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Road map towards Fit 55 and Net Zero 2050

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Abstract
EFACA project considers bespoke state of the art technological solutions for each of the following 4 aviation market segments: IAM (Innovative Air mobility), Regional Market, Medium-range Market and Long-range Market. It determines for each of them the most promising energy and technological solutions to achieve Net Zero objective in the shortest possible time. This paper presents and assessment of **possible EFACA pathways to achieve net-zero direct emissions from aviation**, including changes and trade-offs in demand, energy efficiency, propulsion systems, alternative fuels for both passenger and freight transport and compensatory carbon removals.

1. Introduction

The aviation industry is committed to achieving net-zero emissions by 2050, with growing efforts fuelled by climate change concerns and dedicated resources. Numerous global and regional roadmaps have emerged, outlining strategies to reach this goal [1-7]. A comparative review of these roadmaps reveals significant differences in how technologies and solutions may evolve [8]. Key uncertainties include the scope, assumptions, and potential of various mitigation measures, such as new aircraft technologies, zero-carbon fuels, SAF, and operational improvements.

By 2050, aviation is projected to emit around 21.2 gigatons of CO2 under a "business as usual" scenario. Achieving net-zero emissions will require coordinated efforts from airlines, airports, manufacturers, and government support. However, the transition is uncertain, as technologies and fuel innovations remain under development, and fleet replacement rates are low. There is also uncertainty about the annual percentage improvement in energy efficiency (megajoules per revenue passenger kilometres) between now and 2050. As a result, since most of the transition measures for the aviation sector are not yet available, there is no universal path to net-zero aviation, only multiple alternatives.

To help in this process EFACA project considers bespoke state of the art technological solutions for each of the following 4 aviation market segments: IAM (Innovative Air mobility), Regional Market, Medium-range Market and Long-range Market. It determines for each of them the most promising energy and technological solutions to achieve Net Zero objective in the shortest possible time. [9-16]

EFACA project is focused on the development of new technologies by using electric and hybrid thermoelectric propulsions and new sustainable fuel to replace fossil fuel. EFACA's approach includes small electric urban air vehicles for IAM, hybrid turboelectric power for regional aircraft, and a novel LH2 MSR aircraft for medium-range markets. For long-range aircraft, EFACA emphasizes 100% SAF. For the regional market EFACA considers two designs using gas turbine engines, with electric motors (EM) fed with batteries in the first case and with fuel cells in the second case. The first case is designed in such a way that it can replace the ATR 72-600 even on long flights (more than 1000 km); it is designed based on a gas-turbine engine with reduced power and sises, and the characteristics of this engine correspond to today’s technological level. The second variant of HEA (Hybrid Electric Aircraft) is designed to give maximum benefit for reduction of ecological impact on distances less than 1000 km and it is designed based on the perspective gas-turbine engine corresponding to the technological level of 2035.

Projected improvements in fuel consumption, emissions, and environmental impacts [Emission Indices (EI's) for NOx, CO2, (U)HC, SOx, and non-volatile Particulate Matter (nvPM)] are assessed, projected up to 20250 according to the predicted EIS and fleet removal hypothesis, and integrated into global net-zero strategies. The final roadmap incorporates the latest advancements from ICAO, EU, and EFACA visions. This is completed with analysis of trends

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in aircraft fuel/energy consumption and engine emission in comparison between ICAO, EU and EFACA visions. And finall,y based on this interaction un update roadmap for Net Zero Aviation is presented that incorporates state of the art information regarding the following elements.

2.Analytical approach and methods.

This work develops and analyse a range of mid-century EFACA decarbonization scenarios for the aviation industry decomposing historical and future aviation emissions, by suing a combination of several well stablished methods and hypothesis, among which the most relevant are listed below:

- Specification of **EFACA solutions for each aviation market** segment and assessment of the **prospect for such markets demand.**

- Definition of **reference and EFACA scenarios**. EFACA scenarios considered different tentative EIS dates as a way to valuate windows of opportunity offer by an early availability of the various EFACA technology solutions and aircraft. Scenarios are defined and further quantified in terms of Demand, energy intensity and carbon intensity using the kaya identity.

- A **sector-specific (aviation) variant of the Kaya identity for the estimation of CO_2 emissions from global aviation**. The kaya identity is a Mathematical identity stating that the total emission level of the greenhouse gas carbon dioxide can be expressed as the product of four factors: human population, GDP per capita, energy intensity (per unit of GDP), and carbon intensity (emissions per unit of energy consumed). It has been probed useful in practice to calculate emissions in terms of more readily available data, namely population, GDP per capita, energy per unit GDP, and emissions per unit energy. It furthermore highlights the elements of the global economy on which one could act to reduce emissions, notably the energy intensity per unit GDP and the emissions per unit energy. [17]. The aviation specific variant of the Kaya identity is expressed by equation (1).

$$F = D\left(\frac{E}{D}\right)\left(\frac{F}{E}\right) = Def \qquad (1)$$

  Where:
  - F represents fossil fuel CO2 emissions from global aviation (neglecting life-cycle emissions of the aircraft and the supply chain of fuel),
  - D is demand or distance flown and
  - E is the energy consumed by flying aircraft, such that
  - e is energy intensity of air transport and
  - f is the carbon intensity of energy used for air transport.

  The model allows to analyse different pathways of demand (D) and energy intensity (e) and combine them with different pathways for carbon intensity (f).

- Non-CO2 emissions are calculated based on **Global Warming Potential and Global Temperature Potentials multipliers** by D.S. Lee et al [17]. Global aviation warms Earth's surface through both CO2 and net non-CO2 contributions and also contributes a few percent to anthropogenic radiative forcing. Non-CO2 impacts comprise about 2/3 of the net radiative forcing. This method provides a comprehensive and quantitative approach for evaluating aviation climate forcing terms. Both radiative forcing (RF) and effective radiative forcing (ERF) terms and their sums are calculated for the years 2000–2018., and supporting data are available. These emissions include: contrail cirrus, nitrous oxides, soot emissions, sulphur dioxide and Water vapor. The methods use a **Global Warming Potential** of 100 years (GWP100) and report GWP of 20 and 50 years and **Global Temperature Potentials** (GTP) of 20, 50 and 100 years.

- Finally, the carbon intensity for scenarios including non-CO2 emissions measured in gCO2eq MJ^{-1} is calculated based on estimated total fuel consumption and CO2eq emissions.

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3. EFACA solutions and marked served.

EFACA has desined specific aircraft to serve the regional and medium range markets. For the regional market two THEP (Turbopropulsed Hybrrid Electric Propulsion) configurations are proposed. Both configurations have an electric engine and a combustion engine. In one configuration the electric engine will be powered by hydrogen fuel cells andin the other by batteries. The hybrid configuration will save more fuel in the landing and take-off phases (around 25%). Therefore, the savings will be more noticeable on short-distance routes. This aircraft is expected to be 12% more efficient that the reference ATR72 with an PW127F engine, however with shorter range. The consumptions of the two hybrid configurations and reference ATR72 for a1000km range are shown in **¡Error! La autoreferencia al marcador no es válida.**.

Table 1. Fuel consumption for different regional aircraft configurations.

Aircraft	Kg of fuel consumption for 1000km range
Reference aircraft ATR72	1632,57
EFACA RTHEP with batteries	1232,025
EFACA RTHEP with fuel cells	836,412

According to EFACA technological solutions and aircraft ranges and performances the aviation market is segmented as indicated in table 2. The table also indicates the percentage of the market that each segment represents according to a bespoke routes' analysis with 2023/2024 flight data.

Table 2: Aviation markets according to EFACA aircraft and technological solutions.

Aviation markets	Aircraft ranges	% of the global aviation market
Small /short range market including IAM(Innovative Air Mobility): EFACA envisaged full electric battery aircraft	0-300km	1%
Regional market: 2 EFACA Hybrid Regional models are considered: Hybrid electric with batteries and Hybrid electric with fuel cells	300-1000km	16%
Medium range market: EFACA jet liner aircraft will be fuelled by liquid H2.	1000-2000km	31%
Long range market: EFACA 100% SAF fuelled	>2000km	52%

Note: SAF fuel is also used in the regional hybrid market towards 2025 as substitution of Jet A1.

4. Scenarios analysed.

This work analysed 6 scenarios in total, 3 reference scenarios and 3 EFACA scenarios. Reference scenarios are: 1) BAU: Business As Usual; IP: Industry Projection; and AP: Ambitious Projection. Reference scenarios are detailed in figure 1. Reference scenarios has been considered also by other authors and researches, what allows comparison of the obtained results with available information on the literature. Further detailed information about these reference scenarios might be consulted at [ref].

EFACA scenarios are also 3: EFACA 2035, EFACA 2040 and EFACA 2045. As can be seen in the figure 1, the scenarios are defined in terms of demand (D) and energy intensity (e) and carbon intensity (f). EFACA scenarios are also defined in terms of demand (D) and energy intensity (e) and carbon intensity (f), being the differential factor among the 3 EFACA scenarios the Entry Into Service (EIS) of the EFACA medium range liquid hydrogen

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-LH2- aircraft for which 3 alternatives are analyses 2045, 2040 and 2035. 20245 is considered the more realistic date for EFACA aircraft EIS, and 20240 and 2035 EIS are studied to illustrate the opportunity window and potential benefits what will be achieved in case an earlier EIS was possible.

Table 3: Scenarios analysed.

Reference scenarios	Carbon Intensity (CI)	Historical demand (D) Historical energy intensity (e) Fossil jet fuel (f)	EFACA scenarios	EFACA 2035	Historical demand Historical energy intensity Biofuels 100% of long-haul aviation by 2050, LH2 non-emitting propulsion systems power for medium-haul flights, HETP (batteries and fuel cell) for regional market and electric batteries for short haul and IAM (f) EFACA LH2 medium-haul flights available on 2035 (EIS)
	Reduced Fossil (RF)	Historical demand (D) Historical energy intensity (e) Medium biofuel & low alternative technology deployment (f)		EFACA 2040	Historical demand Historical energy intensity Biofuels 100% of long-haul aviation by 2050, LH2 non-emitting propulsion systems power for medium-haul flights, HETP (batteries and fuel cell) for regional market and electric batteries for short haul and IAM (f) EFACA LH2 medium-haul flights available on 2040 (EIS)
	Net-Zero (NZ)	Historical demand (D) Historical energy intensity (e) High biofuel & medium alternative technology deployment (f)		EFACA 2045	Historical demand Historical energy intensity Biofuels 100% of long-haul aviation by 2050, LH2 non-emitting propulsion systems power for medium-haul flights, HETP (batteries and fuel cell) for regional market and electric batteries for short haul and IAM (f) EFACA LH2 medium-haul flights available on 2045 (EIS)

5. Pathways analysis

As a synthesis of the analyses performed figure 1 present a waterfall diagram of the EFACA scenarios. The water fall diagram presents in a very synthetic view the Total GHG Emissions in Gt CO2-eq based on GWP100 based on multiplier for each scenario. This diagram provides a parametric decomposition for the changes in emissions in GtCO2eq from the reference year up to 2050. Each diagram represents a demand(D) and energy-intensity (e) trajectory combined with a specific carbon intensity (i).

Each bar within each diagram represents a Kaya parameter: historical emissions in the reference year of 2021 (maroon), increase in emissions based on projected demand (blue), decrease in emissions based on energy-intensity improvements (orange), potential further reductions due to changes in carbon intensity of energy (green) and remaining carbon dioxide still to be removed (CDR) needed to reach net-zero by 2050 (grey). The CDR grey bar is divided into two, representing the split between CO2 and non-CO2 equivalent emissions in each scenario.

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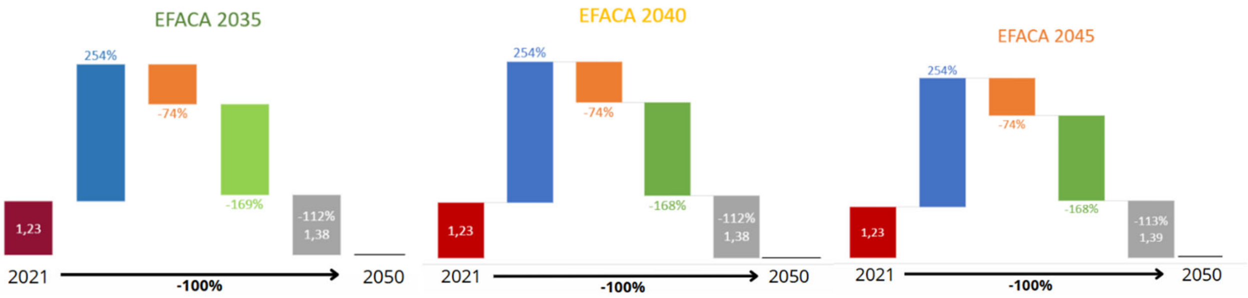

Figure 1. Waterfall analysis for the EFACA escenarios.

The figure illustrates the potential gains from the EFACA scenarios considering both CO2 and non-CO2 equivalent emissions. Here below there is a preliminary analysis of the results based on the different boxes of the graph, following the order from left to right. In other words, a separate analysis of each variable will be made. The first box, the one corresponding to the year 2021, is the same for the 3 EFACA scenarios 1.23 Gt ,CO-2.-eq.

The second box corresponds to the contribution to the equivalent emissions due to the increase in demand. This variation is counteracted by the second variable, energy intensity with a value of roughly 3.46 Gt.

The EFACA scenarios differ little from each other, just one percent, because SAF fuels and liquid hydrogen had similar emissions in the GWP 100 case. The EFACA scenarios are reduced by around 168% compared to 2021, being the remaining emissions due to emissions other than carbon dioxide and would be only 12% or 13% more than the emissions of 2021.

6. Conclusion.

The work presented in this paper has allowed to develop an analysis framework or the analysis of aviation Road map towards Fit 55 and Net Zero 2050 . Results presented are very preliminary and will be further completed in the coming months.

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