

Review

Climate Change Mitigation Pathways for the Aviation Sector

Md Arif Hasan ¹, Abdullah Al Mamun ² , Syed Masiur Rahman ^{3,*} , Karim Malik ⁴ ,
Md. Iqram Uddin Al Amran ⁵ , Abu Nasser Khondaker ³, Omer Reshi ³,
Surya Prakash Tiwari ³  and Fahad Saleh Alismail ^{3,6,7} 

- ¹ Sustainable Land Use Delivery Division, Ministry for the Environment, 23 Kate Sheppard Place, P.O. Box 10362, Wellington 6011, New Zealand; mdarif.hasan@mfe.govt.nz
 - ² Department of Civil and Environmental Engineering, University of Utah, 110 Central Campus Drive, MCE-1435, Salt Lake City, UT 84112, USA; abdullahal.mamun@utah.edu
 - ³ Center for Environment & Water, Research Institute, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia; dr.khondaker@gmail.com (A.N.K.); omer.reshi@kfupm.edu.sa (O.R.); surya.tiwari@kfupm.edu.sa (S.P.T.); fsalismail@kfupm.edu.sa (F.S.A.)
 - ⁴ Department of Geography and Environmental Studies, Wilfrid Laurier University, Waterloo, ON N2L 3C5, Canada; mali3080@mylaurier.ca
 - ⁵ International Union for Conservation of Nature (IUCN), Bangladesh Country Office, Dhaka 1206, Bangladesh; md.iqramuddinalamran@gmail.com
 - ⁶ K.A.CARE Energy Research and Innovation Center (ERIC), King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia
 - ⁷ Department of Electrical Engineering, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia
- * Correspondence: smrahman@kfupm.edu.sa; Tel.: +966-501-928-296



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Abstract: Even though the contribution of the aviation sector to the global economy is very notable, it also has an adverse impact on climate change. Improvements have been made in different areas (i.e., technology, sustainable aviation fuel, and design) to mitigate these adverse effects. However, the rate of improvement is small compared to the increase in the demand for air transportation. Hence, greenhouse gas emissions in the aviation sector are steadily increasing and this trend is expected to continue unless adequately addressed. In this context, this study examined the following: (i) the factors that affect the growth of aviation, (ii) trends in greenhouse gas emissions in the sector, (iii) trends in energy demand, (iv) mitigation pathways of emissions, (v) mitigation challenges for the International Civil Aviation Organization, (vi) achievements in mitigating emissions, (vii) barriers against mitigating emissions, and (viii) approaches of overcoming barriers against emissions mitigation. This study finds that continued research and development efforts targeting aircraft fuel burn efficiency are crucial in reducing greenhouse gas emissions. Although biofuels are promising for the reduction of aviation emissions, techniques to reduce NO_x emissions could enhance large-scale deployment. Pragmatic market-based mechanisms, such as the Emissions Trading Scheme (ETS) and/or carbon tax must be enforced on a global scale to capitalize on a collective stakeholder effort to curb CO₂ emissions. The findings of this study will help in understanding the emissions and energy consumption scenarios, which will provide a comprehensive package of mitigation pathways to overcome future emissions reduction challenges in the aviation sector.

Keywords: aviation sector; greenhouse gas emissions; energy consumption; mitigation; sustainable aviation fuel; ICAO

1. Introduction

Air transportation, providing vital economic benefits through transporting humans and goods, is an important mode of transportation in the modern era. Air transportation plays a vital role in the pull effect of service activities and has a long-term relationship with economic growth [1,2]. According to the Air Transport Action Group (ATAG), the number of global air travel passengers was 4.5 billion in 2019, and the contribution of the aviation

sector in the global GDP was USD 691.3 billion [3]. However, in 2020, the aviation industry observed an overall reduction of around 2.7 billion passengers due to COVID-19, which is a reduction of around 60% from the 2019 levels. The reduction in international passenger travel was around 74%, while it was around 50% for domestic passenger travel [4]. The net financial loss of global commercial airlines in 2020 was USD 118.5 billion [5].

Although COVID-19 has impacted the aviation industry severely in recent days, in the pre-COVID era, the rapid economic growth coupled with the increased demand for air transportation has impacted anthropogenic climate change, which has also led to global warming [6,7]. Increased demand for air transportation due to the growth of the tourism industry has increased energy consumption and, consequently, resulted in a higher emission of pollutants [8]. The emission of pollutants from the aviation industry is a continuous process from the manufacture of aircraft through their landing to takeoff (LTO) [9].

While the global energy-related CO₂ emissions decreased by over 5% between the first quarter of 2019 and 2020 due to COVID-19 [10], the aviation sector was responsible for 915 million tonnes of CO₂ emissions (Mt CO₂) in 2019, which was 2% of the global human-induced CO₂ emissions and 12% of global transport-related CO₂ emissions [3]. The United States of America (USA) was the top emitter of GHGs from aviation bunkers (energy consumption from aircrafts) in the world in 2019 (Figure 1). As of 2019, GHGs released from aviation bunkers in the USA amounted to 179 MtCO₂, which accounts for 19.5% of the world's emissions of GHGs from aviation bunkers. The top five countries (USA followed by China, United Kingdom, Japan, and Germany) account for 40% the world's total emissions of GHGs from aviation bunkers, estimated at around 363 MtCO₂ equivalent in 2019 (Figure 1) [11]. Considering that the aviation sector is one of the fastest-growing sources of GHGs emissions, the emissions are expected to increase rapidly in the future. Hence, strategies for mitigating environmental pollution are critical to the economies, and during the process of trade and economic integration, the implementation of prudent energy policies can play a vital role in reducing CO₂ emissions [12].

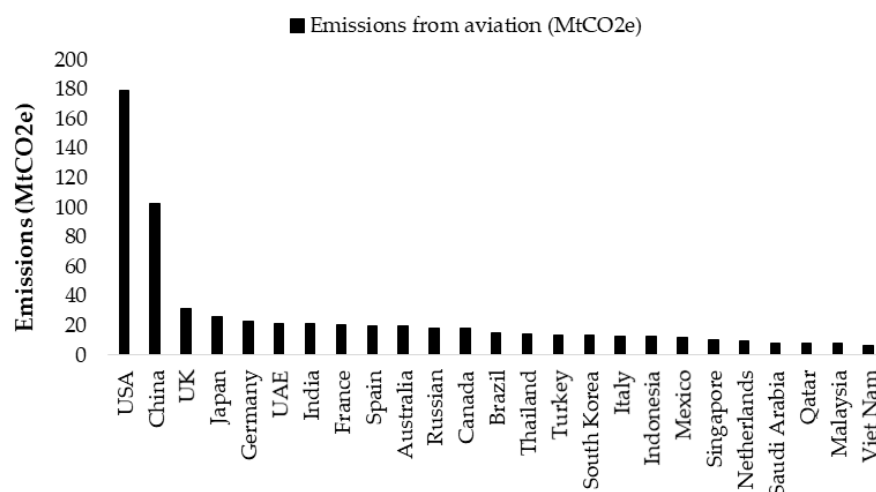


Figure 1. Top 25 countries with the highest contributions to GHG emissions from the aviation sector in 2019 (Source of data: [11]).

The concerned organizations are implementing a range of measures to reduce aviation emissions. The emission of GHGs from the aviation sector has been addressed through different technical and organizational approaches. In 2010, the International Air Transport Association (IATA) envisaged low-carbon aviation growth starting in 2020 and a reduction of 50% in the CO₂ emissions by 2050 with respect to the 2005 levels [13]. The International Civil Aviation Organization (ICAO) required the industrialized countries under the global climate regulation regime—the Paris Agreement—to reduce emissions from international transport through the United Nations Framework Convention on Climate Change (UN-

FCCC) [14]. The Federal Aviation Administration (FAA) has also established different goals for effective mitigation measures and to reduce GHG emissions, based on the current scientific advances of the environmental impacts of the aviation industry, namely improved scientific knowledge. Unfortunately, the lack of synchronization among the policies of various organizations results in a diminishment of the overall benefits of these measures. Thus, it is crucial to move towards a more integrated approach to develop both mitigation and adaptation actions and plans.

Considering the above, this study outlines a roadmap to establish an integrated approach to mitigate emissions of GHGs from the aviation sector. The paper discusses estimates of GHG emissions from aviation operations on a global scale and the GHG mitigation measures implemented by the aviation authorities around the world, explores the challenges against mitigation, and finally proposes a feasible roadmap to mitigate GHG emissions. To conclude, the paper sheds light on several crucial issues pertaining to GHG emissions, mitigation measures, the role of global communities, and initiatives for achieving emissions reduction targets.

2. Analysis of Aviation Emissions

Aircrafts emit different types of pollutants, including gases and particles, and this paper discusses the emitted gases contributing to the greenhouse effect. An analysis of the factors of aviation emissions and an overview of different GHGs from the aviation sector are provided in the following sub-sections.

2.1. Factors of Aviation Emissions

One of the major factors of increased aviation emissions is the increased demand for air travel worldwide. In 1960, the total number of passengers who traveled by air was only 100 million, which increased to 4.5 billion in 2019 [3,15]. This rapid growth of the aviation sector was due to the increased economic growth both in developing and developed countries. Given that air travel demand largely depends on the global economic situation [16], the aviation sector was impacted by global recessions, oil crises and the COVID-19 coronavirus. It is expected that in the post-COVID-19 era, there will be an increased demand for air travel again. Thereby, emissions from this sector are expected to increase in the future.

The increased use of carbon-intensive petroleum fuels such as kerosene, kerosene–gasoline mixture or aviation gasoline in the aviation industry is another major factor for aviation emissions. Given that the propulsion system for most aircrafts is gas-turbine engines, the penetration rate of low-carbon alternative fuels such as biofuels, hydrogen fuels, solar cells and renewable electro-fuels is negligible [17]. Moreover, the technology for most of the low-carbon options is under development. For instance, the technology for electric aircrafts is not mature, and these aircrafts have potential for only short-range flights. The potential for cryogenic hydrogen use is still in the research and development (R&D) process. The use of alcohols as an alternative fuel source is limited as they have low energy density and are incompatible with use in modern gas-turbine engines [17]. Therefore, the increased use of carbon-intensive fuels is likely to continue and hence emissions seem to increase without a pause in the near future.

The manufacturers of aircrafts are delivering small efficiency gains compared to the increasing demand for air travel. Given that the operational lifetime of an aircraft is around 25–30 years and the average age of a fleet is now 11.3 years (it is predicted to be 10.7 years by 2029), ATAG's target is to improve fuel efficiency for fleets by only 1.5% per year [3]. Therefore, the opportunity to reduce aviation emissions through improved fuel efficiency is very limited, and emissions from this sector are likely to increase in the future.

The lack of an efficient carbon price mechanism is another important reason for burgeoning aviation emissions worldwide. The European Union Emissions Trading Scheme (EU ETS) used to cover aviation emissions from flights to, from, and within the European economic area (EEA), but from 2017 onwards, the geographic scope was limited to only

intra-EEA flights. Scheelhaase et al. [18] note that the emissions reduction potential of the current EU ETS from the aviation sector is only 4% by 2036 from the present level. Carbon offsetting and reduction scheme for international aviation (CORSIA) is another offset scheme that has an emissions reduction potential of 18% by 2039, but this scheme is expected to start in 2021, and the potential for emissions reduction for that year is only 1.4% [17].

2.2. Emissions from Aircrafts

About 0.8 million cubic meters of oil are being used by the global aviation industry, resulting in the release of large amounts of CO₂ from aircraft engines. Modern aircraft engines emit 3160 ± 60 g of CO₂ due to the combustion of each 1000 g of fuel [6]. While CO₂ plays a substantial role in global warming [19], the other GHGs CO and NO_x are also important constituents of aviation emissions and are associated with the combustion of conventional as well as alternative jet fuels [20].

NO_x emissions from aircraft engines are likely to alter the atmospheric composition and have impacts on radiative forces [21]. Emissions of NO_x generate ozone (O₃) (warming) on a time scale of weeks to months [22,23]. Holmes, Tang and Prather [22] noted that an increased NO_x also depletes methane and causes a reduction in ozone production, but on a decadal time scale. Therefore, the net radiative forces from NO_x emissions vary depending on the time and location of emissions along with background concentrations, emissions scenarios, and chemical rates of co-efficients [22].

Besides CO₂ and NO_x emissions, aircraft engines emit water vapor and particles including sulfate and soot (black and organic carbon). Cziczo and Froyd [24] claimed that soot particles do not seem to contribute much to forming natural cirrus. However, the model of Zhou and Penner [25] predicted that soot particles emitted from aircrafts have substantial effects on natural cirrus once preconditioned in contrails. The view of Kärcher [26] is that the prediction of Zhou and Penner [25] partly relies on the assumption of how ice forms in the background cirrus. Kärcher [27] acknowledged that there are still challenges in reducing uncertainties related to the effects of particle emissions from aircrafts due to the limited observational evidence.

With regard to climate impacts, the emissions of water vapor and particles from aircraft engines produce contrails, which contribute to human-made climate change [7,27]. Contrails can also be formed due to adiabatic cooling near curved surfaces of an aircraft [28]. According to Schumann [29], contrails can be either short-lived or long-lived, depending on the conditions of the surrounding environment. Contrails that remain for 10 minutes or more are considered as long-lived contrails. Based on the shape of contrails, they can be termed as persistent contrails or contrail cirrus, where persistent contrails mostly retain their linear shape but contrail cirrus does not [27]. A recent assessment shows that contrail cirrus has the greatest warming effects (57.4 milliWatts per meter square) followed by CO₂ emissions (34.3 milliWatts per meter square) and NO_x emissions (17.5 milliWatts per meter square) [7].

2.3. Oil Demand and Emissions

The aviation sector emits a large amount of GHGs each year. However, the emission of GHGs depends largely on the type of fuel used [30]. The two most frequently used main grades of kerosene-type fuels are Jet A-1 and Jet A, while Jet B is another cut kerosene (mixture of kerosene and gasoline) [31]. Jet A (also known as Synjet) can be used as a substitute for Jet A-1 and is generally available in North America with a freeze point maximum of 40 °C [32]. The distinctive characteristics of kerosene, such as the composition and viscosity control, have increased its use in the aviation sector.

Petroleum fuels provide about 99% of jet fuel [33], and the aviation sector consumed around 0.86 million cubic meters of oil equivalent per day (MCMOED) in 2014 [34]. The countries belonging to the Organization for Economic Co-operation and Development (OECD) accounted for 3.1 MCMOED, and the demand in developing countries and Eurasia

was 1.9 MCMOED and 0.3 MCMOED, respectively. According to forecasts, the oil demand of this sector under the business as usual (BAU) scenario will grow by 3 MCMOED, from 5.4 MCMOED in 2014 to 8.4 MCMOED in 2040 (Figure 2). The projections under the low aircraft technology scenario place the oil demand at 9.1 MCMOED and 17.4 MCMOED in 2030 and 2050, respectively [35]. The 1.39% fuel efficiency scenario will see oil demand at 7.3 MCMOED in 2030 and 14.2 MCMOED in 2050. If the ICAO's 2% annual fuel efficiency aspirational goal is achieved, oil demand is predicted to reach 6.1 MCMOED in 2030. The oil demand is projected to reach 11 MCMOED in 2050 under this scenario (Figure 2). Based on the data presented by the International Energy Agency (IEA) for 2015, the global CO₂ emissions from aviation bunker fuels are predicted to reach 600 million tonnes of CO₂ (MtCO₂) in 2020 (Figure 3).

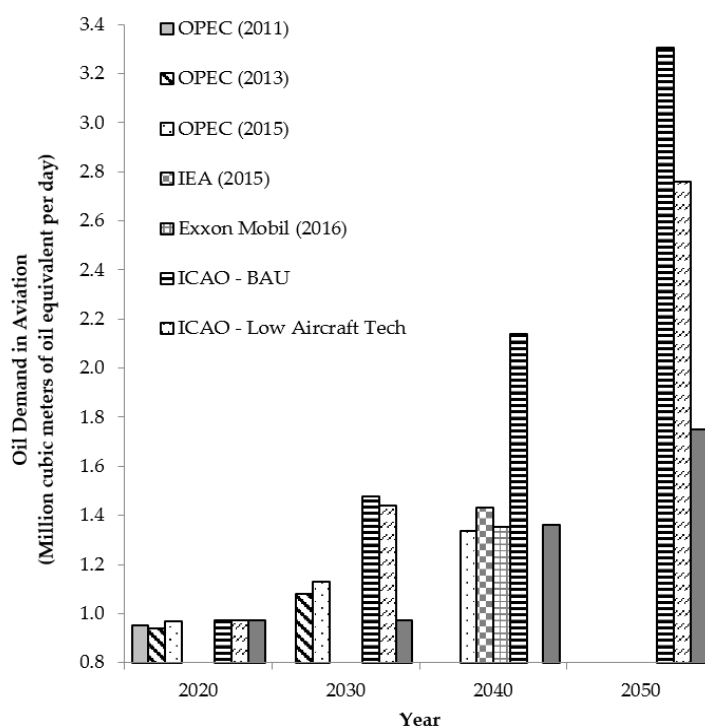


Figure 2. Oil demand forecast in the aviation sector under different scenarios (Source: [34]).

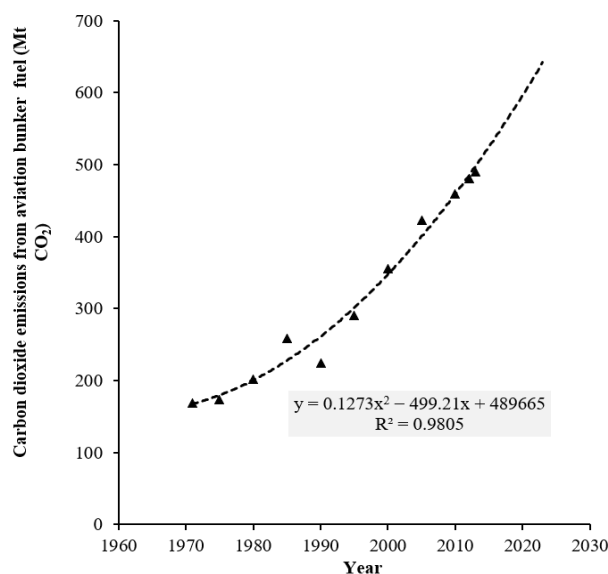


Figure 3. The global CO₂ emissions from aviation bunker fuels: trends and projection (Source: [1]).

2.4. National and Regional Mitigation Measures

National policies and measures enacted by individual countries can play a crucial role in managing and reducing overall emissions from the aviation sector. The government of the United States, for example, aims to reduce 115 million tons of CO₂ (MtCO₂) emissions by 2020 and an additional 60 MtCO₂ by 2026 to achieve a low-carbon growth for commercial aviation in the post-2020 period. Several action plans and programs have been identified and implemented to support the ICAO's goal and the national target of emissions reduction of the United States aviation sector. These plans and programs include research and development (R&D) efforts to improve aircraft and engine technology; the implementation of the NextGen program in Houston, Texas, by the FAA to improve airport operational efficiency; the deployment and commercialization of sustainable aviation fuels (SAFs) with a maximum of 80% lower lifecycle GHG emissions; the introduction of a cleaner emissions standard for aircrafts; the development and implementation of the Continuous Lower Energy, Emissions, and Noise program for commercial aircrafts beginning after 2015; the subsonic fixed-wing program by NASA for improved aerodynamic and structural efficiency of aircrafts; etc. [36].

The government of Australia has undertaken diverse initiatives focusing on infrastructure development, governance, and implementation of legal instruments to contribute to the ICAO's aspirational goal of achieving low-carbon growth by 2020. Measures taken by the Australian airlines to reduce GHG emissions in international aviation include the following: (i) a 2.5 billion Australian Dollar fleet renewal program by Virgin Australia to ensure better fuel efficiency; (ii) the replacement of the turbofan engine with more efficient General Electric Next-Generation turbofan engine by Qantas to save energy consumption by 20%; (iii) reduction of aircraft weight by removing unnecessary cabin items and introducing lighter bottles, cutlery, and fittings; (iv) the fuel optimization program by Qantas and Virgin Australia through the optimization of the flight paths, flight schedules, and aircraft speed; (v) the R&D initiatives to promote SAFs derived from different biomass types such as plants, trees, wastes, and other organic matter; (vi) the procurement of 200 million litres of alternative fuel between 2020 and 2030 by Virgin Australia and Air New Zealand to foster the development of SAF industries in this region; (vii) the carbon offset scheme by Qantas and Virgin Australia to offer low-carbon passenger flight services; etc. [37].

The European Union (EU) has implemented a comprehensive set of measures to reduce GHG emissions from the European aviation sector and guide future aviation growth in an environmentally sustainable manner. These include the introduction of a new CO₂ emissions standard for aircrafts, the establishment of the European Advanced Biofuels Flightpath to produce 2 million tons of biofuels annually by 2020 for commercial aviation, the development of the Single European Sky legislative framework to modernize the air traffic management (ATM) system in Europe, the establishment of the Airport Carbon Accreditation program at 92 airports of Europe, the deployment of emissions charging schemes at more than 100 European airports, the incorporation of the European aviation sector under the European Union Emissions Trading Scheme (ETS) to internalize the external costs of aviation emissions, etc. [37]. The inclusion of the aviation sector in the ETS is projected to result in a reduction of 3.8% CO₂ emissions by 2020 [38]. The EU also intends to regulate the capturing of all relevant species (CO₂, NO_x, H₂O, etc.) responsible for climate change to mitigate the full impact of aviation in the EU ETS [39].

2.5. Achievements in Mitigation

Some of the achievements, measures, and policy interventions that were undertaken by respective organizations and agencies to reduce GHG emissions are as follows.

The ICAO established a Committee on Aviation Environmental Protection (CAEP), which aims to limit the exposure of noise, maintain the local air quality, and reduce GHG emissions [40]. The long-term aspirational goal of the ICAO was to continue the improvement rate of 2% in global fuel efficiency between the years 2021 and 2050 [41]. In order to achieve those goals, the ICAO took some initiatives such as the development

of fuel-efficient technologies, the introduction of state-of-the-art engine technologies, the use of lightweight materials, efficiency in operation through the deployment of modern infrastructure facilities, the promotion of less carbon-intensive alternative fuels, etc. [41]. Besides the ICAO, the IATA, realizing the importance of mitigating GHG emissions from air transportation, also adopted a set of targets. These include the following: (i) an annual average improvement of 1.5% in the fuel efficiency between the year 2009 and 2020, (ii) low-carbon growth in aviation from the year 2020, and (iii) a 50% reduction in CO₂ emissions from aviation by the year 2050 with respect to the level in 2005 [42].

Recently, new standards for the emission of CO₂, NO_x, and particulate matters (PM) were set by the ICAO, and the aircraft are obliged to meet these standards to address issues associated with local air quality. In 2012, the ICAO developed a CO₂ metric system to measure an aircraft's fuel-burning performance and quantify CO₂ emissions. Measures that were identified were helpful when inefficient fuel burning was involved, including the reduction of the weight of aircraft, improvement in aerodynamics, optimization of an aircraft system, and improvement in engine fuel efficiency. A follow-on review workshop on efficient fuel-burning techniques was conducted in the following year (i.e., in 2010) to emphasize the importance of those measures and techniques in reducing GHG emissions due to fuel consumption [35]. The improvement in the design of engines, such as the use of three-dimensional compressor blades, was found effective in reducing GHG emissions from the aviation industry [43]. Improvement in the aerodynamics through the introduction of non-planar wings, laminar flow wing profiles, and active wings are some of the effective technical measures that have an impact on the reduction of GHG emissions. The use of lightweight composite materials to reduce aircraft weight and reconfiguration of the interior of airplanes is suggested by the CAEP to reduce GHG emissions due to fuel consumption.

Achieving operational efficiency through changes in the operation of an airline or air traffic control is another measure of reducing GHG emissions from the aviation industry. According to Poll [16], operational efficiency improvement may not require new technology and could deliver emission reduction benefits immediately. The selection of the best-suited aircraft, along with improved load factor, flexible and efficient ATM system, and the use of prevailing winds could contribute to fuel consumption reduction and thereby emissions. The ICAO published some guiding materials as a circular in 2004 to minimize fuel consumption and reduce GHG emissions from aircraft engines. Information on best practices of ground-level operations and services of aircrafts, auxiliary power units, and in-flight operations were included in that circular. The CAEP is updating the information on that circular and developing an operation guideline manual [44]. According to a study by the ICAO, implementing new communications, surveillance, navigation, and ATM systems are some of the effective measures for reducing fuel consumption resulting in GHG emissions. Therefore, the ICAO is placing a high emphasis for states or nations to introduce those measures. The ICAO is also emphasizing the enablement of direct routes through ATM. The ICAO member states have also begun implementing the Carbon Offset and the CORSIA [45]. The IATA is planning to incorporate new fuel-efficient vehicles into the fleets [46].

In recent times, researchers note that promoting alternative fuels such as biofuels instead of jet fuels could contribute to aviation emissions reduction [7,27,47]. Biofuels derived from organic matter and live plants are more compatible with modern jet engines than fossil fuels. A Boeing 747 flew from London Heathrow to Amsterdam in 2008 with one of its four engines running on biofuels. A mix of coconut oils and babassu was used to produce that fuel. A 50:50 blend of conventional kerosene and synthetic jet fuel is another alternative fuel widely used by the US air force since 2007. As synthetic jet fuel burns cleaner than conventional jet fuels, this alternative fuel emits less pollutants [48].

The above discussion indicates that a range of measures that can play an important role in offsetting the effects of emissions of GHGs is available. However, most of these seemingly successful measures have been implemented focusing exclusively on discrete applications, and an integrated solution to reduce GHGs emissions has not been implemented.

3. Integrated Mitigation Pathways in the Aviation Sector

In the following sections, an integrated mitigation approach based on some of the successful discrete measures, combined with other methods that can pave the way to sustainable mitigation of GHGs from the aviation sector, is addressed.

3.1. Alternate Fuels and Fuel Switching

The use of alternate fuels in the aviation sector is very important for the future fueling of aircraft due to two requirements: diminishing the dependence on fossil fuels and reducing GHG emissions. Researchers in the field of aviation are also trying to find alternatives to traditional jet fuel [49,50]. Several studies have demonstrated the advantageous use of biofuels and synthetic fuels in replacing the traditional oil-derivate jet fuels to reduce the emission of pollutants [51,52]. Among other potential fuels [53], the effect of applying Fischer-Tropsch (FT) fuel on gaseous and particulate emissions was also investigated [30]. It was also concluded that the sulfur-less FT fuel with less aromatic ingredients can minimize the particulate matter and the emissions of their precursors from jet engines [54].

The aviation sector has committed to converting its fuel supply to alternative fuels [55]. The American Society for Testing Materials has approved three alternative jet fuels for blending with jet fuel according to their D7566 specification. However, liquid hydrogen, FT kerosene-type jet fuels, and synthetic bio-based fuels are considered to be the only feasible options [56]. In particular, liquid hydrogen, which can be produced by the electrolysis of water using any renewable energy source, can reduce the use of crude oil resources as well as its consequences of anthropogenic GHG emissions [57]. Ponater, et al. [58] investigated the climate impact reduction potential of liquid hydrogen and found that switching from kerosene to liquid hydrogen could reduce radiative forces by 15% to 50% (best estimate around 30% for a swift transition). In terms of the reduction in surface temperature, their study estimated between 5% and 15%, and the best estimate is about 10%. The IATA launched the SAF initiative and expressed the sector's commitment to low-carbon growth from 2020, and net emissions reduction to half of 2005 levels by 2050 [59]. SAF generates about 80% less CO₂ over its lifecycle, compared to conventional jet fuel. Thus, sustainable biofuel can potentially lessen CO₂ emissions from the aviation sector by 50% to 80%, compared to fossil fuels [60].

Currently, biofuel blends are identified to be the most economically viable option. Within the 2 °C scenario, biofuels are projected to displace about 130 Mtoe of conventional fuels by 2050 [61]. One of the salient features of biomass-derived jet fuels is their blending capacity with conventional kerosene, ensuring the availability of sufficient quantities of this biofuel as well as not having to change the vehicles or infrastructure to achieve low GHG impacts at low costs [62]. Although the IATA aimed to use 10% biofuel as an alternate fuel in the aviation sector by 2017, the most recent update indicates that it has not been able to achieve the goal due to the independence of GHG-emitting coal-to-liquids or gas-to-liquids fuel [62]. Additionally, the aviation industry is expected to supply a substantial amount of sustainable biofuel in the jet fuel mix by 2020 [60].

Not only have fourth-generation biofuels (FGBs) have shown promising potential to power aero-gas turbine engines, but their production process is also not in competition with conventional crops for land use [63]. FGBs are mostly derived from genetically modified (GM) algae, while third-generation biofuels are sourced from algae. First- and second-generation biofuels are often produced from oil-based plants and agriculture residues, respectively [64]. As FGBs are sourced from GM algae and such algae can be cultivated under harsh climatic conditions (high PH, high light intensities, and high salinity), non-arable areas, including wastewater, seawater, marginal farmlands, and unproductive drylands, can be utilized for large scale production of FGBs. This eliminates the concern about competition with crops for arable lands for producing biofuels [64]. The successful production of biofuels with low-lifecycle GHG emissions will also decrease the overall GHG emissions from the aviation sector, although there are still uncertainties [65]. The

IEA's Sustainable Development Scenario (SDS) is anticipating that biofuels will supply nearly 10% of aviation fuel by 2030, and about 20% by 2040 [66].

The ICAO Resolution A38-fi8 includes a strong mandate for the ICAO in the area of alternate fuels. The Resolution has requested that states to consider, evaluate, and implement initiatives regarding SAFs for aviation. Some of the examples of successful implementation of alternate fuels are listed in Table 1 [59].

Table 1. Use of alternate fuels in aviation [59].

Fuel Stock	Airline	Aircraft	Route
Used cooking oil	Jetstar Airways	A320	Melbourne–Hobart
	KLM Royal Dutch Airlines	B737	Amsterdam–Paris
	KLM Royal Dutch Airlines	B777	Amsterdam–Rio de Janeiro
	LAN Airlines	A320	Santiago–Concepcion
	Qantas Airways	A320	Sydney–Adelaide
	Thai Airways International	B777	Bangkok–Chiang Mai
	Thomson Airways	B757	Birmingham–Arrecife
	Air Canada	A319	Toronto Pearson–Mexico City
	Air France	A321	Toulouse–Paris
	Alaska Airlines	B737	Seattle–Washington
	Alaska Airlines	Q400	Seattle–Portland
Camelina	Iberia	A320	Madrid–Barcelona
	Porter Airlines	Q400	Toronto–Ottawa
	Porter Airlines	Q400	Montreal–Toronto
	Aeroméxico	B737	Mexico City–San Jose
Jatropha	Finnair	A319	Amsterdam–Helsinki
	Interjet	A320	Mexico City–Tuxtla Gutierrez
	Aeroméxico	B777	Mexico City–Madrid
Jatropha, camelina, and used cooking oil	Aeroméxico	B777	Mexico City–São Paulo
	Lufthansa	A321	Hamburg–Frankfurt
	Lufthansa	B747	Frankfurt–Washington

However, the use of alternate fuels poses many challenges, including the uncertainty about the availability of sufficient quantities of the alternate fuel, or the extent of GHG reduction. Hence, these fuels are being scrutinized as a substitute [67,68].

3.2. Fuel Cells

Hydrogen has been proposed as an alternate fuel for future aircraft because hydrogen-fueled engines emit zero CO₂ at the point of use, and have also substantially reduced NO_x emissions and minimized the emissions of PM [69]. However, the use of hydrogen has to be evaluated thoroughly for the current aircraft platform due to uncertainties over whether radiative forcing will increase [70]. In 2008, Airbus, German Aerospace Center (DLR), and Michelin have studied the use of a Multifunctional Fuel Cell (MFFC) system and concluded that the use of a fuel cell engine can improve efficiencies over fossil fuels up to three times, with water vapor as the only emission. Even though hydrogen would require pressurized cryogenic tanks with onboard storage that would add about 10% to the weight of the aircraft [71], this approach will improve the overall energy efficiency by minimizing the total gross take-off weight by approximately 20% [72]. Furthermore, these hydrogen-fueled and electric engines are potential candidates for fueling short-distance flights, such as domestic flights [61]. However, fuel-cell aircraft would be economically feasible only when the price of hydrogen fuel is highly competitive against conventional fuels such as kerosene [73].

3.3. Solar Power

Even though solar energy is a highly promising renewable source of environmentally friendly energy, its use on aircraft has not been promoted due to limitations pertaining to

its generation and storage procedures [74]. The Swiss Solar Impulse team, in collaboration with several organizations, has developed Solar Impulse, which is a long-range solar-powered aircraft with day and night flying capability. In March 2015, Solar Impulse 2, a solar-powered airplane with 17,000 solar cells on its wings, began a circumnavigation journey around-the-world aimed at showcasing the potential of renewable energy and spent 23 days in the air without using fossil fuel. Although solar energy can be used as a source of a zero-emission driving force for the aviation industry, so far, the feasibility has been demonstrated only for small aircraft, and more research is underway to determine the feasibility of using it for the larger commercial airliners. Currently, solar energy can provide the required electrical power to operate different services, including loading and unloading, internal heating, ventilation, air conditioning of aircraft obtained through the auxiliary power unit (APU), or receiving power and pre-conditioned air either from a ground power unit or directly from the gate. Research is currently underway to find novel ways of harvesting and storing solar power as well as reducing the cost of operating solar-powered aircrafts [75]. The use of solar energy can save an average of 5.6 kg of CO₂ by replacing the APU for a parked aircraft [35].

3.4. Efficiency Measures

Improved fuel efficiency and non-engine-based efficiency improvement are the major contributors to reducing emissions in the aviation industry. The deployment of fuel-efficient next-generation aircrafts, improved ATM, re-engining, and technically improved flight patterns represent effective efficiency improvement measures [61]. Operational measures such as improved flight scheduling, aircraft-path assignment, and gate assignments can reduce emissions by 11% and improve passenger service level by 31% from the BAU levels [76]. Fuel efficiency in the aviation sector has been improved over the years due to the advent of innovative aircraft designs. According to Boeing, in 2017, fuel accounted for 20% to 30% of the total operating cost of single-aisle and wide-body airplanes. According to Boeing, 29,500 airplanes are expected to be replaced by new ones between 2017 and 2036 [77]. The ICAO's projections for oil demand in international aviation operations predict a decline in future demand (Table 2). The aspirational 2% annual fuel efficiency scenario offers the highest reductions, with approximately 10 MCMOED reductions expected in 2050.

Table 2. Reduction in oil demand in international aviation bunkers (MCMOED) [35].

Year	Low Aircraft Technology	1.39% Per Year Fuel Efficiency Goal	2% Per Year Fuel Efficiency Goal
2020	0	0	1.2
2030	0.2	2	3.2
2040	0.7	3.2	4.9
2050	3.4	6.6	9.8

A change in the global demand for oil is foreseen because of the various mitigation measures that have been already implemented and those measures that are intended to be implemented but have yet to be fully defined. The initiatives of the introduction of improved deployment of low-carbon fuels led the IATA to achieve the target of reducing emissions from aviation [59]. The reduction in energy consumption in the aviation sector has been truly impressive: energy consumption per passenger mile in 1970 was three times higher than the corresponding value today [78]. Researchers from the Massachusetts Institute of Technology (MIT) have determined that the combustion of fuel per unit of the thrust of a new aircraft can be reduced from 15% to 25% by 2025 [79]. The European Commission's Advisory Council on aeronautics research in Europe intends to minimize fuel usage by 50% by 2020 [80].

3.5. Market-Based Policy

In 2010, different states joined the 37th ICAO assembly and agreed to initiate a cost-effective and coordinated skeleton of market-based measures (MBMs) around the world, avoiding any hindrance to the efficiency of international air transportation. Assembly Resolution A35-5 has also encouraged the study of MBMs. In 2016, the ICAO introduced a global MBM scheme for international aviation. This scheme is expected to play a complementary role as a part of the basket of measures to fill the emissions gap and stabilize the net CO₂ emissions or achieve a low-carbon growth of international aviation by 2020. The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) would be the first global MBM scheme for the entire sector [45]. Carbon offsetting is a scheme for airline passengers and corporate customers to reduce their proportion of an aircraft's CO₂ emissions on a particular journey by investing in carbon reduction projects [81]. Over 30 IATA-member airlines have introduced an offset program either integrated into their web sales engines or to a third-party offset provider [82]. The CORSIA and the EU ETS operating in parallel would ensure that international flights, as well as flights within the EU, are subject to CO₂ reduction schemes [18]. Under the carbon allowance allocation scheme, airlines can achieve a reduction in emissions of about 20% [83]. ICAO estimates an offset target of about 2.5 billion tonnes of CO₂ between 2021 and 2035 [84]. The expected mitigation due to the CORSIA scheme is plotted in Figure 4.

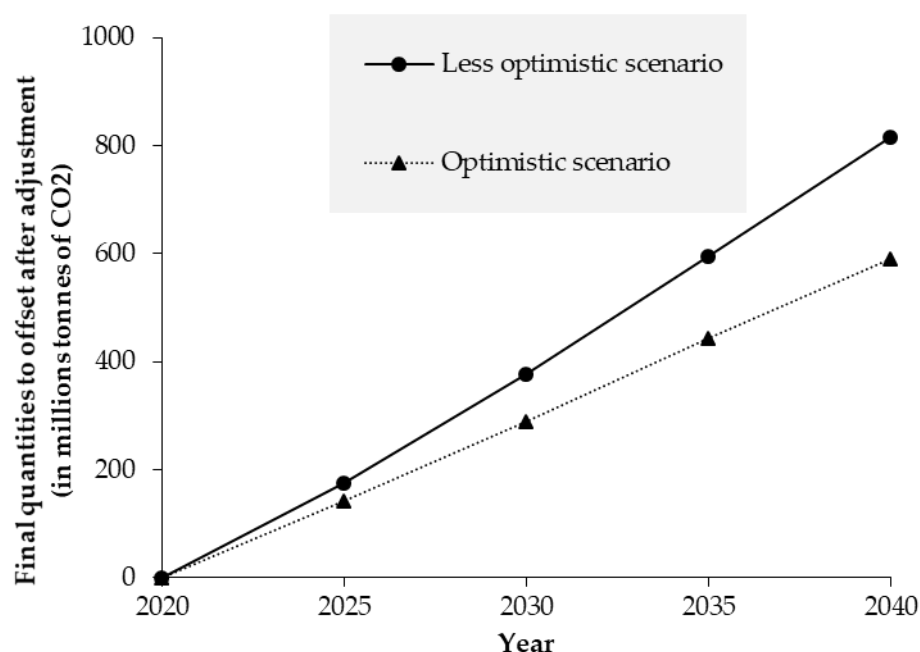


Figure 4. Global market-based measure (MBM) scheme for the aviation sector and expected mitigation from this scheme [45].

3.6. Improved Intermodal Transportation Planning

The emissions resulting from aviation can be reduced by shifting the demand to other modes of transportation with lower emissions. In the sense of energy and total emission, marine transportation outperforms aviation, and it is expected that a flourishing marine transportation sector can reduce short-term emissions within one or two decades [85]. As air freight is approximately 20 times more CO₂-intensive than marine-based shipping, shifting to marine-based shipping can substantially reduce CO₂ emissions. Another feasible solution to reduce GHG emissions is to reduce the demand for short-haul air travel by shifting to high-speed rail. However, the growth of individual income may lead to a modal shift from land-based and sea-based transportation to aviation [86], which can be observed according to the trends in most of the member nations of the OECD [87].

3.7. Fleet Modernization and Operational Approach

New aircraft with improved airframes and efficient engine technologies are effective in the reduction of GHG emissions in this sector [88]. Aircrafts with hybrid power systems (i.e., battery-conventional fuel) have also exhibited promising potential in reducing emissions in the surroundings of airports. Furthermore, modeling results suggest greater fuel savings and potential for reduced emissions by hybrid aircrafts over the existing fleet [89]. Dahlmann et al. [90] have emphasized that replacing the A330-200 fleet with redesigned aircrafts could decrease the climate change impact potential of the existing fleet by 32% without additional operating costs. Besides developing new aircraft, the new geared turbofan engines can be retrofitted to old aircraft to reduce fuel consumption and emissions. The total number of A320 aircraft that are currently in operation is around 7000 [91]. Therefore, the re-engining program could contribute to fuel and emissions reduction [92]. Additionally, modernization of the fleet by retrofitting fuel-efficient airframes and modern blended winglets on existing aircraft have been found to be effective in fuel and emissions reduction [93]. The angled extensions installed at the wingtips of an aircraft are known as blended winglets, which reduce airflow drag and thereby improve fuel efficiency and reduce GHG emissions. Although the installation of blended winglets increases the aircraft's structural weight, it improves aerodynamics and reduces net fuel consumption. For instance, blended winglets help the B737-800 aircrafts to save fuel consumption between 2% and 4%, depending on their stage length [77]. Similarly, blended winglets (which are often known as “Sharklets” for Airbus) reduce fuel consumption of A320ceo by 1% and 3.5% for the stage lengths of 1000 km and 6500 km, respectively [94].

New aircraft with reduced weight can also reduce fuel consumption and thereby GHG emissions (Table 3). Previous studies have revealed that aircraft with improved body shape and tail-less design reduce aircraft weights and improve aerodynamics, which increases the fuel efficiency and reduces GHG emissions [95]. Aircraft weight can also be reduced by introducing different light-weighting components, such as lightweight seats, trolleys, paints, and entertainment materials in the cabin.

Table 3. Expected reduction in CO₂ due to operational changes [96].

Measure	Marginal Abatement Costs in EUR/tCO ₂ by the Year 2020	Possible Abated CO ₂ Emissions in Mto by the Year 2020
New aircraft: early retirement of aircraft	1556.8	12.2
Rfit: Engine replacement	964.3	0.5
Refit: Engine upgrades	789.4	0.1
New aircraft: light weighting	415.9	6.6
Refit: winglets	203.8	1.3
Current fleet: light weighting	81.1	1.8
Polishing instead of painting	19.8	0.2
Taxi-in/out: Ground towing	405	0.2
Reduction of Auxiliary Power Unit used	223.7	0.9
Taxi-in/out: Single Engine Taxi	162.4	0.7
ATM improvement: SESAR system	109.2	21.9
Reduction of contingency fuel	−5.9	1.9
Cyclic engine Wash	−18.4	0.8
Improve load factor	−105.6	7.3

3.8. Integrated Mitigation Pathways

Although the aviation industry set an aspirational target of reducing emissions to 50% from the 2005 level by 2050, global emissions from this sector have been increasing over the past two decades [97]. Between 1990 and 2014, global aviation emissions increased at an annual average rate of 2.6% [98]. Under the BAU scenario, emissions from this sector may increase to 2019 MtCO₂e. Therefore, a future roadmap to reduce emissions from this sector is crucial to achieve the aspirational emissions reduction target. The emissions reduction potential of the aviation sector in 2030 is estimated to be 0.37 GtCO₂e/year (range 0.32 to

0.42 GtCO₂e/year) under the current policy scenario, which is around 18% of the 2030's BAU emissions level [99,100].

The proposed roadmap for achieving 2050 mitigation targets for the aviation sector is listed in Table 4 and graphically presented in Figure 5. In order to develop the mitigation roadmap, firstly, all possible emissions reduction options are identified based on studying past literature (see Table 4). Then, all mitigation options are categorized under five broad mitigation pathways. While deciding on the share of emissions reduction for each category, relevant past literature is thoroughly examined [101,102], and the feasibility of each mitigation pathway is considered. Finally, the costs and benefits for each mitigation pathway are discussed. The details of each mitigation pathway are as follows.

The role of Power to Liquid (PtL) in achieving future emissions reduction targets is crucial as about 66.6% of the emissions reduction target will be achieved through PtL. An example of PtL could be drop-in electrofuels, where hydrogen (produced from electrolysis) will be combined with CO₂ (captured from the atmosphere) to produce a drop-in electrofuel or hydrocarbon fuel (Transportation and Environment) [103]. One of the advantages of PtL is that it requires minimal or no modifications to existing aircrafts, engines, and ground refueling infrastructure. Thus, the emissions reduction through PtL is expected to be moderate during its transition period, i.e., 2015–2025. However, increasing uptake of PtL will be observed between 2026 and 2050. The cost of reducing emissions through PtL is USD 120 per tonne of CO₂ [103]. Given that the cost for PtL to reduce emissions is much lower than the social cost of carbon for 2050 (i.e., USD 250) [104] and PtL adapts with existing aircraft engines, the proposed road map presented in Figure 5 considers reducing over 1000 MtCO₂ by 2050 through using this mitigation pathway. Therefore, the estimated cost for this pathway is likely to be USD 120 billion. However, it is important to note that the price of PtL varies considerably based on the types of fuel used (gasoline, diesel, kerosene), the price of fuels, the process used (hydrogenation, co-electrolysis), the geographic location, the size and efficiency of aircrafts, etc.

The contribution of biofuels in the 2050 mitigation pathway is considered to be about 11%. This means around 165 MtCO₂ of emissions will be reduced by increasing the uptake of biofuels in the aviation industry. Wastes could be a major source of biofuels [105] along with other non-crop options such as third-generation biofuels (from algae) or fourth-generation biofuels (from genetically modified algae) [64]. In terms of the cost of reducing emissions through biofuels, Hong, et al. [106] predicted that the cost of emissions reduction for 2050 through biofuels is around USD 300 per tonne of CO₂ emissions. It is important to note that the price of biofuel is assumed to be twice of the jet kerosene, while the price of biofuels could vary with the price of raw materials (algae, wastes, crops), geographical location, labor and land costs, agricultural subsidies, and oil prices. Given that 165 MtCO₂ of emissions are expected to be reduced through biofuels, the total costs of reduction for 2050 would be around USD 50 billion.

In the mitigation pathway, it is assumed that 12% of the total emissions reduction (i.e., 180 MtCO₂ of emissions) would be possible by putting a high price on carbon. The social cost of carbon for 2050 is used to determine the price of carbon [107]. The estimate of Nordhaus [108] for the social cost of carbon for 2050 was USD 135 per tonne of CO₂ emissions, while IEA [109] estimated it to be around USD 250 per tonne of CO₂ emissions. Therefore, USD 190 per tonne of CO₂ emissions is considered as the social cost of carbon for 2050 for this study. The cost of reducing 180 MtCO₂ is therefore USD 34 billion.

Generation II (Gen II) aircrafts and fleet efficiency are the other two mitigation pathways that are considered in this study. Generation II aircrafts are still in the development phase and require evolutionary technologies in the area of aerodynamics, propulsions, aircraft equipment systems, structures, and materials to deliver emissions reduction benefits [101]. The large-scale deployment of Gen II aircrafts is expected to be after 2040. These next-generation aircrafts are assumed to be 30% more fuel-efficient compared to present aircrafts, while the target for annual fuel efficiency improvement is 1.5%. The mitigation roadmap considers that Gen II aircrafts will deliver 4.2% emissions reduction benefits

(around 63 MtCO₂), while annual targeted fleet efficiency will deliver 6.3% emissions reduction benefits (95 MtCO₂). Kharina, et al. [110] found in their research that the financial benefits of purchasing a modern aircraft are 3 times its costs over a 17-year ownership period. Benefits outweigh the costs through fuel savings and lower maintenance requirements. They note that US airlines could save 200 million tonnes of oil equivalent (Mtoe) by a 19% fleet fuel efficiency, which could lower the ticket price for short-haul by up to USD 20 and USD 105 for international long-haul flights. The emissions reduction benefits could be around 630 MtCO₂.

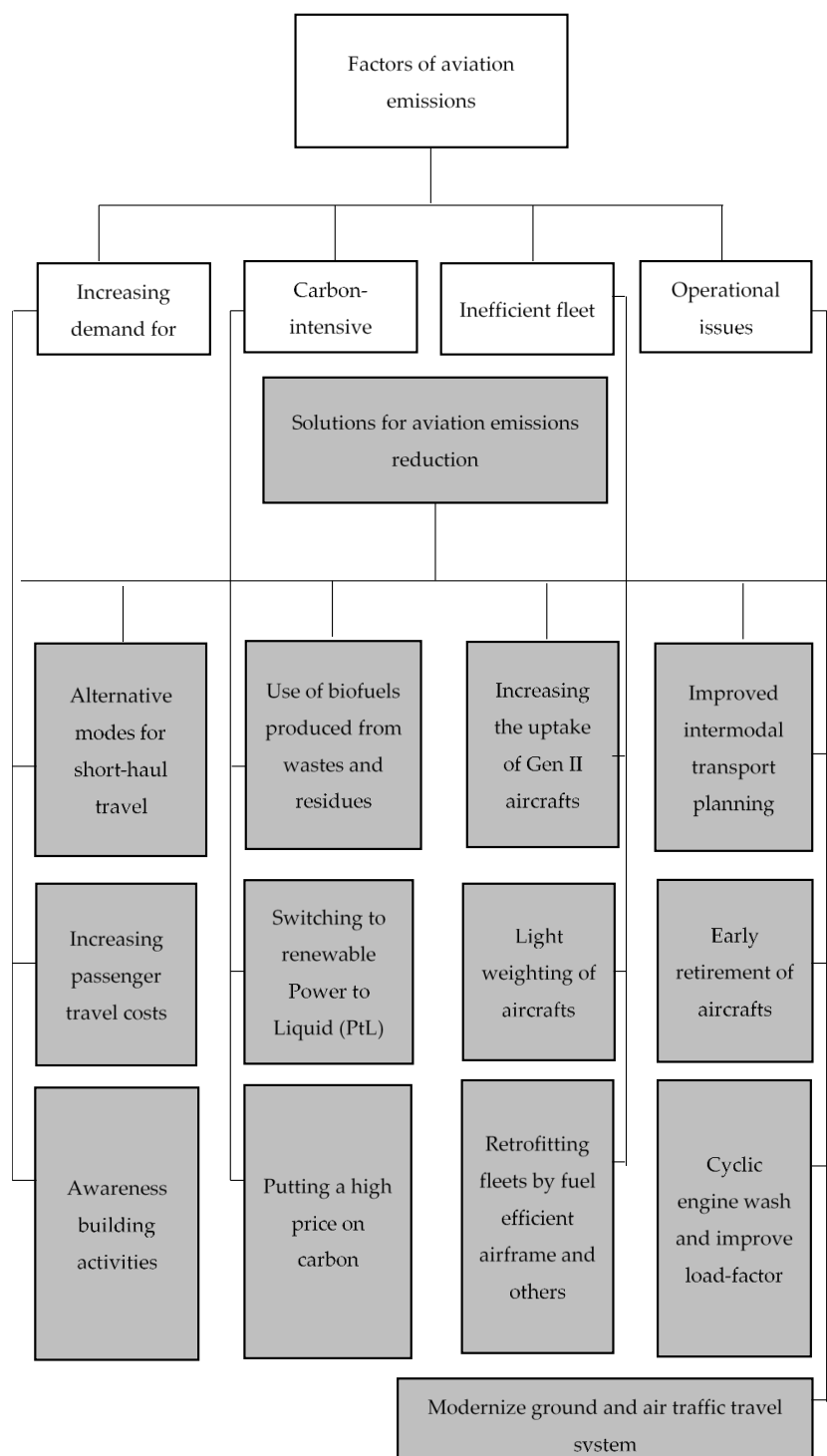


Figure 5. Issues and potential solutions for aviation emissions reduction (Generated by the authors).

Table 4. Roadmap for achieving 2050 emissions reduction targets in the aviation sector (adapted from Transportation and Environment) [102].

Measures	Policy	Assumptions	Impact by 2050
Fleet efficiency	Improve fleet efficiency by 0.5% per year on top of the current fleet fuel efficiency of 1% per year	There will be no rebound effect (i.e., fuel efficiency might reduce ticket prices and lead passengers to travel more)	Around 6.3% of the 2050 emissions reduction target is expected to be achieved (Figure 6).
Gen II aircrafts from 2040	By 2050, 1% of air travel demand will be met through Gen II aircrafts	Gen II aircrafts are expected to be in operation on a large scale from 2040 and assumed to be 30% more efficient than conventional aircrafts.	It is expected to contribute to achieving 4.2% of the 2050 emissions reduction target.
Carbon price	Introduction of a high carbon price equivalent to USD 190/tCO ₂ for 2050	The price elasticity of demand for fuel is adjusted by income elasticities and assumed to be −0.48. It indicates that a 10% increase in price will reduce demand by 4.8%.	Around 12% of the 2050 emissions reduction target is expected to be achieved.
Biofuels uptake	Increase the share of biofuels in the aviation energy mix to 11.4% by 2050	Biofuels will be produced from general wastes and residues, and not from crops.	It is expected to contribute to achieving 11% of the 2050 emissions reduction target.
Renewable power to liquid (PtL)	Increase the share of PtL in the aviation energy mix to 44% by 2050	The primary source for PtL will be renewables and the PtL is expected to be 66% more efficient than regular aviation fuels.	It might help to achieve 66.5% of the required emissions reduction target by 2050.

Mitigation pathways presented in Figure 6 have some advantages as well as challenges. For instance, biofuels have some emissions reduction potential, and many airline companies have already started using them as alternative fuels, but there are limited arable lands for producing biofuels. In addition, land-based biofuels production has impacts on food security and carbon sequestration. Putting a price on carbon is another option to reduce emissions [107], and aviation emissions in Europe are covered by European Emissions Trading Scheme (EU ETS). Although EU ETS has been contributing to aviation emissions reduction, the amount of emissions reduction so far has been very low. The oversupply of emissions permits resulted in a poor price signal to reduce a large amount of emissions from the sector. Among various mitigation pathways, power-to-liquid (PtL) from renewable sources has high emissions reduction potential [111]. However, like biofuels and jet fuel, PtL produces water vapor, and the climate impacts of water vapor and contrail changes are still uncertain and under investigation [58]. In addition, this type of electrofuel is currently expensive and needs policy support for large-scale production and use. Carbon pricing (an ETS or a carbon tax) or blending mandates are some of the key policy instruments that can help promote PtL [111]. Carbon pricing instruments are also found effective to promote biofuels [112]. Therefore, instead of looking into various mitigation measures individually, it is imperative to consider them as a package policy [113].

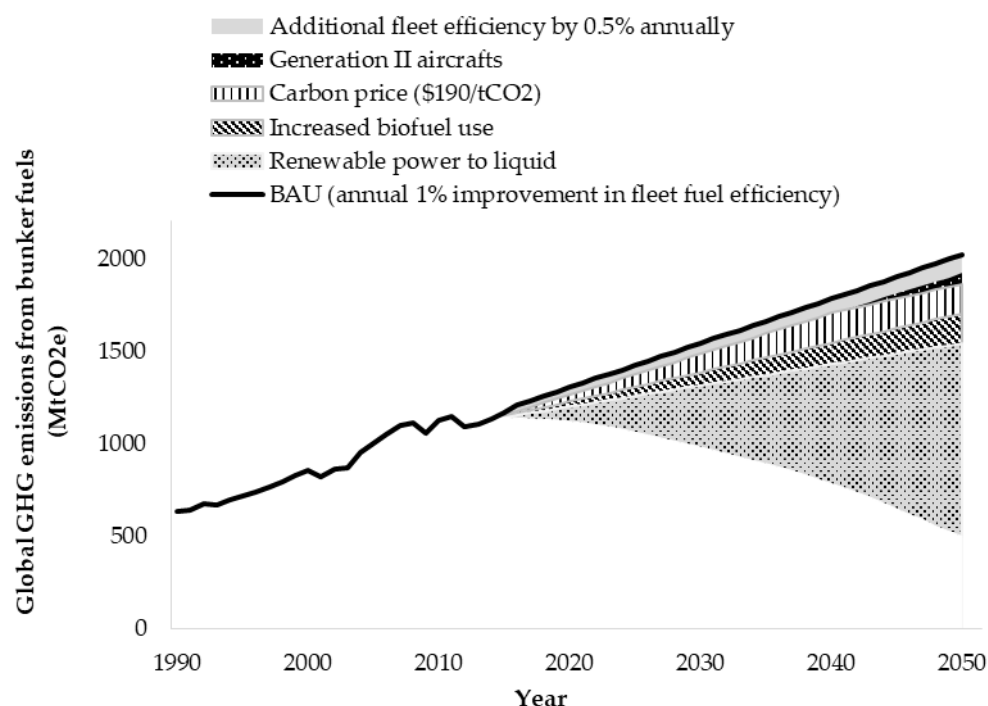


Figure 6. Mitigation roadmap to achieve the aspirational emissions reduction targets in the aviation sector [102].

4. The Feasibility of Proposed Mitigation Pathways

This section presents the barriers of various mitigation options and discusses challenges for ICAO and possible solutions.

4.1. Barriers to Mitigation Options

The assessment of cost-effectiveness in reducing GHG emissions from air transportation shows that a high cost is involved in reducing GHG emissions in this sector. The high demand for air transportation for passenger travel and goods transport, low fuel price elasticity, and dependency on carbon-intensive fossil fuels are some of the major challenges in reducing GHG emissions in the aviation industry [114]. Moreover, the lack of improvement in marginal fuel efficiency is expected to contribute to future GHG emissions in the aviation sector. Emissions trading schemes may lack stringent measures to encourage airlines to improve their fuel efficiency. For example, in the EU emissions trading scheme, changing the carbon prices from 10 Euros to 30 Euros was found to have a less profound effect on the efficiency of reduction of emissions by most airlines [115]. Other challenges are the over-allocation of emissions allowances causing price drops as well as the potential for airlines to pass the costs to customers [116].

The growth in air transportation across the world is one of the barriers to reducing GHG emissions from this sector. Over the last 20 years, the annual average increase in air transportation activity in North America and Europe was 5.7% and 5%, respectively. Likewise, the traffic level of the Asia-Pacific region exhibited rapid growth of 8.8% annually, while an annual average growth rate of 13% was observed in the Middle East [43]. The growing air transportation activity is anticipated to increase energy demand, though low carbon fuels are expected to reduce the aviation carbon footprint. The increasing air transportation and the accompanying surge in fuel demand are likely to offset emission reductions realized from the implementation of national standards and technological improvements [117].

The time constraints to develop and introduce new technologically advanced airplanes into fleets is yet another challenge facing the reduction of GHG emissions. As the life expectancy of an aircraft is very high and this industry is a capital-intensive industry,

the rate of adoption of new technology in aircrafts to mitigate GHG emissions is very small [118].

The competitiveness of SAFs must be equal to or above the conventional sources to spur its widespread adoption by the aviation industry. Unfortunately, there is a sheer lack of governmental support to introduce ample quantities of affordable SAFs to the market. Another intense argument often leveled against the introduction of SAFs is that the production of biofuels from plants, timbers, food, agricultural wastes, sugars, oils, starches, fats, or other types of biomass can affect the environment negatively due to deforestation. The utilization of crops to produce biofuels for the growing aviation industry will also require the monoculture of crops in large areas. A study has shown that the human food chain may be affected if large-scale fertile lands are used for cultivating plants to produce biofuel [119]. Moreover, new land areas have to be cleared for the production of biofuels and a large amount of water, fertilizer, and manpower will be required to meet the large-scale demand. Clearing forests for growing plants to produce biofuels may also destroy the natural CO₂ sequestering process. Biofuels may produce substantial amounts of NO_x during combustion [20]. The emission of CO and NO_x from biofuels (fuel mixed with *Jatropha Methyl Ester*) has been shown to be similar to the emissions from conventional Jet-A fuels [120]. Another study has provided further evidence to indicate that higher NO_x emissions are produced from the combustion of biofuels [121]. This could raise great concerns for widespread deployment of biofuels given that NO_x has a profound influence on the formation of tropospheric ozone, which is an essential GHG. However, a recent study shows that NO_x emissions from biodiesel engines can be reduced by 37% to 50% by adopting water injection and emulsification technologies [122].

Additionally, the benefits of the reduction of emissions may not be justified by the energy efficiency of the production processes of all alternate biofuels [123]. Furthermore, on the supply side, there is growing skepticism on biofuel price volatility and the capability of current production methods of producing one or two biofuels to satisfy the increasing demand for biofuel [124,125]. Moreover, presenting biofuels to overcome the increasing GHG emissions in the aviation industry is complicated by societal perceptions of the sustainability of biofuels and the lack of policies and material support for affordable, sustainable, large-scale supply of biofuel [126–128]. Large-scale deployment of SAFs requires investment in new production facilities, an appreciable reduction in production costs, and substantial investments in ASTM certification [129]. Low carbon innovations in general require profound governmental policy support to be effective in reducing the global emissions gap [100]. In addition, investor uncertainty, coupled with poor policy awareness, militate against progress and large-scale production of biojet fuel [130].

Climate financing to address climate change in the medium- and long-term is very inadequate. A study by UNFCCC shows available funds currently will be insufficient to implement required future adaptation and mitigation measures of climate change. The amount of funds that the developing countries are receiving currently to implement climate change mitigation and adaptation measures is only 20% to 25% of the required amount. Though some states and nations have their own financial support to combat climate change, many developing nations do not have the required resources. Nonetheless, developing nations are expected to contribute to meeting about 68% of the total global emission reduction target by 2030, while the contributions of the developed nations are expected to be 32% [35].

4.2. Challenges for the ICAO

A critical examination reveals that the ICAO standards and recommended practices (SARP) provisions are inadequate for addressing reductions in aviation-related emissions because the SARP is mostly concerned with engine certification rather than the whole aircraft [52]. Fuel efficient engine and aircraft design are essential and need to be considered in tandem to effectively control emissions [52]. Evidence shows that the ICAO and its member states have not implemented the introductory mandatory policy interventions

to stabilize or reduce GHG emissions from the aviation sector. For example, the first implementation phase, 2021–2026, of CORSIA is considered voluntary [131]. In addition, this organization and its member states have interrupted most of the conceivable policy measures for GHG emission reduction. They prefer aspirational goals for emissions reduction targets rather than binding mitigation measures and did not set a mitigation target before 2020 [132]. Moreover, to date, there is no definite scheme for the distribution of offset responsibilities among participating airlines [133]. Notable advancements were not achieved in the production and use of alternative fuels, and measures that could affect the growth of the aviation industry were avoided.

Under the Chicago Convention and the UNFCCC, the ICAO has some oversight powers over aviation emissions, yet lacks exclusive stewardship, leaving states free to work with or without the Organization to develop an emission reduction scheme [134]. A typical example is the EU ETS initiative [116]. Thus, the application of the Chicago Convention and the UNFCCC either enables or disables any state action to reduce aviation-related emissions. This indicates that the ICAO's explicit authority to regulate aviation pollution may be characterized as weak or nonexistent. For instance, Annex 16 to the Chicago Convention outlines limited standards for aircraft engines with respect to the discharges of hydrocarbons, carbon monoxide, and nitrogen oxides, while excluding CO₂, which profoundly contributes to global warming. Furthermore, states failing to comply with any SARP provisions are only expected to notify the ICAO, but are not penalized for such failures [134].

Although the ICAO organizes triennial assemblies to analyze the sector's role in climate change, the progress towards emission reduction initiatives is very slow. This necessitates the EU's unilateral adoption of the EU ETS, a variant of CORSIA to reduce emissions [135,136]. Political disagreement over reduction initiatives between developed and developing nations is one of the major causes behind this scenario. Even though some developed countries are in favor of introducing ambitious emission reduction initiatives, most fast-growing developing nations are concerned with the implications of such initiatives. The UNFCCC's principle of common but differentiated responsibilities (CBDR) often insists that developing nations rule out specific obligations proposed by the ICAO since they believe that such targets might constrain their growth [132].

The only action proposed by the ICAO in 23 years after the introduction of the Kyoto Protocol in 1997 is the target of low-carbon growth from 2020, i.e., to offset GHG emissions above the level of 2020. A study on a sample of twenty-eight airlines suggests that airlines may not be able to meet the target set under the low-carbon growth mechanism due to the nature of emissions limit set by ICAO [137]. Even this emission reduction concept of the ICAO is often highly criticized, as it allows GHG emissions for the sake of growth initiatives and then sets the target to offset emission at a certain point. As the ICAO is obliged by Paris Agreement to limit and reduce GHG emissions from aviation and offsetting does not limit or reduce emissions, the target of carbon offsetting is often treated as a questionable action [132].

Despite MBMs' potential as effective tools for the reduction of GHG emissions from aviation, the ICAO has been slow in devising an appropriate MBM. In 2004, the ICAO first endorsed the trade of emissions in existing emission trading schemes for aviation. However, the insistence of mutual agreement on the proposed MBM methodologies by Canada, the USA, and Mexico has delayed the process. Then, at the ICAO's 38th session in 2013, the member states of the ICAO were again unsuccessful in coming up with a market-based proposal for reducing emissions from the aviation sector. However, in this session, the member states of the ICAO agreed to come up with their proposal for a global MBM in the 2016 assembly. The 39th assembly of the ICAO was held in 2016 with the goal that the member states finalize the global market-based scheme and thus enable the aviation sector to achieve low-carbon growth from 2020 [138], yet progress on it is not equal in all member states. MBMs are generally not immune to carbon leakage; in this

regard, airlines' behavior holds the potential to result in a substantial increase in emissions outside any given policy scope [139].

Ensuring an annual improvement in fuel efficiency by 2% is another aspirational target set by the ICAO in response to global climate change. Between the years 1960 and 2008, the aviation sector experienced an annual average fuel efficiency of 1.5% due to the incorporation of new fleets in the industry [132]. A recent study further suggests that US air-carriers met IATA's 1.5% annual fuel efficiency improvements target between 2010 and 2018 [140]. However, the improvement in the overall fuel efficiency of the entire global fleet has remained constant since 2000. Studies show that achieving fuel efficiency is a measure of performance improvement and not a measure of emission reduction. Therefore, this aspiration target of an annual 2% improvement in fuel efficiency may not make a difference in terms of global emissions reduction. Additionally, the ICAO agreed not to impose any obligations on its member countries to ensure fuel efficiency. Hence, achieving such unenforceable goals of efficiency improvement is mostly questioned by all involved [132].

New and updated emission standards for aircraft engines are another effective tool of GHG emissions reduction in the aviation industry. However, even a couple of decades after the introduction of the Kyoto Protocol in 1997, the ICAO has failed to establish new standards for the emissions of CO₂ and particulate matter (PM) by aircrafts. In 2001, an attempt made by the ICAO to establish GHG emissions standards was ruled out by the member states of the ICAO at that time. Later in 2013, the member states of the ICAO again failed to reach a consensus regarding global standards for aircraft engine emissions. The only emissions standard that has been established so far is the emissions standard for NO_x. However, other emissions standards such as the emissions standard for CO₂ and PM were expected to be established at the 39th session of the ICAO in 2016 [138].

The development and deployment of biofuels for the aviation industry is another challenge for the ICAO and its member states. The sustainability of biofuels is often questioned by researchers, as there are environmental, financial, and regulatory issues associated with it. Although the aviation industry is trying to put its efforts into the production of second- and third-generation biofuels, these activities might cause land use change and will not reduce emissions from this sector.

The standards set by the ICAO are supposed to be legally binding, as the member states of the ICAO are expected to adopt them as national laws. However, standards associated with climate change are seldom incorporated in the national laws of the member states, and they are often considered as guidance and resolutions, which are not legally binding on the member states. As the Kyoto Protocol or the Paris Agreement did not make individual countries responsible for their international aviation emissions and made the ICAO responsible for their emissions, achieving mutual agreement among member states regarding climate change policy issues and guidance has now become most challenging for the ICAO. Considering this fact, the ICAO formed the GIACC (Group on International Aviation Climate Change), a group of 15 experts from each region, to develop non-binding aspirational goals that member states may adopt [132]. On top of this is the fact that progress in meeting the ICAO resolution standards for emissions reduction is not always uniform across the member states. For example, as of 2016, 46.8% of the 188 ICAO members met the 2014 Performance-Based Navigation (PNB) resolution target, while only 35.1% met the full 2016 target [141].

4.3. Approach to Overcome Mitigation Barriers

Financing for the mitigation of climate change, including adopting comprehensive GHG mitigation measures in their aviation industries, is one of the biggest challenges that most countries are facing. The situation in developing countries is worse than that in developed countries. There are several mechanisms for financing climate change mitigation measures, such as the Global Environment Facility, Special Climate Change Fund, Least Developed Countries Fund, Clean Development Mechanisms, Climate Investment Fund, and Community Development Carbon Fund. However, the international aviation industry

does not have any access to those funds [35]. If these funds coordinate with the international aviation industry to access these financial instruments and benefit from some of the climate funds, the aviation industry can implement their climate change programs and actions. Most importantly, ensuring adequate support for developing countries, not only in terms of financial resources but also in terms of capacity building and technology transfer, is important.

An appropriate market-based measure is another instrument for financing climate change interventions in the aviation industry. The necessity of a single global MBM is recognized by all stakeholders in the aviation industry, and some general principles were established in this regard. These principles include preserving fair competition in the market; ensuring uniformity in the standards, procedures, and regulations; taking account of all types and levels of operator activities; and avoiding duplication of existing measures. There are three possible policy mechanisms for global MBMs that the ICAO has proposed to adopt. These are (i) carbon offsetting, (ii) carbon offsetting with a revenue-generating component, and (iii) a global emission trading system (ETS). Among the three possible MBMs, carbon offsetting is often regarded as the most cost-effective, quickest, and easiest to implement. The key criteria that any aircraft operator must fulfill under a single global MBM are to maximize environmental integrity, minimize competitive distortions, and reduce administrative complexity [41]. Proper emissions allocation schemes that consider various indicators of airlines, such as the income and the number and age of aircrafts, are also fundamentally important for yielding dividends from the reduction efficiency of airlines emissions [83]. Setting benchmark emission intensities while offering airlines options to sell and/or purchase permits is also proven to incentivize airlines to reduce emissions [142]. Additionally, it is shown that some air trips lack importance, e.g., leisure flights [143]. Therefore, introducing a harmonized air passenger tax system that increases ticket prices based on distance can potentially reduce demand for air travel and thus emissions. Educating passengers to improve their knowledge on the impacts of aviation on climate change and the potential rewards from carbon offsetting is likely to encourage them to embrace carbon offsetting while reducing the number of flights taken [144–146].

Improving operational efficiency does not require any new equipment or technology, and it can contribute to minimizing GHG emissions due to fuel consumption. Hence, improving the efficiency in flight management is often viewed as a win-win solution for the mitigation of GHG emissions [35]. Optimization of ground operations by introducing single-engine taxis, optimizing ground paths, using tow-tugs in lieu of engine-powered taxis, and minimizing queues are some of the measures effective in reducing energy-related GHG emissions. Reducing cruise speeds, optimizing climb or descent paths, operating at optimum cruise level, optimizing flight routes, and using a descent approach are some of the flight-operation-related optimization techniques that can improve operational efficiency and reduce GHG emissions from this sector. Wells, et al. [147] investigated the minimum time routes for flights between London and New York using optimal control theory and revealed that travel distance for flights could be saved between 0.7% and 7.8% when flying to the west, while the distance saving could be between 0.7% and 16.4% when flying to the east. Since a reduction in travel distance also reduces fuel consumption, emissions could be reduced by bringing this operational efficiency. Furthermore, reducing aircraft weight through operational practices, such as minimizing fuel ferrying, or limiting weight and number of baggage is an effective operational measure in reducing GHG emissions. The aviation system block upgrades (ASBU) are a potentially effective CO₂ emissions reduction initiative. The CAEP modeled the reduction potential of CO₂ emissions by the implementation the ASBU modules and concluded that apart from the direct fuel savings, additional fuel can be saved and CO₂ emissions can be further reduced when aircraft can carry less fuel on-board owing to the improved system efficiency [44].

The introduction of new technologies to manage traffic is very important to mitigate GHG emissions from the aviation sector. The implementation of Reduced Vertical Separation Minimums (RVSM) is one of those technologies that can potentially reduce GHG

emissions due to fuel consumption. A study has shown that the introduction of the RVSM as a standard in US airspace in 2005 has reduced annual fuel consumption by around 1.9 million cubic meters [40]. Required Navigation Performance is another measure that was found to be effective in reducing fuel consumption in the aviation sector in the US. Ensuring an efficient aviation network through improved meteorological information and management of yield tools are also crucial in this regard. The deployment of low-emission measures, such as the use of low-emission airport vehicles for airport operations, is one of the techniques that were found to be effective in reducing GHG emissions from the aviation industry.

Switching from conventional jet fuels to alternate fuels such as biofuels is very effective in reducing GHG emissions in the aviation industry. Biofuels can be produced from a wide variety of sources, such as starches, oils, fats, sugar, forest residues, domestic wastes, industrial wastes, etc. [148]. However, the production of biofuels from foods can affect the human food chain as a large amount of land will be used to cultivate plants to produce biofuels. Therefore, algae, jatropha, halophytes, and switch grass are some of the examples of sustainable nonfood biomass that can be used to produce biofuels for the aviation industry [48]. The current production cost of hydro-processed esters and fatty acids (HEFA) may be between three and four times that of the production cost of fossil jet fuels [149]. Hence, continued R&D efforts in advanced technologies that can potentially reduce the production cost of SAFs is essential for improving the competitiveness of SAFs and commercializing and scaling up of production to meet the demand [150]. Given that NO_x are key components in biofuel emissions, novel approaches to reduce their levels could speed up the widespread adoption of biofuels. For example, exhaust gas recirculation and retarding fuel injection timing are proven to be effective techniques to reduce NO_x [121]. Furthermore, to accelerate commercial and wider-scale deployment of sustainable biofuels, governmental incentives, financial and MBMs, and applied research partnerships are crucial [151]. Carbon pricing can be of substantial help in shifting from energy consumption based on traditional fossil fuels to biofuels.

Short-flight induced emissions are only a small fraction of total aviation emissions, but short-haul flights produce the highest emissions per passenger compared to long-haul flights. Thus, replacing such flights with land-based transportation modes can cut some emissions [152]. Substituting short aviation trips by rail, buses or car-pool is an effective measure in reducing GHG emissions from the aviation industry [153,154]. Incentives for building infrastructure for electric vehicles with low emissions, such as trolley buses, tramway, monorail, or metro-rail can help to shift demand from aviation for short-distance travel. It would also help to encourage commuters and travelers to use teleshopping, teleconferencing, telecommuting, and distance learning as alternate modes of communication [155,156].

The policy interventions of the governments of respective nations or states are crucial for reducing GHG emissions from the aviation sector. Though the ICAO intends to address GHG emissions from international aviation globally, the success of reducing GHG emissions largely depends on the decisions and policy interventions of the governments of the sovereign states or nations. Incentives for technological research, development of novel aircraft engines, promotion of SAFs, and the introduction of modern airport infrastructure are some of the important measures for emission reduction, where interventions of governments are crucial [157].

5. Conclusions

The aviation sector plays a crucial role in the facilitation of domestic and international trade, commerce, and tourism. Over the past two decades, the aviation sector has experienced rapid growth. However, the growth is not sustainable. As the environmental consequences, including the amount of GHG emissions released, are also increasing rapidly. Both the number of flights and the amount of GHG emissions have increased

by 80% between 1990 and 2014. If the current low level of technological improvements continues, GHG emissions will increase by another 45% by 2035 [37].

Challenges associated with the reduction of GHG emissions from the aviation sector are highly diverse. Some of these challenges are associated with technological innovation and design, SAFs, aircraft operations, air traffic and airport management, MBMs, etc. Costs associated with a change in design and technological innovation are very high. There is also a time constraint to develop and introduce new technologically advanced airplanes into the fleets. Low fuel price elasticity and high dependency on carbon-intense fossil fuels have limited the production and use of low-carbon alternate fuels in this sector. Moreover, researchers often pose questions on the sustainability of the use of biofuels, as there are major environmental, financial, and regulatory issues attached to it.

Challenges faced by the ICAO also contribute to the increase in GHG emissions from this sector. Except for the aspirational goals, ICAO has not set mitigation targets or binding measures before 2020. Political disagreements between developing and developed nations on ambitious emissions reduction targets are hindering many emissions reduction initiatives. In addition, disagreements among the ICAO member states on aircraft engine emissions are impeding the establishment of new emissions standards for CO₂ and particular matter for the aircraft. The ICAO's failure in establishing mandatory MBM and appropriate emissions allocation strategy seems to be slowing down global efforts to curb emissions. Moreover, the ICAO member states seldom adopt the ICAO standards on climate change as their national laws.

Although scientific knowledge and technological advancement have resulted in improvements in the aviation sector, aggressive and sophisticated technologies are required to reduce emissions beyond the current levels to achieve ICAO's low-carbon growth. Continued R&D efforts are necessary to ensure that efficient emission reduction technologies become affordable and commercially viable for large-scale deployment. Specifically, technological advancements that target aircraft design and fuel-burn reduction, while reducing the GHG emissions, should be the prime focus and objective of the R&D efforts. The adoption of SAFs such as liquid hydrogen, FT kerosene-type jet fuels, and synthetic bio-based fuels has to be increased rapidly, while improving technologies capable of reducing NO_x emissions. Technological improvement, alternate fuels, and operational efficiencies alone are not enough to achieve future emissions reduction targets in the aviation industry. Hence, modernization of the airports and the ATM systems are also required for the steady reduction of GHG emissions. The necessity of different MBMs also has to be realized. Effective market-based policies such as the ETS, carbon tax, and the CORSIA must be established and implemented globally. Carbon offsetting, for example, can be an immediate and pragmatic approach to encourage various stakeholders (i.e., airline passengers and corporate customers) to take collective and concerted action to curb CO₂ emissions and climate change impacts. Given that air travels are likely to increase in the post-COVID-19 era due to increased economic activities both in developing and developed countries, rigorous implementation of market-driven policies is likely to incentivize the development and adoption of low-emission technologies. Additionally, it is essential to educate and enhance the knowledge of passengers as well as airline workers on the climate change impacts of aviation emissions. Finally, a national emissions mitigation plan must be incorporated by the member states of the ICAO, together with building public awareness along with other initiatives. New or updated nationally determined contributions of the ICAO member states that ratified the Paris Agreement would be essential for assessing the progress made in national emission reduction efforts.

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Abbreviations

ASBU	Aviation system block upgrades
ATM	Air traffic management
BAU	Business as usual
CAEP	Committee on aviation environmental protection
CO ₂	Carbon dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
EEA	European economic area
ETS	Emissions trading scheme
EU ETS	European Union emissions trading scheme
FAA	Federal aviation administration
FGBs	Fourth generation biofuels
FT	Fischer-Tropsch
Gen II	Generation II
GHG	Greenhouse gas
GM	Genetically modified
IATA	International air transport association
ICAO	International civil aviation organization
IEA	International energy agency
ktCO ₂	Kilo-tonnes of CO ₂
MBMs	Market-based measures
MCMOED	Million cubic meters of oil equivalent per day
MtCO ₂	Million tonnes of CO ₂
Mtoe	Million tonnes of oil equivalent
NO _x	Nitrogen oxide gases
OECD	Organization for economic co-operation and development
PM	Particulate matters
PtL	Power to liquid
R&D	Research and development
RVSM	Reduced vertical separation minimums
SAF	Sustainable aviation fuels
UNFCCC	United Nations Framework Convention on Climate Change

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