it can be adapted to make use of the more electric engine and other technical solutions.

Massachusetts Institute of Technology (MIT) and NASA engineers have shared the design of a completely new kind of aircraft wing. [194].The radical wing is made of hundreds of tiny identical pieces. The wing can change shape to control the aircraft's flight (Figure 85).

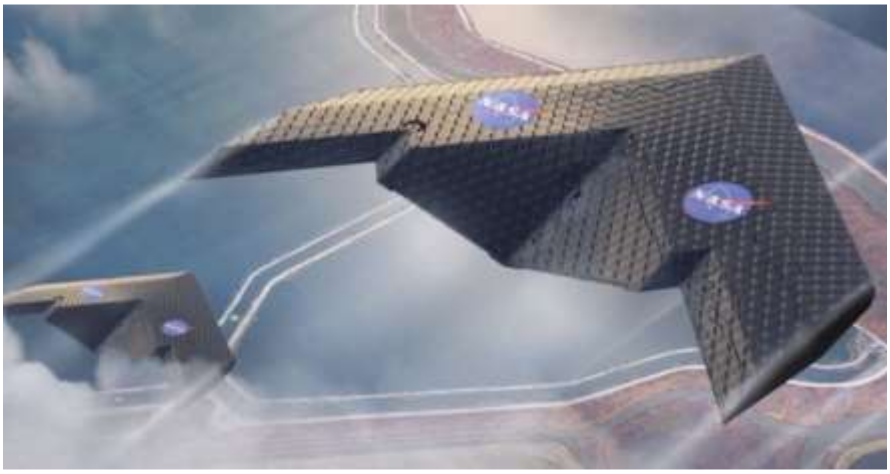


Figure 85. Radical new wing

The wing's developers say the efficient design may boost aircraft production, flight, and maintenance efficiency. The wing was tested in a NASA wind tunnel. Typical wing designs have separate moveable surfaces such as ailerons to control the roll and pitch of the aircraft (Figure 86).

The combined pieces form a "metamaterial" that is stiff like a polymer but extreme light like an aerogel. Traditional wing designs are a compromise of the best shapes of a wing that are required for each different stage of flight from take off to cruising.

This new wing design could change shape to be in the optimal design for each stage of the flight. The wing will self-shift its shape according to the different aerodynamic loading conditions. The passive self-moving wing is only achieved through the very careful placement of struts with different amounts of flexibility or stiffness. This allows the wing to bend in specific ways according to its current state (Figure 87).

Figure 86. Wing design

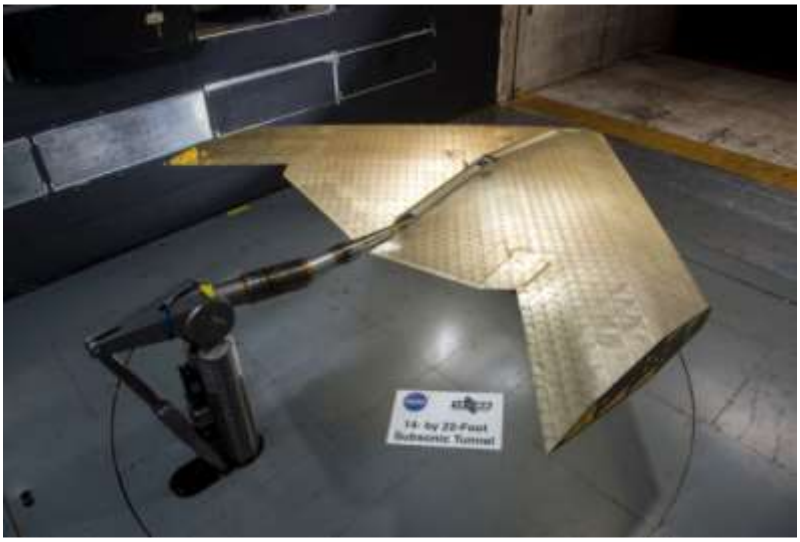


Figure 87. Investigation of wing's characteristics in free air

The prototype wing was hand-assembled by students. Future iterations could easily be built by simple autonomous assembly robots. Each piece is made using injection moulding and a complex 3D mould. Each piece resembles a hollow cube made up of matchstick-size struts along each edge. One- piece takes just 17 seconds to create. By combining small parts, wing construction in the form of an aeroplane can be manufactured (Figure 88).

Figure 88. New flying wing construction.

The result is a much lighter wing, and thus much more energy-efficient than those with conventional designs, made from metal or composites. [195]

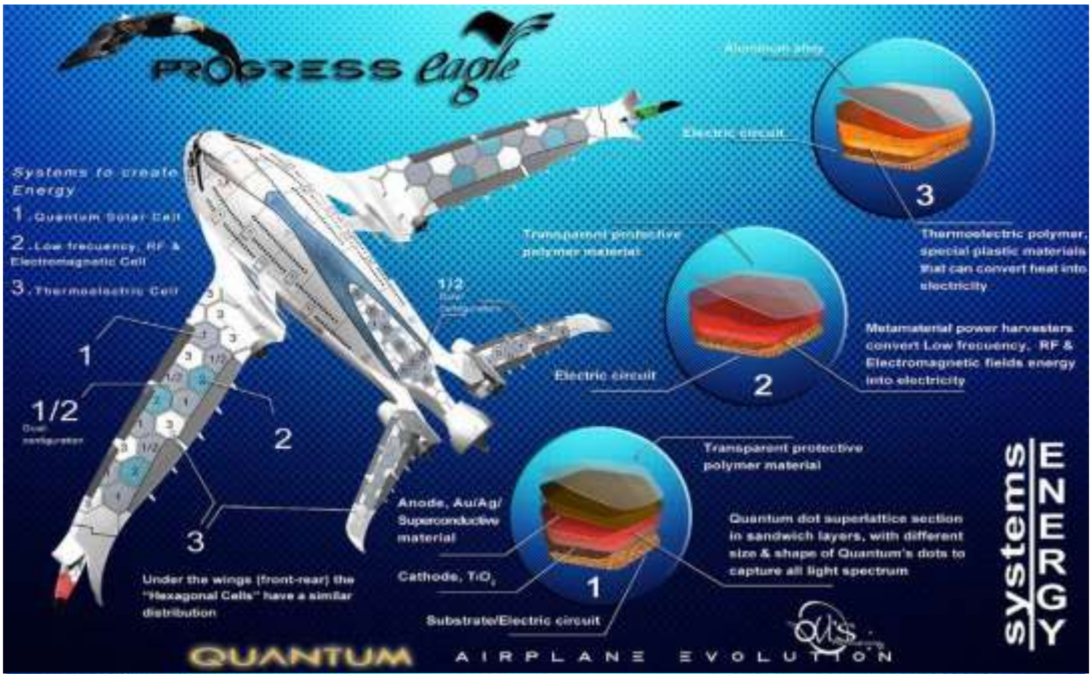
The authors of [196] cite the justification and the experiment for the investigation of ultralight materials. The paper shows a programmable material system applied as a large-scale, ultralight, and conformable aeroelastic structure. The use of a modular, lattice-based, ultralight material results in stiffness typical of an elastomer (2.6 MPa) at a mass density typical of an aerogel. This, combined with a building block-based manufacturing and configuration strategy, enables the rapid realization of new adaptive structures and mechanisms. The heterogeneous design with programmable anisotropy allows for enhanced elastic and global shape deformation in response to external loading, making it useful for tuned fluid-structure interaction. An experiment was carried out with full-scale wind tunnel testing.

The paper [197] addresses a new concept of big passenger aircraft "Progress Eagle". The aircraft design (Figure 89) uses the future advanced technologies of the 21st century, based in Quantum properties of nanoparticles and knowledge about subatomic particles. This concept is based on the idea of a "safe transport", with high performance and totally environment friendly.

Figure 89. Schemes of advanced QG "Progress Eagle" airplane

The concept includes three passenger's decks and special cockpits, located on the second floor with panoramic views that allow the pilots to have a direct reference's views up to 70% of the airplane.

The construction is equipped with Smart and self–repairing wings composed of carbon nanotubes and carbon fibres, meta-materials with the hexagonal structure on the surface and a hollow endoskeleton of titanium and graphene (Figure 90; using the graphene material in the form of a micro-super capacitor (fast electrical storage that can charge and discharge thousand times faster than standard batteries) as a reinforce of the internal wing structure.



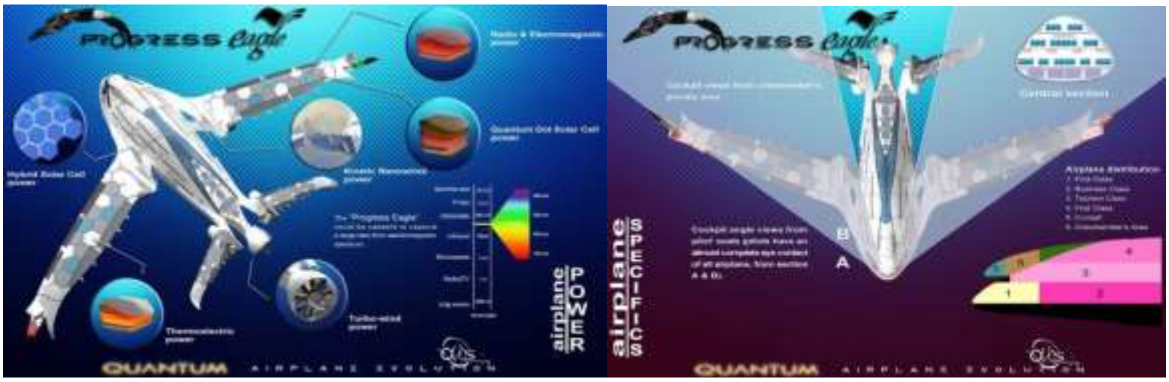


Figure 90. Features of the QG "Progress Eagle" construction

The geometry of the wings includes triple winglets, everyone with a different angle and orientation.

The AWWA·QG "Progress Eagle" could be equipped with six electric engines, one of which is a mixed engine (wind generator/electric engine). The airplane could generate all the necessary energy to feed its engines, only will need "external" hydrogen fuel to start engines in flight and on the ground.

18.9.10.4 Configurations of supersonic commercial aircraft

The most considerable drawbacks of supersonic aircraft are the sonic boom, the specific fuel consumption, the aerodrome noisiness, and the operating difficulty.

Despite the failure to implement some supersonic and transonic passenger projects (Boeing 2707, Boeing Sonic Cruiser, Douglas 2229, Lockheed L-2000, Tu-244, Tu-344, Tu-444, SSBJ, and others) as well as the removal from service of two implemented aircraft projects (Tu-144, Concord), projects of hypersonic passenger airliners (including the suborbital ones) like ZEHST, SpaceLiner, and rapid response troop carriers were developed in the past and exist now.

A firm order for 20 Aerion AS2 supersonic business jets was placed in 2015 with delivery to begin in 2023. [198]. The aircraft manufacturer Boeing will provide technical support to Aerion Corporation. The baseline cost of new aircraft was announced in 2019 to be $120 million that is almost twice as much as its rival the Bombardier Global 7000. [199]

Figure 91 to Figure 99 show the configurations of supersonic commercial aircraft that are developed by different developers in the world.

Figure 91. Supersonic aircraft design

Figure 92. Supersonic aircraft design

Figure 93. Supersonic aircraft design

Figure 94. Supersonic aircraft design

Figure 95. Supersonic aircraft design

Figure 96. Supersonic aircraft design

Figure 97. Supersonic aircraft design

Figure 98. Supersonic aircraft design

Figure 99. Lockheed Martin Supersonic green machine

18.9.10.5 Propeller propulsion configurations

Figure 100 to Figure 117 show topical configurations of aircraft with propeller propulsion that are under development by different companies in the world and expected to be implemented during the next 5-15 years.

Figure 100. Propeller propulsion aircraft design

Figure 101. Propeller propulsion aircraft design

Figure 102. Propeller propulsion aircraft design

Figure 103. Propeller propulsion aircraft design

Figure 104. Propeller propulsion aircraft design

Figure 105. The AW609 aircraft

Figure 106. . Propeller propulsion aircraft design

Figure 107. Propeller propulsion aircraft design

Figure 108. Propeller propulsion aircraft design

Figure 109. Propeller propulsion aircraft design

Figure 110. Propeller propulsion aircraft design

Figure 111. Propeller propulsion aircraft design

Figure 112. Agusta Westland design

Figure 113. Propeller propulsion aircraft design

Figure 114. UCA concept

Figure 115. Passenger aircraft design

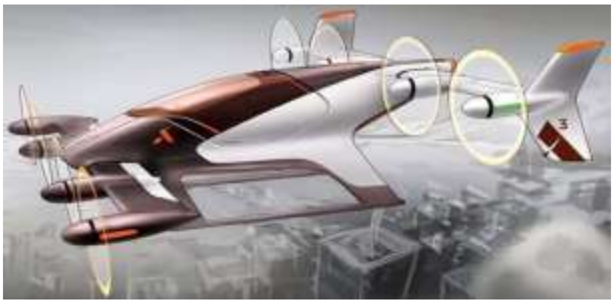


Figure 116. Light passenger aircraft concept (air taxi)

Figure 117. Light aircraft design

18.9.10.6 Promising designs based on "nervous systems"

Adaptation of any aviation technology — researches, prototypes, testing, integration — usually takes about 10 years. So if considering that the transition to a new fuel will occur in the middle of the century, today it makes sense to focus on other innovations: other air foil profiles and schemes, materials, etc.

Putting together this increase in computational power and decrease in circuit size, and adding in the progress made with 3D-printing, at some point in the next decade we will be able to produce integrated computers powerful enough to control an aircraft in near real-time.

Using digital “nervous system” with receptors arranged over the aircraft sensing forces, temperatures, and airflow states could drastically improve the energy efficiency of aircraft. Once electric aircraft are established, the next step will be to integrate a gimballed propulsion system, one that can provide thrust in any direction. This will remove the need for the elevators, rudders, and tailplane control surfaces that current designs require, but which add significant mass and drag.

Figure 118 - Figure 121 shows as an example, new aircraft designs and their power plants of various companies in the world.

Figure 118. –E-Thrust concept (EADS)

Figure 119. Airbus 2050 - Bionic Aircraft

Figure 120. «Electric aircraft design», NASA

Figure 121. randtl Plane Air freighter concept (Pisa University)

The German design institute Bauhaus Luftfahrt, which is part of the Airbus group, announced its intention to test "more electric aircraft" with a hybrid thrust by 2022 [200]. It is planned to test a reduced unmanned aircraft model, and the checks themselves will be carried out as part of the European Clean Sky 2 program, aimed to develop environmentally friendly and economical civil aviation (Figure 122).

Figure 122. Hybrid thrust Aircraft Tail Model

Development is carried out as part of the DISPURSAL project using propulsive fuselage technology. The promising "more electric aircraft" will use two smaller turbofan engines, which will not only be responsible for the movement of the aircraft but also generate electricity for its on-board systems and an electric fan engine in the tail. The contribution of this engine to the total thrust developing will be 23%.

In addition to reducing specific consumption, the possibility of suctioning the boundary layer through fans driven by electric motors of distributed power plants is being explored (Fig. 81).

Some aircraft concepts that are being developed as part of promising programs have other design configurations (Figure 123 - Figure 124). According to the developers, such configurations will allow aircraft to travel long distances using the minimum amount of fuel and achieve environmental performance requirements. Together with innovative engine technologies, this will allow advanced airliners to be more economical than current aircraft.

Figure 123. Concepts of aircraft with the distributed control system and suction of the boundary layer (NASA)

Figure 124. – Passenger aircraft concept

Figure 125. PARSIFAL passenger aircraft

Thus, in the short and medium-term, the dominance of turbofan engines will remain on heavy transport systems. Improving the power plants will be aimed, first of all, at increasing the efficiency of both the engine itself (by increasing the bypass ratio, increasing the gas temperature, compression ratio, etc.) and the aircraft as a whole (application of the concepts of a "more electric" aircraft distributed power plants, the suction of the boundary layer, etc.)

18.9.10.7 Conclusions

Based on existing information available in the public domain in the promising directions of development of radically new aircraft designs until 2050, the following basic concepts can be distinguished:

- "Transforming aircraft";
- "Flying Wing" (BWB, HWB, LWB);
- Aircraft with electric or hybrid engines with propellers, "open rotor" configuration;
- "Link & Fly";
- "Flying-V";
- Wing with morphing technology (ACTE, MIT NASA);
- Convertiplane;
- Supersonic commercial aircraft;
- "Progress Eagle" concept.

A brief analysis of the main aspects for assessing the level of implementation or dissemination of the concept is given in Table 11.

Table 11. Basic concepts of aircraft radical design

Key aspects for concept evaluation	Concept name								
	"Transformer aircraft"	"Flying wing" (BWB, HWB)	Aircraft with electric or hybrid engines with propellers, "open rotor" configuration	"Link&Fly"	"Flying-V"	Wing with morphing technology (ACTE, MIT NASA)	Convertiplane	Supersonic commercial aircraft	AWWA QG "Progress Eagle"
Potential CO_2 savings and timeframe	Potential CO_2 savings will not be substantial, as the main problem will be to increase the mass of the structure due to additional mechanisms for aircraft transformation	Potential CO_2 savings are substantial because it is used a "flying wing" configuration and economical hybrid engines with minimal harmful emissions.	Potential CO_2 savings are substantial because efficient hybrid engines with minimal emissions or electric motors are used.	Potential CO_2 savings will be advantageous because three types of clean energy are claimed	CO_2 savings will be substantial with the use of "flying wing" configuration and economical engines of leading engine manufacturers	Potential CO_2 savings will be substantial as the "flying wing" configuration with morphing technology and fuel-efficient engines are used.	Potential CO_2 savings are substantial because efficient hybrid engines with minimal emissions or electric motors are used.	Potential CO_2 savings are not foreseen due to engines with augmented cycle	CO_2 savings are substantial because they use an efficient aerodynamic design of the aircraft bearing surface with nanotechnology and electric motors
Economic implications	Economic gain will not be substantial, since these designs will first be used on military equipment.	The cost per passenger-kilometre is significantly reduced due to the large number of passengers on board.	Economic gains will be substantial as operating costs are reduced.	Economic gain will be substantial, as operating costs are reduced and the time spent by a passenger at the airport is significantly reduced.	Economic gain from the use of such a concept will be substantial since the new design of the aircraft provides increased comfort for passengers on board.	Economic gain from the use of such a concept will be significant, since the new design of the aircraft provides a	Economic gain will be substantial as operating costs are significantly reduced	No economic gai expected	Cost per passenger-kilometre is significantly reduced.

Key aspects of concept evaluation	Concept name								
	"Transformer aircraft"	"Flying wing" (BWB, HWB)	Aircraft with electric or hybrid engines with propellers, "open rotor" configuration	"Link&Fly"	"Flying-V"	Wing with morphing technology (ACTE, MIT NASA)	Convertiplane	Supersonic commercial aircraft	AWWA QG 'Progress Eagle'
Economic implications	An assessment of the economic impact on civilian technology has not been carried out	Economic impact assessment was not carried out due to the small amount of information about the concept.		Economic impact assessment was not carried out due to the small amount of information about the concept	Economic impact assessment was not carried out due to the small amount of information about the concept	Large passenger capacity onboard, respectively, reducing the cost per passenger-kilometre. An assessment of the economic impact was not carried out due to the small amount of information about the concept			Economic impact assessment was not carried out due to the small amount of information about the concept.

Maturity, feasibility and time to market	Maturity of technical solutions has a second level, feasibility and time of entrance to the market is expected after 2035	Maturity of technical solutions has a second level, feasibility and time of entrance to the market is expected after 2040	Maturity of technical solutions has the fourth level, feasibility and time of entrance to the market is expected after 2025	Maturity of technical solutions has the first level, feasibility and time of entrance to the market is expected after 2035	Maturity of technical solutions has a second level, feasibility and time of entrance to the market is expected after 2040	Maturity of technical solutions have a second level, feasibility and time of entrance to the market is expected after 2040	Maturity of technical solutions has the eighth level, feasibility and time of entrance to the market is expected after 2025	Maturity of technical solutions has the fourth level, feasibility and time of entrance to the market is expected after 2030	Maturity of technical solutions has the first level, feasibility and time of entrance to the market is expected after 2040

Key aspects of concept evaluation	Concept name								
	"Transformer aircraft"	"Flying wing" (BWB, HWB)	Aircraft with electric or hybrid engines with propellers, "open rotor" configuration	"Link&Fly"	"Flying-V"	Wing with morphing technology (ACTE, MIT NASA)	Convertiplane	Supersonic commercial aircraft	AWWA QG 'Progress Eagle'
Cross impact with other industries and mode of transport.	Cross impact of technical solutions can be with objects type "flying car"	Not applicable	Cross impact of technical solutions can be with objects of marine applications	It is possible with objects of railway and automobile transport	Not applicable	Not applicable	Cross impact of technical solutions can be with objects type "flying car"	It is possible with objects of space applications	Not applicable

Prerequisites or constrains.	The use of universal components of aviation technology which leads to a reduction in operating costs. A limitation may be the reliability of design during operation.	Existing military aviation objects of the type F-117 or B-2 (USA) are the background for the creation of such equipment. Future speed issues may be a limitation, as flight time will play a significant role.	The use of universal components of aviation technology, which leads to a reduction in operating costs. Noise level of propellers may be a limitation.	The use of universal components of aviation technology, which leads to a reduction in operating costs. Limitations may include flight safety and structural reliability in the ground and air applications.	The use of universal components of aviation technology, which leads to a reduction in operating costs. Future speed issues may be a limitation, as flight time will play a significant role.	New design. A limitation may be related to ensuring the specified aerodynamic and technological characteristics since the claimed materials were not studied at high flight speeds.	The use of universal components of aviation technology, which leads to lower operating costs. Noise level of propellers may be a limitation.	Modern business requires operational air transportation. Limitations on certification requirements for aircraft of this type (sound impact, flight path, emission of harmful substances)	The use of universal components of aviation technology, which leads to lower operating costs. A limitation may be the provision of specified aerodynamic and technological characteristics, since the

4

Key aspects of concept evaluation	Concept name								
	"Transformer aircraft"	"Flying wing" (BWB, HWB)	Aircraft with electric or hybrid engines with propellers, "open rotor" configuration	"Link&Fly"	"Flying-V"	Wing with morphing technology (ACTE, MIT NASA)	Convertiplane	Supersonic commercial aircraft	AWWA QG 'Progress Eagle'
Prerequisites or constrains.									claimed materials and flight principles were studied only by theoretical methods
Possible transition cost	Not investigated	Not investigated	Not investigated	Not investigated	Not investigated	Not investigated	Not investigated	Not investigated	Not investigated

Achievements and lessons learned in the past from similar previous experiences	Such developments were partially carried out and implemented on military aircraft in the USA and the USSR in the 1980s. In the USSR there were developed variable-sweep aircraft like MiG-23, Su-17, Su-24, Tu-22M, Tu-160.	No previous similar experience or developments	There is a high level of continuity in the development of propellers in the world. Nowadays, the technologies of design of the propeller engines are almost similar all over the world.	No previous similar experience or developments	No previous similar experience or developments	No previous similar experience or developments	There is a sufficient level of continuity in the development of VTOL aircraft, for example, V-22 Osprey, Bell V-280 Valor and others.	There is development experience in the field of military and civil aviation, for example, Tu-144, Concord.	No previous similar experience or developments

5

Key aspects of concept evaluation	Concept name								
	"Transformer aircraft"	"Flying wing" (BWB, HWB)	Aircraft with electric or hybrid engines with propellers, "open rotor" configuration	"Link&Fly"	"Flying-V"	Wing with morphing technology (ACTE, MIT NASA)	Convertiplane	Supersonic commercial aircraft	AWWA QG 'Progress Eagle'
Achievements and lessons learned in the past from similar previous experiences	In the USA there were created variable – sweep aircraft like B-1, F-111, F-14, Tornado. Other in-flight variable parts of aircraft have not been implemented. Tu-144 had the fuselage nose section which deflected electrically during the take-off and landing		A new method for improving the propeller effectiveness in the air is required.						

The potential market for such a solution.	The potential market for variable shape aircraft exists, but much of it is for aircraft with MTOW of about 4 to 5 tons.	Mainly for intercontinental routes	For regional routes	For regional routes, especially in very large airports	For intercontinental and regional routes	For intercontinental and regional routes	For regional routes and urban use	For intercontinental routes	For intercontinental routes

6

Key aspects of concept evaluation	Concept name								
	"Transformer aircraft"	"Flying wing" (BWB, HWB)	Aircraft with electric or hybrid engines with propellers, "open rotor" configuration	"Link&Fly"	"Flying-V"	Wing with morphing technology (ACTE, MIT NASA)	Convertiplane	Supersonic commercial aircraft	AWWA QG "Progress Eagle"
The potential market for such a solution.	When MTOW exceeds this range, the weight of electric drives increases significantly.								

Synergies with other solutions.	Not investigated	Not investigated. The new configuration of fuselage implements high lift characteristics of the fuselage together with a wing. Integral fuselage actively contributes to the increase in aircraft lift and produces lower drag	Investigations are carried out on the propeller - air intake, and propeller - aircraft fuselage elements integration properties.	Not investigated	Not investigated. The new configuration proposed implements the synergy of fuselage and wing. The fuselage actively contributes to the increase in aircraft lift and produces lower drag	Not investigated. The new configuration proposed implements the synergy of fuselage and wing. The fuselage actively contributes to the increase in aircraft lift and produces lower drag	Investigations are carried out on propeller - aircraft fuselage elements integration properties	Investigations are carried out on airframe-power plant integration properties at high flight speeds.	Not investigated. The new configuration of fuselage implements high lift properties together with a wing. The fuselage actively contributes to the increase in aircraft lift and produces lower drag.

Key aspects of concept evaluation	Concept name								
	"Transformer aircraft"	"Flying wing" (BWB, HWB)	Aircraft with electric or hybrid engines with propellers, "open rotor" configuration	"Link&Fly"	"Flying-V"	Wing with morphing technology (ACTE, MIT NASA)	Convertiplane	Supersonic commercial aircraft	AWWA QG 'Progress Eagle'
Potential for accelerate or early delivery of results.	Not expected	The potential is possible in the acceleration of study on the properties and aerodynamics of flying wing lifting surface. This is because other companies use similar solutions.	The potential is possible in the acceleration of study on the properties and aerodynamics of new types of BoxProp propellers.	Not expected because of poor project implementation arrangement	The potential is possible in the acceleration of study on the properties and aerodynamics of flying wing lifting surface. This is because other companies use similar solutions.	The potential is possible in the acceleration of study on the properties and aerodynamics of flying wing lifting surface. This is because other companies use similar solutions.	The potential is possible in the acceleration of study on the properties and aerodynamics of new types of propellers.	Not expected because of complicated engine cycle and process on the aircraft lifting surface at supersonic flight	The potential is possible in the study of the properties of new materials. This is because of the necessity to meet the aircraft certification requirements.
Uncertainties.	The error is not known as this theme is nowhere addressed explicitly in the public information	The error is not known as this theme is nowhere addressed explicitly in the public information	The error of technical and economic solutions was not investigated before.	The error is not known as this theme is nowhere addressed explicitly in the public information	The error is not known as this theme is nowhere addressed explicitly in the public information	The error is not known as this theme is nowhere addressed explicitly in the public information	The error of technical and economic solutions was not investigated before.	The error of technical and economic solutions was not investigated before.	The error of technical and economic solutions is not known as this theme is nowhere addressed explicitly in the public information

Key aspects of concept evaluation	Concept name								
	"Transforming aircraft"	"Transformer aircraft"	"Flying wing" (BWB, HWB)	Aircraft with electric or hybrid engines with propellers, "open rotor" configuration	"Link&Fly"	"Flying-V"	Wing with morphing technology (ACTE, MIT NASA)	Convertiplane	Supersonic commercial aircraft
Restrictions or constraints derived from such a the solution, impacts with other industries or modes of	Non-existent	Non-existent	Non-existent	The influence of restrictions on other means of transportation does exist as the integration into road transport or railway infrastructure is required. The the issue has no	Non-existent	Non-existent	Non-existent	The influence of restrictions on the development of spaceplanes	Non-existent

Failure severity and risks, that is derived serious consequences for the sector in case of partial or total failure to achieve that solution.	Serious consequences are not expected	There will be serious consequences for the aircraft sector in case of complete or partial failure to implement the solution. The main the task of the project is to use the new configuration of aircraft to ensure better operating performance. This should lead to significant reduction in operating expenses for this type of	There will be serious consequences for the aircraft sector in case of complete or partial failure to implement the solution. The main task of the project is to use the new configuration of aircraft to ensure better operating performance.	Serious consequences are not expected	There will be serious consequences for the aircraft sector in case of complete or partial failure to implement the solution.	Serious consequences are not expected	Serious consequences are not expected	Serious consequences are not expected	Serious consequences are not expected

9

Key aspects of concept evaluation	Concept name								
	"Transformer aircraft"	"Flying wing" (BWB, HWB)	Aircraft with electric or hybrid engines with propellers, "open rotor" configuration	"Link&Fly"	"Flying-V"	Wing with morphing technology (ACTE, MIT NASA)	Convertiplane	Supersonic commercial aircraft	AWWA QG 'Progress Eagle'
Failure severity and risks, that is derived serious consequences for the sector in case of partial or total failure to achieve that solution.		If it is not the case, there is a possibility of losing the project development cost and switching to different types of aircraft that are developed by other manufacturers.	If it is not the case, there is a possibility of losing the project development cost and switching to different types of aircraft that are developed by other manufacturers.						
Technology readiness level	2	2	5	1	1	3	8	5	1

18.9.11 Annexe 11: Electric aircrafts

Europe's Vision for Aviation the Flightpath 2050 documents[ii] the key areas of aeronautical R&D which are essential for the development of the aerospace sector in Europe. Besides, e.g. societal & market needs, maintaining and extending industrial leadership, the protection of the environment and the energy supply are very important points.

The environmental and energy targets of the Flightpath 2050 are compared with the respective numbers from the year 2000:

- A 75-percent reduction in aircraft CO2 emissions,
- A 90-percent drop in nitrous oxide emissions
- 65-percent cut in noise levels

To reach these ambitious numbers different ways are to go.

The situation is similar to automobile and truck transportation which is to 74 % involved in the total emissions of all transportation modes. The aviation part amounted to 11 % at the total transport emission; and the total transport emission to 22 % of the total global emissions (electricity and heat, manufacturing and construction, transport, residential, others).

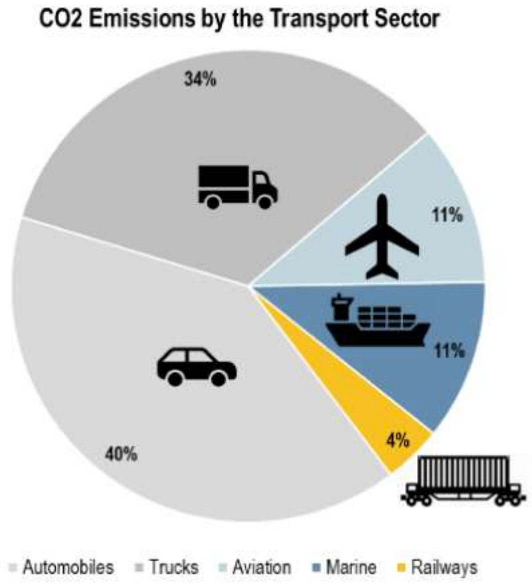
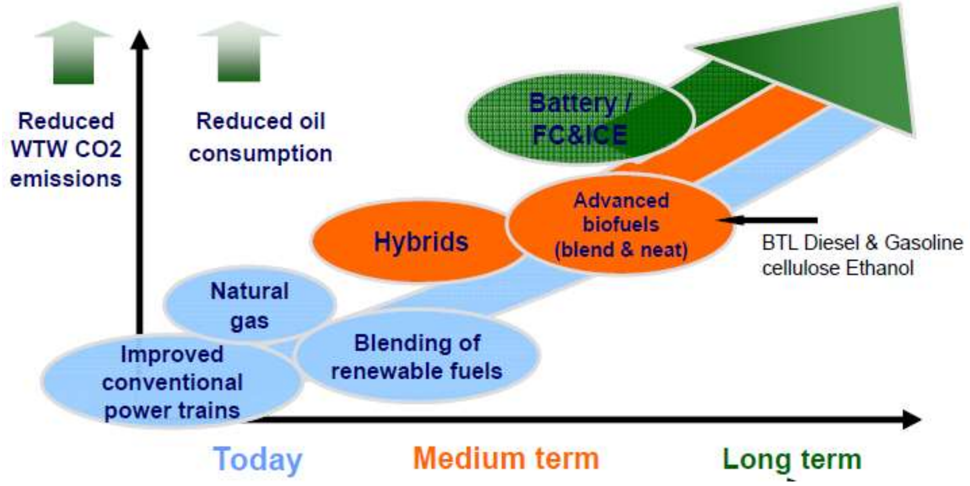


Figure 126: Global greenhouse gas emissions by the transportation sector[iii]

To reach the environmental and the energy targets the following technology open ways are gone in the automobile industry, which is concentrated on fuels and the power train.



The advanced power train propelling options of the automotive industry, like the battery, fuel cell, and hybrids are the same for the aviation industry.

The following Figure 1 shows the possibilities for the use of batteries and fuel cells in airplanes in different versions. For batteries are besides secondary batteries (accumulators) also primary batteries as IFR reserve are used.

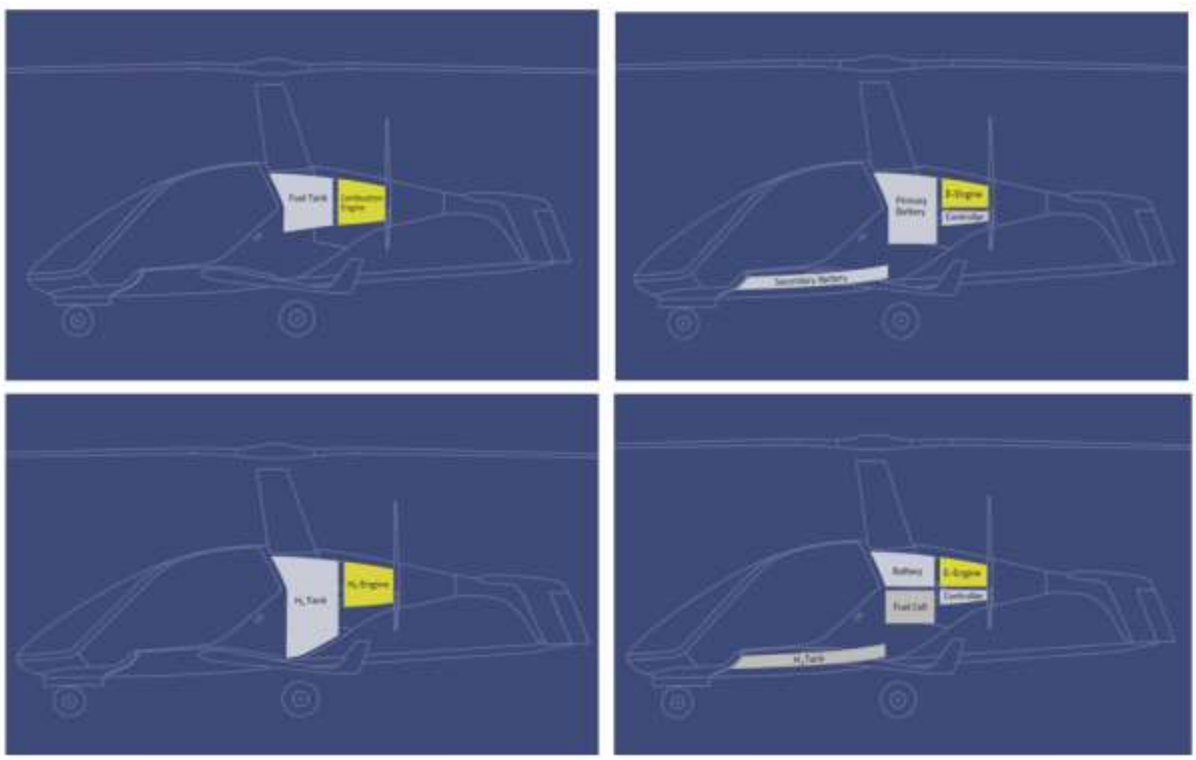


Figure 1: Scheme of use of batteries (secondary and primary) and fuel cells in planes about conventional combustion engine concepts[iv]

CO2 saving potentials and efficiency

For the consideration of CO_2 emission of batteries and fuel cells planes, it is to take into account the phases of their production, operation up to disposal.

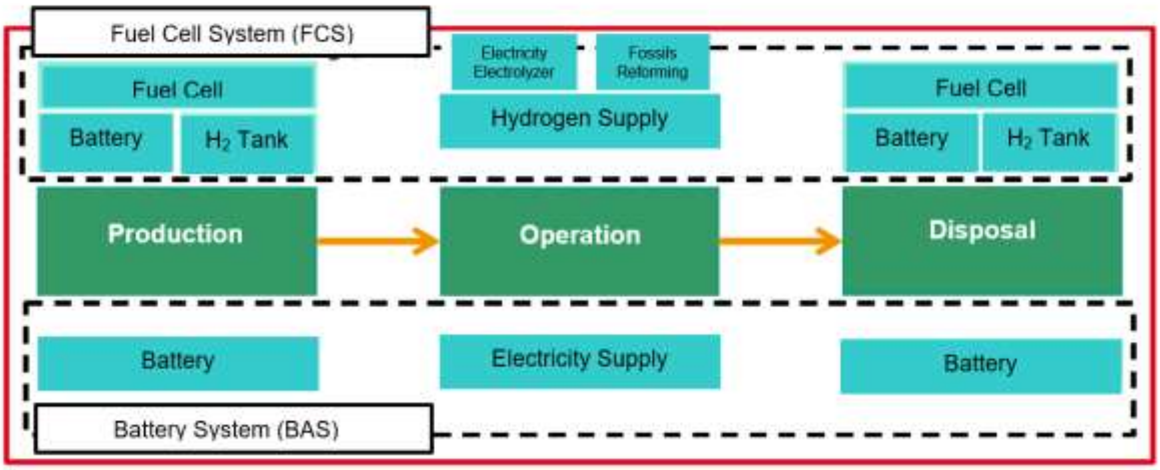


Figure 2: The life cycle of batteries and fuel cells for battery and fuel cell plane systems

Fuel cell systems usually consist of the fuel cell stack, the hydrogen tank and especially for the take-off a battery (energy is related to the application).

For batteries Figure 3 shows the greenhouse gas emissions for the best, base and worst case in 2020 and 2030. The three cases are reflecting the today literature[v], which is in the region of 60 – 200 kg CO_2-equ/kWh battery, whereas the larger part of the emissions is related to materials and the lower one to the production process.

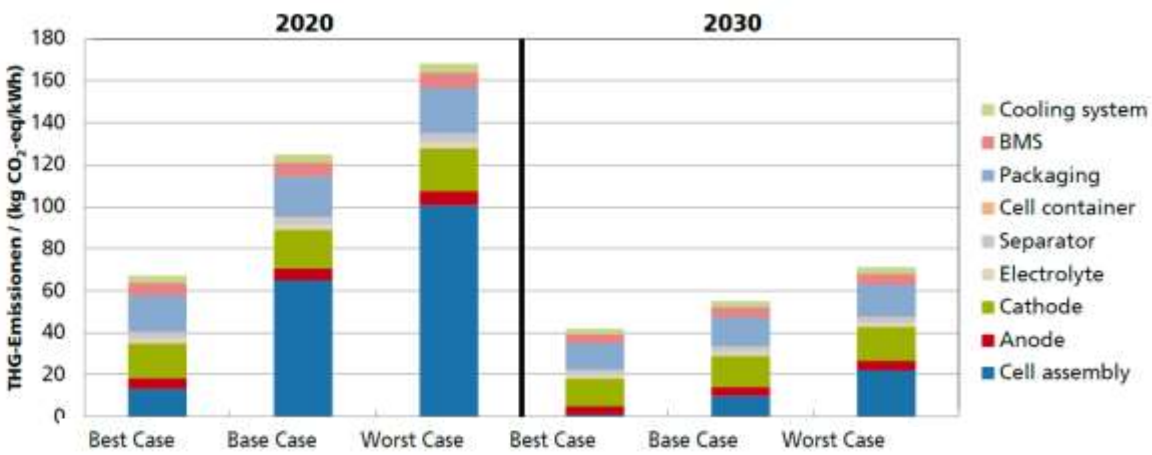


Figure 3: Greenhouse gas emissions (THG) for batteries in kg CO_2-equ/kWh (2020:– NMC622, 135 Wh kg^{-1}; 2030:– NMC90.50.5, 185 Wh kg^{-1})[vi]

Figure 4 shoes for the production of PEMFCs the GHG emissions in kg CO_2-equ/kW fuel cell for different Pt-catalyst contents and specific powers in 2020 and 2030.

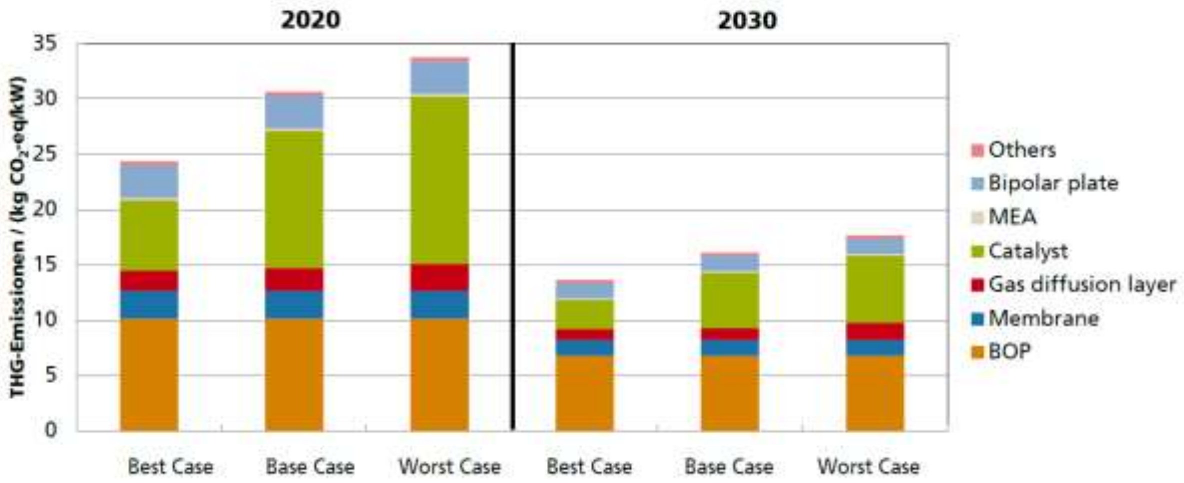


Figure 4: Greenhouse gas emissions for fuel cells in kg CO_2-equ/kW (2020: Pt – 0.4 mg cm^{-2} , 0.43 g/kW; power – 1.06 W cm^{-2}; 2030: Pt – 0.2 mg cm^{-2} , 0.165 g/kW; power – 1.31 W cm^{-2} [vii])[vi]

Figure 5 shows for the production of hydrogen tanks the GHG emissions in kg CO_2-equ/kg H_2 storage capacity for 2020 and 2030.

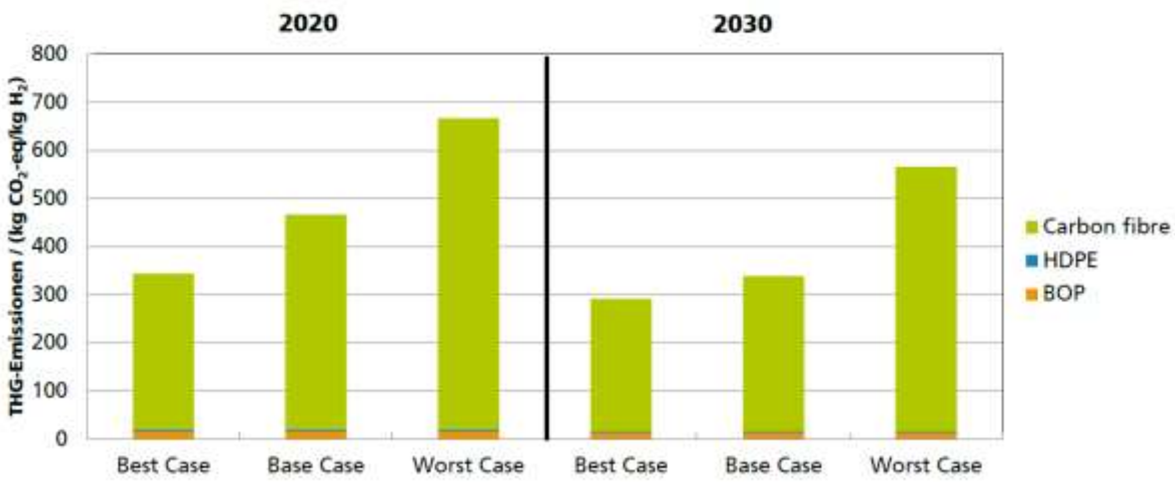


Figure 5: Greenhouse gas emissions for hydrogen tank production in kg CO_2-equ/kg H_2 (2020, 2030: Type IV-700 bar; two-tank system; 5.6 kg H_2; material 2030 15 % lower than 2020)[vi]

The largest part of the emissions is related to the by high temperature (ca. 2000 °C) produced carbon fibres.

The CO_2 Emission for the disposal of a 120 kWh battery is in the order of 0.75 t CO_2-eq (2020) and 0.3 t CO_2-eq (2030) [vi]

The fuel for electrical planes are electrons (electrical energy), for both batteries and fuel cells, if the hydrogen is produced via electrolysis.

The electricity today is strongly CO_2 emission loaded, as long the electrical energy is not from renewable sources. But even in the renewable case still, a small CO_2 contribution based on the production of the renewable facilities is to note - wind: 11 g CO_2/kWh [viii], solar: 48 g CO_2/kWh [vi].

The CO_2 emission burden is shown in Figure 6.

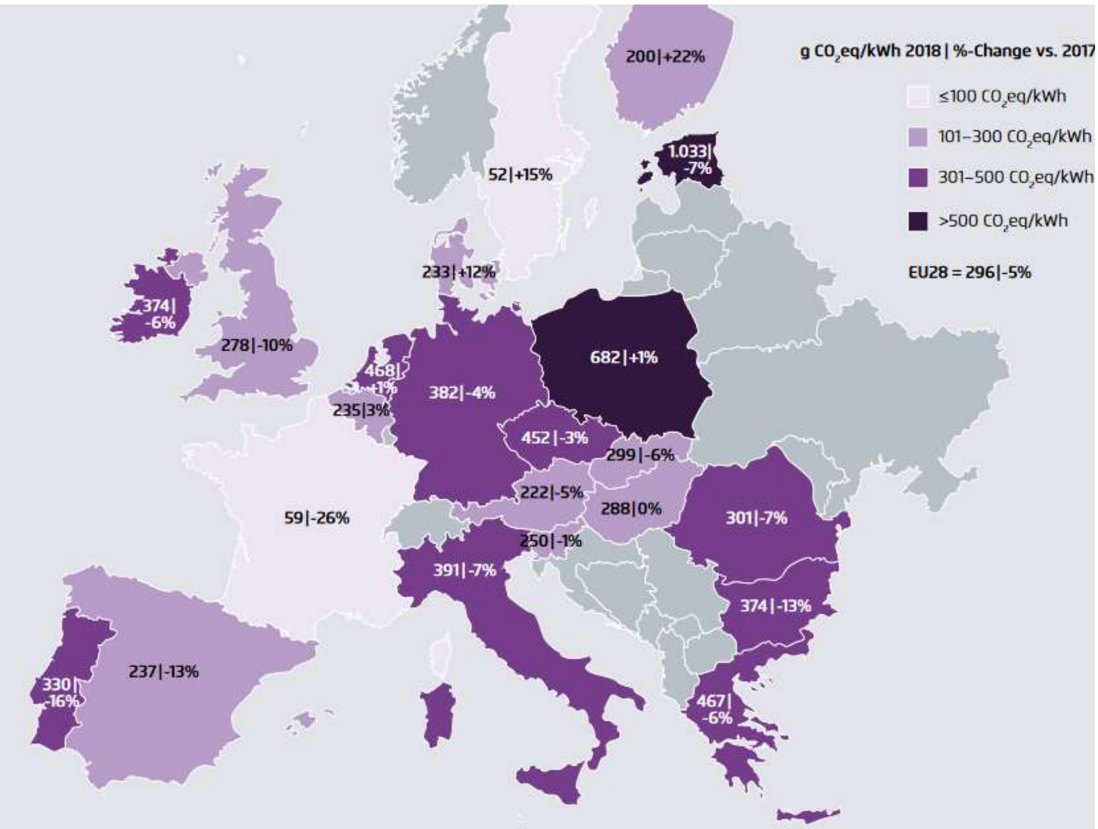


Figure 6: CO_2 intensity of generated kWh (g CO_2/kWh: 450 gas, 820 coal - no distinction of lignite or hard coal, 11 wind)[viii]

Figure 6 shows the large differences in Europe: min - France 59 g CO_2/kWh, max - Estonia 1,033 g CO_2/kWh, EU28 296 g CO_2/kWh.

But these values will be decreased in the future by a continuous expansion of renewable energies (EU28: 32 % (2018) => 54 % (2030)) and therefore the CO_2 pollution will be reduced as well.

Figure 7: Share of renewable electricity in Europe[viii]

The energy conversion efficiency for different drives is given in Figure 8.

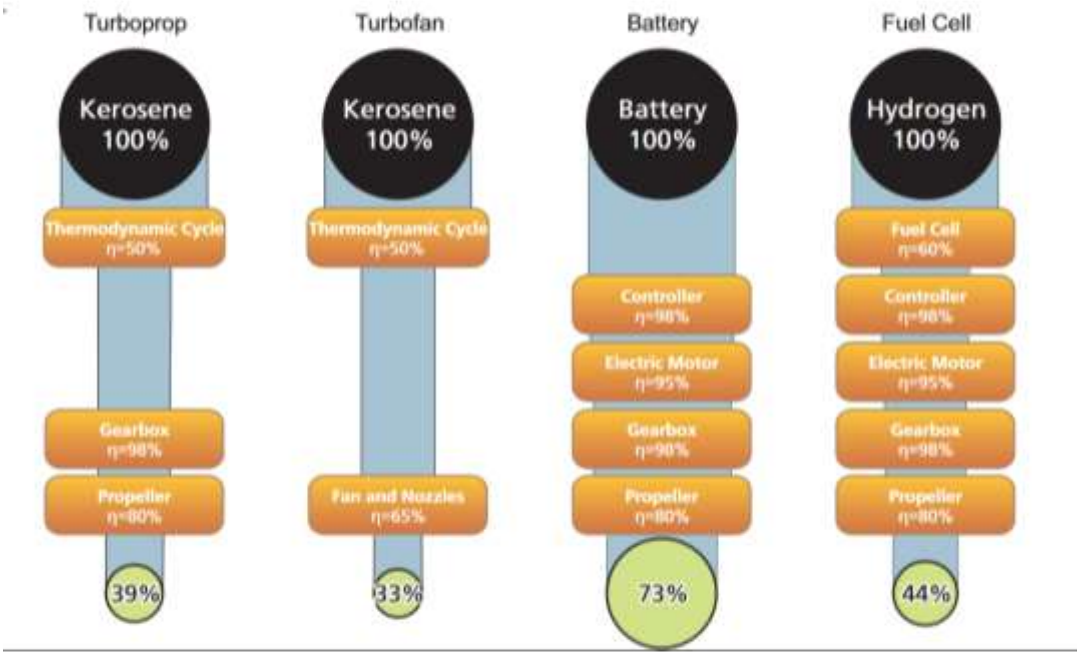


Figure 8: Typical on-board conversion chains with typical component efficiencies and total chain efficiency[ix]

The best efficiency has the battery, followed by fuel cells, turboprop, and turbofan.

While the fuel of conventional turboprop and turbofan planes is the fossil Kerosene the fuel for batteries are electrons and for fuel cells hydrogen, which is today mainly generated from fossil fuels by reforming (85 %) and in the future particularly from renewable energy by electrolysis (75 %). I.e., it is to take electrical energy as the starting point of 100 % for fuel cells as well. Therefore, the H2/FC technology efficiency is reduced to 33 %.

The strong environmental impact of the battery and fuel cell production is reflected also in the environmental impact of battery and FC airplanes. This leads in comparison with kerosene airplanes to a starting handicap of electrical airplanes. Only during the operation, the handicap is first neutralized and then overcompensated. The mileages of neutralization depend on the electricity sources/mix.

The following Figure shows the comparison of Greenhous gas emissions via the mileages for battery electric vehicles (BEV), fuel cell electric vehicles (FCEV) and diesel vehicles. The hydrogen for the FCEVs is coming from fossils (natural gas via reforming) and renewables (wind via electrolysis). The 90 kWh BEVs take their current from the German electricity mix and renewables (PV).

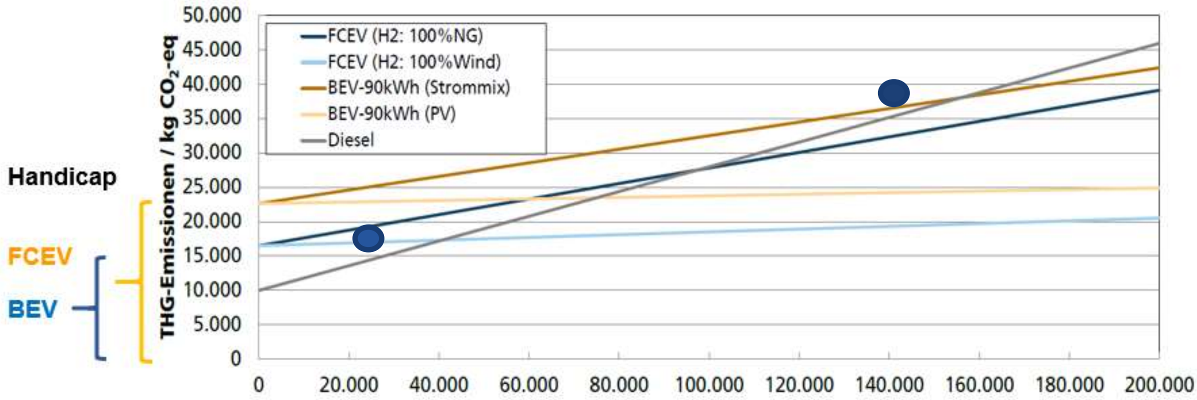


Figure 9: Greenhous gas emissions via the mileages for battery electric vehicles (BEV), fuel cell electric vehicles (FCEV) and diesel vehicles

While the neuralization point of the handicap in case of an FCEV propelled with renewable hydrogen is already reached at 40,000 km the neutralization point in case of a 90 kWh BEV which is driven by electricity from the German electricity mix with 35 % renewables is reached only after 160,000 km.

Qualitatively the same situation will be observed with electrical and kerosene driven aircraft. Caused by the longer flying distance in relation to cars the neutralization time in years will be earlier.

Possibilities of electric flying

The flight range (without take-off) is given[ix] by

$$R = E^* \cdot \eta_{total} \cdot \frac{1}{g} \cdot \frac{L}{D} \cdot \frac{m_{batt}}{m}$$

E^* - Specific battery energy [Wh/kg]

η_{total} - System efficiency from battery to propulsive power (~ 75 %)

L/D - Lift over drag ratio; depends on aircraft design (~10…15 for larger aircraft)

m_{batt} - Battery mass

m - Airplane mass ($m_{empty} + m_{payload} + m_{battery}$)

m_{batt}/m - Battery mass fraction
g - Gravity acceleration

Based on this equation is the range (R in km) calculated vs. the specific energy of the battery (E^*) for η_{total} = 0,75; different L/D values (40 – glider, 10 - passenger aircraft) and different battery mass fraction $m_{batt}/m_{airplane}$, whereas values of 0.1 – 0.4 are today practically realistic.

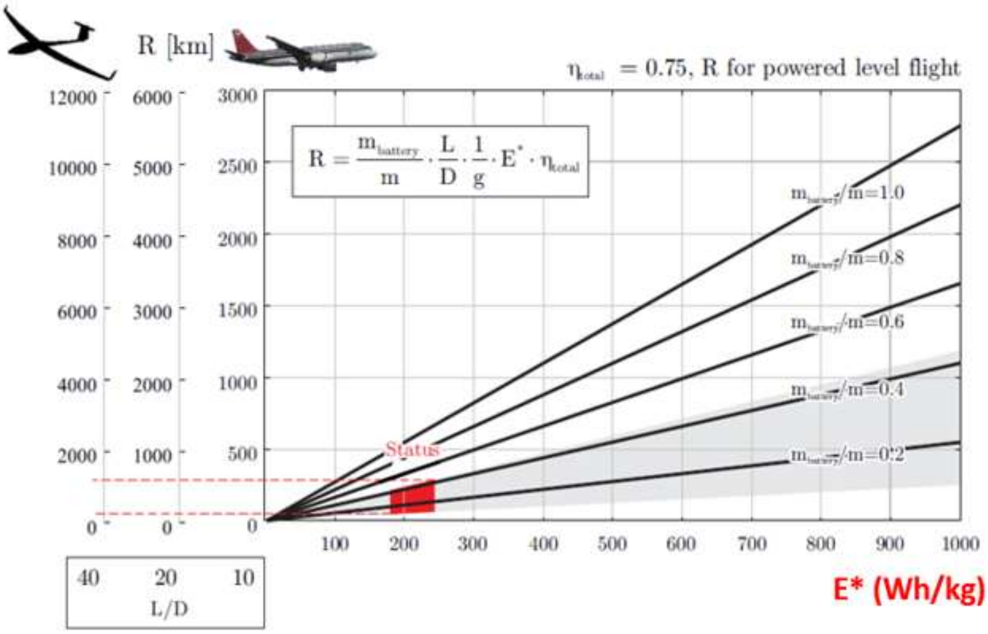


Figure 10: Airplane range (R in km) vs. specific energy of the battery (E*) for η_{total} = 0,75; different L/D values and different battery mass fraction $m_{batt}/m_{airplan}$[ix]

In the red area in the low left corner of Figure 10 the status quo is shown.

For L/D 10 (passenger aircraft), with E*: 200 Wh/kg, $m_{batt}/m_{airplane}$: 0.4 the range (R) amounted to ≈ 250 km

For L/D 20 (aircraft with larger wingspan), with E*: 200 Wh/kg, $m_{batt}/m_{airplane}$: 0.4 the range (R) amounted to ≈ 500 km

This flight range is normally not enough for passenger flights. But applications with a limited weight of the aircraft, and low total weight, i.e. small passenger numbers and/or low payload as well as limited endurance and speed are possible with the today batteries. Vertical take-off and landing (VTOL) taxis, general aviation & recreational aircrafts, and regional & business aircrafts, and drones fit reasonable the above-given limitations in weight and range.

The strongest development takes place at VTOL taxis normally with a range between 50...100 km and partially larger. One example is the German company Lilium with their Lilium Jet with 36 all-electric engines and a flight time of one hour and max. 300 km. Other developers are Rolls-Royce, Even Aston Martin, Vertical Aerospace, Karem Aircraft, SAMAD aerospace and Urban Aeronautics.

Larger flight ranges could be possible by

A - By battery charging during the flight with PV

B - By battery charging during the flight with a kerosene gas turbine (hybrid)

C - By better plane design: larger L/D and/or battery mass fractions

D - By higher specific battery energy

E - By use of hydrogen and fuel cells

A – Solar Powered Aircrafts

Solar-powered aircrafts (SPA) are solar generator/ECPS hybrids, which should eliminate the current disadvantage of all-electric aircrafts, i.e. the limited range caused by the low specific battery energy.

Solar panels are the electricity generator to power the electric motor of the aircraft and to charge the battery for night flights. With about max. 250 W/m^2 PV panel for 50 kW electricity a wing area of at least 200 m^2 panel area have to covered with solar panels.

One main future application is the use of UAV solar-powered aircraft acting as a transmission or relay station over a limited geographical area as a much cheaper alternative to geostationary satellites in about 36,000 km altitude with about $400-500 mill. These high-altitude pseudo satellites (HAPS) fly above cloud cover at an altitude of about 20 km.

Examples are the Odysseus developed by the Boeing daughter Aurora Flight Sciences with a wingspan of 74 m and an extremely high payload of 25 km.

Figure 11: Solar-powered aircraft Odysseus of Aurora Flight Sciences [x]

The Odysseus can be used also as High -altitude, long-endurance (HALE) UAV. Another HAPS example is the Zephyr of the Airbus daughter Qinetiq which flews in 2018 25 days. Zephire S technical data: wingspan 25 m, weight 80 kg, payload 5 kg, Li-ion battery of Amprius with 100 % silicon nanowire anodes and 435 Wh/kg as well as 1200 Wh/litre.

Also, round the globe flight or long-time flights by solar-powered aircraft are possible. These solar-powered planes are used either as unmanned platforms for sensors or manned for demonstration and leisure.

At the beginning of the 1990s the NASA has developed different solar-powered aircraft as Pathfinder, Pathfinder Plus, Centurion, Helios, as well as Airbus/Siemens. and also have developed prototypes. The Solar Impuls, developed by the Swiss B. Piccard and A. Borschberg, at beginning of the 2010th was a milestone. The Solar Impulse 2 has had a wingspan of 72 m, 270 m² PV panels and 4 x 41 kWh Li-ion batteries (164 kWh, 633 kg, 260 Wh/kg) ultra-high-energy NMC batteries from Kokam. The circumnavigation of the earth with 42,438 km and in summarized 23.25 days was done 2015/16 in 17 stages. The longest leg was with 7,212 km and 117 h from Japan to Hawaii

But all these good results reached with solar-powered aircraft are to secure also under all-weather round-the-clock operations with sophisticated light plane designs (very large wings for high lift values and area for PV modules). A commercial introduction will be only in ≥ 2035.

B - Battery-Turbine-Generator Hybrid

Besides PV modules also a generator driven by a kerosene gas turbine could charge the battery during the fly. The gas turbine/generator, however, has normally a high CO_2 footprint and is noisy. But the turbine can continuously operate within its ideal speed range, which saves fuel (CO_2) and reduces the noise level.

Turbine/battery hybrids work mostly as parallel hybrid, the generator powers the electric motors for the rotors. In this way several small electric motors could be used, leading to new forms in aircraft design with improved aerodynamics and efficiency. But the aerodynamic advantages have to overcompensate the weight drawback of hybrid systems.

Besides turbine/battery hybrids there are also ICE/battery hybrids, where both powertrains (ICE, electrical motor) work independently of each other, as e.g. in the twin-engine Ampere 337 (based on Cessna 337) where one Continental engine was replaced with a battery-driven electric-propulsion system – first fly June 2019. Airbus is developing at the same time the 100-seater (!) regional aircraft E-Fan X in the first step by replacing one of the four engines with a 2 MW electric motor.

Critical for the hybrid design is the main goal of the application: range, CO2 footprint, or/and cost, which determines the degree of hybridization.

Other developments are from the US company Zunum Aero which plans in cooperation with Boeing and JetBlue a hybrid electric drive system for 12-passenger, with 550 km/h; first flights will be 2020/21. The three French aerospace companies Airbus, Daher and Safran are developing a hybrid-electric plane based on the Turboprop-Einmot Daher TBM with the name EcoPulse (5 passengers). The engine drives the main rotor on the fuselage of the aircraft. The electric motors drive six smaller propellers attached to the wings – three on each side; 2022 will be the first flight

The success of turbine-ICE/battery hybrids depends strongly on the reachable fuel savings, which should be > 30 %. It is predicted that only in the year 2035, hybrid-electric aircrafts with about 100 passengers and 1000 km range will be commercialized.

C – Optimization of the Airplane Design

As shown in the range equation above the airplane design parameter L/D and $m_{batt}/m_{airplane}$ take linearly influence on the range of the airplane.

L/D the lift over drag ratio is mainly determined by the wingspan of the airplane. Sophistic L/D values of ≥ 40 of the solar-powered Odysseus, as shown in Figure 11 are not realistic for passenger airplanes; a value between 15 ... 20 should be aimed.

The battery mass fraction consists of the battery mass (m_{batt}) and the airplane mass ($m_{airplane}$), whereas $m_{airplane}$ is determined bythe sum of m_{empty} + $m_{payload}$ + $m_{battery}$.

To the m_{batt} see below section D.

Also, the empty airplane mass (m_{empty}) could be reduced by ultra-light all-composition airframes and special electric motors.

The Israeli company Eviation took that into account with its all-electric airplane ALICE.

Figure 12: Scheme of the all-electric airplane ALICE

The ALICE plane is a 9+2-seater, with an ultra-light all-composite airframe, an exceptional battery mass fraction of 0.65, and a battery consists of 900 kWh Li-ion battery and a primary Al-air system (as IFR reserve) with exceptional value of 400 Wh/kg.

First flights were already done, a pilot production should start in 2021.

D – Advanced batteries

The state of the art (Generation 2) of the specific energy of cells is about 250 Wh/kg, which is related to about 160 Wh/kg for batteries.

Very great efforts are being made to increase the specific energy, especially pushed by the car manufacturers. There are 4 general ways to go for the increase in the specific energy:

A - Material optimization

b - Electrode/cell optimization

c - New materials for Li-Ion

d - New battery systems

a – Material optimization

The aim is to improve the specific capacity of the state-of-the-art active materials by the refinement of the shape (e.g. nano sizing) and the structure (e.g. nanostructures, channel structures, 3D structures), by doping (e.g. homogenous, surface or core-shell doping), and by coating (e.g. for surface protection and/or better electronic conductivity).

b – Electrode/Cell optimization
This way goes back on the cell design optimization via electrode area, thickness and density of the active material layer, percentage of conductivity agents and binder, thickness of electrode collector foil, separator, and metal cell case.

c - New materials for Li-Ion systems
There are some new or better further developed materials, as for the anode Si-graphite materials and the cathode NMC ($LiNi_xMn_yCo_zO_2$) materials with a higher content of Ni. From today NMC622 (x:y:z) materials one goes in the direction of NMC811 and even NMC8.50.750.75 (see Figure 13) and even to some higher Ni-content NMC90.5.0.5 with a much higher specific capacity. But these new/advanced materials have lower thermal stability and lifetime (see also Figure 13).

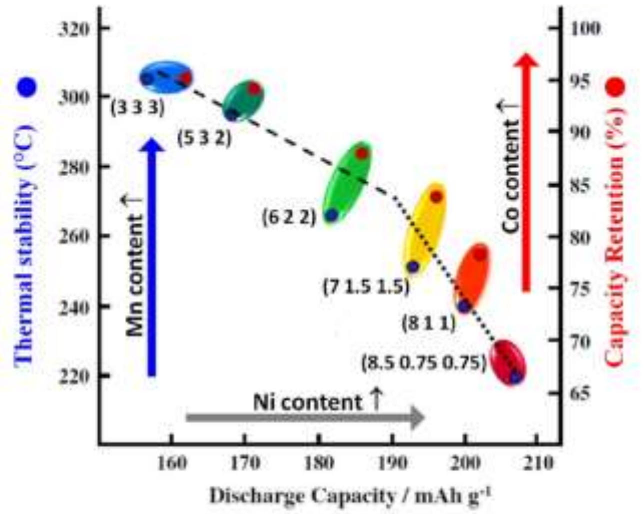


Figure 13: Discharge capacity, thermal stability and capacity retention in dependence of the mixing ration of Ni:Mn: Co[xi]

d - New battery systems

The so-called Post- Li-ion systems are

- Li-S, Li-Air, Li solid-state systems, Na, Mg, Al systems

The motivation for the

- Li-S and Li-Air systems are the high specific energy (Li-S: 400 Wh/kg, Li-Air: > 600 Wh/kg) and the low costs of the cathode materials. Low power and low lifetime are disadvantages of these systems.

- Solid-state battery systems are the higher specific energy (400 Wh/kg), which is based on the use of a metallic Li-anode, which is compatible with the solid electrolytes and not with the organic liquid electrolyte of the conventional LIB. Furthermore, a significantly higher safety is observed caused by the non-flammability of the solid electrolytes.

- Na, Mg, Al systems are especially material resources. These systems will not increase the specific energy but the materials are much more available in the earth's crust.

In general with following developments of batteries related to the specific energy and time of market introduction can be expected - Figure 14.

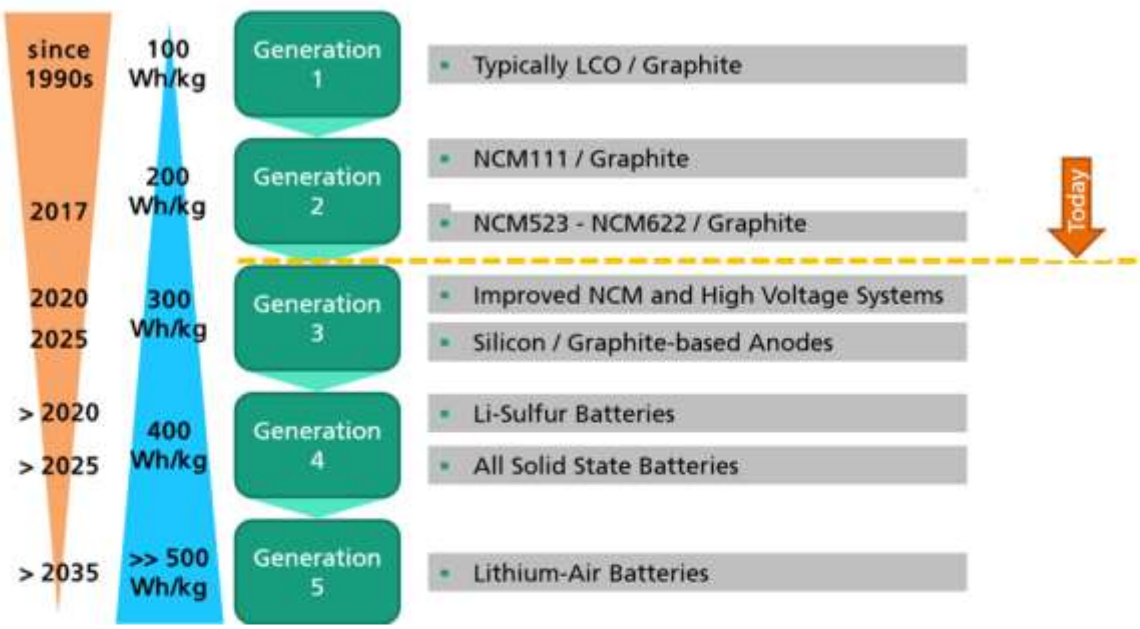


Figure 14: Roadmap of the battery development related to the specific energy and time of market introduction[xii]

That means between 2025- 2030 cells are available with 400 Wh/kg or on the battery level of about 270 Wh/kg. From 2030...35 cells will have > 500 Wh/kg and batteries 333 Wh/kg.

This is an engrave improvement over the state-of-the-art, but not yet enough for the electrification of larger passenger airplanes with ranges of < 1000 km.

The costs of batteries are dramatically decreased in the last years from about 1,200 $/kWh in 2010 to about 160 $/kWh today and expected 60 $/kWh in 2030[xiii].

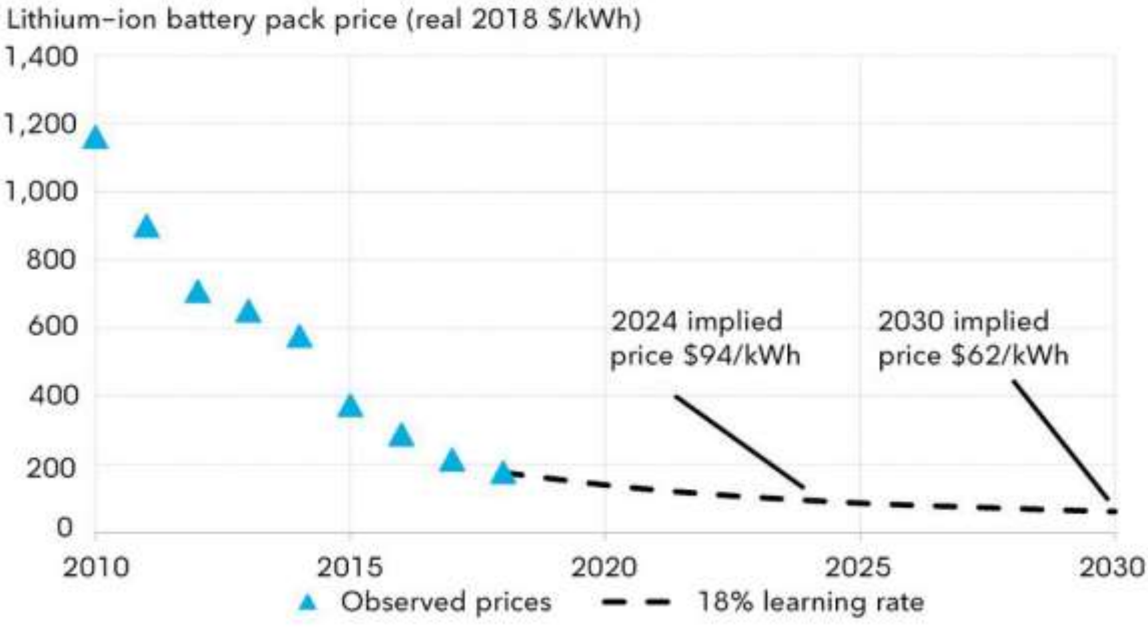


Figure 15: Cost development of LI-Batteries[xiii]

E - Hydrogen and Fuel cells

Hydrogen as an energy carrier could be used as fuel in airplanes in two different ways:
A - Use of hydrogen as a fuel for turbines instead of kerosene in big airplanes,
B - Use of hydrogen in hydrogen fuel cells in small electrical propeller airplanes.

Prototypes for case A with reduced CO_2 pollutions are the Tupolev TU 155 (1989), and the Boeing UAV Phantom Eye (2010). But they are not electric aircrafts and caused by still many disadvantages their developments were discontinued. The drawbacks were NO_x, noise, and larger production of water vapour (based on H_2 fuel and not C_xH_y) which has a larger lifetime at higher altitudes. Water vapour is known to be Earth's most abundant greenhouse gas.

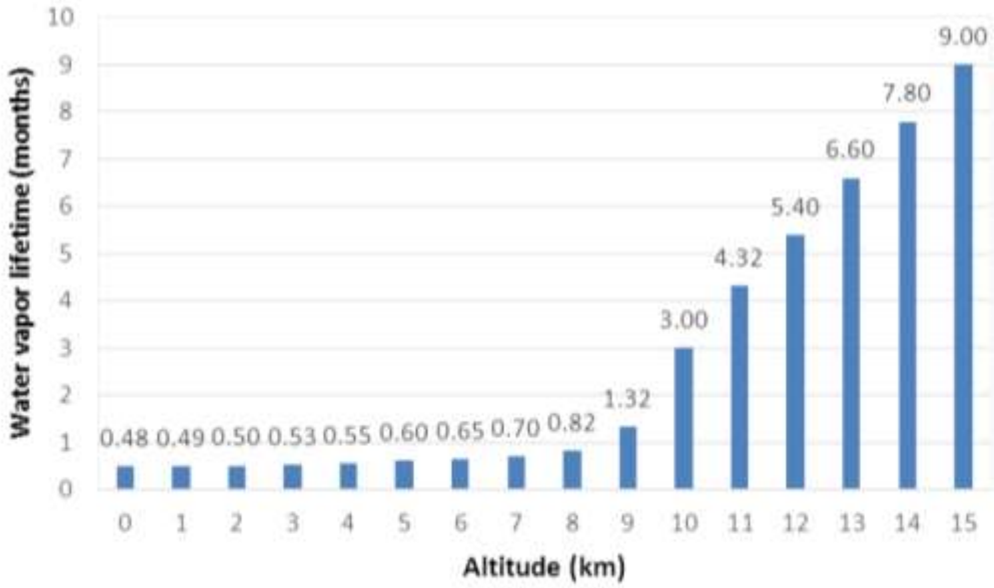


Figure 16: Water vapour lifetime as a function of altitude [xiv]

The case B, fuel cell driven airplanes give the possibility for longer flight ranges, caused by the relatively low weight of the hydrogen which determines the FC energy and therefore the flight range. The power of FCs is determined by the fuel cell stack, whose mass is constant and independent on the flight range. To increase the power of the FC powertrain also Li-ion batteries are used – FC/battery hybrids (see Figure 1).

Hydrogen was used in liquid form for larger airplanes with jet engines (case *A*) and is used in the pressurized form (300 – 700 bar) for smaller PEMFC aircraft. The volume for both liquid and pressurized hydrogen is much larger but the weight is lower as kerosene of the same energy content. So, the higher volume has to manage by design but the lower H_2 weight leads to only one-third of the kerosene mass. In the future will be probably liquid hydrogen the only options for long-range passenger airplanes caused by the volume problem, although the liquefaction of hydrogen needs much more energy as to pressurize hydrogen (see chapter 9.22 - Hydrogen from Water Electrolysis).

The above-given equation for the range of electrical airplanes is valid also for fuel cells, whereas E* is then the specific FC system energy [Wh/kg], m is the $m_{FC\ System}$ and $m_{FC\ systemt}$/m is the FC system mass fraction. The concrete specific energy depends on the hydrogen storage capacity. Usually 500 – 1000 Wh/kg are reachable with H2 tanks, which fit the plane.

As already mentioned, the mass of the FC system is composed of the FC stack, which is responsible for the power and the H_2 tank responsible for the capacity/energy.

I comparison to the battery with no independent optimization of power and energy the following connection between the mass of the electrochemical power sources ECPS (battery, FC) and the energy/operating time is given.

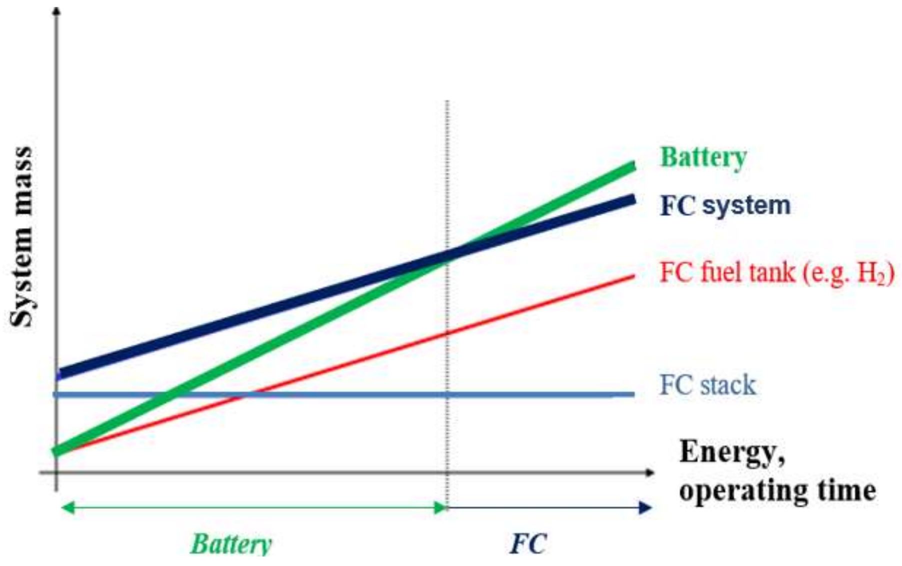


Figure 17: System mass vs. Operating time for batteries and fuel cell systems (FC + H_2 tank)

Figure 17 shows, that fuel cells are suitable for longer ranges. Furthermore, analogue to classic fossil driven airplanes the mass of the airplane, i.e., the mass of the H_2 tank is decreased with increasing flight time.

The operating conditions of PEMFCs in the air are caused by changing altitudes with changing air pressures and temperatures more demanding as terrestrial applications.

In 2008 Boeing Research & Technology Europe (BR&TE) tested a civilian 2-seat Diamond Aircraft Industries DA20 (called Theator Airplane) running on a fuel cell (UK Intelligent Energy) and Li-ion battery. A further development was 2009 the Antares DLR-H2 plane based on the Antares 20E aircraft of Lange Aviation driven only by a 25 kW PEMFC (hydrogenics) with 44 % efficiency. In 2010 in the framework of the EU "ENFICA-FC" project (Environmentally Friendly Inter City Aircraft powered by Fuel Cells) a two-seater all-electric aircraft was developed driven by a PEMFC (20 kW)/Li-Ion battery (20 kWh) hybrid system with 350 bar hydrogen storage. Based on the Antares experiences the HY4 all-electric plane the DLR developed in 2016 a four-seater powered by a PEMFC/Li-ion battery hybrid system. HY4 technical data: weight - 1,500 kg; e-motor - 80 kW; max./cruising speed - 200/145 km/h, range - 750 – 1500 km, PEMFC - 45 kW; 100 kg; H_2 – 9 kg, 437 bar, 170 kg; LCO battery - 21 kWh, 130 kg. With liquid hydrogen ranges of >, 2,000 kam would be possible Studies for a 6 and also a 40 seat PEMFC/Li-Ion hybrid-powered all-electric aircraft are done also by the DLR Stuttgart.

Furthermore, PEMFCs together with Li-ion batteries are demonstrated to power small unmanned aerial vehicles UAVs (drones) for ≥ 10 h (e.g. FAUCON H2, LH2 Ion Tiger 48 h)[xv].

The costs of the fuel cell systems are strongly dependent on the annual production volume as Figure 18 shows for total FC system cost (FC stack + BoP, without H2 storage unit). The calculations were done by the US-DoE for 80 kW PEMFCs for a light-duty vehicle (LDV) and 160 kW PEMFC for medium-duty vehicles (MDV).

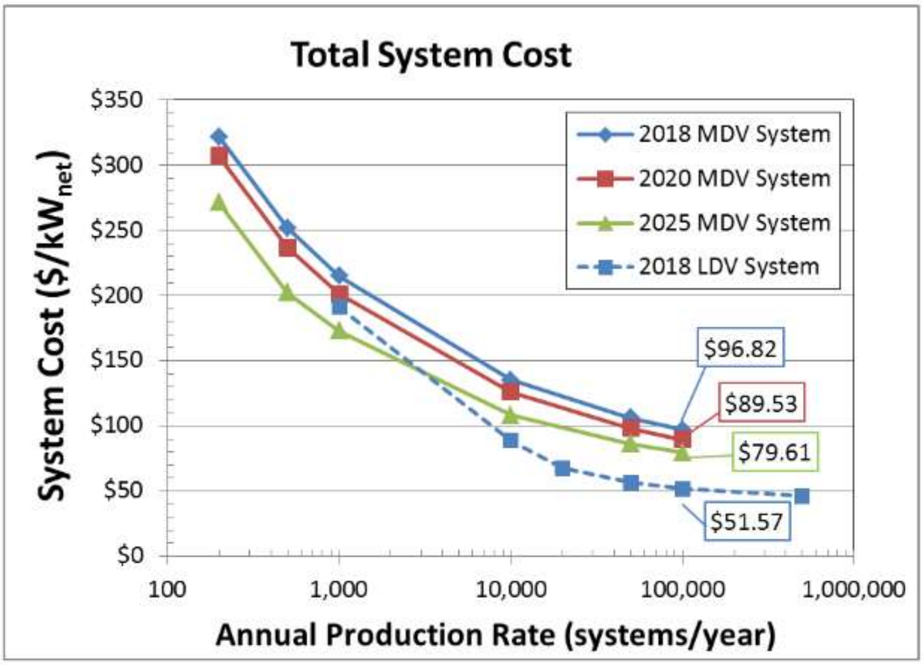


Figure 18: Cost estimation for PEMFC systems for light-duty vehicles (LDV) with 80 kW and medium-duty vehicles (MDV) with 160 kW vs. annual production rate and 208, 2020, and 2025[xvi]

The costs for the hydrogen pressure tank type 4 (64,4 l H_2 @ 700 bar) are also dependent on the annual production rate. For 1,000 tanks/year are the costs at ~$1,250, for 100,000 tanks at ~$580 and for 500,000 tanks at $565 [xvii].

All these costs analysis are made for car applications. The car manufacturers are the main driver of the development and market introduction of fuel cell systems. The aviation industry is so a windshield beneficiary of the OEM developments - but they should create soon their specifications which addresses also the specific aviation requirements as e.g. low temperatures and low and changing air pressures.

Outlook

Caused by the permanent air traffic growth of about 5 % annually[xviii] (doubling every 15 years) and the worldwide climate problems the air industry has to find solutions to reduce its harmful contribution to the environment.

The targets of the European program *Flightpath 2050* are compared with the respective numbers from the year 2000:

- 75-percent reduction in aircraft CO2 emissions,

- 90-percent drop in nitrous oxide emissions

- 65-percent cut in noise levels

There are many approaches to meet these numbers. A very important one is the electrification of airplanes with electrochemical power sources (batteries, fuel cells).

It is, however, to mention that the production of electrochemical power sources is environmentally harmful. In a comparison of greenhouse gas emissions summarized via the total flown milages of the aircrafts the electrical airplanes stating with an environmental handicap (see Figure 9). This handicap will be neutralized only after a certain time, which depends on the sources of electricity. If there is a higher renewable part in the electricity mix then the neutralization time is shorter.

For the time being the flying range of electrical aircraft is limited by the specific energy of batteries and fuel cells. For today batteries with a specific energy in the region of about 200 Wh/kg, and planes with an L/D relation of 10 and a $m_{batt}/m_{airplane}$: relation of 0.4 the flight range amounted to ≈ 250 km. By changing the aircraft design by larger wingspans, which leads to an L/D relation of 20, the range is increasing to 500 km.

This relatively low specific energy of the battery limits flights with passenger aircrafts over long distances. Even if the specific battery energy is increased by a factor of 2…2.5, as foreseen at ≥ 2030, long-range flights will be not possible with medium size airplanes (≥ 100 passengers). Besides the range also the power of the electric motor (plus turbines in case of hybrids) is an important parameter, which is related to the weight of the airplane.

But for flights with the shorter region and smaller planes and/or low payload the batteries specific energy are sufficient. Vertical take-off and landing (VTOL) taxis, general aviation & recreational aircrafts, and regional & business aircrafts, and drones fit the general limitations in weight and range. So, with a market introduction of these applications can be expected by in this decade.

Larger ranges with > 100 passenger aircrafts have only a change as battery/turbine hybrid, i.e. with the help of a conventional turbine.

Based on the power of the electric motor/ turbine the following is expected[xix]

- *Power Range 100 kW, market introduction by 2025* UAVs, helicopters with hybrid turbo shaft engine
- *Power Range 500 kW, market introduction by 2025+*VTOL aircraft, commuters with 10 passengers
- *Power Range 1 MW, market introduction by 2030+*Hybrid electric propulsion (turbofan electrically assisted) for short/medium range regional aircraft for 40 passengers.
- *Power Range 10 MW, market introduction beyond 2040…2050*Distributed propulsion on aircraft with 100 Pax

General, also fuel cells are driven with hydrogen are a solution for larger airplanes and larger ranges, because the stored hydrogen volume determines their range, and an increase of the stored hydrogen volume leads only to a relatively low increase of the mass. First developments of FC aircrafts exist but in general, the activities are on a low level. A commercial introduction of FC airplanes will be not before 2035.

A business case of electrical airplanes will be only developed if the costs and the environmental advantages are > 20 % of the conventional planes. Government restrictions as CO_2 emission limits as for cars could be political support the development of electrical airplanes.

References

[1] I. C. Inc, "Estimating Air Travel Demand Elasticities. Final report," 2007.

[2] 1astudybyTransport & Environment, "Roadmap to decarbonising uropeaEn aviation," 2018.

[3] Transport & Environment (2018), " Roadmap to decarbonising European aviation, Retrieved from https://www.transportenvironment.org/publications/roadmap-decarbonising-european-aviation," 2018.

[4] UBA, [Online]. Available: https://www.umweltbundesamt.de/en/press/pressinformation/high-costs-when-environmental-protection-is.

[5] EASA, 2020. [Online]. Available: https://www.easa.europa.eu/eaer/topics/market-based-measures.

[6] B. Görlach, "What constitutes an optimal climate policy mix? Defining the concept of optimality, including political and legal framework conditions, CECILIA2050 Deliverable 1.1,".

[7] S. S. B. P. v. B. Y. D. S. F. A. G. V. v. G. K. G. H. G. D. d. J. E. K. W. P. M. S. E. d. V. T. W. K. Alberici, "Subsidies and costs of EU energy – Final report," Ecofys, 2014.

[8] M. C. a. S. Stagl, Ecological Economics. An Introduction., Cambridge University Press., 2009.

[9] [Online]. Available: https://ec.europa.eu/clima/policies/transport/aviation_en.

[10] ATAG, "How a global carbon offsetting scheme for aviation would work," 2016. [Online]. Available: https://aviationbenefits.org/media/136900/atag_carbon_offset_infographic.pdf .

[11] ICAO, "Report on the Assessment of Market-based Measures," Retrieved from: https://www.icao.int/Meetings/GLADs-2015/Documents/10018_cons_en.pdf , 2013.

[12] ATAG , "Brief: Global Offsetting Scheme Cost, Retrieved from: https://www.verifavia.com/bases/ressource_pdf/370/FACT-SHEET-GMBMcosts-Sept2016-1-.pdf," 2016.

[13] ATAG , "Brief: Global Offsetting Scheme Cost," Retrieved from: https://www.verifavia.com/bases/ressource_pdf/370/FACT-SHEET-GMBMcosts-Sept2016-1-.pdf, 2016.

[14] A. E. T. S. &. J. Å. Jörgen Larsson, " International and national climate policies for aviation: a review," *Climate Policy*, vol. 19, no. 6, pp. 787-799, 2019.

[15] A. L. M. M. D. S. &. M. T. Mu Huang, "The Potential Financial Impact of CORSIA on Airline Companies & Carbon Markets," 2019.

[16] T. &. E. (2019), " Ryanair joins the club of Europe's top 10 carbon polluters,," [Online]. Available: https://www.transportenvironment.org/press/ryanair-joins-club-europe%E2%80%99s-top-10-carbon-polluters.

[17] [Online]. Available: http://www.consilium.europa.eu/en/meetings/european-council/2014/10/23-24/.

[18] "Directive (EU) 2018/410 of the European Parliament and of the Council of 14 March 2018 amending Directive 2003/87/EC to enhance cost-effective emission reductions and low-carbon investments, and Decision (EU) 2015/1814," 2003.

[19] "Report on the functioning of the European carbon market, COM(2017) 693 fina".

[20] [Online]. Available: https://ec.europa.eu/clima/policies/ets/auctioning_en.

[21] "Greenhouse gas emission allowance trading system.," [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=LEGISSUM%3Al28012.

[22] [Online]. Available: https://www.ecologique-solidaire.gouv.fr/en/understand-and-implement-eu-emissions-trading-scheme.

[23] "International Carbon Action Partnership ETS Detailed Information.," [Online]. Available: https://ec.europa.eu/clima/policies/ets/allowances/aviation_en.

[24] INTERNATIONAL MONETARY FUND. , "Market-Based Instruments for International Aviation and Shipping as a Source of Climate Finance," 2011.

[25] AGF, "Report of the Secretary-General's High-level Advisory Group on Climate Change Financing.," New York: United Nations. , 2010.

[26] AGF, "Work Stream 2: Paper on Potential Revenues from International Maritime and Aviation Sector Policy Measures. Addendum No. 2 to Report of the Secretary-General's High-level Advisory Group on Climate Change Financing," New York: United Nations, 2010.

[27] R. G. &. E. B. Hosoda, "Environmental impact of aircraft emissions and aviation fuel tax in Japan," 2016.

[28] European Commission, "European Commission (2003), Council Directive 2003/96/EC of 27 October 2003 restructuring the Community framework for the taxation of energy products and electricity," 2003.

[29] E. M. &. A. M. Y. Kelly de Bruin, "The Impacts of Removing Fossil Fuel Subsidies and Increasing Carbon Tax in Ireland, The Economic and Social Research Institute, RS98, DOI: https://doi.org/10.26504/rs98," 2019.

[30] THE INTERNATIONAL CIVIL AVIATION ORGANIZATION., ""Criterios de la OACI sobre impuestos en la esfera del transporte aéreo internacional" (online: https://www.icao.int/publications/Documents/8632_cons_es.pdf)," 2000.

[31] A. KRENEK and M. SCHRATZENSTALLER, "Sustainability-oriented EU Taxes: The Example of a European Carbon-based Flight Ticket Tax" (online: https://ec.europa.eu/budget/mff/Library/hlgor/selected-readings/41-Carbon-basedFlightTicketTax-Schratzenstalle.," 2016.

[32] UNITED NATIONS HIGH COMISSIONER FOR REFUGEES. , "¿Cuál es el objetivo de los impuestos pigovianos? (online: https://eacnur.org/blog/objetivo-los-impuestos-pigouvianos/)," 2017.

[33] B. JONES, M. KEEN and J. STRAND, " "Fiscal Implications of Climate Change" (online: http://documents.worldbank.org/curated/en/778871468332985467/pdf/WPS5956.pdf)," 2012.

[34] P. FORSYTH, "Aviation Taxes – Impacts, Costs and Benefits" (online: http://greenfiscalpolicy.org/wp-content/uploads/2019/06/1560238770_AviationTaxesImpactsCostsandBenefits.pdf)," 2019.

[35] B. JONES, M. KEEN and J. STRAND, "Fiscal Implications of Climate Change" (online: http://documents.worldbank.org/curated/en/778871468332985467/pdf/WPS5956.pdf)," 2012.

[36] R. G. &. E. B. Hosoda, Environmental impact of aircraft emissions and aviation fuel tax in Japan, 2016.

[37] Ministry of the Environment, "Greening of Whole Tax System and Carbon Tax in Japan: Environment-related Tax in Japan, https://www.env.go.jp/en/policy/tax/20170130_greening.pdf," 2017.

[38] World Bank Group, "State and Trends of Carbon Pricing 2019, Retrieved from http://documents.worldbank.org/curated/en/191801559846379845/pdf/State-and-Trends-of-Carbon-Pricing-2019.pdf," 2019.

[39] I. P. &. P. Psaraki-Kalouptsidi, " Econometric supply-and-demand models to analyse carbon pricing policies," *International Journal of Transportation Science and Technology*, vol. 7, no. 4, pp. 274-282, 2018.

[40] S. GÖSSLING, F. FICHERT and P. FORSYTH, "Subsidies in Aviation. online: https://www.mdpi.com/journal/sustainability," *Sustainability*, 2017.

[41] Transport and Environment (2017), " Decarbonisation of aviation: why EU and ICAO action is needed," [Online]. Available: https://www.transportenvironment.org/publications/decarbonisation-aviation-why-eu-and-icao-action-needed.

[42] CAN & ICSA (2018), "Contribution of the Global Aviation Sector to Achieving Paris Agreement Climate Objectives," [Online]. Available: https://icsa-aviation.org/wp-content/uploads/2018/04/CAN-ICSA-Aviation-TD-submission.pdf.

[43] F. F. P. F. &. H.-M. N. Stefan Gössling, "Subsidies in Aviation," *Sustainability*, vol. 9, no. 8, p. 1295, 2017.

[44] European Commission, "The European Green Deal, Retrieved from https://ec.europa.eu/info/sites/info/files/european-green-deal-communication_en.pdf," 2019.

[45] European Commission (2008), "Regulation (EC) No 1008/2008 of the European Parliament and of the Council of 24 September 2008 on common rules for the operation of air services in the Community, Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/," 2008.

[46] IEA, "Are aviation biofuels ready for take-off?, Retrieved from https://www.iea.org/commentaries/are-aviation-biofuels-ready-for-take-off".

[47] "SUSTAINABLE AVIATION FUELS ROAD-MAP: Fueling the future of UK aviation," 2020. [Online]. Available: https://www.sustainableaviation.co.uk/wp-content/uploads/2020/02/SustainableAviation_FuelReport_20200231.pdf.

[48] ICAO, "ICAO'S CO2 STANDARD FOR NEW AIRCRAFT, ICAO, 2017," 2017.

[49] ICAO, "Committee On Aviation Environmental Protection (CAEP) Tenth Meeting Montréal, Canada, 1 to 12 February 2016. Agenda Item 5: CO2 Standard development/ REPORT OF THE WG3 CO2 TASK GROUP (Presented by WG3 CO2 Task Group)," 2016.

[50] ICAO, "Convention on International Civil Aviation - Doc 7300, Annex 16, Volume IV, ICAO, 2018.," 2018.

[51] "5. Assembly — 39th Session Executive Committee. Agenda Item 22: Environmental Protection – International Aviation and Climate Change – Policy, Standardization and Implementation Support/ ICAO'S CO2 STANDARD FOR NEW AIRCRAFT," [Online]. Available: https://www.transportenvironment.org/sites/te/files/publications/wp_207_en%20ICSA%20CO2%20Standard.pdf.

[52] "Q&A: the ICAO CO2 standard for aircraft. Issued by Air Transport Action Group February 2016.," [Online]. Available: www.enviro.aero.

[53] B. Silva, " Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) and Sustainable Aviation Fuels," in *Sustainable aviation fuels at ISCC meetings and conferences (2019)*, 2019.

[54] S. Csonka, "CAAFI – CORE-JetFuel Cooperation Workshop," 2016. [Online]. Available: Available at: www.core-jetfuel.eu.

[55] V. Raznoschikov, "Analysis of the efficiency of transport aircraft on alternative fuels.," *Aviation engineering and equipment.*, no. 1, pp. 26-30, 2012.

[56] N. F. E.P. Fedorov, " Development of synthetic jet fuel from bio-raw materials," *Ram jets and Chemmotology. .Proceedings of CIAM. - 2010. - No. 1340. - P. 107-116.].*, no. 1340, pp. 107-116, 2010.

[57] "Boeing 777X.," [Online]. Available: http://www.boeing.com/commercial/777x/by-design/#/ge9x-technology. . [Accessed 03 03 2020].

[58] "Boeing 787 Dreamliner," [Online]. Available: http://www.boeing.com/commercial/787/#/design-highlights/.. [Accessed 03 03 2020].

[59] " https://www.airbus.com/aircraft/passenger-aircraft/a350xwb-family/a350-1000.html.," [Online]. Available: Airbus A350 XWB . [Accessed 03 03 2020].

[60] "Sonic boom: do airports need to prepare for the supersonic revolution?," [Online]. Available: https://www.airport-technology.com/features/supersonic-passenger-aircraft/. . [Accessed 03 03 2020].

[61] "EU, 2018, EU climate and energy framework for 2020, 2030 and 2050.," 2018.

[62] EASA, "European Aviation Environmental Report 2019.," 2019.

[63] "IATA Technology Roadmap 2013. 2013. Available online: http://www.iata.org/whatwedo/environment/Documents/ technology-roadmap-2013.pdf (accessed on November 8, 2019)".

[64] "IATA. Aircraft Technology Roadmap to 2050. [Electronic source]. - Access mode: https://www.iata.org/contentassets/8d19e716636a47c184e7221c77563c93/ technology20roadmap20to20205020no20foreword.pdf. - (access 16.12.2019).]".

[65] "Bezos-O'Connor, G .; Mangelsdorf, M .; Nickol, C .; Maliska, H .; Washburn, A .; Wahls, R. Fuel Efficiencies through Airframe Improvements. In Proceedings of the 3rd AIAA Atmospheric Space Environments Conference, Honolulu, HI, USA, 2730 June 2".

[66] "Kimmel, W. Systems Analysis Approach for the NASA Environmentally Responsible Aviation Project. In Proceedings of the 3rd AIAA Atmospheric Space Environments Conference, Honolulu, HI, USA, 2730 June 2011; American Institute of Aeronautics and Astronautics".

[67] "Graham, W.R.; Hall, C.A.; Vera Morales, M. The potential of future aircraft technology for noise and pollutant emissions reduction. Air Transp. Environ. 2014, 34, 3651".

[68] *Palkin V. Concepts of Aero Engines for Future Civil Aircraft. Aero Engine Simulation and Test Technology in China and Russia. The 2nd Aero Engine Technology Development Forum, 5 November 2018. Zhuhai, P.R. China.*

[69] *Babkin V., Palkin V. R&D Concepts of Future Wide Body Aircraft Engine. Aero Engine China 2016 – Next Generation Aero Engine To Take Off. October 25–26, 2016. Shanghai, P.R. China.*

[70] *Babkin V.I. Scientific foundations of aircraft engine manufacturing. Engine No.2 (92), 2014. P. 12-15.*

[71] *Del Rosario R. A Future with Hybrid Electric Propulsion Systems: A NASA Perspective. Turbine Engine Technology Symposium, Strategic Visions Workshop, Dayton, OH, September 11, 2014. NASA.*

[72] *Jankovsky A. NASA. Hybrid Gas-Electric Subproject Overview. Interchange with Meggitt Aircraft Braking Systems, Aug 31, 2016. NASA, 2016.*

[73] CE Delft, "Taxes in the Field of Aviation and their impact. Final Report," European Commission, 2019.

[74] European Commission, "Energy Tax Directive 2003/96/EC (Article 14(1)(b))26," 2003.

[75] European Commission, "EC directive on the common system of Value Added Tax (2006/112/EC)23," 2006.

[76] S. B. Stephen Devlinand, Managing Aviation Passenger Demand With A Frequent Flyer Levy., Managing Aviation Passenger Demand With A Frequent Flyer Levy. Stephen Devlinand Sandra Bernick New Economics Foundation © 2015 The New Economics Foundation, 2015.

[77] Air Transport Department, Cranfield University European Commission contract TREN/05/MD/S07.52077, "Fuel and air transport.".

[78] European Commission, "VAT Directive (2006/112/EC)," 2006.

[79] C. f. E. a. S. Research, "Study on the economic effects of the current VAT rules for passenger transport. Final Report TAXUD/2012/DE/334," 2014.

[80] J. B. S. a. J. W. S. Charles L. Ballard, "General Equilibrium Computations of the Marginal Welfare Costs of Taxes in the United States," *The American Economic Review*, vol. 75, no. 1, pp. pp. 128-138, 1985.

[81] M. S. Andersen, S. Speck, P. Ekins, S. Scott and F. Gerald, "COMETR: Competitiveness effects of environmental tax reforms - policy brief. EU FP6 report, 2007.," 2007.

[82] T. &. G. J. &. V. L. &. T. R. Conefrey, "The Impact of a Carbon Tax on Economic Growth and Carbon Dioxide Emissions in Ireland.," *Journal of Environmental Planning and Management.* , 2008.

[83] H. G. D. B. r. ,. J. C. C. b. a. R. D. M. Roberton C. Williams III, "The Initial Incidence of a Carbon Tax across Income Groups," RFF's Center for Climate and Electricity Policy, 2014.

[84] P. N. E. P. R. Patuelli, "Environmental tax reform and the double dividend: A meta-analytical performance assessment," *Ecological Economics*, vol. 55, no. 4, pp. pp. 564-583, 2005.

[85] INTERNATIONAL MONETARY FUND. , "Market-Based Instruments for International Aviation and Shipping as a Source of Climate Finance .".

[86] Statista, [Online]. Available: https://www.statista.com/statistics/591285/aviation-industry-fuel-cost/.

[87] IATA, jet fuel price monitor, [Online]. Available: https://www.iata.org/en/publications/economics/fuel-monitor/.

[88] [Online]. Available: https://www.flightdeckfriend.com/2020/05/05/how-much-does-jet-fuel-cost/.

[89] statista, [Online]. Available: https://www.statista.com/statistics/655057/fuel-consumption-of-airlines-worldwide/.

[90] International Monetary Fund, "Promising Domestic Fiscal Instruments for Climate Finance.," Washington, DC., 2011.

[91] J. A. R. Morris, " A Framework for Estimating the Marginal Costs of Environmental Abatement for the Aviation Sector.," Omega and Cranfield University.

[92] K. A. a. K. V. D. Small, "Fuel Efficiency and Motor Vehicle Travel: The Declining Rebound Effect," *Energy Journal*, vol. 28, p. 25–52., 2006.

[93] T. I. H. L. G. (IHLG), "Aviation Benefits Report 2019. The Industry High-Level Group (IHLG). ICAO, ACI, CANSO, IATA, ICCAIA, ATAG and ABBB.," 2019.

[94] Airbus, "Airbus Global Market Forecast / Cities, Airlines & Aircraft, 2019–2038".

[95] IATA, "IATA Updates COVID-19 Financial Impacts -Relief Measures Needed-IATA Press Release," [Online]. Available: https://www.iata.org/en/pressroom/pr/2020-03-05-01.

[96] [Online]. Available: https://en.wikipedia.org/wiki/ Impact_of_the_COVID-19_pandemic_on_aviation.

[97] 2. Doyle A., "Coronavirus: plane-free skies spur research into warming impact of aviation," [Online]. Available: https://www.climatechangenews.com/2020/04/09/coronavirus-plane-free-skies-spur-research-warming-impact-aviation/.

[98] ICAO. [Online]. Available: https://www.icao.int/sustainability/Pages/Economic-Impacts-of-COVID-19.aspx.

[99] IMF. [Online]. Available: https://www.imf.org/en/Publications/WEO/Issues/2020/04/14/weo-april-2020.

[100] I. .. CORSIA-and-Covid-19. [Online]. Available: https://www.icao.int/environmental-protection/CORSIA/Pages/CORSIA-and-Covid-19.aspx.

[101] IATA-OACI, "IATA starts discussions with ICAO on changing the CORSIA baseline to exclude 2020 emissions," [Online]. Available: https://www.greenaironline.com/news.php?viewStory=2686 .

[102] ICAO, "ICAO Resolution A40-19, 2019. Consolidated statement of continuing ICAO policies and practices related to environmental protection – Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)," 2019.

[103] "Impact of COVID-19 onCORSIA baseline calculation," [Online]. Available: https://www.greenaironline.com/photos/File339.pdf.

[104] "ICAO Council agrees CORSIA baseline change to protect Covid-stricken airline sector from higher carbon costs," [Online]. Available: https://www.greenaironline.com/ news.php?viewStory=2715.

[105] I. Wegener Center, "2019 State of the EU ETS Report ERCST.," [Online]. Available: https://ercst.org/wp-content/uploads/2019/05/2019-State-of-the-EU-ETS-Report.pdf.

[106] L. Z. Milan Elkerbout, " Can the EU ETS weather the impact of Covid-19? No 2020-14," [Online]. Available: www.ceps.eu .

[107] M. G. K. 2. Ovaere, "The Heterogeneous Value of Solar and Wind Energy," 2019. [Online]. Available: https://sites.google.com/view/marten-ovaere/research.

[108] "Statista, 2020. Year-on-year change in daily airport passenger traffic in Europe from February 24 to March 22, 2020.," [Online]. Available: https://www.statista.com/statistics/1107029, Last accessed: April 14, 2020..

[109] R. J. R. K. H. E. R. Reyer Gerlagh, "COVID 19 Tests the Market Stability Reserve.," *Environmental and Resource Economics. Springer.* ., 2020.

[110] M. O. Kenneth Bruninx, " Estimating the Impact of COVID-19 on Emissions and Emission Allowance Prices Under EU ETS BY.," *International Association for Energy Economics. IAEE Energy Forum / Covid-19,* 2020.

[111] G. W. M. Perino, " EU-ETS Phase IV: allowance prices, design choices and the market stability reserve.," *Climate Policy*, vol. 17, no. 7, p. 936–946. , 2017.

[112] K. O. M. G. K. D. E. Bruninx, " The unintended consequences of the EU ets cancellation policy. KU Leuven Energy Institute Working Paper EN2019-11.," [Online]. Available: www.mech.kuleuven.be/en/tme/research/energy-systems-integra.

[113] ICAO, "Carbon offsetting and reduction scheme for international aviation (CORSIA) implementation plan. ICAO, 2019," 2019.

[114] ICAO, "2019 Environmental Report - Aviation and Environment, ICAO, 2019," 2019.

[115] ICAO, "Resolutions of the 37th Session of the ICAO Assembly (2010)," 2010.

[116] ICAO, "Resolutions of the 38th Session of the ICAO Assembly (2013)," 2013.

[117] ICAO, "Resolutions of the 39th Session of the ICAO Assembly (2016)," 2016.

[118] ICAO, "Resolutions of the 40th Session of the ICAO Assembly (2019)," 2019.

[119] ICAO, "Environmental Technical Manual (Doc 9501), Volume IV, ICAO, 2018.," 2018.

[120] ICAO, "10. COMMITTEE ON AVIATION ENVIRONMENTAL PROTECTION (CAEP) STEERING GROUP MEETING Montréal, Canada, 11 to 15 September 2017. Agenda Item 3: Global Market Based Measure Technical (GMTF) ICAO/ CORSIA PACKAGE (Presented by GMTF co-Rapporteurs), ICAO, 2019.," 2019.

[121] ICAO, "CORSIA Emissions Unit Eligibility Criteria. ICAO, 2019," 2019.

[122] "3. Directive 2008/101/EC of the European Parliament and of the Council of 19 November 2008 amending Directive 2003/87/EC so as to include aviation activities in the scheme for greenhouse gas emission allowance trading within the Community," 2003.

[123] [Online]. Available: http://ec.europa.eu/clima/policies/transport/aviation/documentation_en.htm.

[124] "Decision No. 377/2013/EU derogating temporarily from Directive 2003/87/EC establishing a scheme for greenhouse gas emission allowance trading within the Community," 2003.

[125] "6. Regulation (EU) 2017/2392 of the European Parliament and of the Council of 13 December 2017 amending Directive 2003/87/EC to continue current limitations of scope for aviation activities and to prepare to implement a global market-based measure from 20," 2003.

[126] "Report on the functioning of the European carbon market, COM(2017) 693 final".

[127] "Regulation (EU) No 601/2012 of the European Parliament and of the Council of 21 June 2012 on the monitoring and reporting of greenhouse gas emissions under Directive 2003/87/EC of the European Parliament and the Council," 2012.

[128] "Understanding the indirect land-use change analysis for Corsia," [Online]. Available: https://www.transportenvironment.org/publications/understanding-indirect-land-use-change-analysis-corsia.

[129] "ICAO Council adopts new CO2 emissions standard for aircraft. ICAO News release," [Online]. Available: https://www.icao.int/Newsroom/NewsDoc2017/COM.05.17.EN.pdf..

[130] ICAO, "2016 Environmental Report - Aviation And Environment/ the CAEP/10 recommendation on a new ICAO AEROPLANE CO2 EMISSIONS STANDARD b. ICAO, 2016," 2016.

[131] "IATA Sustainable Aviation Fuels Fact Sheet 6".

[132] "Sustainable Aviation Fuels Guide, ICAO-UNDP-GEF assistance project, 2018".

[133] [Online]. Available: http://www.bio4a.eu/.

[134] [Online]. Available: http://www.besustainablemagazine.com/cms2/flexjet-project-converts-organic-waste-into-sustainable-aviation-fuel/.

[135] "Sustainable Aviation Fuels Guide, ICAO-UNDP-GEF assistance project, 2018".

[136] "AirBP," [Online]. Available: https://www.bp.com/en/global/air-bp/news-and-views/sterling-card-newsletters/what-is-sustainable-aviation-fuel-saf-and-why-is-it-important.html.

[137] "ASTM (2016) "ASTM D7566-16, Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons"," [Online]. Available: http://www.astm.org/Standards/D7566.htm.

[138] A. O. L. L. M. Prussia, "Analysis of current aviation biofuel technical production potential in EU28," *Biomass and Bioenergy*, vol. 130, 2019.

[139] [Online]. Available: https://www.icao.int/environmental-protection/GFAAF/Pages/default.aspx.

[140] J. Lane, "Biofuels Digest," 2012.

[141] X. K. K. C.-J. S. T. E. a. D. G. Hui, "Experimental studies on the combustion characteristics of alternative jet fuels.," *Fuel*, vol. 98, pp. 176-182; , 2012.

[142] T. F. J. D. K. T. M. H. G. C. G. F. L. G. P. Z. Y. A. D. M. L. C. L. J. A. J. M. G. A. K. R. R. J. R. H. M. J. M. a. A. G. B. Rahmes, "Sustainable Bio-derived Synthetic Paraffinic Kerosene (Bio-SPK) Jet Fuel Flight and Engine Tests Program Results," in *9th AIAA Aviation Technology, Integration and Operations Conference, Hilton Head, SC*, 2009.

[143] ITAKA project (2016), "Press release. ITAKA provides sustainable fuel for worldwide's first biojet supply via hydrant system at Oslo Airport".," [Online]. Available: http://www.itaka-project.eu/Shared%20Documents/20160122_ITAKA_airportusage_start.pdf.

[144] G. (2016), " "United begins regular use of commercial-scale volumes of AltAir's renewable jet biofuel on flights from LAX".," [Online]. Available: http://www.greenaironline.com/news.php?viewStory=2208.

[145] S. C. (2016), " "CAAFI – CORE-JetFuel Cooperation Workshop".," [Online]. Available: www.core-jetfuel.eu.

[146] A. (2016), "ASTM D7566-16, Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons".," [Online]. Available: http://www.astm.org/Standards/D7566.htm.

[147] I. (2013), "ICAO environmental report 2013. Aviation and climate change".," [Online]. Available: http://cfapp.icao.int/Environmental-Report-2013/files/assets/common/downloads/ICAO_2013_Environmental_Report.pdf.

[148] ". m. f. b. f. F. report"., " "Accounting methods for biojet fuel. Final report".," [Online]. Available: http://www.ecofys.com/files/files/ecofys-2015-accounting-methods-for-biojet-fuel.pdf.

[149] I. p. (2016), " "Press release. ITAKA provides sustainable fuel for worldwide's first biojet supply via hydrant system at Oslo Airport".," [Online]. Available: http://www.itaka-project.eu/Shared%20Documents/20160122_ITAKA_airportusage_start.pdf.

[150] E. B. F. (2016), " "2 million tons per year: A performing biofuels supply chain for EU aviation".," [Online]. Available: https://ec.europa.eu/energy/sites/ener/files/20130911_a_performing_biofuels_supply_chain.pdf.

[151] C. A. Moses, "Evaluation of Synthesized Aromatics Co-Produced with Iso-Paraffinic Kerosene for the Production of Semi-Synthetic Jet Fuel," New Braunfels, 2013.

[152] ASTM, "Alcohol To Jet Synthesized Paraffinic Kerosene (AT-SPK) Task Force Report – D02.J6"," in *ASTM D02 Committee week – San Diego*, 2014.

[153] E. N. Coppola, "Evaluation of Hydro processed Esters and Fatty Acids (HEFA) Synthetic Kerosene containing Aromatics (SKA)," *Renewable Jet Fuel*, 2014.

[154] "EU Parliament votes for 55% emissions cuts by 2030.," [Online]. Available: https://www.euractiv.com/section/energy-environment/news/eu-parliament-votes-for-55-emissions-cuts-by-2030/. [Accessed 06 02 2020].

[155] [. E. T. S. (. E. .. [. s. –. A. m. h. -. (. 06.03.2020)]., "EU Emissions Trading System (EU ETS)," [Online]. Available: https://ec.europa.eu/clima/policies/ets_en.. [Accessed 03 06 2020].

[156] "IATA. Aircraft Technology Roadmap to 2050.," [Online]. Available: https://www.iata.org/contentassets/8d19e716636a47c184e7221c77563c93/technology20roadmap20to20205020no20foreword.pdf. . [Accessed 16 12 2019].

[157] "IATA. Aircraft Technology Roadmap to 2050.," [Online]. Available: https://www.iata.org/contentassets/8d19e716636a47c184e7221c77563c93/technology20roadmap20to20205020no20foreword.pdf.. [Accessed 16 12 2019].

[158] "Flightpath 2050 Europe's Vision for Aviation.," [Online]. Available: https://ec.europa.eu/transport/sites/transport/files/modes/air/doc/flightpath2050.pdf. - (access 06.02.2020).. [Accessed 06 02 2020].

[159] N. R. U. H. S. o. E. L.M. Hochberg. Moscow: Ministry of Education and Science of the Russian Federation, "Forecast of scientific and technological development of Russia: 2030," 2014.

[160] A. V. E. I. F. K. V. V. Loginov, "Methodological foundations for the formation of the parametric concept of the power plant of a promising combat trainer: monograph," 2016.

[161] "Flightpath 2050 Europe's Vision for Aviation. [Electronic source]. – Access mode: https://ec.europa.eu/transport/sites/transport/files/modes/air/doc/flightpath2050.pdf. - (access 06.02.2020).".

[162] "Liu, Y. Exploring Vehicle Level Benefits of Revolutionary Technology Progress via Aircraft Design and Optimization / Y. Liu, A. Elham, P. Horst, M. Hepperle // Energies, 2018, 11, 166; DOI:10.3390/en11010166.].".

[163] "Kimmel, W. Systems Analysis Approach for the NASA Environmentally Responsible Aviation Project. In Proceedings of the 3rd AIAA Atmospheric Space Environments Conference, Honolulu, HI, USA, 2730 June 2011; American Institute of Aeronautics and Astronautics".

[164] *Mashinostroenie. Entsiklopediia [Engineering. Encyclopedia]. Vol. IV-21. Aviatsionnye dvigateli [Aircraft engines]. Book 3. Edited by V.A. Skibin, Iu.M. Temis, V.A. Sosunov. - Moscow: Mashinostroenie, 2010. - 720p.*.

[165] *Babkin V., Palkin V. R&D Concepts of Future Wide Body Aircraft Engine. Aero Engine China 2016 – Next Generation Aero Engine To Take Off. October 25–26, 2016. Shanghai, P.R., China.*

[166] D. Kellari, "What's next for the airliner? Historical Analysis and Future Predictions of Aircraft Architecture and Performance.," Massachusetts Institute of Technology. , 2016.

[167] Are major efficiency gains for the turbofan still in reach?, "Are major efficiency gains for the turbofan still in reach?," [Online]. Available: https://www.wearefinn.com/topics/posts/are-major-efficiency-gains-for-the-turbofan- still-in-reach. [Accessed 06.12.2019].

[168] The ultimate technologies. , "The ultimate technologies.," [Online]. Available: http://www.ultimate.aero/page/en/ultimate-technologies.php. [Accessed 08.02.2020].

[169] L. Mo, "Conceptual Design Study for In-Flight Refueling of Passenger Aircraft. PhD. Thesis," Delft University of Technology, The Netherlands, 2017.

[170] V. K. K. L. J. R. Zheng Min, " Aircraft morphing wing concepts with radical geometry change," *The IES Journal Part A: Civil & Structural Engineering.* , vol. 3, no. 3, pp. 188-195, 2010.

[171] W. J., " Introducing the Airplane of the Future," *Popular Mechanics.* , no. 8, 2006.

[172] S. B. O. A. R. M. F. M. I. I. D. J. Barbarino, "A Review of Morphing Aircraft. Journal of Intelligent Material Systems and Structures," *Journal of Intelligent Material Systems and Structures*, vol. 22, no. 9, p. 823–877, 2011.

[173] A. D. I. L. L. &. P. R. Concilio, Morphing Wing Technologies. Large Commercial Aircraft and Civil Helicopters. 1st Edition, Butterworth-Heinemann, 2017.

[174] E. &. M. A. Benini, "Aerodynamic Optimization of a Morphing Leading Edge Airfoil with a Constant Arc Length Parameterization.," *Journal of Aerospace Engineering.* , vol. 2, no. 31, 2017.

[175] L. Campos, "On Physical Aeroacoustics with Some Implications for Low-Noise Aircraft Design and Airport Operations," *Aerospace.* , vol. 2, pp. 17-90, 2015.

[176] Technological roadmaps. , "Technological roadmaps.," [Online]. Available: https://sunjet-project.eu/content/technological-roadmaps. - (доступ 05.02.2020);. [Accessed 05.02.2020].

[177] FLYING IN 2050, "FLYING IN 2050:," [Online]. Available: http:// www.academie-air-espace.com/upload/doc/ressources/CP-2050-VOLUME2.pdf. . [Accessed 12.11.2019].

[178] O. A. J. B. R. B. L. Wiart, "Aeropropulsive performance analysis of the nova configurations," in *30th congress ICA-*, 2016.

[179] C. G. G. R. V. C. a. V. P. Atinault O., "Development of NOVA Aircraft Configurations for Large Engine Integration Studies," in *33rd AIAA Applied Aerodynamics Conference*, Dallas, TX., 2015.

[180] "Numerical and Experimental Aerodynamic Investigations of Boundary Layer Ingestion for Improving Propulsion Efficiency of Future Air Transport," in *31st AIAA Applied Aerodynamics Conference*, San Diego, CA., 2013.

[181] European Aviation Environmental Report 2019. , "EU, 2018, EU climate and energy framework for 2020, 2030 and 2050. –," 2018.

[182] R. F. B. W. a. D. o. BLI, "Reduce Fuel Burn With a Dose of BLI," 2017. [Online]. Available: https://www.nasa.gov/aero/reduce-fuel- burn-with-a-dose-of-bli (access 06.02.2019) . [Accessed 06.02.2019].

[183] "Advanced hybrid engines for aircraft development," [Online]. Available: https://www.ttalents.com/hybrid-engines-for-aircraft//. [Accessed 06.02.2019].

[184] A. K. P. Kumar, "Blended Wing Body Propulsion System Design.," / *International Journal of Aviation, Aeronautics, and Aerospace,* vol. 4, no. 4, pp. 6-43, 2017.

[185] G. Warwick, "Lockheed, NASA Advanced Airlifter Tests Validate Fuel Savings.," *Aviation Week and Space Technology.,* vol. 177, no. 348.31.2015., 2015.

[186] E. O. R. T. C.L. Burley, "Hybrid wing body aircraft system noise assessment with propulsion airframe aeroacoustic experiments," *International Journal of Aeroacoustics.* , vol. 11, no. 3,4, 2017.

[187] " Air Traffic" National Oceanic and Atmospheric Administration.," [Online]. Available: https://sos.noaa.gov/Datasets/dataset.php?id=44]. [Accessed 3.2.2017].

[188] R. H. T. Y. Guo, "System noise assessment of hybrid wing body aircraft with open rotor propulsion.," *Journal of Aircraft. Vol. 52. 2015,* vol. 52, 2015.

[189] "Airborne giants: what will an airplane look like in the future?," [Online]. Available: https://www.voestalpine.com/blog/en/mobility/aerospace/airborne-giants-what-will- an-airplane-look-like-in-the-future/. [Accessed 06.08.2017].

[190] "Visionary List Of 6 Future Aviation Changes Pose Regulatory Challenges," [Online]. Available: http://jdasolutions.aero/blog/visionary-list-6-future-aviation-changes-pose-regulatory-challenges/. [Accessed 06.08.2017].

[191] "Flying trains could be coming your way.," [Online]. Available: https://techcentral.co.za/flying-trains-could-be-coming-your- way/82348/. [Accessed 06.09.2019].

[192] "Link&Fly - Air transport of the future.," [Online]. Available: https://www.akka-technologies.com/case-study/linkfly-air-transport-of-the-future/. [Accessed 08.02.2020].

[193] "[Radical New Aircraft 'Flying-V'. What Is It?," [Online]. Available: https://aviationvoice.com/radical-new-aircraft-flying- v-what-is- it-201906071621. [Accessed 16.12.2019].

[194] " [Miley, J. MIT and NASA unveil radical new airplane wing design.," [Online]. Available: https://interestingengineering.com/mit-and-nasa-unveil- radical-new-airplane-wing-design. . [Accessed 02.04.2019].

[195] D. L. Chandler., "MIT and NASA engineers demonstrate a new kind of airplane wing.," [Online]. Available: http://news.mit.edu/2019/engineers-demonstrate-lighter-flexible-airplane-wing-0401.. [Accessed 31.03.2019].

[196] D. W. C. O. B. F. C. E. G. [. o. Nicholas B Cramer, "Elastic shape morphing of ultralight structures by programmable assembly.," *Smart Materials and Structures, Volume 28, Number 5,* vol. 28, no. 5.

[197] O. Viñals., "Progress Eagle" Quantum Airplane," [Online]. Available: https://www.behance.net/gallery/20804291/AWWAQG-Progress-Eagle-Quantum- Airplane.. [Accessed 06.02.2020].

[198] "Flexjet order dor 20 Supersonic Jets Boosts Aerion.," *Aviation Week,* 17.11.2015.].

[199] J. Bogaisky., "Boeing to help Aerion Develop Supersonic Jet as Lockheed Martin exits.," 02.02.2019.

[200] [Online]. Available: https://nplus1.ru/news/2016/02/08/hybrid.

[201] "IMF Quotas.," [Online]. Available: https://www.imf.org/en/About/Factsheets/Sheets/2016/07/14/12/21/IMF-Quotas. . [Accessed 03 06 2020].

[202] E. L. S.V. Levitsky, "Methodology for assessing the transport efficiency of a long-range passenger aircraft," *Scientific Bulletin of MSTU GA. 2014.* , Vols. 99-106, no. 205, 2014.

[203] Perspectives for Aeronautical Research in Europe., "Perspectives for Aeronautical Research in Europe.," [Online]. Available: http://www.pareproject.eu. . [Accessed 02 January 2020.].

[204] Expansion, "Expansion," 07 2019. [Online]. Available: https://datosmacro.expansion.com/impuestos/iva. [Accessed 07 2020].

[205] Uscib, "Uscib," [Online]. Available: https://www.uscib.org/value-added-tax-rates-vat-by-country/. [Accessed 07 2020].

[206] https://www2.deloitte.com/content/dam/Deloitte/cn/Documents/international-business-support/deloitte-cn-ibs-turkmenistan-int-tax-en-2017.pdf, "Deloitte," 2017. [Online]. Available: https://www2.deloitte.com/content/dam/Deloitte/cn/Documents/international-business-support/deloitte-cn-ibs-turkmenistan-int-tax-en-2017.pdf. [Accessed 07 2020].

[207] T. Economics, "Trading Economics," 2019. [Online]. Available: https://es.tradingeconomics.com/central-african-republic/sales-tax-rate. [Accessed 07 2020].

[208] Airbus, "Airbus," 2019. [Online]. Available: https://www.airbus.com/aircraft/market/global-market-forecast.html. [Accessed 07 2020].

[209] Boeing, "Boeing," 2019. [Online]. Available: https://www.boeing.com/commercial/market/commercial-market-outlook/. [Accessed 07 2020].

[210] REPSOL, [Online]. Available: https://www.repsol.com/es/productos-y-servicios/aviacion/jp-8/index.cshtml.

[211] G. E. C. o. t. M. W. C. o. T. i. t. U. States, "Charles L. Ballard, John B. Shoven and John Whalley Source," *The American Economic Review*, vol. 75, no. 1, pp. pp. 128-138, 1985.

[i] S. DUBOIS, Clean Sky 2 JU, Innovation Takes Off: What kind of aircraft configuration to expect by 2050?, Batterieforum, Berlin (Germany), 23rd January 2020

[ii] https://ec.europa.eu/transport/sites/transport/files/modes/air/doc/flightpath2050.pdf

[iii] https://transportgeography.org/?page_id=15778

[iv] https://www.fraundorfer.aero/

[v] - M.Romare, L. Dahllöf, : The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries - A Study with Focus on Current Technology and Batteries for light-duty vehicles. Stockholm: IVL Swedish Environmental Research Institute, 2017

- IVL comments to reactions in media on battery study. In: www.ivl.se/english/startpage/top-menu/pressroom/news/nyheter---arkiv/2017-07-03-ivl-comments-to-reactions-in-media-on-battery-study. Stockholm: IVL Swedish Environmental Research Institute, 2017
- E. Emilsson, L. Dahllöf, Lithium-Ion Vehicle Battery Production Status 2019 on Energy Use, CO2 Emissions, Use of Metals, Products Environmental Footprint, and Recycling, Stockholm: IVL Swedish Environmental Research Institute, 2019

[vi] Ch. Hebling, FhG ISE, CO_2-Bilanzen alternativer Antriebe, 15.11.2019, Berlin

[vii] M. Miotti, et al., Integrated environmental and economic assessment of current and future fuel cell vehicles, The International Journal of Life Cycle Assessment, 22 (2017), 94-110

[viii] https://www.agora-energiewende.de/fileadmin2/Projekte/2018/EU-Jahresauswertung_2019/Agora-Energiewende_European-Power-Sector-2018_WEB.pdf

[ix] M. Hepperle, DLR, Electric Flight – Potential and Limitations, Oct. 2012, https://elib.dlr.de/78726/1/MP-AVT-209-09.pdf

[x] https://www.aurora.aero/odysseus-high-altitude-pseudo-satellite-haps/

[xi] P. Rozier, JM Tarascon, JES 162 (2015) A2490

[xii] Li-Ionen Battery Roadmap of FhG Institute for System- and Innovation Research (ISI)

[xiii] Bloomberg NEF study, 2019; https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/

[xiv] I. Dincer; C. Acar, A review on potential use of hydrogen in aviation applications International Journal of Sustainable Aviation, Vol. 2, No. 1, 2016

[xv] B. Omar, chapter Experimental studies of using a PEMFC/battery hybrid system to power small UAVs, in Energy and Sustainability V (ed. by, H.H. Al-Kayiem, C.A. Brebbia, S.S. Zubir) WIT Press, 2015, p. 273 -

[xvi] B.D. James, 2018 Cost Projections of PEM Fuel Cell Systems for Automobiles and Medium-Duty Vehicles, https://www.energy.gov/sites/prod/files/2018/04/f51/fcto_webinarslides_2018_costs_pem_fc_autos_trucks_042518.pdf

[xvii] B.D. James, C. Houchins, Hydrogen Storage Cost Analysis 2018, https://www.hydrogen.energy.gov/pdfs/review18/st100_james_2018_o.pdf

[xviii] http://www.airbus.com/company/market/forecast

[xix] S. DUBOIS, Clean Sky 2 JU, Innovation Takes Off: What kind of aircraft configuration to expect by 2050?, Batterieforum, Berlin (Germany), 23rd January 2020