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Reducing Carbon Emission Towards Sustainable Aviation

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***Abstract*—Aviation is a highly energy-intensive sector, making it the second-biggest source of greenhouse gas emissions in the transportation sector, with road transport leading the way. Emissions continue to rise despite advancements in aircraft efficiency over the past six decades due to the increasing demand for air travel. Reviewing the reduction of carbon emissions in aviation is essential to protect the environment, drive innovation and secure a sustainable future in aviation. Stakeholders responsible for reducing carbon emissions are primarily found in the industrial sector. The challenges and opportunities related to reducing carbon emissions in aviation are investigated with a focus on Sustainable Aviation Fuels (SAF), advancements in fuel-efficient aircraft, and improvements in air traffic management. Studies have shown that using SAF, derived from renewable resources such as waste oils, algae, and municipal waste, can reduce lifecycle carbon emissions by up to 80% compared to conventional jet fuel. The use of SAF is limited due to cost and the difficulty in producing it. In addition, the use of electric and hydrogen-powered aircraft is highlighted, as it can revolutionise the industry by offering zero-emission alternatives for both short- and long-haul flights. Recommendations are provided to achieve net-zero emissions by 2050, aligning with the Sustainable Development Goals (SDGs) set by the United Nations, specifically SDG 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action).**

Keywords*—Net-zero emissions, Sustainable Aviation Fuels (SAF), Electric aircraft, Climate change.

I. INTRODUCTION

Flying is one of the major modes of travel that has been widely utilised ever since it was commercially available. The emissions produced by aviation was the highest and fastest growing of individual emission before the pandemic with the passenger count world-wide in 2019 at 4.56 billion and estimated to be close to 9.5 billion in 2024. The emissions produced is high even though there has been significant improvement in aircraft efficiency and flight operations over the last 60 years [1]. In past records, the commercial aircraft uses jet fuel (kerosene), and the global consumption has increased each year since 2009 and reached 95 billion gallons in 2019 which was an all-time high. The fuel consumption dropped to 52 billion gallons in 2020 due to the coronavirus pandemic. It is forecasted that to increase to 99 billion gallons in 2024 as commercial airlines increased their fuel consumption as of 2021 [2]. Approximately 2% of carbon dioxide (CO_2) emissions globally are contributed by aviation, which contributes 3% of the total greenhouse gas emissions together besides causing nitrogen oxides (NO_X) and other emissions [3]. Based on the projected growth of passenger air travel and freight, the emissions produced is estimated to triple by year 2050 [1].

Figure 1 shows how flying affects the climate in more ways than just CO_2 emissions. Aircraft also release other gases and particles like NO_X, water vapour, soot and aerosols. These emissions happen at high altitudes, where they can create clouds called

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contrails and increase ozone levels. These effects trap heat and make the climate warmer. The figure uses the Radiative Forcing Index (RFI) to show how much stronger the total warming effect is when these non-CO_2 emissions are included. The chart in the figure shows that air travel affects the climate not only through CO_2 emissions but also through other emissions that increase warming [4].

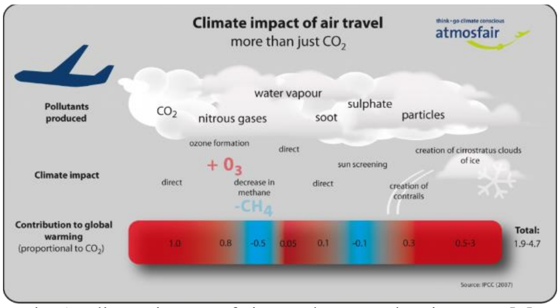

Fig. 1. Climate impact of air travel – more than just CO_2 [5].

Climate changes are significantly contributed by emissions from aviation. Burning fossil fuels in planes also causes strong warming effects that aren't from CO_2. These come from NO_x emissions, vapour trails, and clouds formed at high altitudes [6]. These other emission byproducts (NO_x, water vapour, soot and aerosols) contribute substantially to global warming when, at altitude, react with the atmosphere [7]. The impact on climate change extends beyond carbon emissions caused by the aviation industry, contributing to significant warming through non-CO_2 effects. Condensation trails, or contrails, form artificial clouds that trap heat, often spreading into cirrus clouds and this intensifies their warming effect. Nitrogen oxide (NO_x) emissions from aircraft generate ozone, a potent greenhouse gas, the net result is increased warming as well as reduces methane levels. These high-altitude emissions are amplified, as pollutants released at cruising altitudes have a stronger climate impact than those at ground level. These factors accelerate global warming, exacerbating heatwaves, extreme weather, ice melt, and sea-level rise, with cascading consequences for the ecosystems and human health [7].

Representatives of the world's major aviation industry stakeholders released a long-term commitment to achieve net-zero carbon emissions by 2050. This reflects the urgent need to transform aircraft propulsion toward greener and more sustainable energy sources. The article outlines the responsibility of relevant bodies and stakeholders who play direct or indirect roles in the aviation industry. The article summarises key challenges and limitations, while also highlighting recent advancements to urge industries and policymakers to take immediate action toward achieving sustainable aviation.

II. STEP IN REDUCING CARBON EMISSIONS

Aviation represents one of the most significant sources of air pollution. Aircraft release greenhouse gases that cause global warming through fuel combustion, producing not only carbon dioxide but also nitrogen oxides and sulfur dioxide [8]. Sustainable Aviation Fuel (SAF) has emerged as an alternative to reduce these emissions [9]. SAF is a proven way to cut greenhouse gas emissions by up to 80% over its lifecycle compared to kerosene and regular jet fuel [10].

Many different groups are important in helping reduce aviation's carbon emissions. Table I presents projected CO_2 emission reductions in aviation through different abatement measures from 2019 to 2070, showing each measure's expected contribution, implementation timeframe, and important considerations affecting effectiveness.

Table I. Projected CO_2 Emissions Reductions in Aviation by Abatement Measure (2019-2070).
Data adapted from [11, 12], and other sources listed in the table.

Abatement Measure	Contribution to Emissions Reduction	Timeframe	Notes	Source
Sustainable Aviation Fuel	24%-70%	By 2050	Contribution depends on investment, production scale, and policy support	[10, 11]
Aircraft Technology Improvements	~20%	2020-2050	Gradual improvements in fleet design and performance	[12, 13]
Operational Efficiency Enhancements	~10%	2020-2050	Includes better air traffic control, route planning, and reduced airport congestion	[14, 15]
Electric and Hydrogen Aircraft	<5% (initial impact)	Post-2035	Currently in development; more relevant for long-term emissions strategies	[16, 17, 18]
Market-Based Measures (e.g., Offsetting)	Remaining emissions to reach net-zero	2020-2070	Used to balance emissions not eliminated by other measures	[19, 20]

A. Roles of Scientists

Sustainable Aviation Fuel (SAF) was first introduced in 2008 as an alternative to conventional jet fuel. Early tests showed that SAF can reduce greenhouse gas emissions by up to 80% over its lifecycle compared to traditional jet fuel [21]. SAF resembles conventional kerosene-based aviation fuel but produces lower carbon emissions through various pathways, including carbon capture technologies and biogenic-carbon feedstock such as biomass [22]. SAF requires no modifications for use, reducing implementation costs as it can be blended with regular jet fuel in existing aircraft. SAF can be produced from wet waste, creating carbon-negative fuel from food waste, animal manure, and other organic materials. Researchers are studying other aviation fuels like bio-jet fuels, electro-jet fuels, liquefied methane, hydrogen, and ammonia [23].

SAF is important for helping the aviation industry reach its net-zero carbon emissions goal by 2050. Since 2008, industry adoption has increased significantly. ASTM International's certification of SAF since 2011 has enabled over 750,000 flights to use sustainable fuel [24].

Fuel-efficient aircraft represent another carbon reduction strategy through precise fuel consumption calculations for each journey. The Boeing 747's automated docking system helps save fuel and lower carbon emissions [25]. Fuel efficiency optimization determines the minimum fuel required per flight, directly reducing CO_2 emissions through decreased fuel consumption. Modern aircraft designs incorporate improved aerodynamics, reducing drag and fuel consumption. New aircraft types feature enhanced aerodynamics and improved engine systems, contributing to reduced fuel consumption and carbon emissions [13].

Removing carbon directly from the air using carbon capture is a new and promising technology. Direct Air Capture (DAC) systems take carbon molecules from the air. There are different types of DAC, like solid and liquid sorbents. DAC systems can be small or large, capturing from a few kilograms to a million kilograms of carbon [26]. At the research stage, it is important to measure low levels of CO_2 and humidity accurately to check how well the capture works, understand the process, and improve it. Accurate CO_2 measurement is also needed when removing CO_2 from the sorbent [27].

B. Roles of Industry

Neste is the main producer industry of the sustainable aviation fuel. Sustainable aviation fuel is a type of new alternative jet fuel which is 100% made from renewable raw materials. It can be produced by waste oil, animal fats, green and municipal waste, and food waste [28]. Moreover, the new sustainable aviation fuel can be manufactured by converting alcohols such ethanol and iso-butanol into fuel. Hence, sustainable aviation fuel is not refined from crude oil [3].

It is a more environmentally friendly source of aviation fuel due to crude oil is not a renewable source. Sustainable aviation fuel is fully synthesized from the renewable and sustainable resource [29]. From the other side, production of this environmentally friendly fuel has been reducing the waste from the environment. Sustainable aviation fuel is also chemically identical to the conventional kerosene jet fuel and has the specifications of the jet fuel [30]. This fuel is compatible with existing aircraft engines and airport fuel infrastructure. Therefore, European Aviation Safety Agency (EASA) and the US Federal Aviation Administration (FAA) have already put in approved the usage of the sustainable aviation fuel [3].

The aviation industry has been leading efforts for sustainable development and working toward the aviation carbon-neutral growth (CNG2020) plan. The CNG2020 plan has three goals: to improve fuel efficiency by 1.5% each year by 2020, to reach carbon-neutral growth by 2020, and to cut emissions by 50% from 2005 levels by 2050 [12]. In 2021, a new plan was made to reach net zero carbon emissions in air travel by 2050. It aims to reduce carbon dioxide emissions as much as possible using solutions like sustainable aviation fuels, new aircraft technology, better operations, and new zero-emission energy sources [12].

60% of market in Airbus industry has the aircraft that can fly on a maximum of 50% blend of sustainable aviation fuel and kerosene fuel. Airbus also plans to manufacture the Airbus aircraft which can fly with 100% of sustainable aviation fuel by year 2030 [3]. On the other hand, Boeing is also making the usage of the sustainable biofuel in aviation. This biofuel is also already available at key airports around the world, such Changi Airport, Frankfurt Airport, and San Francisco International Airport [31]. Combustion of fuel manufactured from the renewable waste in aircraft is no longer an experimental project to reduce carbon emission. Approval from both largest aircraft manufacturers and airports in the world have proven that sustainable biofuel is a reliable and important step to reduce the carbon emissions effectively.

Electric and hybrid-electric aircraft (HEAs) use both traditional fuel engines and electric motors to fly. The electric motors are mainly used during take-off and landing, while the fuel engines provide power during flight. These motors are powered by batteries or other energy storage systems, such as fuel cells [16]. Compared to conventional aircraft, HEAs use less fuel because they rely less on combustion engines during certain parts of the flight [17].

The potential to reduce emissions and improve the environmental impact of air travel is one of the most significant benefits of HEAs. There are growing concerns about climate change and air pollution worldwide and the interest in green technology has increased over the years. Reduction of fuel consumption and maintenance costs could also be achieved airlines with the use of HEAs [32]. Finally, HEAs are quieter than regular airplanes, especially during take-off and landing with battery help, which could reduce noise near airports [33].

C. *Roles of Airlines*

Airline is also responsible to reduce carbon emissions. Airlines are encouraged to use route plan optimising software to plan the most efficient flight route which can minimise the flight distance and the flight time [34]. At the same time, optimisation of flight route minimises the flight distance to reduce the emission of carbon gases from the aircraft in the air. Choosing a best route for every flight must rely on various factors and each factor is important to the cost of each flight. For instance, flight distance, the average number of passengers of each flight, and the weather conditions of the flight route are considered to plan a new flight route [35]. Shorter flight route can reduce the carbon emission to the atmosphere effectively.

On top of that, airport should improve the air traffic management and route optimization can reduce carbon emissions [14]. This is because the Air Traffic Control (ATC) shall choose the most appropriate aircraft for a certain journey and can determine how much fuel to be used by that aircraft. The introduction of AI in the aviation industry, has helped airlines make better and informed decisions [15]. AI can make various possibilities forecast according to the analysis of the weather conditions and the length of flight, so that it can come up with solutions [15]. It can also determine the fuel needed during the whole flight even in emergencies. Improving aircraft spacing and air traffic control can stop planes from bunching up and being delayed. This happens when planes must wait in the air, using extra fuel [13].

Airlines should also choose to operate modern aircraft that include higher fuel efficiency engines. Long-haul flight can be operated with modern twin engines aircraft such as Airbus A350 and Boeing 787 instead of using the standard four engines aircraft which is Airbus A380 and Boeing 747 [34]. The modern engines on aircraft can utilise the fuel efficiently and produce less soot in the air. Airlines should operate their optimised flight route with the modern aircraft to create flight with efficiency and eco-friendly. For example, British Airways has showcased their decarbonising effort through a combination of using sustainable aviation fuel on new Airbus A320neo and route optimisation [36]. Through these effort on reducing carbon emission is not only able to sustain the environment but also airlines are able to reduce costs and increase productivity from each flight. Sustainable aviation should be highly regarded to all airlines to create a "perfect flight" which include sustainability and productivity [37].

Figure 2 shows the different groups that are helping to reduce carbon emissions from aviation. These groups include scientists, industries, airlines, and governments. Scientists work on new fuels and cleaner technologies. Industries produce sustainable aviation fuel and design better aircraft. Airlines try to fly more efficiently and use better route planning. Governments make rules and policies to support cleaner aviation. The figure shows how all these groups have an important role in working towards lower emissions and a more sustainable aviation sector.

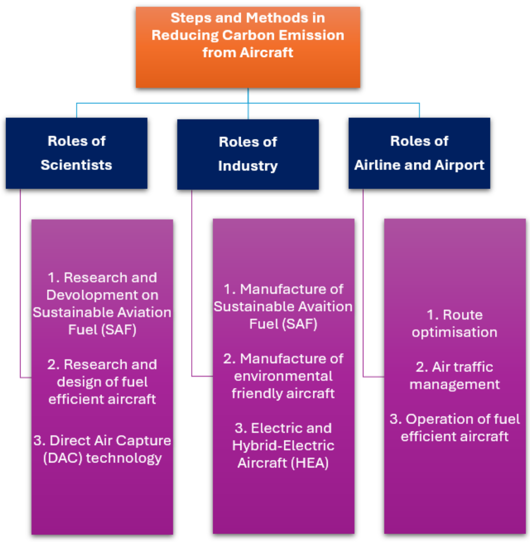

Fig. 2. Roles of different stakeholders in reducing carbon emissions.

III. CHALLENGES AND LIMITATIONS

Reaching net zero emissions by 2050 requires using existing clean energy like solar and wind, along with developing new low-carbon technologies. However, many challenges to adopting these technologies go beyond just the cost. "Transition barriers" is currently framed as challenges faced to transition to net-zero. The barriers are grouped into seven areas: climate, management, technological progress, fuel changes, funding, governance, and social factors [38].

Technological innovation encompasses the anticipated performance improvements of next-generation aircraft, including advancements in airframe and engine design, as well as the rate at which existing fleets are replaced with newer models. A key challenge is that new technologies and fuels—like electric, hydrogen, and e-fuel systems—are still not available and may not be ready within the expected timelines. Slow development of sustainable fuels which are crucial to decreasing carbon emissions due to their expensiveness and not being widely available.

Governance plays a critical role in enabling systemic transitions. It is shaped by political interpretations of net-zero obligations—specifically, the extent to which responsibility is attributed to airlines, aircraft manufacturers, travellers, or governmental bodies. At the international level, while the International Civil Aviation Organization (ICAO) formally contributes to shaping the sector's climate strategy, its Carbon Offsetting and Reduction Scheme for International Aviation has been widely viewed as inadequate [19]. Advancing aviation decarbonization largely depends on national-level initiatives, as global coordination remains limited. Various governments and regulatory entities, including the European Union, have integrated aviation into their Nationally Determined Contributions (NDCs) [39 – 42], implementing measures such as emissions trading systems, fuel blending mandates, carbon pricing, surcharges on premium-class tickets [40 – 42], and targeted interventions like short-haul flight restrictions in France [43] and airport slot reductions in the Netherlands [44].These kinds of policies need to be adopted worldwide to ensure a level playing field and to have relevance. Some important questions still need answers, such as whether governments will provide funding for research and development or help reduce the higher cost of cleaner fuels. Many groups are asking for government support to help with the transition. Governments may be reluctant to impose strict regulations due to potential economic impacts on the airline industry.

Increasing air travel demand represents another barrier that offsets emission reductions, making net-zero goals difficult to achieve. Fast growth in developing countries leads to more flights and higher emissions. Air transport prioritizes demand increases and profitability, with the system primarily focused on capacity expansion and passenger numbers expected to double by 2041 [45]. Aircraft designs feature specific seating arrangements with premium-class seats occupying substantial space [46]. Many flights operate with empty seats and unused cargo space, while average flight distances continue increasing. Future fuel consumption may increase if aircraft modify routes to avoid congested airspace and reduce climate impact.

Supply chain challenges also hinder net-zero goals through limited SAF production and high costs that prevent widespread adoption. Despite SAF's promise, current adoption remains limited. As of 2023, SAF output reached 600 million litres, representing 0.2% of global jet fuel demand. SAF's higher cost compared to conventional fuels remains a key impediment to broad deployment [11]. The transition to new fuel sources involves numerous challenges and complexities, including future fuel mix determination affecting energy requirements (electricity or biomass), production limitations, fuel sustainability, alternative fuel scaling speed, required infrastructure (charging stations, storage, transport), lifecycle CO_2 avoidance including extraction, refining, and transport, and comparison with non-CO_2 effects such as high-altitude soot and water vapor emissions. E-fuels are promising for cleaner aviation [47] but are not yet produced, even at small scales. Although ICAO lists many SAF and e-fuel production sites on its dashboard, it provides no production information or operational timelines. Some sites are marked as 'in service' despite not operating.

While progress is being made, overcoming these challenges requires a mix of technological innovation, policy changes industry investment and consumer willingness to tackle these challenges.

IV. RECENT ADVANCEMENT TOWARDS SUSTAINABLE AVIATION

The question of viability in the aviation industry is gaining popularity as environmental consciousness rises. Due to aviation's substantial contribution to global carbon emissions, sustainability is more crucial than ever. This approach goes beyond merely lessening our influence on the environment. It's also about building an efficient and eco-friendly aviation industry for the future.

A British business named Firefly Green Fuels is looking into using hydrothermal liquefaction to create kerosene from human waste. According to tests, this fuel can cut CO_2 emissions by more than 90% while compared to regular kerosene. Airlines like Wizz Air hope to implement this SAF on a portion of their flights by 2030, with production set to start in 2028 [48].

To increase aviation sustainability, sustainable aviation fuels, SAFs, are necessary. Plant oils, rubbish, and algae are examples of renewable resources that are used to make these fuels. Their carbon emissions can be cut by up to 80% compared to regular jet fuels. SAF helps reach the goal of net-zero carbon emissions by 2050 and lowers the environmental impact of flying. Airlines are using SAF more and more to reduce their effect on the environment [18].

The aviation sector aims to have net-zero carbon emissions by 2050. This lofty aim necessitates considerable changes in how aircraft are powered and controlled. SAF adoption, fuel efficiency improvement, and investment in new technology are all examples of sustainability measures. Carbon offset schemes and reforestation projects will also be part of the net zero strategy [20].

Electric and hydrogen-powered planes are the future of eco-friendly aviation. They aim to reduce carbon emissions during flights. Electric planes are good for short trips, while hydrogen planes can fly longer distances. Both are being developed and tested now. As these technologies improve, they will be more important for sustainable aviation [18].

Converting all ground vehicles to electric power represents another important step, including airside and landside vehicles such as baggage carts, airport shuttles, and maintenance vehicles. Using electric vehicles instead of diesel reduces carbon emissions and air pollution. Many airports are purchasing electric vehicles and building charging stations to support this transition, making airports more sustainable and cleaner for workers and travellers [18].

European Union mandates require European aircraft to blend at least 2% SAF into their fuel beginning in 2025, with targets rising to 70% by 2050. This regulatory drive aims to significantly reduce aircraft CO_2 emissions [48].

The European Aviation Environmental Report 2025 provides numerous recommendations to reduce aviation's negative effects on air quality, noise pollution, and climate change, emphasizing initiatives including fuel-efficient technology implementation, air traffic control improvements, and expanded SAF usage [49].

V. CONCLUSION AND RECOMMENDATIONS

In conclusion, the aviation industries play a huge role in our global transport, moreover it is also one of the biggest contributors to greenhouse gases emission. Even after staggering achievements in the aim of increasing aircraft efficiency in the past few decades, emission of greenhouse gases continues to rise due to the fact of the increasing demand for air travel. Sustainable Aviation Fuel (SAF) and other low-carbon technologies are emerging to combat this emission of greenhouse gases with great success. Nevertheless, the research and innovate in sustainable aviation practices need to be continued, so that long-term environmental goals are achievable while maintaining the efficiency and accessibility of air travel for everyone whenever and wherever.

Policymakers in the aviation industry, including the International Civil Aviation Organization (ICAO), International Air Transport Association (IATA), National Civil Aviation Authorities, International Energy Agency (IEA), and other important bodies, should meet regularly to discuss emerging industry problems and appropriately modify and add new air travel regulations. For example, frequent flyer taxes could reduce aircraft carbon emissions through decreased demand while generating substantial government revenue for aviation industry improvements [50].

ICAO organization members must follow established air travel rules to achieve objectives and SDGs. For instance, environmental protection objectives require all member countries to comply with regulations such as reducing sulphur-containing jet fuel usage to minimize SO_2 gas release, which is toxic and corrosive during combustion.

All the stakeholders and policy makers including the government, industries and researchers must band together to achieve these advancements to create a better tomorrow.

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