

Multi-Level Aircraft Design Modelling Including the Effects of Disruptive Propulsion Technologies on Environmental Impact [†]

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Abstract

The EU EFACA project considers two conceptual aircraft design configurations for cleaning European air traffic in future decades. Recently, several different technologies have led to propulsion designs with potential to reduce greenhouse gas emissions and replace existing conventional engine technologies—such as the use of fossil fuel—for aviation. The results of an assessment of the environmental impacts of new technologies are considered using a multidimensional approach, ranging from aircraft certification requirements (noise, local and global engine emission, and aircraft fuel efficiency) to regional/global assessments of new designs in air traffic. Each technology for factor reduction is simulated and compared to a reference, usually the aircraft currently best in its class, providing the possibility of assessing the efficiency of the technology, both for necessary certification requirements and for the forecasted operational conditions due to ICAO long-term aspirational goals and ACARE Fly Green Deal goals.

Keywords: aircraft design concept; disruptive propulsion technology; fuel burn; engine emission; noise

1. Introduction

The global aviation sector is growing rapidly, driving globalization, but it also emits about 2% of CO₂ and other greenhouse gases (GHGs), thereby creating more than 4% of radiative forcing and directly contributing to rising global temperatures [1,2]. The UN Intergovernmental Panel on Climate Change (IPCC) continues to consider human development strategies for the near future and identify scenarios (options) for preventing global warming by more than 1.5 °C. In the European region, these IPCC global policies and ICAO sectoral policies [2] have been translated into strategies such as the Green Deal Directive for the entire EU economy and Direction 2050 for European aviation in particular. These strategies require that global and regional emissions from aviation must be reduced; however, at the same time, air traffic must continue to grow in line with humanity's need for air travel. The ICAO continues to assess future trends in fuel burn and emissions in the aviation sector [3] and take appropriate action to reduce them. European experts use a similar approach, breaking down the global solution into individual tasks and solutions at airport and aircraft level by introducing new, more efficient technologies into aircraft design and operation.

At the aircraft level, new ICAO standard limits [4] require that growth in air traffic and the impacts of climate change must be taken into account, with the aim of achieving the



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long-term aviation target (LTAG) adopted in 2022, guided by UNFCCC decisions within the framework of the Paris Agreement, which points out that exceeding the 1.5 °C threshold could lead to much more severe climate change impacts. For example, in 2025, new ICAO standards [3,4] defining the trade-off between noise levels and fuel consumption were developed based on average projected global air traffic growth by 2070, with priority obviously being given to reducing fossil carbon emissions. At the same time, at the regional level, especially in Eastern Europe, this increase will be 2–3 times higher than the average [1], and noise levels at airports will not be the same as before COVID-19 if air traffic (aircraft fleets and their operations) operates in accordance with current ICAO aircraft noise requirements and management principles. According to the ACARE Fly Green Deal, at the airport level, air quality, noise levels and their impacts should remain at the same level as before the COVID-19 pandemic. This is necessary to ensure that the ICAO's balanced approach continues to support environmental management in the aviation sector at the local level, extending its principles to all relevant factors and helping airports to successfully coexist with communities.

2. EU EFACA Project for Aircraft Flight Hydrogenization

Analysis of trends in reducing fuel burn by conventional engine and aircraft designs has revealed that existing reduction technologies are inadequate, if the ICAO long-term aspirational goal (LTAG) is to be achieved [3]. The CAEP taxonomy proposed by ICAO for sources of emission and technologies for fuel burn reduction has evidently confirmed these findings [3]. Propulsion plays the fundamental role in fuel burn reduction. For turbofans, an increase in bypass ratio to the values characteristic of propfans or open rotors is still considered as the basic reduction technology. However, this tremendous next step will be insufficient to reach the NetZero Technology goal [5] in aviation, which is necessary for ICAO LTAG if traditional technological innovations alone are applied.

The EFACA project considers the conceptual design of two new types of aircraft [6]—an 80-seat regional jet (RA) with a hybrid electric propulsion system (HEP) powered by electricity from hydrogen fuel cells [7–9], and a 150-seat short–medium range (SMR) [10] jet with engines fueled by liquid hydrogen (LH₂). For both types, the Top-Level Aircraft Requirements (TLARs) are defined, but the conceptual aircraft layouts, their main dimensions and flight masses, and their means of power supply during flight are still the subject of studies. Analysis of these baseline aircraft have identified the reference aircraft for both types: ATR72-600 for HEP aircraft, and Airbus-320neo for LH₂-fueled aircraft. The current HEP RA is powered by a propeller (combined electric/turboprop) engine [7,8], while the SMR (usually a narrowbody single-aisle aircraft-SA) and long-range (LR, usually widebody twin-aisle aircraft-TA) aircraft are powered by turbofans. More than 80% of the world's civil aviation fuel consumption is covered by these two aircraft groups—SA and TA—with a split of approximately 40:60 between them [3]. This is because although the number of SA flights is significantly higher than the number of TA flights, LR flights have a much longer duration.

The HEP system represents an interim solution for reducing carbon dioxide emissions in flight, replacing the all-electric propulsion system that is currently being considered for RA-class aircraft also; however, similar solutions may be implemented on SA-class aircraft at later stages. At TRL3, a test rig is being developed for a hybrid gearbox that combines a turbogas and electric drive [8], with the gearbox, electric drive, and propeller all being completely new developments within the EFACA project. However, effective temperature management is critical for fuel cells, especially during peak load periods such as aircraft takeoff and climb, as the water-to-air heat exchangers used in modern fuel cell systems create significant drag in the aircraft environment. A TRL3 test rig will demonstrate the

PCHP-cooling concept [9]. Effective storage solutions are crucial to aircraft usefulness, because LH_2 typically requires voluminous, heavy, and well insulated tanks [11].

Six alternative configurations of the HEP RA [7] and LH_2 SMR [10] were developed to explore possible design directions differing in terms of aerodynamic layout, cabin layout, and approaches to integrating onboard liquid hydrogen tanks. The concepts also differed in terms of the number of cryogenic tanks and their placement, with options for the latter including underfloor, wing nacelles, or a dedicated rear fuselage section. All performance-related parameters were evaluated, considering the consistency of design points and mission profiles across all configurations. Comparisons of the LH_2 SMR with the conventional reference aircraft Airbus-320, and the HEP4 RA with the ATR-72-600/500, were also used to verify the consistency of the methods for dimensioning and flight performance evaluation at the conceptual design level.

The principles of environmental impact analysis for the preliminary baseline vs. reference aircraft assessment in the EFACA project were formulated in accordance with the ICAO aircraft standard requirements [4]. In subsequent stages, they were transformed for three levels of assessment of current and future air traffic—aircraft, airport and fleet scenarios [12]—from a European perspective.

3. VALDES Approach for Environmental Assessment of New Technologies

All models for the environmental assessment of new technologies in aircraft design are combined using the VALDES approach, i.e., in the **Vehicle/Airport/fLeet DESign** space, using ICAO/CAEP and Eurocontrol methodologies, with EFACApport at the center, this being a virtual EU regional airport for considering flight scenarios utilizing fleets with reference and baseline aircraft, as well as their environmental impacts [12].

3.1. Global Fleet Level of Environmental Assessment

Aviation contributes GHG concentrations and other RFs (Figure 1 [13]) in exactly the same regions where temperature increases are highest [1]. Globally, around 100 airports serving dominant destinations account for around two-thirds of all passenger-flight CO_2 emissions [14]. CO_2 emitted from fossil carbon fuel is the main RF factor, but not the only one. Other GHGs, such as methane (CH_4), water vapor (H_2O), and nitrogen oxides (NO_x) can also contribute to the impact of the aviation sector and to specific factors such as contrails, due to the specific conditions of flights within the troposphere as well as ozone depletion in the stratosphere where supersonic flights are effective.

An important finding from the global air traffic scenario analysis (Figure 1) is that aviation GHG emissions are concentrated along and near aircraft flight profiles. The impact of such emissions on the environment and on climate change should therefore be assessed, starting with a flight profile analysis. Contrails in the wakes of aircraft are due to condensation of exhaust gases and water vapor from the environment over appropriate nucleation sites, such as soot particles and sulfur aerosols emitted by aircraft engines [15]. Effective RF is used for non- CO_2 forcings. This better accounts for fast feedbacks, e.g., from clouds or aerosols, and has a better relationship with temperature change ΔT , due to the relationship expressed in Equation (1) below.

GHGs emitted exist in the atmosphere for a long time. In the case of CO_2 , this may be thousands of years. Aviation emissions are spread in the atmosphere by several independent phenomena, including transport by engine jets, transport in the wake of the aircraft, transport by wind, and atmospheric and molecular diffusion. Because of the long-term existence of GHGs in the atmosphere, molecular diffusion can also contribute to

a distribution of emitted gases in the atmosphere at concentrations that are globally and temporally equilibrated and definitive for RF.

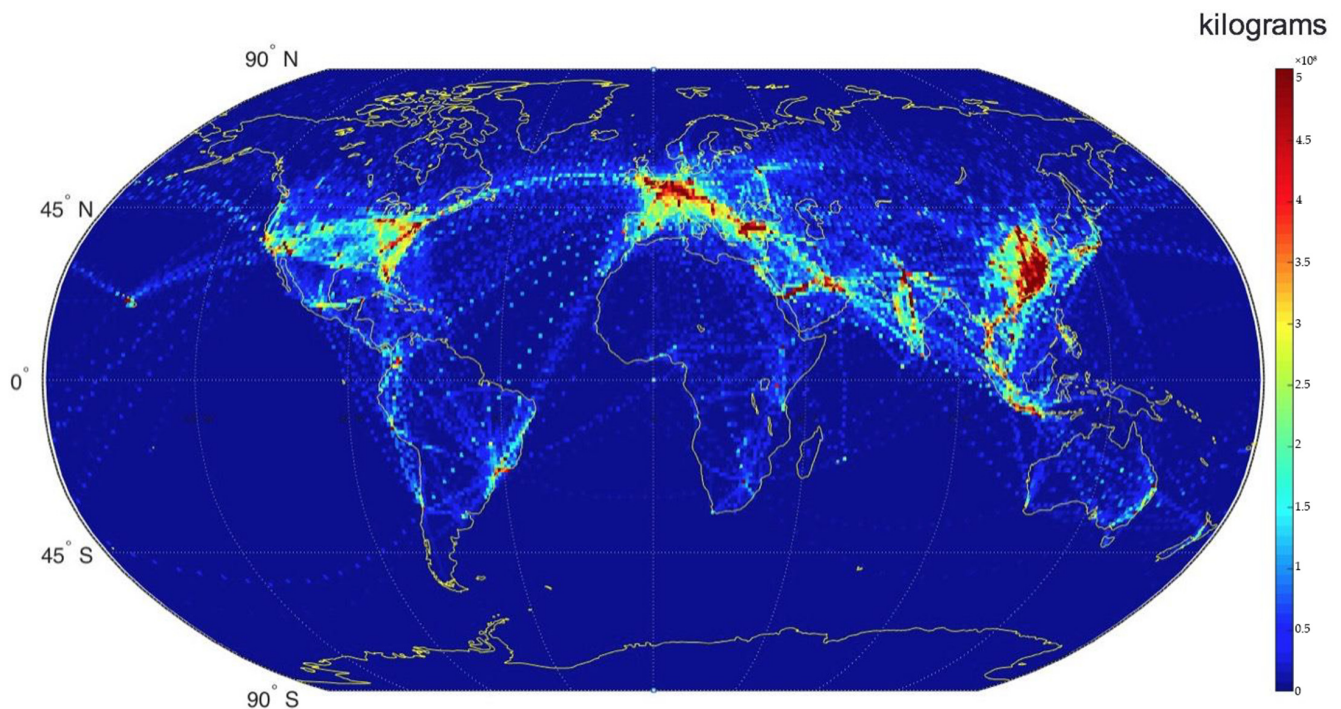


Figure 1. Annual fuel consumption assessed for a global air traffic scenario across origin–destination airport pairs. Source: [13].

The following good approximation is proposed, involving a combination of CO₂ emissions and cumulative non-CO₂ radiative forcing over the observation interval Δt [16]:

$$\Delta T = \chi(\bar{E}\Delta t + L^{-1}\bar{F}\Delta t), \quad (1)$$

where χ is the transient climate response to emissions of CO₂, E is the CO₂ emission factor, and F is other RF contributing to the effect, while operator L converts CO₂ emission to RF using IPCC values. In the IPCC vision, every sector emitting GHG into the atmosphere may be assessed separately for its carbon footprint and its appropriate temperature rise. Aviation emissions are calculated based on the air traffic scenario for each flight, using a manual calculation scheme [17] depending on the aircraft type, the flight mode, and the emission factor EF for the pollutant in consideration. This emission factor EF is a principal value in technological assessment and in improving engine emissions for each assessed traffic scenario.

3.2. Airport Level of Environmental Assessment

Aviation emissions at airports are assessed with reference to local air quality (LAQ); this includes concentrations of pollutants (nitrogen oxides (NO_x), particulate matter (PM), volatile organic compounds (VOCs), sulfur dioxide (SO₂), carbon monoxide (CO), and ultrafine particles (PM_{UF})) in the atmosphere at ground level over relevant time periods of hours, days or years, depending on the type of relevant LAQ standard being considered. Air pollutants in airports are emitted from a variety of sources, including emissions from aircraft engines, ground support vehicles, passenger transport, and on-site energy generation. Modelling studies have shown that air pollution near airports can be substantially higher than in surrounding residential areas, particularly in the case of NO₂.

The main source of emissions at airports is engines of aircraft during landing and take-off (LTO) operation [17], with the emission factor EF being dependent on engine type, flight mode, and environmental conditions (temperature, first of all). The ICAO Manual [17] describes the algorithm for analysis of emission inventory E_i for the traffic scenario using the following basic calculation equation:

$$E_i = \sum_j N (F_j \times \sum_m T_m \times EF_{ijm} \times NE_j), \quad (2)$$

where emission E_i (kg) of pollutant i is calculated for aircraft type j with number of engines NE_j for each flight and the total number of flights F_j ; T_m is the duration of aircraft engine mode m during each flight stage of the LTO cycle (take-off, climb-out, cruise, descending, approach and taxiing, etc.) (s); and EF_{ijm} is the emission factor for pollutant i in mode m per engine used on aircraft type j ($\text{kg s}^{-1} \text{ engine}^{-1}$).

Equation (2) is used for assessment of emission E in Equation (1) for CO_2 and non- CO_2 GHG, where the emission factor EF is characteristic of cruise flight mode dependent on the mass of fuel (or fuel flow— FF) used, and the emissions index EI for the pollutants (CO , HC , NO_x , nvPM mass or nvPM number) in each mode, these being included in ICAO aircraft engine emissions databank (EEDB) for LTO only [18]. The ICAO guidance provides a simple method for estimating LTO emissions, involving standard flight segments (approach, taxiing, take-off and climb-out, traditionally up to the altitude 914 m above ground level), using EI and FF data from the ICAO EEDB for thrust settings (7%, 30%, 85%, 100%) and operating time (26, 4, 2.2, 0.7 min). It also proposes an improved use of the BFFM2 approach to correct for the effects of factors affecting EI and FF ; these include real thrust settings and operating times for engine modes, as well as ambient temperature and other influencing conditions. This ensures aircraft emissions are obtained more accurately than when calculated by the simple LTO method which supports aircraft engine emission certification, the conditions of which are usually very different from reality.

The LTO emission inventory set out in the ICAO requirements is not a fully suitable concept for assessing LAQ in airports, where air pollution should be assessed and compared with standard limits for the environment. A dispersion calculation is needed which includes meteorological parameters (wind speed and direction, atmospheric stability class, ground surface roughness, etc.), additional transport effects such as precipitation or chemical transformations, and dynamic properties of the emission release—especially for aircraft engine exhausts. None of these dispersion stages for aircraft emission are strictly covered by the ICAO calculation methodology [17]; most of them are subjects of national approaches and rules. ICAO CAEP is working on a “gold standard” for LAQ dispersion modelling which involves coordination and inputs from various LAQ modelling tools used in CAEP.

3.3. Aircraft Level of Environmental Assessment

The certification process for LAQ aircraft engine emissions is based on the LTO cycle, which is considered by the ICAO standard [4] as an average value representative of emissions emitted in the vicinity of airports. The CO_2 emissions evaluation metric is defined in terms of the average of the $1/\text{SAR}$ (Specific Air Range in km/kg) values and the Reference Geometric Factor (RGF) [4]:

$$\text{CO}_2 \text{ Emissions evaluation metric value} = (1/\text{SAR})/(\text{RGF})^{0.24}. \quad (3)$$

The CO_2 metric value aims at measuring the technology performance of an aircraft type with respect to its fuel efficiency and absolute CO_2 mass emitted on a specific flight:

$$\text{CO}_2 \text{ Emissions} = (\text{Flight Distance}/\text{SAR}) EF_{\text{CO}_2}. \quad (4)$$

Annex 16, Volume II [4] sets limits on the amounts of gaseous emissions and nvPM masses and numbers allowable in the exhausts of most civil aircraft engine types based on the LTO cycle with four modes of operation. Efforts to regulate emissions through the ICAO certification standard have been recognized. The primary focus of these efforts has been on NO_x and nvPM emissions, due to their significant impact on LAQ and on human health.

4. VALDES Approach Results for HEP and LH_2 Aircraft

Figure 2 shows flight profile data for the EFACA HEP aircraft compared to corresponding data for the reference aircraft ATR-72-600. The necessary operational parameters were modelled by means of the forecasting tool for calculating the whole flight profile of the aircraft with conventional (reference aircraft) or HEP- or LH_2 -fueled (baseline aircraft) propulsions [19]. Using the PolEmiCa model, fuel flow mass values (Figure 3) and emissions of NO_x , CO , CO_2 , SO_x and H_2O were determined for each segment of the flight for aircraft with conventional or hybrid propulsion.

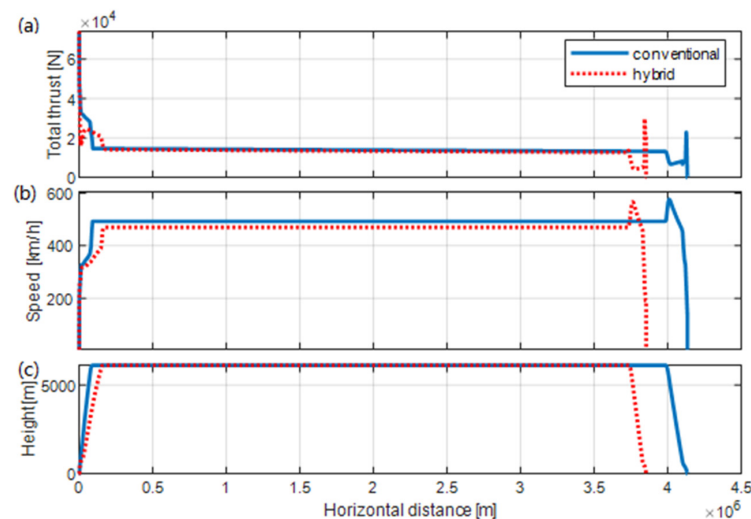


Figure 2. Comparison of flight profiles of an aircraft with a conventional (blue solid line) and hybrid (red dashed line) power plant: (a) engine thrust; (b) true flight speed; (c) geometric flight altitude [19].

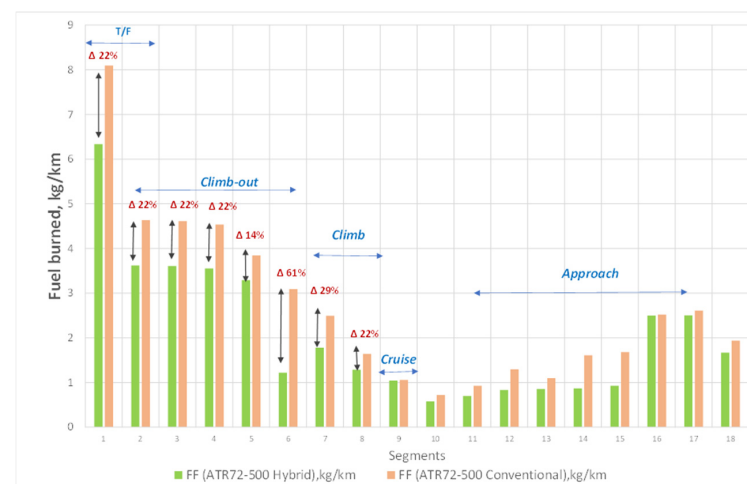


Figure 3. Fuel flow calculated by PolEmiCa for each segment of the flight profile for conventional and hybrid ATR-72-600 [19].

The comparison results demonstrate a reduction in CO_2 of 5–8% during the whole flight defined by TLAR for the HEP and ATR-72/600 aircraft. Particularly, reduction in

CO₂ emissions was an average 24% for the take-off and climb-out segments of flight, and 28% for the segment of climbing to cruise altitude. The results obtained for the cruise flight mode highlighted the efficiency of the thermal part (TGE) of the HEP propulsion systems alone—the TGE was optimized for the HEP and showed reductions in fuel burn and carbon emission, even during flight where electric engine (EE) contribution was absent. The efficiency of the EE of the HEP for NO_x emission reduction along the same flight profile was an average 40% for take-off mode, 45% for climb-out mode, and 43% for climb mode.

Dispersion modelling and analysis of NO_x emissions in EFACApport demonstrated an fourfold decrease in hourly concentrations to 24.0 µg/m³ from the maximum value 101.53 µg/m³ in the reference scenario (11 operations per peak hour). A similar trend was observed for the area of NO_x influence, with a 68% reduction being recorded, as shown in Figure 4.

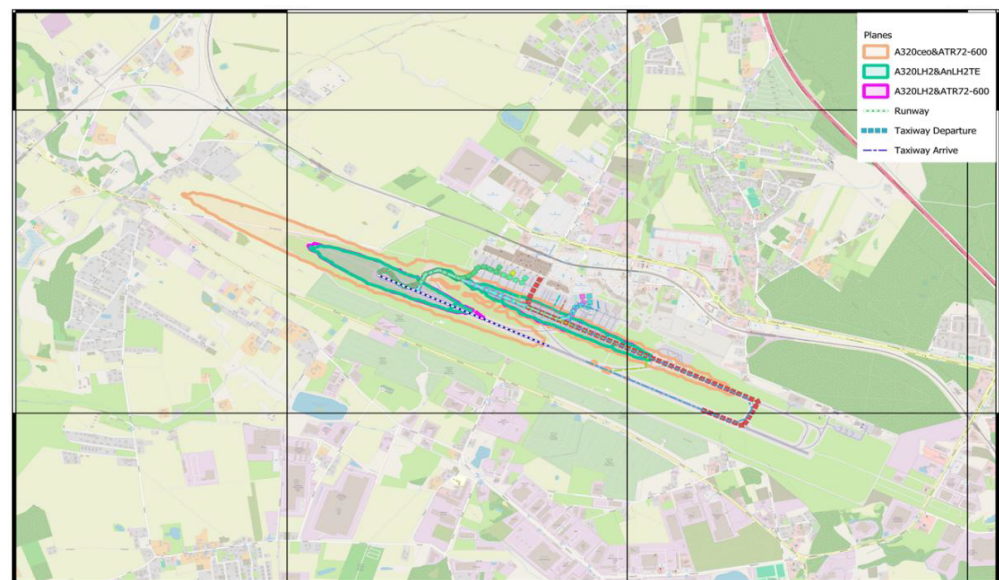


Figure 4. Area of LAQ influence (hourly NO_x isopleth for 10.00 µg/m³) for traffic scenarios in EFACApport. Orange line indicates the reference aircraft in a fleet. Green line indicates LH₂-fuel aircraft in a fleet. Pink line indicates LH₂-fuel and HEP aircraft in a fleet [19].

5. Conclusions

The EU EFACA project proposed a new approach based on the VALDES calculation platform for analysis of HEP and LH₂-fueled aircraft with respect to their fuel burn and engine emissions in comparison with reference aircraft, these being the best aircraft in class currently in operation powered by conventional engines and fuels. Efficiency is determined for three levels of assessment. Aircraft level concerns fulfillment of the current and future ICAO standard requirements [4]. Airport level concerns the ACARE Fly Green Deal future goals for the environment. Fleet level concerns the ICAO Long-Term Aspirational Goal [2]. Preliminary results of the EFACA project show that hydrogen aircraft may contribute essentially to Net Zero Aviation by 2050 [5]; however, these aircraft require specific hydrogen infrastructure in airports, and this may delay the introduction of hydrogen aircraft into operation.

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Data Availability Statement: The data presented in this study are available in [EFACA] at [<https://efaca.eu/>] (accessed on 13 June 2026).

Conflicts of Interest: The author declares no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ACARE	Advisory Council for Aviation Research and Innovation In Europe
CAEP	Committee on Aviation Environmental Protection
EFACA	Environmentally Friendly Aviation for All Classes of Aircraft
EEDB	Engine Emissions Data Bank
GHG	Green-House Gases
HEP	Hybrid Electric Propulsion
ICAO	International Civil Aviation Organization
IPCC	Intergovernmental Panel on Climate Change
LAQ	Local Air Quality
LTAG	Long-Term Aspirational Goal
LTO	Landing and Take-Off
TRL	Technology Readiness Level
UNFCCC	United Nations Framework Convention on Climate Change
VALDES	Vehicle/Airport/fleet Design Space

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