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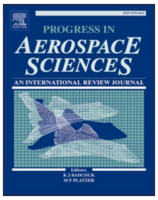

# An open thinking for a vision on sustainable green aviation

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## ABSTRACT

The main goal of this paper is to present a vision for the future of aviation. Developing such a vision is always a complex matter, but in times of environmental emergencies and unjustifiable wars it becomes even more difficult. One of the main reasons of this paper is to show that there is still room for advancing clean technology developments and to demonstrate that the aviation sector is ready for embarking on new challenge.

Green and environmentally sustainable aviation, in our opinion, can be achieved with continuous improvements along multiple parallel paths, ramp up of SAF (Sustainable Aviation Fuel) production, and of course, breakthrough technologies. The latter will require a significant amount of research, testing and probably mistakes need to be made before reaching the level of transportation efficiency and mission safety obtained with traditional propulsion, but these drawbacks should only encourage scientists, engineers, politicians and visionaries to strongly pursue the objectives of a new eco-aviation.

Aviation decarbonization requires a strategy change from near term improvements in aircraft fuel efficiency to long term (from neutral to zero carbon emissions) fuel switching. The successful introduction of long-term solutions requires transdisciplinary research into technological, operational and economy fields.

New technologies should probably be introduced into smaller aircraft segments first then migrate into the larger segments as the technologies mature. We should expect a first electric and hydrogen fuel cell commuter aircraft entry into service by the end of this decade, with hydrogen combustion-powered narrow bodies around 2040.

In 2019, aviation accounted for approximately 2.3% of global greenhouse gas emissions, with global commercial fleet $CO_2$ emissions totaling 0.918 Gigatonnes. Narrowbody and widebody aircraft produce over 95% of the industry's greenhouse gas emissions, therefore, while the introduction of new technologies on smaller aircraft will be important for the development of sustainable solutions, they will have minimal impact on the overall carbon footprint until they make their way onto larger platforms. However, carbon-free fueled (electric, hydrogen) aircraft will require significant infrastructure investments to develop the novel transportation network and the re-fueling procedures that will be required to support their use. Therefore, their success will require the coordinated combined efforts of the entire industry (airlines, airports, air navigation service providers, manufacturers) and significant government support.

This paper tries to summarize the most important aspects for a vision on sustainable green aviation and to indicate a possible roadmap for reaching this goal.

## 1. Introduction

The airplane evolution and progress is strongly related to the development and improvement of its propulsive system. The history of aviation is primarily the history of the aircraft engines, from the propeller to the jet-age and to the turbofan and high bypass ratio engines installed on modern widebodies like A350 and B777, [1].

The contribution of aviation to society, human development, prosperity, and growth is unquestionable and, moreover, aviation is a challenging business, where technical, regulatory, financial aspects – just to name a few – must be evaluated for any development or change implementation. The demanding regulatory environment in which aviation operates ensures that a remarkable safety record is maintained. This makes aviation a difficult-to-abate business.

We should consider ourselves as lucky persons, from an aviation perspective, because we are at the beginning of a new revolution of the aircraft propulsion which, as in the recent history, will change the architecture of future flying vehicles, opening new frontiers and opportunities.

The driving factor for such new, still not available, aircraft is the stringent requirement for an environmentally sustainable aviation. Many institutions worldwide are addressing the environmental impact as one of the principal requirements for the next decades.

In Europe, the guidelines are set by the European Commission in association with the Advisory Council of Aviation Research (ACARE), under Vision 2020, now through Flightpath 2050 and the corresponding strategic research and innovation agenda [2,3]. Environmentally Responsible Aviation N+ series programs sponsored by the National Aeronautics and Space Administration (NASA) lead the guidelines and performance goals for the civil aviation industry in the USA [4]. The key

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aspect of these goals is to make the fleet operation more energy-efficient, reliable, and to reduce the emission and community noise related impacts. Many technology paths are being explored for improvements in the airframe and structural designs, in the propulsion system, and of the air-traffic management system to achieve such ambitious expected targets, [5,6].

Current research guidelines are aligned towards the use of sustainable aviation fuel (SAF), the conversion toward more electric power in propulsion system, the implementation of hydrogen combustion, the application of hydrogen fuel cells, the combination of hybrid solutions, [7–11].

The sustainable aviation roadmap has the goal to achieve the target of net zero carbon in commercial aviation by 2050, considering how the new technologies will impact the commercial aircraft fleet and simultaneously key industry stakeholders, Fig. 1. This paper will focus, based on the authors' perspectives, on the analysis of market trends, aircraft design evolution, sustainability developments, technology maturity, operators' requirements, and public acceptance.

Increasing viable industrialization end efficient production of SAF appears to be, at the moment, the most effective way to reduce the carbon impact of commercial aviation and therefore procedures for accelerating production, incentivizing the use, and reducing the cost should be prioritized.

In parallel, speeding up the implementation of operational and navigation enhancements such as those planned in the FAA NextGen and EASA SESAR programs are expected to reduce greenhouse gas emissions immediately and again they deserve priority.

New technologies should be introduced into smaller aircraft segments first to be used as experimental platform [12–14], then migrate into the larger segments as the technologies mature, [15]. It could be expected to see the first electric and hydrogen fuel cell small commuter aircraft enter into service this decade, with hydrogen combustion-powered narrowbodies around 2040, Fig. 2.

This is the result of a delicate balance between market, technological, operational, strategical factors: different technologies have different abilities to satisfy market requirements (aircraft ranges, utilization, size and capacity to name a few), technology penetration will be different in different geographical regions (supply of fuels, maturity of infrastructure, ..), Technology readiness timing alignment with new aircraft programs Entry Into Service, Production capacity of potential OEMs, Market Share trade-off between alternative solutions, Large OEMs product development strategies and, probably most importantly, the political will to fund such developments which as we know, are not homogeneously spread worldwide.

Just recently H2FLY, a German based company, has accelerated the progress toward zero-emission flight expecting first passenger aircraft flying on liquid hydrogen in 2023, [16]. Zeroavia, early this year has completed a 10-min test flight of a 19-seat aircraft powered in part by hydrogen fuel cells, [17]. Airbus has launched the ZEROe demonstrator program with the aim of ground and flight-testing hydrogen combustion technology on an A380 platform, [18].

Carbon-free fuels (electric, hydrogen) will require significant infrastructure investments to develop the novel transportation network and the re-fueling procedures that will be required to support their use. The timing for the introduction of new technology programs will be influenced by the lifecycle of existing aircraft programs which typically last 20–25 years. The enormous investment required to validate and certify a new program dictates a cautious approach to novelty. Regional aviation provides a vital service to smaller communities ensuring connectivity and supporting the economy. A rapid roll-out of clean, quiet technologies in the smaller aircraft segments will be crucial to supporting growth in these markets, [19].

Acting now to improve efficiency today is vital. Despite reductions in air travel demand due to COVID-19, the aviation industry forecast is for a still strong growth propelled by increased GDP and propensity to travel. Aviation decarbonization will require strategies both in near term improvements in aircraft fuel efficiency and long-term propulsive switching which will encompass transdisciplinary research. Many stakeholders will have an impact on the rate of acceptance of the various sustainability solutions available to commercial aviation, Fig. 3. It will be crucial to have a coordinated and synchronized effort by all of those involved including airlines, airports, manufacturers, governments, certification authorities, and fuel suppliers, among others, [20–23].

In the near future significant improvements toward green transportation (land and sea) are expected and cross-fertilization of the outcomes are foreseen to affect also air transportation for the application of such new technologies, [24–26].

One of the motivations of this paper is also for recalling the attention

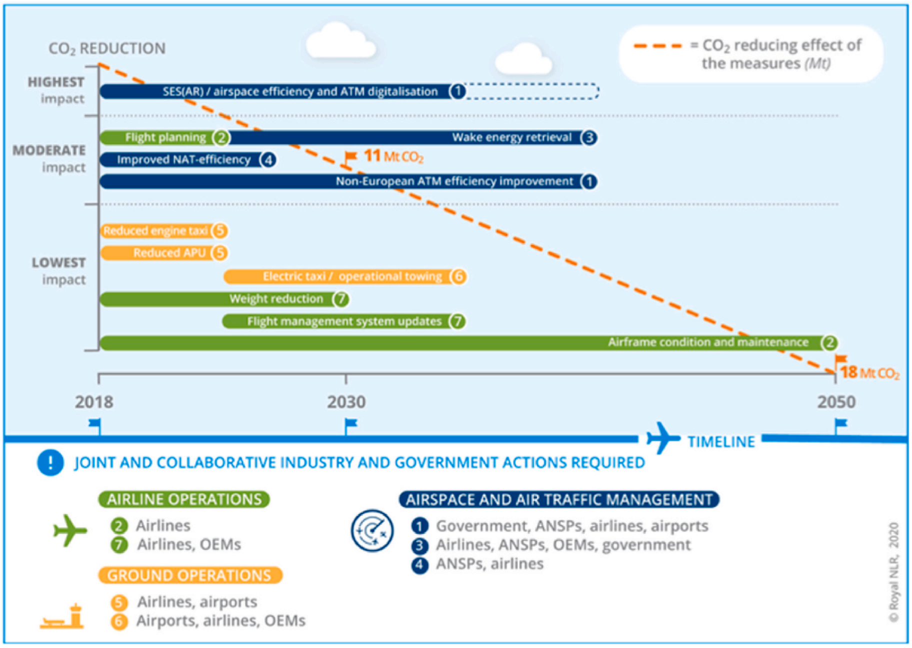


**Fig. 1.** Potential improvements in ATM and aircraft operations for $CO_2$ emission reduction (from. Ref. [19]).

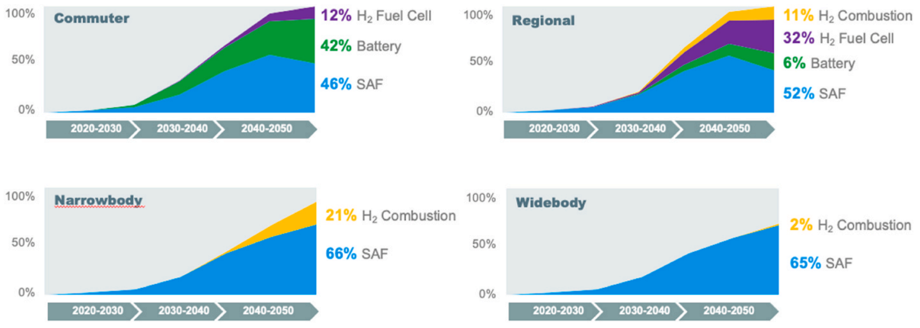


**Fig. 2.** Fleet forecast by fuel type (from. Ref. [27]).

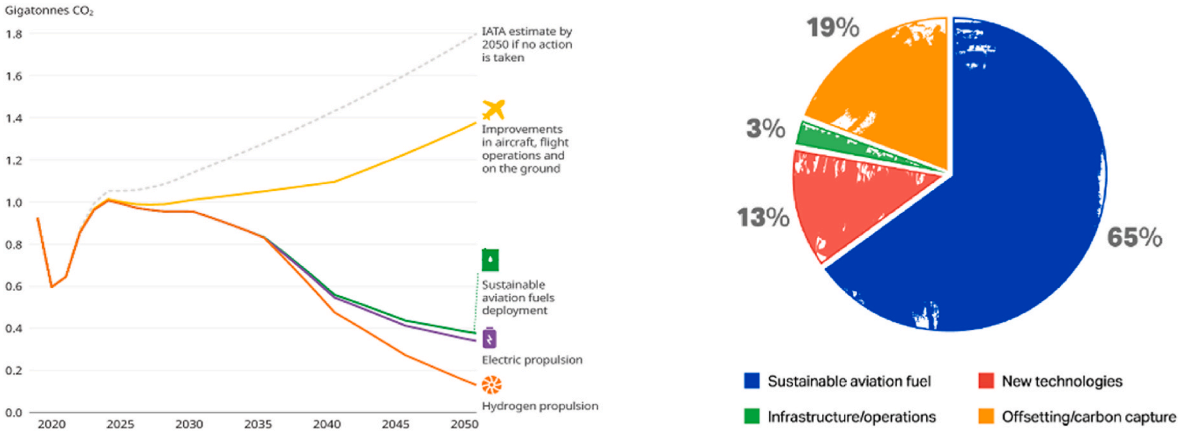


**Fig. 3.** Roadmap to achieve 21.2 Gt $CO_2$ abatement by 2050 (from. Ref. [24]).

of scientists, researchers, technicians and social managers on the real challenges required for a better quality of life and for finding solutions for using environmentally sustainable energies. The knowledge and the intelligence should be used for progressing by showing respect for Nature, instead of regressing back to the instinct actions and rules of the animal world.

## 2. Strategies to lower chemical pollution

According to IATA (International Air Transport Association) individual air passenger travels in 2050 could exceed 10 billion which, projecting a 2.3% annual compound growth in $CO_2$ emissions, would reach, on a *business as usual* path, approximately 21.2 Gigatons of $CO_2$, Fig. 4.

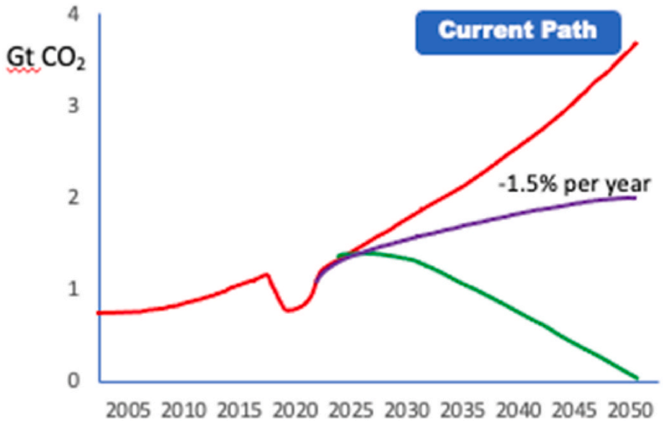


**Fig. 4.** Gt $CO_2$ Emissions from Aviation (expected and desired).

The definition and the pursuing of strategies for lowering (or, even better, zeroing) chemical pollution (together with other polluting agents) is mandatory.

Several different approaches currently available may be adopted to reduce the impact of greenhouse gas production, from simple already available operational changes, even though with small impact, to complete re-designs of aircraft and their related infrastructure that will have a large impact on emissions which, unfortunately will require many years for the technology to become mature and to be implemented, Fig. 5. Achieving sustainability will necessarily involve a combination of these technologies. Civil aviation is always on an improved efficiency path per year, which translates directly into several advantages including lower carbon emissions, [27].

Each generation of aircraft design represents a stepwise improvement in efficiency. While the absolute $CO_2$ emissions have increased in line with the growth of the global fleet, significant improvements in aircraft efficiency have limited the impact. The introduction of the A320neo and the 737 MAX are both promising fuel savings of approximately 20% compared to the models that they replaced. Similar savings were achieved for the C Series/A220, Embraer E2, 787 and A350 models. In other words, simply replacing an older generation model with a new, more efficient model, will yield important savings. Looking forward, the next generation of aircraft engines will deliver comparable efficiency gains, claiming a 20% more efficient solutions for both narrow and widebody next generation engines. More revolutionary and therefore long-term solutions include distributed propulsion and hybrid configurations.

Aerodynamics and structural solutions are other topics which are improved generation by generation. New materials, lighter airplanes with additive manufacturing components, new winglet designs (Sharklets, Split Scimitar), higher aspect ratio wings, folding wingtips are examples of improvements for increasing the efficiency which generally

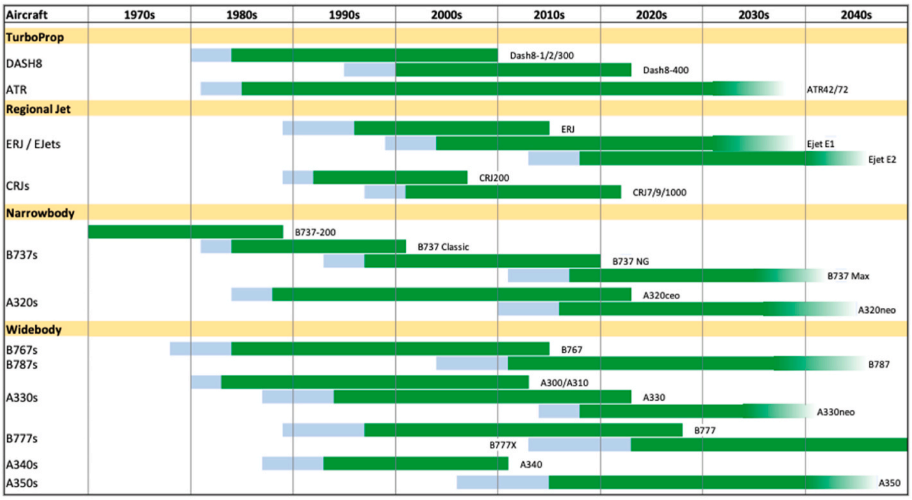


**Fig. 5.** Typical commercial aircraft replacement cycle.

translates in pollution mitigation. Future developments include greater use of laminar flow surfaces, morphing wing surfaces, or more extreme arrangements such as truss-braced wings and blended wing body configurations which could also lead to innovative cabin configurations.

Aircraft systems also contribute to improved efficiency, and they can have a direct impact on fuel burn. Improvement of the operational efficiency, and the best use of the airspace design can also have a significant impact on the improved sustainability. However, continuous improvement alone will not be enough to achieve the target of Net Zero carbon by 2050 and it will be necessary to look for additional solutions to close the gap.

One of the potential first priority is the increased use of SAF which is obtained from renewable sources (biomass, electricity or hydrogen).

Rapid adoption of sustainable aviation fuels is the quickest and most effective way to start decarbonizing aviation. There is a pull from the market, with support from governments, for committing to using 10% SAF by 2030. Consequently, there is interest among fuel providers in the construction of biofuel refineries. A distinction can be made between SAFs, as drop-in SAF which can be blended with fossil kerosene allowing the use of current powertrain structure, and non-drop-in SAF which require extensive modifications to current powertrain. Drop-in SAF obtained from biomass is referred as Biofuel. Drop-in SAF from power and Sun is referred as Synthetic fuel.

Biofuel uses a sustainable biomass feedstock that is modified into SAF through a chemical process. Beyond its lower $CO_2$ footprint, biofuel allows for it to be sourced locally providing extra revenue for farmers and communities, increasing biodiversity, reducing methane generation and watershed pollution, and is potentially less susceptible to market swings and dependence on OPEC. Today the cost of biofuel is about 2–3 times that of kerosene.

SynFuel is produced with sustainable hydrogen created using renewable electricity and carbon capture to form SAF through a synthesis process. Today, this process is only at the demonstration level resulting in a production cost that is about 5 times higher than kerosene.

Today almost all flights are powered by kerosene, a petroleum product made from refining crude oil which, when burned, produces $CO_2$, NOx, soot and other pollutants that impact the environment. The production and the use of SAF may result in a 50%–80% net reduction of aircraft $CO_2$ emissions. SAF also burns cleaner than kerosene since it does not contain sulphur and other pollutants. In Europe the long-anticipated ReFuelEU aviation proposal imposes a mandate on fuel suppliers to include SAF in aviation making it available at EU airports. The obligation would commence from 2025 at 2% SAF, gradually increasing to 63% in 2050, Fig. 6.

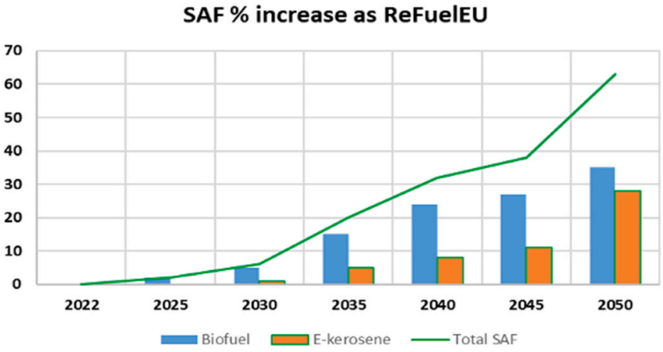


**Fig. 6.** SAF Percentage increase according to ReFuelEU.

Strong benefits for the environment are expected from hydrogen combustion which offers many desirable attributes over carbon-based fuels, most importantly it does not generate $CO_2$ when burned. Hydrogen can be produced by several different methods which are categorized based on their sustainability impact. Green Hydrogen is produced on a $CO_2$-neutral basis through the electrolysis of water using electricity generated from renewable energy sources such as wind energy, hydropower or solar energy.

For hydrogen combustion, the conventional turbofan or turboprop engine is modified to burn hydrogen gas instead of kerosene fuel. This approach maintains the conventional engine design with systems adapted for the unique properties of hydrogen. The biggest challenge involves the onboard storage of hydrogen. Unlike kerosene, which is a liquid and can be stored in the wings of the aircraft, hydrogen is a gas and must be stored in tanks under pressure. In order to minimize the volume, cryogenic liquid hydrogen is used, which is cooled to 21 K (−253 °C). Even at this low temperature, hydrogen has a volumetric efficiency 1⁄4 that of kerosene, which means that it requires 4 times the volume of hydrogen for an equivalent amount of energy. These super-cooled storage tanks are located in the fuselage and take up space that would otherwise be allocated to passengers or cargo. Hydrogen has a much higher gravimetric density than kerosene whereby 1 kg of hydrogen has the same amount of energy as 2.9 kg of kerosene. Ideally the lighter weight of the hydrogen will offset the increased structure required for its storage. While hydrogen combustion does not generate any $CO_2$, it does produce NOx and water vapor which results in contrails.

At this stage, the long-term outcome of hydrogen combustion is less clear. While the potential is definitely massive, being the only zero-carbon fuel source that is likely to deliver the performance required for jet-powered aircraft for the foreseeable future, it will also require massive investments to bring it to market and overcome the challenges of hydrogen storage. SynFuels offer many of the same benefits with less technical challenge, Fig. 7.

Similar to hydrogen combustion, hydrogen fuel cells use hydrogen as a fuel source. The big difference is that instead of burning hydrogen, fuel cells use a chemical reaction to generate electricity, like a battery. Fuel cells are clean, quiet and produce water vapor as the only exhaust. Hydrogen fuel cells have been available for many years and are used for warehouse logistics, standby power and trucking. Newer technology is increasing the power density and reliability of these systems, making them more suitable for aviation applications. In addition to the hydrogen storage issues, a fuel cell-powered aircraft requires an entirely new electric powertrain and electric systems. The new design also brings new opportunities such as distributed propulsion, higher redundancy and more efficient systems. The weight and volume of the fuel cell, including its cooling system, limits the application to smaller aircraft today; however, developments that increase power output and reduce the amount of cooling required will lead to more compact systems in the future.

The clean and quiet nature of hydrogen fuel cell aircraft should make them popular with passengers and neighbors, providing excellent sustainability credentials.

In order to accommodate hydrogen-fueled aircraft (whether it is for hydrogen combustion or hydrogen fuel cell technology), the entire fuel supply chain must be developed for aviation. Airports will need to invest in new infrastructure to store, liquefy and deliver the hydrogen to the aircraft. This will involve the development of new safety procedures on account of the cryogenic temperatures and will take longer to refuel the aircraft due to the higher volume required. It is anticipated that by the time the technology matures sufficiently for aircraft use, the hydrogen economy will have grown so that sources of green hydrogen will be more plentiful, and a transportation network will be in place.

Today, the production cost of green hydrogen is about 5 times that of kerosene and the higher volume required increases the transportation cost. Sources of renewable electricity are expected to grow four-fold by 2030, which means that local production of hydrogen could be feasible, even on-site at the airports, which will dramatically reduce its cost.

The electrification of the propulsion system is expected to strongly change the propulsion system design, with merits and associated bottlenecks. Three primary domains are characterizing the electric propulsion system: full electric, turboelectric and hybrid electric, Fig. 8.

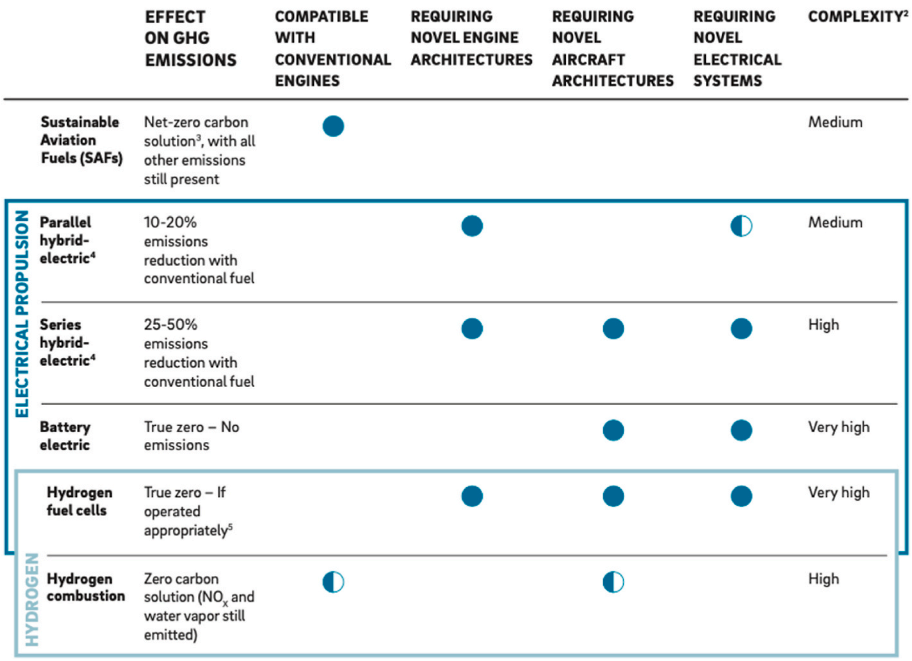
A full electric system relies upon a battery or some other means of electrical energy source. Turboelectric configurations maintain fuel as main source converting the chemical energy of the fuel into electrical power, fully or partially, to drive the propulsor. Hybrid electric stands for more than one type of energy sources and consequent powertrain arrangement. The use of battery-electric propulsion is diffusely used in the automotive world and the research in the field may be beneficial for aviation industry, too. One example are the new Advanced (or Urban) Air Mobility projects which are based on battery electrical propulsion.

Batteries provide greater flexibility in aircraft design; they can be located almost anywhere. Additionally, the weight does not decrease during the flight as the energy is consumed, which means that there is no impact on the aircraft center of gravity either. The batteries can be located close to the electric motors to reduce the amount of wiring required and distributed propulsion systems can improve efficiency and add redundancy. Electric motors and systems tend to be very reliable and require less maintenance than combustion-based alternatives. An electric propulsor also weighs less than the turbine equivalent.

Weight is a major factor limiting the penetration of battery technology in aviation. With a system energy density of about 1/15 that of kerosene, battery-powered aircraft end up weighing significantly more than kerosene-powered models, which limits the payload and range capabilities, Fig. 9. Since batteries do not become lighter as the energy is consumed, there is an increasing penalty on landing performance versus kerosene-powered aircraft.

In order to re-charge a battery-electric aircraft, an airport will need to have fast-charging stations available. Similar to the high-energy DC charging stations for automotive use, these could bring an aircraft back to full charge in about 30 min and could be located either at the gates or remotely. In order to be a sustainable solution, the electricity used must be from a renewable source. On-site solar panels could supplement the electricity required.

When using renewable electricity, the battery-electric aircraft delivers zero greenhouse gas emissions. It is anticipated that large investments into battery technology should yield a stepwise improvement in energy density in the coming years that could double the available range for this technology.



| | | EFFECT ON GHG EMISSIONS | COMPATIBLE WITH CONVENTIONAL ENGINES | REQUIRING NOVEL ENGINE ARCHITECTURES | REQUIRING NOVEL AIRCRAFT ARCHITECTURES | REQUIRING NOVEL ELECTRICAL SYSTEMS | COMPLEXITY[2] |
|---|---|---|---|---|---|---|---|
| | **Sustainable Aviation Fuels (SAFs)** | Net-zero carbon solution[3], with all other emissions still present | ● | | | | Medium |
| ELECTRICAL PROPULSION | **Parallel hybrid-electric[4]** | 10-20% emissions reduction with conventional fuel | | ● | | ◐ | Medium |
| ELECTRICAL PROPULSION | **Series hybrid-electric[4]** | 25-50% emissions reduction with conventional fuel | | ● | ● | ● | High |
| ELECTRICAL PROPULSION | **Battery electric** | True zero – No emissions | | | ● | ● | Very high |
| ELECTRICAL PROPULSION<br>HYDROGEN | **Hydrogen fuel cells** | True zero – If operated appropriately[5] | | ● | ● | ● | Very high |
| HYDROGEN | **Hydrogen combustion** | Zero carbon solution ($NO_x$ and water vapor still emitted) | ◐ | | ◐ | | High |

**Fig. 7.** Landscape of potential revolutionary aviation solutions.

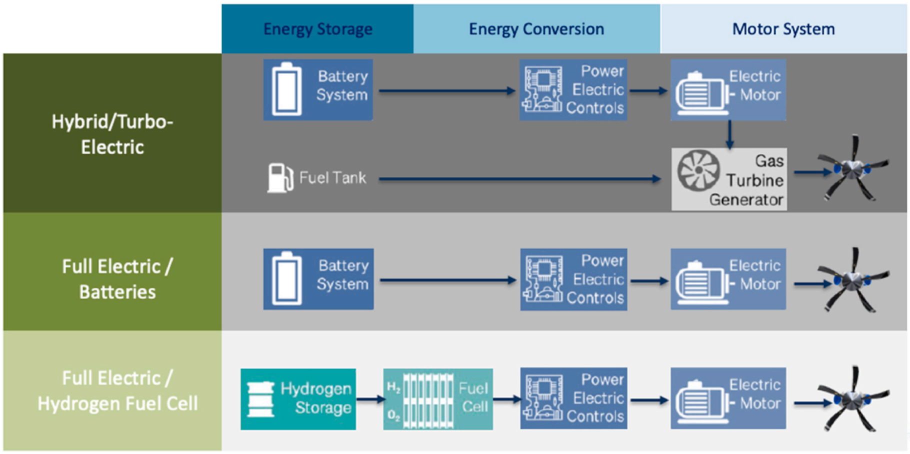


**Fig. 8.** Primary domains for electric propulsion system.

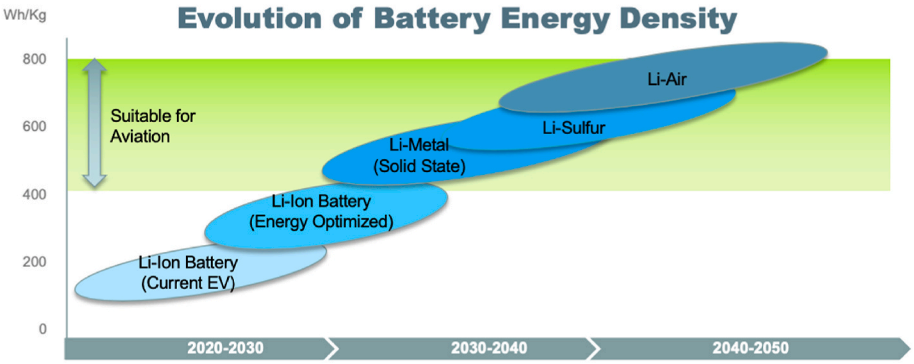


**Fig. 9.** Evolution of Battery energy and technology (source MHIRJ Aero Advisory Services).

## 3. Business and commercial aviation

The air transport industry is a key driver of the global economy, providing connectivity, supporting 87.7 million jobs, and transporting 4.5 billion passengers in 2019. Commercial aviation generated about 915 Mt of $CO_2$ in 2019, which accounts for approximately 80% of the total aviation emissions, with 18% for cargo and 2% for business aviation.

Emissions are correlated with Available Seat Kilometers (ASK), the passenger-carrying capacity of an aircraft. So, while commuter and regional aircraft account for approximately 30% of the fleet in use, they represent only 4% of the greenhouse gas emissions. It means that the biggest impact on sustainability will come from addressing emissions of the narrowbody and widebody segments, Fig. 10.

With reference to business aviation, between 2010 and 2020, this aviation sector has improved its fuel efficiency by 2% per year, achieving one of its main objectives across its fleet of about 38,000 aircraft. The group is now renewing that same goal through 2030, Fig. 11.

It is committed to reach net-zero $CO_2$ emissions by 2050, while short term targets can be reached thanks to technology improvements, significant adoption of sustainable aviation fuel and fleet turn over. While SAF is now in too short supply to satisfy the needs of commercial aviation, a ramp up in production could more easily satisfy private flights, considering also those private customers are prepared to pay a bit more for SAF. More flexibility may be introduced by the book-and-claim service to allow more SAF usage by enabling business aircraft operators who choose to use the renewable fuel to purchase it even where it is not physically present. The idea behind the Book-and-Claim Service is that an airline wishing to use SAF at an airport that doesn’t have it can buy (or “book”) it from elsewhere. Then their flight would receive normal Jet-A or Jet-A1 fuel and at the SAF-capable airport, another

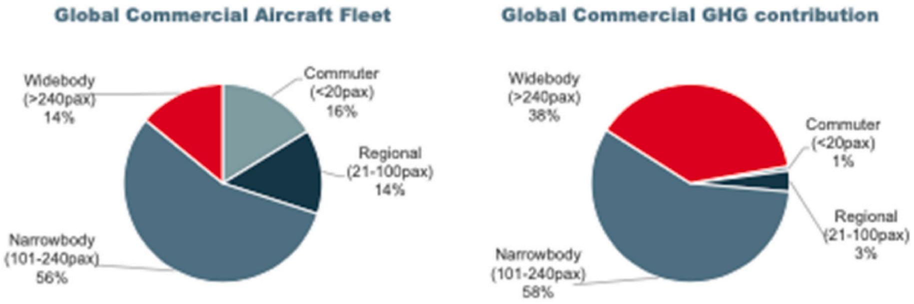


**Fig. 10.** Market share vs. greenhouse gases (GHG) emissions.

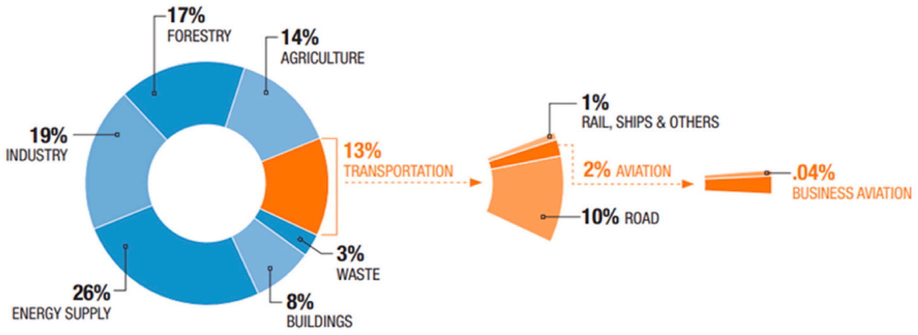


**Fig. 11.** Contribution of Business aviation to GHG emissions.

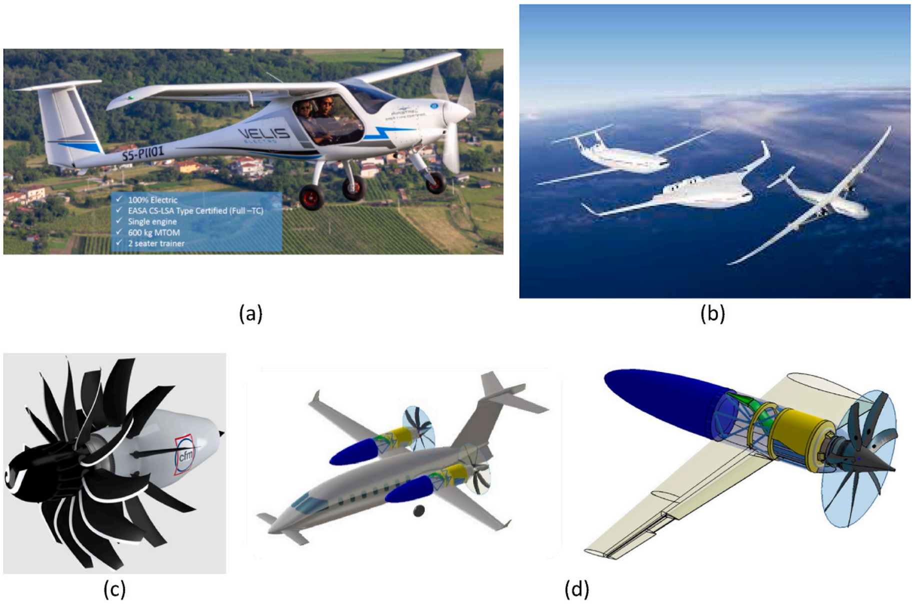
airline's flight would get the SAF. All this is possible because now all jets can use up to 50% SAF, but in practice, airlines typically fly with much smaller amounts, usually between 3 and 5%, more rarely up to 10%. So with Book-and-Claim, a single flight at an airport with SAF availability could account for multiple flights' SAF use, elsewhere, and extend worldwide th use of SAF. The path to Net Zero consists of multiple technologies and fuels that will be introduced to various segments at different times. In the current decade, the biggest impact on aviation emissions will come from continuous improvement. The replacement of older narrowbodies with new generation aircraft, combined with operational efficiency improvements will be the major contributors. Furthermore, a ramp-up of SAF availability with several airlines, committing to 10% SAF use by 2030, is expected. By the next decade the implementation of the most promising technology that is under development today should become operative at high TRL. New engine technologies will deliver a further 20% efficiency improvement along with the potential to burn alternative fuels such as hydrogen. Electric systems are expected to increase their efficiency, leveraging the development of electric powertrains mainly on smaller aircraft. More radical aerodynamic improvements, such as truss-braced wings and higher aspect ratio wings, will be introduced on new models. SAF will become widely available and take over as the primary contributor to reducing greenhouse gases. New aircraft designed for taking advantage of hydrogen fuel cells and hydrogen combustion are expected to enter into service, Fig. 12. The vision for transportation in the middle of this century is for all new road vehicles to be electrified. AAMs are commonplace and the availability of clean, quiet battery and fuel cell-powered aircraft has led to a boom in regional aviation as these aircraft can access small, local airfields without disturbing the neighbors. SynFuel production will ensure that there is enough SAF to meet the demand of the in-service fleet and the challenging widebody market. Hydrogen combustion will provide a zero-carbon solution for the narrowbody market and improvements in aircraft efficiency will have lessened the penalty from the greater storage volume that hydrogen requires.

## 4. Impact on the infrastructure and supply chain

Sustainability challenge in aviation requires a tremendous effort by all impacted stakeholders and a strong support from the government of high-technology countries. The nature of the aviation business is highly complex with many competing requirements and limitations such as: aircraft performance, safety, reliability, regulatory, economic, financial, and so on. Each actor will have its own role and responsibility, Fig. 13.

Airlines are probably the most impacted by the need for sustainability, being the direct public interfaces with the aviation business. They should optimize their operations, improve their fleet, engage passengers and get prepared for the future.

Airports will play an important role in the sustainability of aviation



(a)

(b)

(c)

(d)

**Fig. 12.** Flying and potential design evolution for green aviation
(a) Pipistrel Velis Electro; (b) NASA Studies for Next Generation Hybrid/Electric Aircraft; (c) CFM RISE Engine; (d) Future Full Electric Propulsion Concept for P180; (e) NASA Studies for Next Generation Hybrid/Electric Aircraft.

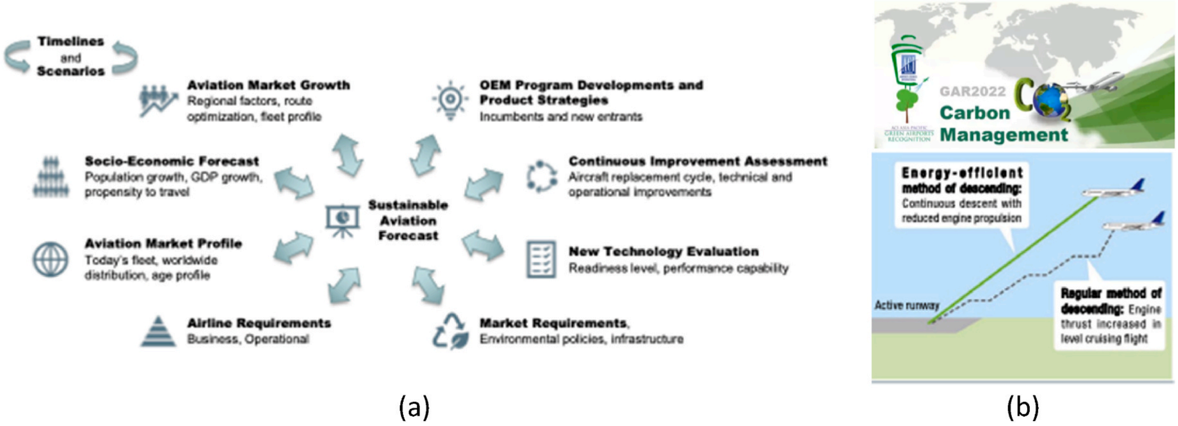


**Fig. 13.** Examples Sustainable Aviation Forecast
(a) Timeline and scenarios; (b) Airport and operational strategies.

both directly and indirectly. As new fuel sources such as SAF and hydrogen are introduced to the aviation market, airports will need to develop the necessary support infrastructure. While the incorporation of SAF should be relatively straightforward, until local sourcing is readily available, airports will need to support book-and-claim accounting to provide for airlines that have committed to using SAF. The introduction of hydrogen will require new infrastructure as well as new protocols for fueling aircraft. The ultra-low temperatures required for cryogenic liquid hydrogen will dictate new handling procedures and storage facilities.

Design and manufacturing of an airplane is not the commitment of a sole company. Each aircraft program is supported by hundreds of Tier 1 and thousands of sub-tier suppliers working together and depending on each other. Aircraft design is likely to change due to new requirements for fuel storage, new powerplant configurations and aerodynamic step-changes. Details are still under development; however, it is foreseen that these designs will require greater integration of aircraft and engine systems than actual supply chains. Aircraft and engine manufacturers, along with system providers, will have to work even more collaboratively and intimately to achieve the necessary optimization.

Governments need to provide the leadership, guidance, and vision to support sustainability. Considering the near-term challenge to increase the availability of SAF, subsidies for investment into production industrialization are the most effective path to meet the current need and provide a long-term supply. Nevertheless, there is a great opportunity in developing markets where investments will also serve to stimulate the local economy. Rather than adding more punitive taxes on airlines and passengers for GHG (greenhouse gas) emissions, governments should incentivize airlines when they take concrete steps to reduce emissions, for example by using SAF, to diffuse broad-based sustainable behavior.

Similarly, in order to develop the hydrogen economy, there needs to be an investment in green hydrogen production. Multilateral agreements between governments to ensure harmonized rules and regulations across jurisdictions is another important activity. This will create a level playing field and align efforts towards the most productive outcome. Change is always difficult and decarbonizing aviation will require change for many stakeholders. The role of governments will be to remove the barriers to change and reduce the friction. Words which are easy to write but difficult to implement, considering the actual global political situations.

The adoption of new technologies will require a reworking of certification and operational standards, starting with commuter and regional aircraft. Aircraft and engine certifications, airline operating rules and manuals, flight and ground procedures, maintenance procedures, all will have to be adapted to reflect new requirements. Implementation of regulatory changes is a lengthy process to provide adequate time for comments and revisions. The result could be a slowdown of the process for sustainability, therefore harmonization of the different roadmaps should be also considered, Fig. 14.

Many other stakeholders in the aviation ecosystem will be impacted to a greater or lesser degree by the actions toward sustainable aviation. Actually, petroleum producers provide over 300 Mt of kerosene per year for commercial aviation. A switch to SAF will redefine their business model. Other stakeholders – such as financiers, lessors, airlines, airports, etc. – will have to define or adapt their policies with a focus on operating newer, greener aircraft. This is increasingly becoming a must to attract financing, satisfy investors and secure new business.

## 5. Some examples

Airplanes which may claim to be fully environmentally sustainable are not available so far, but it is possible to list some examples of existing airplanes which for their special characteristics and performances have resulted best in the class for fuel consumption and reduction of $CO_2$ emissions. One of these airplanes is the Piaggio P180, a revolutionary airplane developed in the 70's, during the global energetic crisis, with an unconventional design which was considered the only viable solution for a very demanding challenge: to define an airplane with jet speed and significantly low fuel consumption, [28]. And nowadays, Avanti EVO, the last P180 version, is already approved to operate under blended use of SAF (Biofuel). It is also interesting to highlight in these times how important has been the unconventional design for complying with the requirement. Unconventional design will be required for future airplane to meet the sustainability objectives.

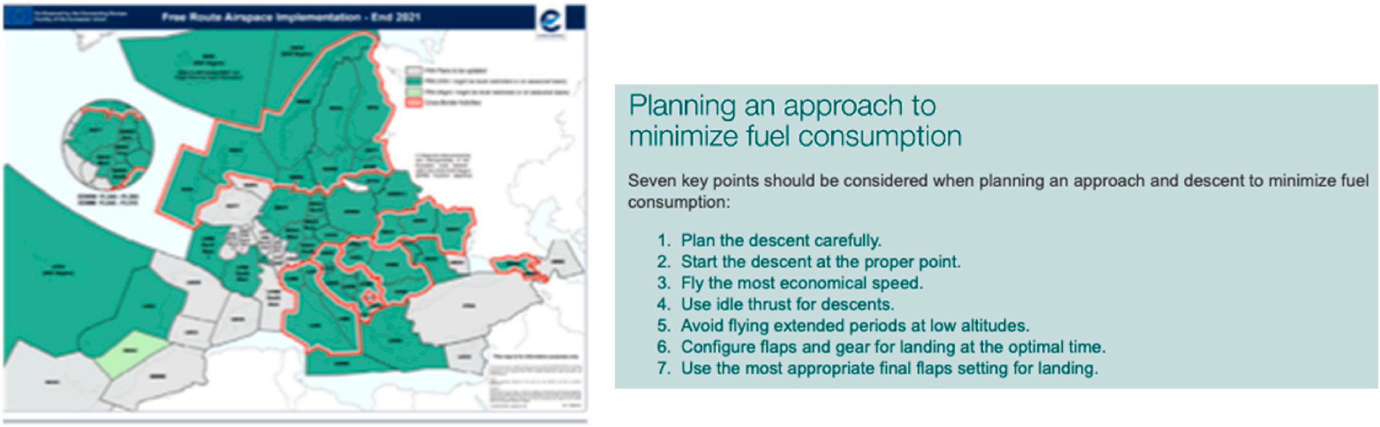
Other examples are the coming NASA X-57, the Pipistrel Velis Electro, first certified full electric two-seat aircraft.

As anticipated in this paper, first applications of the new technologies are in the small airplane sector, which should pave the way for the bigger commuter vehicles and subsequently the narrowbody and widebody configurations.

Novel configuration concepts are under exploration. In the near term the potential of electrical powerplant based on current available technology as far as battery is concerned drives toward the eP180, for example which, together with X-57 appear to be concept studies for being prepared for the coming technological achievements. Industrial maturity for production appears still far to get, Fig. 15.

## 6. Conclusions

It is possible for commercial aviation to achieve Net Zero by 2050, but it is a very demanding objective. It will require the cooperation of all the stakeholders: airlines, governments, aircraft manufacturers,



Planning an approach to minimize fuel consumption

Seven key points should be considered when planning an approach and descent to minimize fuel consumption:

1. Plan the descent carefully.
2. Start the descent at the proper point.
3. Fly the most economical speed.
4. Use idle thrust for descents.
5. Avoid flying extended periods at low altitudes.
6. Configure flaps and gear for landing at the optimal time.
7. Use the most appropriate final flaps setting for landing.

(a) (b)

**Fig. 14.** Examples Sustainable Aviation Forecast
(a) New Route Implementation; (b) New approach procedures.

(a) (b)

**Fig. 15.** Evolution of airplanes for greener solutions
(a) P180 EVO; (b) NASA X-57.

airports, air traffic management and fuel suppliers, just to name a few. There are simple operational improvements that can be implemented today allowing immediate results evenif in a small quantity. New technologies can be incorporated incrementally as older aircraft are retired and substituted by new more aerodynamically efficient and less fuel burn engine using increased percentage of SAF. It is expected that these new technologies will be applied first on local and regional flights and these small aircraft will be the incubators for battery-electric and hydrogen fuel cells that mature the technology for broader implementation.

However, it is the industrialization of SAF that will achieve the biggest impact for a fast decarbonization, because it can be used with existing in-service aircraft and is the only solution for narrowbody and widebody aircraft in the short term. Since these aircraft are responsible for the majority of the carbon emissions in the commercial aviation, the increased production and the broader use of SAF is going to be the priority for the aviation industry.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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