D3.3 – Performance Analysis of Aircraft Concepts

Document Authors	Pascal Bertram (DLR), Thierry Lefebvre (ONERA)
Document Contributors	Lukas Söffing (NLR), Svitlana Zhukovska (DLR), Volker Grewe (DLR), Patrick Ratei (DLR)

Abstract

This document presents the final output of Task 3.5, delivering a comparative assessment of advanced aircraft concepts and technologies in terms of environmental performance, with a focus on their climate impact. The study focuses on use cases inspired by Clean Aviation in the hybrid-electric regional and short- to medium-range segments, benchmarked against state-of-the-art reference aircraft, and accounts for both CO_2 and non-CO_2 effects. The primary objective is to demonstrate a methodology for evaluating climate impact using the climate metrics ATR100 and EGWP100 proposed in D2.2. The analysis applies the four-layer climate impact technology assessment developed in this project, following a two-step approach: (1) applying predefined improvement factors from reference aircraft to mission-level emission inventories; and (2) modelling advanced aircraft concepts to generate mission performance and emissions data. These outputs enable fleet-level climate impact estimation for the purpose of technology comparison. Results illustrate the method's applicability for evaluating and comparing innovative aircraft technologies, supporting future research and innovation in climate compatible aviation.

Keywords

Technology Assessment, Climate Metrics, Framework

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

Information Table

Contract Number	**101140632**
Project Title	Clean Aviation Support for Impact Monitoring
Topic	HORIZON-JU-CLEAN-AVIATION-2023-02-CSA-01
Type of Action	HORIZON JU Coordination and Support Actions
Project Start Date	2024-01-01
Duration	18 Months
Project Coordinator	Deutsches Zentrum für Luft- und Raumfahrt e. V. (DLR)
Deliverable Number	D3.3
Deliverable Title	Performance Analysis of Aircraft Concepts
Version	1.1
Status	Final
Responsible Partner	ONERA & DLR
Deliverable Type	Report
Contractual Date of Delivery	2025-06-30
Actual Date of Delivery	2025-08-29
Dissemination Level	PU

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

Authoring & Approval

Prepared by		
Name & Organization	**Position and title**	**Date**
Thierry Lefebvre (ONERA)	WP3 Task Lead	2025-08-01
Pascal Bertram (DLR)	WP3 Participant	2025-08-01

Reviewed by		
Name & Organization	**Position and title**	**Date**
Lukas Söffing (NLR)	WP3 Lead	2025-08-12
Patrick Ratei (DLR)	WP3 Participant	2025-08-18
Svitlana Zhukovska	WP2 Lead	2025-08-18

Approved for submission by		
Name & Organization	**Position and title**	**Date**
Lukas Söffing (NLR)	WP3 Lead	2025-08-18
Prajwal Shiva Prakasha (DLR)	Project Coordinator	2025-08-19

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

Document History

Version	Date	Status	Author	Description
0.6	2025-04-29	Draft	PB, TL	First Draft Version
0.9	2025-06-30	Draft	PB, TL	Revised Draft Version
1.0	2025-08-20	Final	PB, TL	Final Version
1.1	2025-08-28	Final	PB, TL	Revised Final Version

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

Acronyms and Abbreviations

Acronym / Abbreviation	Description / Meaning
AS4D	AirClim Surrogate Model for Aircraft Design
ATM	Air Traffic Management
ATR	Average Temperature Response
BPR	Bypass Ratio
CO_2e	CO_2 equivalent
CPACS	Common Parametric Aircraft Configuration Schema
DoE	Design of Experiments
EIS	Entry-into-Service
EI	Emission Index
FEI	Fleet Environmental Impact
HER	Hybrid-Electric Regional
ISA	International Standard Atmosphere
LHV	Lower Heating Value
NGAPA	Next Generation Aircraft Performance Analysis
OEM	Operating Empty Mass
PHEA	Plug-in Hybrid Electric Aircraft
PtL	Power-to-Liquid
RCE	Remote Component Environment
SESS	Simplified Emission Sensitivity Study
SMR	Short-Medium Range
SAF	Sustainable Aviation Fuel
TLAR	Top-Level Aircraft Requirements

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

Disclaimers

The project is supported by the Clean Aviation Joint Undertaking and its members.

Clean Aviation is the EU's leading research and innovation program for transforming aviation towards a sustainable and climate neutral future.

As a European public-private partnership, Clean Aviation pushes aeronautical science beyond the limits of imagination by creating new technologies that will significantly reduce aviation's impact on the planet, enabling future generations to enjoy the social and economic benefits of air travel far into the future.

Visit the website to find out more about Clean Aviation: www.clean-aviation.eu

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Table of Contents

1. Introduction 10
2. Methodology and Study Setup 11
2.1. Overview 11
2.2. Tools 12
2.3 Overview of Baseline and 2035 Aircraft Concepts 14
2.3.1. Reference Aircraft Selection 14
2.3.2. Future Aircraft Technology Considerations 16
2.4. Implementation of Technology Assessment Studies 22
2.3.1 Simplified Emission Sensitivity Study (SESS) 22
2.3.2 Next Generation Aircraft Performance Analysis (NGAPA) 27
2.5 Climate Metrics for Technology Impact Assessment 28
3. Results 31
3.1. Simplified Emission Sensitivity Study (SESS) 31
3.2. Next Generation Aircraft Performance Analysis (NGAPA) 42
3.2.1 Regional EIS 2035 42
3.2.2 Short-Medium EIS 2035 47
3.3. Influence of Climate Metric Selection on 2035 Aircraft Concepts 52
3.4. Limitations 54
4. Summary and Conclusions 56
References 58

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

List of Figures

Figure 1: The Four-layer Approach for Climate Impact Technology Assessment 11
Figure 2: HER improvements fields 17
Figure 3: D70-PHEA aircraft based on reference ATR72-600 similar aircraft 18
Figure 4: Block Energy share for battery and fuel across operational range 19
Figure 5: F25 aircraft based on reference SMR aircraft 20
Figure 6: DLR-F25 technology assessment on aircraft level for 800 NM mission 21
Figure 7: Workflow for the Simplified Emission Sensitivity Study, with 2020 aircraft technology status 22
Figure 8: SESS workflow implementation using RCE 24
Figure 9: Generic mission profiles for regional & short medium range aircraft for SESS 25
Figure 10: Workflow for the Simplified Technology Integration Study, with 2035 aircraft technology status 27
Figure 11: Overview on the process chain from aviation emissions to climate change 28
Figure 12: HER overall results scatter presentation for areas of improvement and normalized Fleet Environmental Impact 32
Figure 13: SMR overall results scatter presentation for areas of improvement and normalized Fleet Environmental Impact 33
Figure 14: CO_2e breakdown in comparison of HER & SMR for Baseline and Combined Technology with SAF 35
Figure 15: CO_2e breakdown for HER & SMR for best DoE combinations for each Area of Improvement 36
Figure 16: Sensitivity plot of soot vs NOx for the const. values of CO_2 and H_2O =0.2 for SMR & HER 38
Figure 17: SMR-Baseline total emission mass and total climate agent breakdown 39
Figure 18: Interpretation of Clean Aviation Target translated into Fleet Environmental Impact in ATR100 Target for HER & SMR 41
Figure 19: Comparison of the generic mission profiles for HER-baseline & HER-2035 43
Figure 20: Normalized overall network emissions baseline vs. HER-2035 44
Figure 21: Normalized breakdown of climate impact contributors for baseline vs. HER-2035 45
Figure 22: Total Fleet Environmental Impact in ATR-100 for HER-baseline, DoE points and HER-2035 46
Figure 23: Comparison of the generic mission profiles for baseline & SMR-2035 aircraft 48
Figure 24: Normalized overall network emission reduction baseline vs. SMR-2035 49
Figure 25: Normalized breakdown of climate impact contributors for baseline vs. SMR-2035 50
Figure 26: Total Fleet Environmental Impact in ATR-100 for Baseline, DoE results and SMR-2035 52
Figure 27: Comparison of CO_2e factors for the climate metrics ATR100 and EGWP100 53
Figure 28: Comparison of total results for SMR-2035 use case 54

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

List of Tables

Table 1: TLARs of ATR72-600 similar aircraft 15
Table 2: TLARs of D239 16
Table 3: Assumption for Battery Aircraft Modelling with EIS 2040 18
Table 4: Key characteristics and emission properties in comparison 21
Table 5: DoE for simplified study 23
Table 6: Emission Indices for SESS 26
Table 7: Assumptions for HER and SMR for SESS 27
Table 8: Scenario Assumptions & Key Parameters for the HER-2035 Study Case 43
Table 9: Scenario Assumptions & Key Parameters for the SMR-2035 Study Case 47
Table 10: Overall Fleet-Level Emission Reductions & Normalized FEI for Baseline & SMR-2035 scenarios 51

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

1. INTRODUCTION

Clean Aviation Joint Undertaking will contribute to Europe's climate neutrality by 2050 by developing and implementing new and more environmentally friendly technologies in the aeronautical sector. In Clean Aviation's Strategic Research and Innovation Agenda (SRIA) 2035, future aircraft concepts with advanced technologies and the projections of environmental performance improvements are described. For instance, a hybrid electric regional aircraft concept and a short-/medium range aircraft concept, both with a tube and wing configuration, have the overall target of 30% CO_2 emission reduction and up to 86% with SAF compared with aircraft with 2020 state-of-the-art technology. [1]

Within the project "Clean Aviation Support for Impact Monitoring" (CLAIM), Task 3.5 "Preliminary aircraft environmental-performance analysis" aims at providing an initial analysis performance assessment of the aircraft concepts: "Short and Medium Range" (SMR) and "Hybrid-Electric Regional" (HER) considering the potential benefit that is possible to obtain by the adoptions of the relevant innovative technologies. Those aircraft will be benchmarked with reference counterparts in terms of their impact on performance and emissions including non-CO_2 effects.

This report proposes a comprehensive approach to evaluating the climate impact of advanced aircraft technologies at both the mission and fleet levels. While the data used are not sourced directly from Clean Aviation projects, the concepts are merely inspired by ongoing research and innovation within the Clean Aviation programme. The proposed methodology built on a selection of coupled tools for trajectory analysis and climate impact assessment, integrated in specific workflows to achieve the objective. Relying on these workflows, the study first assesses the sensitivity of mission-based emission inventories. In a second step, the climate impact of potential new aircraft with an entry into service in 2035 is investigated, focusing on the potential of innovative aircraft concepts targeting the regional and short- to medium-range market segments.

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

2. Methodology and Study Setup

2.1. Overview

To assess the changes in emissions and climate effects of advanced aircraft technologies on a broader level, the 4-layer approach outlined in [2] was applied to scope the study. Starting from market segmentation, network considerations, EIS timelines, and the temporal evolution of technology, 3D (or 4D) emission inventories are generated which capture the operational characteristics of the aircraft (Figure 1). Based on these inventories, radiative forcing and temperature changes can be calculated and evaluated using appropriate climate metrics.

This structured approach forms the backbone of the technology impact assessment conducted in this study. In particular, we employ a dedicated workflow for simplified technology assessment that integrates and connects the necessary modeling tools. The evaluation itself follows a two-step procedure, designed to assess the climate impact of specific technologies at the fleet level.

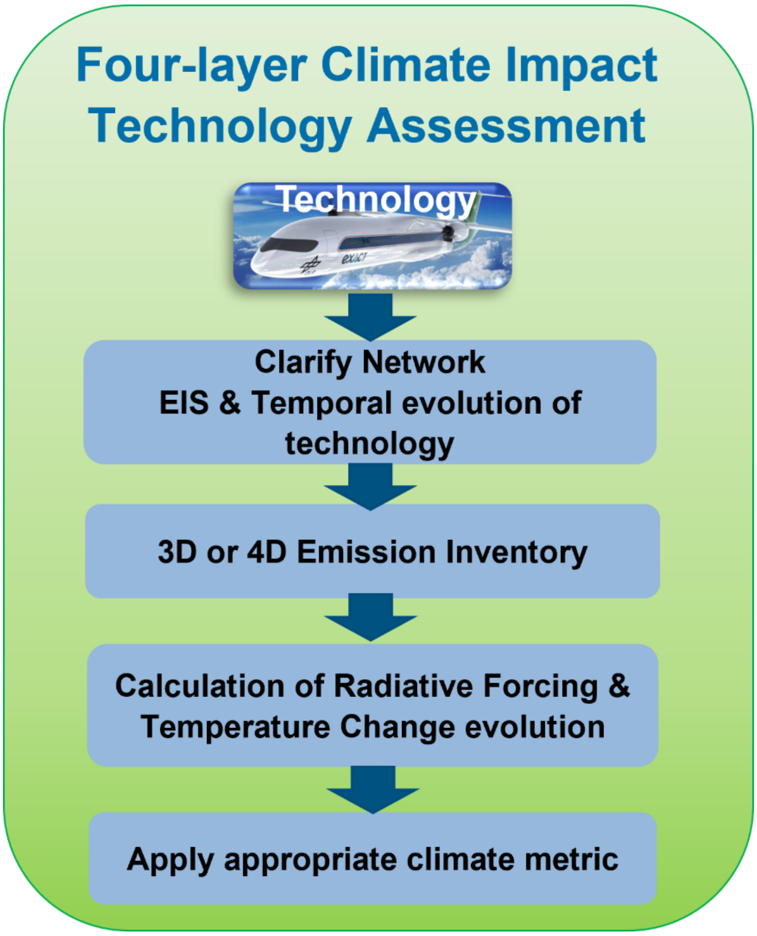


Figure 1: The Four-layer Approach for Climate Impact Technology Assessment outlined in [2]

CLEAN AVIATION

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

The first step focuses solely on technological improvements that directly influence mission-based emission inventories according to their proposed performance-improvement characteristics. In the second step, the referenced study applies aircraft concepts that were preliminarily sized using multi-fidelity domain tools for aircraft design. Based on the resulting configurations, mission performance tools are subsequently employed to calculate emission inventories for specific aircraft trajectories.

The following sections introduce the tools applied for both approaches, explain the logical sequence for integrating these tools into a cohesive workflow, and outline the selection of reference aircraft used for modeling. The subsequent technology assessment process is described with a focus on baseline improvement factors at the mission level in the first step and at the aircraft design level in the second step. To evaluate the effects of variations in these improvement factors, the response of climate metrics and their sensitivity to these changes will be analyzed in the following chapters. In addition, the potential benefits of different technologies with regard to climate impact mitigation will be discussed.

2.2. Tools

This section outlines the tools employed, their specific characteristics, and the underlying assumptions. In the subsequent Workflow section, these tools will be systematically integrated to conduct workflow studies. In particular, the step-1 and step-2 studies mentioned earlier will be detailed within the logical workflow, including their underlying structure and methodology.

OpenAD – Open Aircraft Design (DLR)

OpenAD is a preliminary aircraft design tool that leverages well-understood and mostly publicly available handbook methods. It is implemented using object-oriented programming in Python and is easily expandable, providing a consistent initial evaluation of an aircraft design. The current design space of OpenAD covers aircraft sizes ranging from small 19-passenger aircraft to large 800-passenger aircraft. [3]

Aircraft Design and Sizing Tool (ONERA)

FAST-OAD [4] is an open-source aircraft sizing and optimization tool developed by ISAE-SUPAERO and ONERA. It is based on the OpenMDAO framework and a previous sizing tool called FAST developed since 2015. To fully use the MDAO capabilities of OpenMDAO, the aircraft sizing methodologies have been written as components.

FAST-OAD codes come by default with models adapted for CS-25 aircraft which are grouped by aircraft design disciplines. It includes: Geometry, Aerodynamics, Weight and Performances among others.

Even though the FAST-OAD framework has been extended for the preliminary sizing of unconventional architectures [4, 5], which proves the adaptability of the framework, the models used in the current open-source distribution correspond to a classical tube and wing configuration. Said models are valid for commercial transport aircraft and the code uses an A320-type aircraft as reference.

CLEAN AVIATION

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

FAST-OAD also allows to compute 2D trajectories based on propulsive and aerodynamic performance inputs, mission input data, weight and balance data, and general input data.

AMC – Aircraft Mission Calculator (DLR)

The tool Aircraft Mission Calculator is used to model the flight time and mission fuel based on variable flight distance inputs. This tool generates 2D trajectories based on propulsive and aerodynamic performance inputs, mission input data, weight and balance data, and general input data. These trajectories are defined by the distance and altitude of the aircraft, providing detailed outputs on fuel consumption, energy flow, drag/lift, thrust, mass properties, and emissions flow.

In detail, AMC uses fuel fractions for the taxiing, take-off, approach and landing phases to determine the dynamic change of the total aircraft mass, due to fuel burn. For high-speed performance, these changes are estimated by solving the 2D total motion equations and analysing the climb, cruise, and descent phases with a clean wing configuration, where control surfaces such as flaps and slats are retracted. The tool optimizes the initial cruise altitude to determine the optimal cruise level for the current aircraft configuration. During the cruise phase, a combination of constant altitude and step-climbs is applied. The timing of the step climb is dependent on the specific range, considering both aerodynamic and engine performance factors. [6]

AS4D – AirClim Surrogate Model for Aircraft Design (DLR)

The AS4D model was developed with the objective of assessing the potential climate impact of an aircraft at the pre-design level. To evaluate the effects of different aircraft designs on a global scale in a relatively fast manner, a simplified model has been utilized.

The tool is built upon three main pillars. The first is aircraft design, which is defined by input parameters such as seat capacity, wingspan, lower heating value, and pre-computed generic trajectories that include design-specific performance values, such as mission-based emission inventories. The second pillar is the global network modelling, which represents the potential operational context for these aircraft categories. This is crucial for climate impact assessments, as spatial dependencies significantly influence non-CO_2 emissions, thereby affecting overall climate impact. The global route network incorporates current air travel demand, represented as the number of flights these aircraft types would perform to meet that demand.

To predict future operations, a forecast scenario has been applied. This scenario introduces new aircraft designs starting from 2030, with a five-year production ramp-up period and a ten-year fleet renewal cycle. As a result, the market share of these newly introduced models is assumed to reach 100% by 2045. After this point, demand is expected to continue growing, though at progressively slower rates, reflecting a dynamic of saturation driven by population trends. As population growth slows or stabilizes in many regions, the corresponding demand for air travel also reaches a plateau, limiting the potential for significant growth beyond certain thresholds. This reflects the natural limits of demand expansion when the primary drivers, such as population and economic activity, begin to stabilize. Fuel efficiency improvements are also incorporated into this forecast. However, starting from 2030, the rate of improvement in fuel burn is expected to decline, as traditional gains in fuel efficiency will have largely been maximized.

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

The third pillar involves calculating the climate impact based on flown trajectories. To achieve this, global flight connections are modelled as individual missions comprising climb, cruise, and descent profiles, with variations in climb angles and cruising altitudes included. These models provide emission inventories for each phase: climb, cruise, and descent. Using this data, the flight phases are analysed in terms of fuel consumption, emission indices, and overall propulsion efficiency. Subsequently, the flight phases are mapped to pre-calculated representative flight trajectory/phase data, utilizing a response surface sub model.

This sub model then outputs the corresponding climate impact, along with detailed information on climate impact contribution of individual species. Currently, the model outputs only the average temperature response (ATR) with a time horizon of 100 years as indicator for the climate impact. Later we will describe the selection of this metric in regards to aeronautical impact assessment applications in more detail. [7]

RCE – Remote Control Environment

The workflow executioner, RCE (Remote Control Environment), is an open-source software tool designed to facilitate collaborative and distributed work across multiple simulation tools. It provides a workflow environment that enables the integration of various simulation tools and supports the development of complex systems, such as aircraft. In this study, RCE was used for two main purposes: first, to efficiently couple various tools within a single central application; and second, to execute these workflows automatically by making use of functional blocks, such as the Design of Experiments (DoE) block. [8]

2.3 Overview of Baseline and 2035 Aircraft Concepts

This section provides an overview of the aircraft technologies considered in this study. Both a baseline aircraft with 2020 state-of-the-art technology and future aircraft concepts targeting an EIS in 2035 are introduced.

2.3.1. Baseline Aircraft Selection

Regional

The Top-Level Aircraft Requirements (TLARs) for the baseline HER aircraft concept has been derived, where feasible, from publicly available data on the ATR72 [9]. This aircraft was chosen as a benchmark due to its status as the most representative model in the regional turboprop market, holding over 75% market share.

In addition, the TLAR from Hybrid-Electric Regional Aircraft (HERA) project draws heavily from the same aircraft [10]. Table 1 summarize the key TLAR key Parameters of the baseline aircraft.

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

Table 1: TLARs of ATR72-600 similar aircraft, depicted from [9]

Parameter	Unit	Value
Max. Take Off Weight (MTOW)	[kg]	23000
Max. Landing Weight (MLW)	[kg]	22350
Operating Empty Weight (OEW)	[kg]	13600
Max. Payload	[kg]	7400
Max. PAX	[-]	78
Mass per PAX	[kg]	95
Max. Fuel	[kg]	5000
TOFL (ISA +0K SL) @MTOW	[m]	1315
LFL (ISA +0K) @MLW	[m]	915
Reference speed at landing	[kts]	113
Climb speed	[kts]	170
Max. cruise speed (ISA FL240) @ 95% MTOW	[kts]	270
OEI ceiling (ISA +10) @ 95% MTOW	[ft]	9800
Range with max pax	[nm]	740

Short-Medium Range

To select a baseline aircraft that represents the current state-of-the-art technology while also maintaining a significant market share, it is essential to choose an aircraft type that is widely used both now and in the future. For the short- to medium-range category, aircraft with high market shares and advanced technological capabilities include the Airbus A320neo family—comprising models such as the A320neo and A321neo—and the Boeing 737 MAX family, including the 737-8 and 737-9.

Current order numbers and forecast studies indicate a trend toward airlines increasingly utilizing higher seating capacity aircraft in the short- to medium-range segment. This shift is driven by factors such as rising passenger demand projections, airport movement constraints, and the potential for greater revenue efficiency. Airport movement constraints, in particular, limit airlines' ability to increase flight frequencies, leading to a shift toward larger-capacity aircraft to accommodate more passengers per flight. Additionally, higher seating capacity aircraft within the same family enable airlines to enhance operational profitability while maintaining nearly the same operational costs. [11, 12]

For this reason, a higher seating capacity aircraft, similar to the B737-9/10 or A321neo, was selected as the reference. Specifically, the D239, an aircraft similar to the A321neo with a seating capacity of 239 passengers, was chosen instead of the A320neo, which has a lower seating capacity of around 186 passengers. The D239 has been designated as the primary aircraft type for the initial assessment in the *Simplified Emission Sensitivity Study*, which incorporates 2020 aircraft technology status. Since no market study was conducted to inform the TLARs, the same TLARs from the A321neo informed the D239 baseline aircraft, based on

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

its latest technology status as depicted in Airbus aircraft characteristics and the airport planning manual. The TLARs depicted can be found in Table 2.

Table 2: TLARs of D239, depicted from [13]

Parameter	Unit	Value
Design range	[nm]	2500
Design PAX (single class)	[-]	239
Mass per PAX	[kg]	95
Design payload	[kg]	25000
Max. payload	[kg]	25000
Cruise mach number	[-]	0.78
Max. operating mach number	[-]	0.82
Design dive speed	[kts]	380
Max. operating speed	[kts]	350
Max. operating altitude	[ft]	40000
TOFL (ISA+0K SL)	[m]	2200
Rate of climb @ TOC	[ft/min]	>300
Approach speed (CAS)	[kts]	136
Wing span gate limit	[m]	<36
Alternate distance	[nm]	200
Holding time	[min]	30
Contingency	[-]	3%

2.3.2. Future Aircraft Technology Considerations

Regional EIS 2035 – HER-2035

The target configuration of the regional EIS 2035 is the Ultra-Efficient Regional Aircraft concept built on Clean Aviation proposal. It is expected to remain tube-and-wing, targeting an Entry into Service (EIS) in 2035. This concept is designed for 50–100 passengers (PAX) with a range of up to 500 NM and optimized for typical missions of around 250 NM. It aims to achieve a 30% reduction in CO_2 emissions through advanced technology, excluding the net effects of Sustainable Aviation Fuel (SAF). The aircraft will also be compatible with 100% SAF to ensure future adaptability. The concept should incorporate advanced design features affecting critical systems and components, along with an innovative hybrid-electric powerplant that uses batteries. The propulsion system will combine an advanced thermal engine with an electric motor/generator and batteries, forming a hybrid solution that aims to deliver more than a 20% CO_2 reduction at the aircraft level. This system will include a high-efficiency propeller to meet operational constraints and a redesigned nacelle and pylon to revise wing aerodynamics, ensuring new load and flight control effectiveness. Aerodynamic optimization

CLEAN AVIATION

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

of the overall aircraft shape, particularly the wing, will complement the new propulsion system, improving aerodynamics and flight control surfaces. Along with enhancements to the fuselage and empennage, this optimization could achieve a further 10% reduction in CO_2 emissions. Structural improvements to the fuselage, cabin, cargo areas, and empennage will aim to offset the additional weight from hybrid propulsion components like batteries. Finally, all on-board systems will be updated or redesigned to adopt all-electric or more-electric solutions, reducing energy consumption and emissions. Systems such as thermal management, electrical systems, battery storage, and energy management will be optimized to support hybrid-electric propulsion and achieve further sustainability gains. Figure 2 highlights the main areas of improvements.

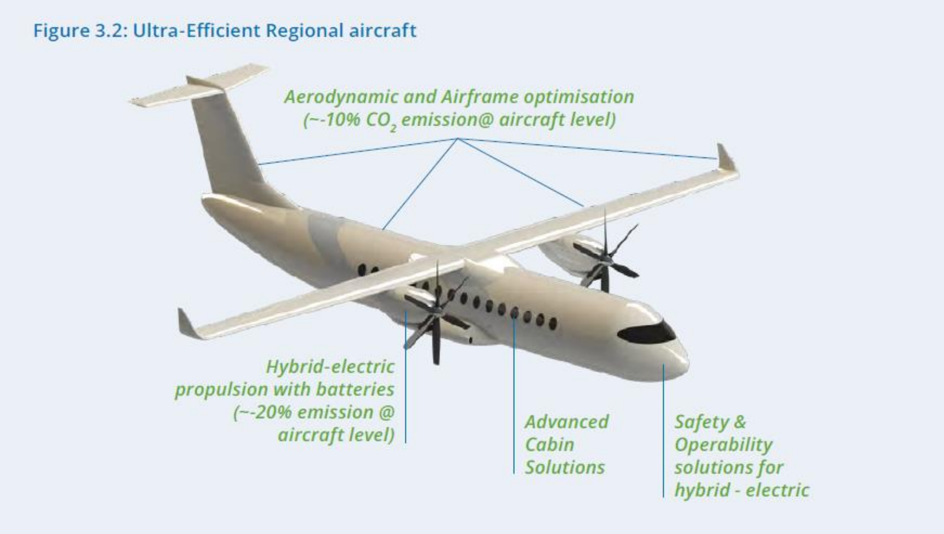


Figure 2: HER improvements fields, adopted from [2]

In the context of the CLAIM project, the regional HER concept presented in this report refers to a hybrid-electric aircraft design with technology assumption around 2040. The concept is based on the TLARs of the ATR72-600, with an adapted design range of 1,000 NM, chosen to cover the majority of globally operated regional flights.

This aircraft uses hybrid-electric powertrain, combining battery-electric propulsion with a conventional gas turbine powered by kerosene or SAF. The propulsion system includes distributed electric fans, reducing take off power due to redundancy and blowing wing effect. This configuration supports flexible operational strategies, allowing for optimization of range and energy/fuel usage (Figure 3). [14]

In particular, for missions up to 1,000 NM, the aircraft can operate fully electric, with mission reserves and diversion provided by the gas turbine running on bunkered fuel, thereby reducing battery sizing requirements for these cases (Figure 4). For missions exceeding 1,000 NM, a different operational strategy is applied: taxi and take-off are performed using battery power. Once airborne, the gas turbine takes over to handle the main portion of the mission, consuming fuel and gradually reducing aircraft weight. When a sufficient fuel buffer for reserves and diversion is reached, the aircraft switches back to battery power for the rest of the cruise, descent, and landing phases.

CLEAN AVIATION

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

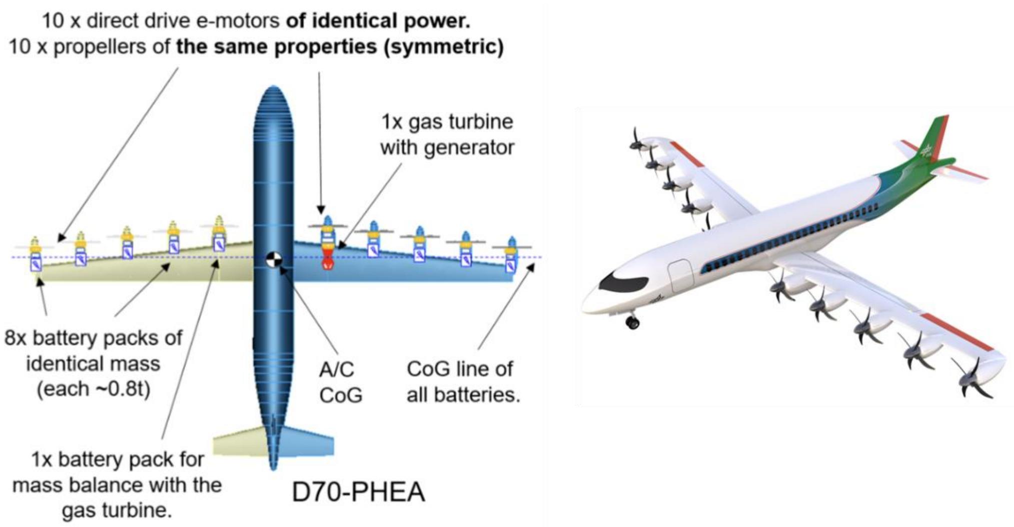


Figure 3: D70-PHEA aircraft based on reference ATR72-600 similar aircraft from [14]

The assumptions for the electric powertrain components are as follows: the specific energy for a single battery cell is assumed to be 500 Wh/kg, while the specific energy for the complete battery pack (including structural and thermal management components) is assumed to be 400 Wh/kg. For the electric motors, including the inverter, a specific power of 10 kW/kg is assumed, with an efficiency of approximately 97%. The generator is assumed to have a specific power of 12.5 kW/kg and an efficiency of around 98%. A summary of the assumed electric powertrain parameters is provided in Table 3. [14]

Table 3: Assumption for Battery Aircraft Modelling with EIS 2040, adapted from [14]

Parameters Assumptions	Value	Comment
	Component: Electric Motors	
Spec. power e-motors w/ inverter	10 kW/kg	Direct drive assumed
Efficiency w/ inverter	97.5%	Direct drive assumed
Spec. power generator w/ rectifier	12.5 kW/kg	Direct drive assumed
Efficiency w/ rectifier	98.0%	-
Installation mass penalty	10.0%	-
	Component: Batteries	
Spec. energy battery cells	500 Wh/kg	@1 cycle discharge (2 cycle discharge capability)
Spec. energy battery pack	400 Wh/kg	-
1 cycle charge-discharge efficiency	90.0%	-

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

This aircraft concept, with its distinctive operational strategy, achieves an overall fleet energy reduction of approximately 46% through the integration of advanced hybrid-electric technologies. This is despite an increase in Maximum Take-Off Weight (MTOW) of about 40%, driven by the addition of the hybrid-electric powertrain components. [14]

Figure 4 illustrates the block energy advantage of this concept across its operational range, compared to the baseline D70 aircraft, which offers performance comparable to the ATR72-600. As aforementioned, the aircraft operates fully electric up to approximately 300 NM, resulting in zero in-flight emissions when considering only ground & flight-phase emissions. Beyond this range, the gas turbine engages to enable extended mission ranges, supporting operations up to the 1,000 NM. [14]

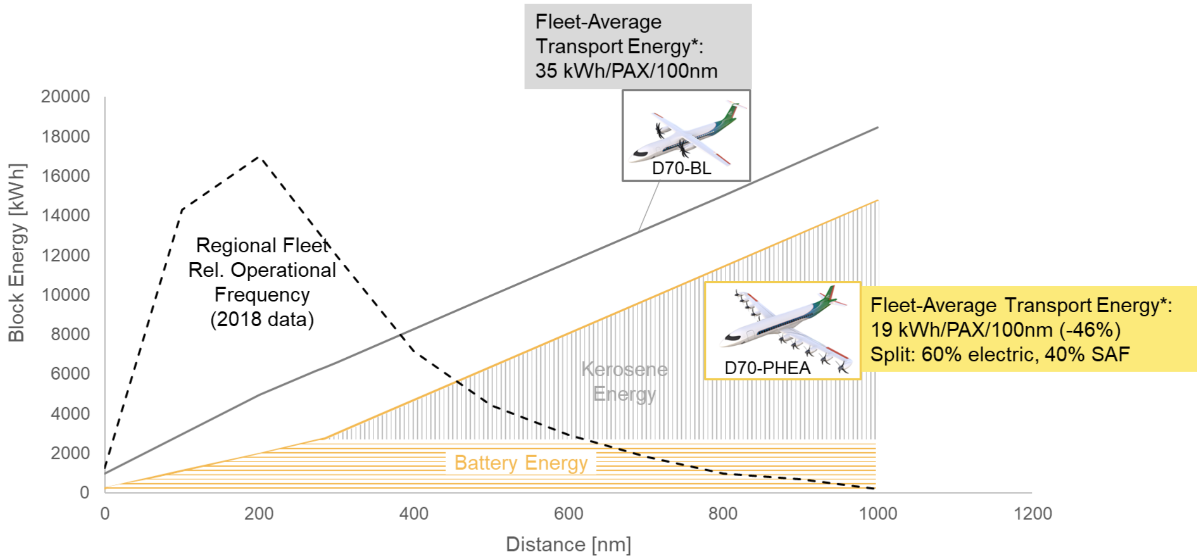


Figure 4: Block Energy share for battery and fuel across operational range, adapted from [14]

Short-Medium EIS 2035 – SMR-2035

The DLR-F25 aircraft design is based on the D239 baseline model. The F25 serves as the representative baseline aircraft and technology integration platform. This baseline models a kerosene/SAF-powered conventional ultra-high bypass ratio (UHBR) turbo fan engine configuration with a 2035 technological level (see Figure 5) and has been selected as the SMR-2035 aircraft concept for this study.

The primary focus of the F25 lies in the integration of an ultra-high aspect ratio wing designed to enhance aerodynamic performance and efficiency. To remain compatible with airport infrastructure, the wing incorporates foldable wing tip devices that ensure compliance with the 36-meter wingspan limit for category C aircraft. This approach allows for an extended wingspan during flight while maintaining operational feasibility on the ground. Additionally, the wing design features movable high-lift devices and adaptive trailing edge mechanisms, which enhance lift performance and support low-speed operations. The wing's structure and

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

geometry are refined through iterative aero-structural coupling to optimize lift distribution, reduce drag, and minimize mass.

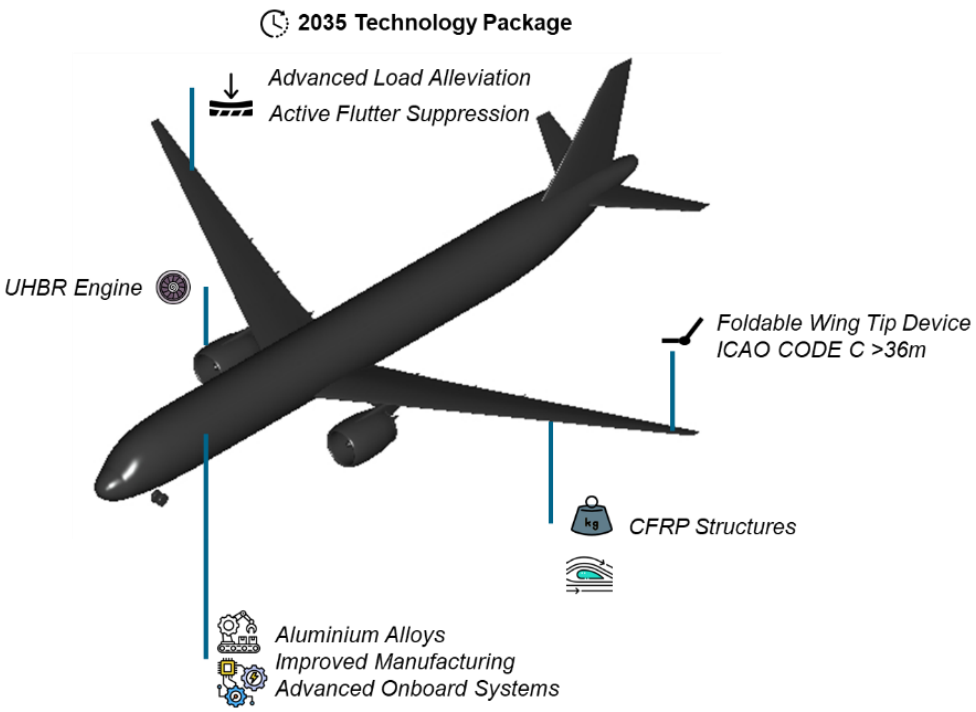


Figure 5: F25 aircraft based on reference SMR aircraft, adopted from [15]

The slender root chord of the wing and the center of gravity placement make wing-mounted landing gear infeasible; instead, the landing gear is attached to the fuselage. This configuration requires reinforced attachment points and an optimized belly fairing to handle associated structural loads.

The fuselage design retains consistency with the D239 in terms of cross-section, overall height, width, and cabin layout. Structural resizing is performed iteratively to account for aerodynamic loads, gust conditions, and landing forces, ensuring an efficient and robust integration of the wing and fuselage. To further enhance performance, an engine design block has been added to the F25 configuration. This block allows for resizing the engine based on the iterative resizing of the F25 itself. Additionally, advanced materials are utilized within the engine design, improving thermal cycle efficiency and contributing to overall fuel efficiency.

This resizing of the aircraft leads to an overall block fuel reduction of about 17.7%, whereas only the wing-aeroelastic structure technology contribute by 15.6% to the block fuel reduction (see Figure 6). [15]

In this project, the assessment goes beyond conventional metrics such as fuel burn and CO_2 emissions, addressing non-CO_2 emissions as well. Non-CO_2 emissions, such as contrail formation, significantly contribute to the aviation's overall climate impact. To mitigate these effects, this study incorporates not only technological improvements from classic disciplines for the F25 but also explores the use of revolutionary fuels.

CLEAN AVIATION

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

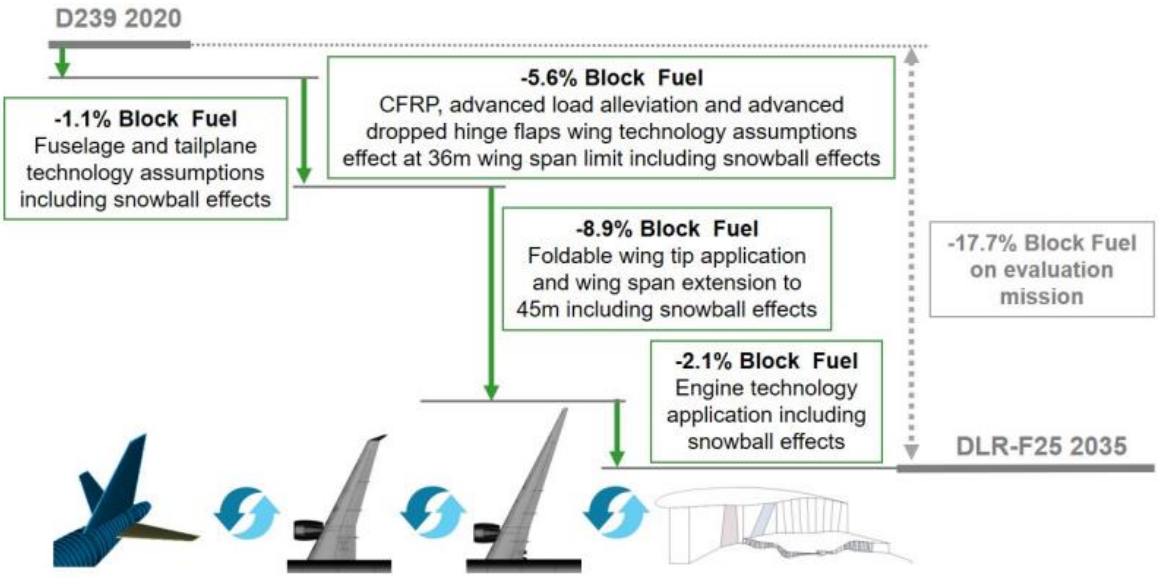


Figure 6: DLR-F25 technology assessment on aircraft level for 800 NM mission from [15]

Sustainable Aviation Fuels (SAF) have been selected as the primary propellant for the F25 in this assessment. SAFs are expected to lower both CO_2 and non-CO_2 emissions, potentially reducing the climate impact more effectively than conventional kerosene. The mission assessment for the F25 will consider the use of SAF and their implications on emissions, specifically on soot. Based on that fleet-level climatological impact can be assessed through the use of AS4D. There are various types of SAF, each with different blend shares and operational characteristics. For example, Power-to-Liquid (PtL), which offers a unique advantage: it can be operated without any blending with conventional kerosene. This characteristic makes PtL optimal in terms of its potential for mitigating climate impact, particularly when it is produced using renewable energy sources and carbon air capture technology. Under these conditions, PtL achieves significantly lower lifecycle emissions, and can potentially be operated as a carbon neutral fuel type. Table 4 shows an overview of relevant fuel properties for Jet A-1 and SAF (assuming 100% synthetic paraffinic kerosene 'SPK100'). [16]

Table 4: Key characteristics and emission properties in comparison, from [16]

Fuel Characteristics	Unit	Jet A-1	SAF
LHV	[MJ/kg]	43.25	44.04
EI CO_2	[kgCO_2/kgFuel]	3.156	3.104
EI H_2O	[kgCO_2/kgFuel]	1.239	1.367

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

2.4. Implementation of Technology Assessment Studies

This chapter outlines the methodological and software setup used to assess the impact of aircraft technology improvements on emissions and climate performance. The assessment workflow is grounded in the aforementioned 4-layer approach, which provides a structured basis for capturing the temporal, spatial, and operational implications of aircraft design in order to predict the fleet-level environmental impact of a given concept.

The first part describes the *Simplified Emission Sensitivity Study (SESS*), which serves as the foundation for systematically analysing how potential technological modifications influence emissions and, subsequently, climate impact. The workflow implementation, trajectory generation, emission prediction, and underlying assumptions are outlined in detail. Building on these results, the *Next Generation Aircraft Performance Analysis (NGAPA)* focuses on assessing fully iterated aircraft concepts for the 2035 timeframe, as described in *Section 2.3.2. Future Aircraft Technology Considerations*.

2.3.1 Simplified Emission Sensitivity Study (SESS)

The *Simplified Emission Sensitivity Study (SESS)* represents the first phase of the climate impact assessment. Its primary objective is to analyse how changes in aircraft emissions directly influence selected climate metrics. To achieve this, emission sensitivity studies are conducted, leading to alterations in exhaust emission masses. The general concept underpinning this approach is to analyse how changes in emissions influence climate impact directly.

Figure 7: Workflow for the Simplified Emission Sensitivity Study, with 2020 aircraft technology status

Workflow Implementation

The underlying high-level workflow for SESS is illustrated in Figure 7 and was implemented using the RCE. The workflow begins with a set of generic trajectories that have been pre-computed for the evaluated aircraft type. These trajectories provide vectorized data, including flown distance, time, altitude, overall efficiency, and emission flow rates for CO_2, H_2O, SO_2 and NO_x, resolved for each mission stage. To systematically account for the influence of different technology types on individual emission species, a dedicated DoE approach was applied in this study. The simplified DoE involves directly modifying the emission flows within the mission trajectory file to represent technology-induced improvements and using the updated trajectories as input for the AS4D model. This enables an efficient assessment of the expected climate performance for digitized, simplified aircraft concepts derived from the baseline configuration.

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

Table 5: DoE for simplified study (Regional & SMR concept)

		Aero/Airframe only	Propulsion only	Combined	Combined + SAF*	
Area of improvement - Concept Level	**Aero/ Airframe**	**YES**	NO	**YES**	**YES**	
	Propulsion	NO	**YES**	**YES**	**YES**	
	SAF	NO	NO	NO	**YES**	
Percentage reduction of emission flows w.r.t. baseline aircraft	**CO_2**	[10-15-20]	[15-20-25]	[25-30-35]	[25-30-35]	
	H_2O	[10-15-20]	[15-20-25]	[25-30-35]	[25-30-35]	
	NO_x	[10-15-20]	[20-30-40]	[30-40-50]	[30-40-50]	
	Soot	[10-15-20]	[20-30-40]	[30-40-50]	[60-70-80]	**Total**
DoE size (full factorial)		**81**	**81**	**81**	**81**	**324**

**SAF: Emission scope only tank-to-wake (deliberately excluding the CO_2 lifecycle savings)*

The DoE is structured into four parts, each representing a specific area of improvement targeted by Clean Aviation: aerodynamic and airframe optimization, propulsion improvements, combined enhancements, and combined enhancements with Sustainable Aviation Fuel (SAF). For each area, three levels of emissions reduction are defined for CO_2, H_2O, NO_x, and soot. A full-factorial DoE is applied within each area, covering all possible combinations of the defined reduction levels. This results in a total of 324 evaluated cases for each aircraft concept, providing a systematic basis for assessing the sensitivity of climate metrics to technological improvements. An overview of the applied reduction levels and DoE setup is provided in Table 5.

The technical implementation of this workflow is illustrated in Figure 8. The process starts with the Trajectory & Assumptions Input Handler (1), which reads in the generic trajectories generated by the preprocessing workflow, which is described later. These data, along with the emission factors from the DoE block, are then passed to the DoE Preprocessor script (2). This script processes the current DoE improvement factors and applies them to selected parameters, specifically EI soot and the emission flows for CO_2, H_2O, and NO_x, from the generic trajectories and assumption file. These manipulations ultimately influence the modeled aircraft performance and represent mission-level alterations driven by potential technology

CLEAN AVIATION

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

improvements (3). The modified generic trajectories and the updated assumption file are then passed to the AS4D module, which computes the corresponding climate response (4). AS4D generates an ASCII output file, which is subsequently processed by the postprocessor script (5). This script extracts all relevant assessment outputs, saves the data locally, and after completing all iterations, compiles the results into an Excel file via the output handler (6).

After extracting the AS4D output within the iteration loop, a new DoE iteration is triggered. This generates updated manipulation factors for the aforementioned parameters, which are then applied to modify the base generic trajectories, repeating the process until the final iteration is completed.

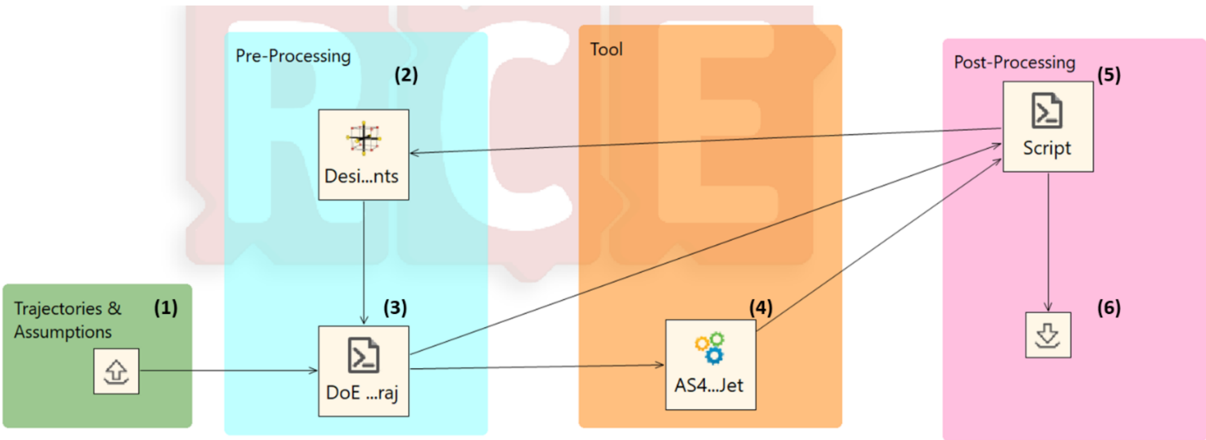


Figure 8: SESS workflow implementation using RCE

Trajectory Calculation and Emission Prediction

The foundation for these workflow steps is the set of generic mission trajectories provided to the AS4D module as an input. These generic trajectories were first computed using the AMC and FAST-OAD tools, based on digitized aircraft models and relevant performance assumptions. Therefore, an upstream pre-processing workflow was developed, which processes digitized aircraft models and calculates performance parameters such fuel flow, aircraft mass, time step, along the 2D mission profile.

Specifically, for the HER aircraft, trajectories were computed for mission ranges of 100 NM, 300 NM, and 1000 NM. For the SMR aircraft, mission trajectories were generated for ranges of 200 NM, 300 NM, 2000 NM, and 3000 NM. The computed trajectory results were subsequently post-processed to conform to the required CSV input structure for use within the AS4D tool. These generic trajectories are then used to link the generic trajectories with the global trajectory dataset within AS4D. Based on this linkage, a response surface look-up table is then applied to predict the resulting climate impact (see *2.2 Tools: AS4D*).

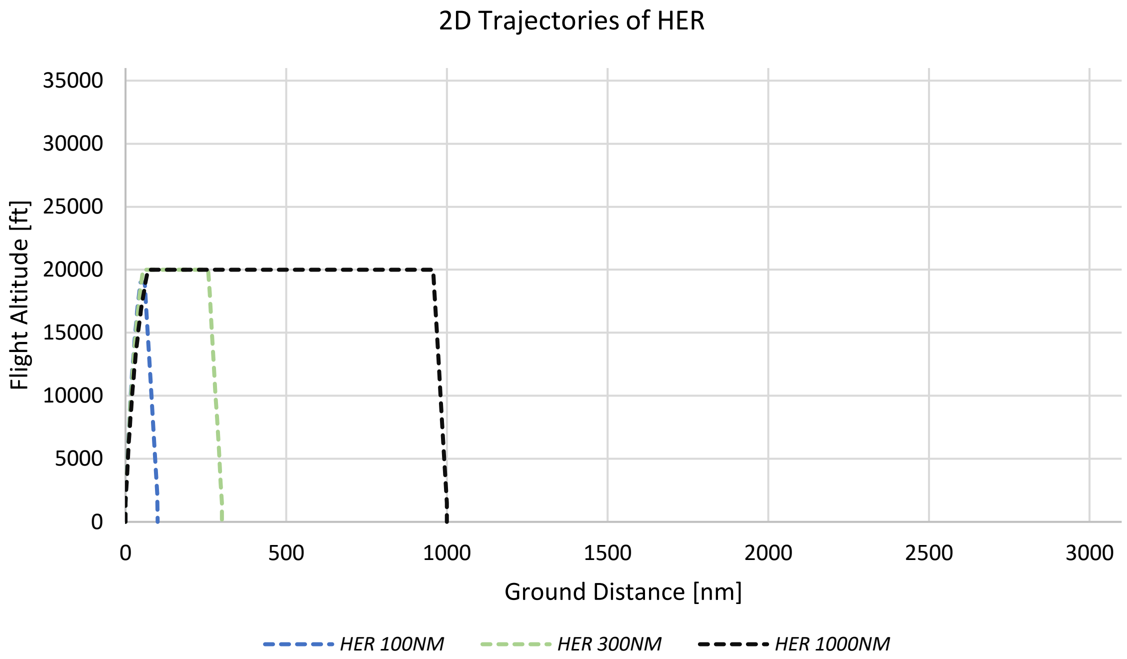
In general, the calculated generic trajectory files included detailed information for each mission, such as: Flight Phase, Distance [nm], Time [min], Altitude[ft], Overall Propulsion Efficiency [-], and emission flows for CO_2 [kg/s], H_2O [kg/s] and NO_x [g/s].

CLEAN AVIATION

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union



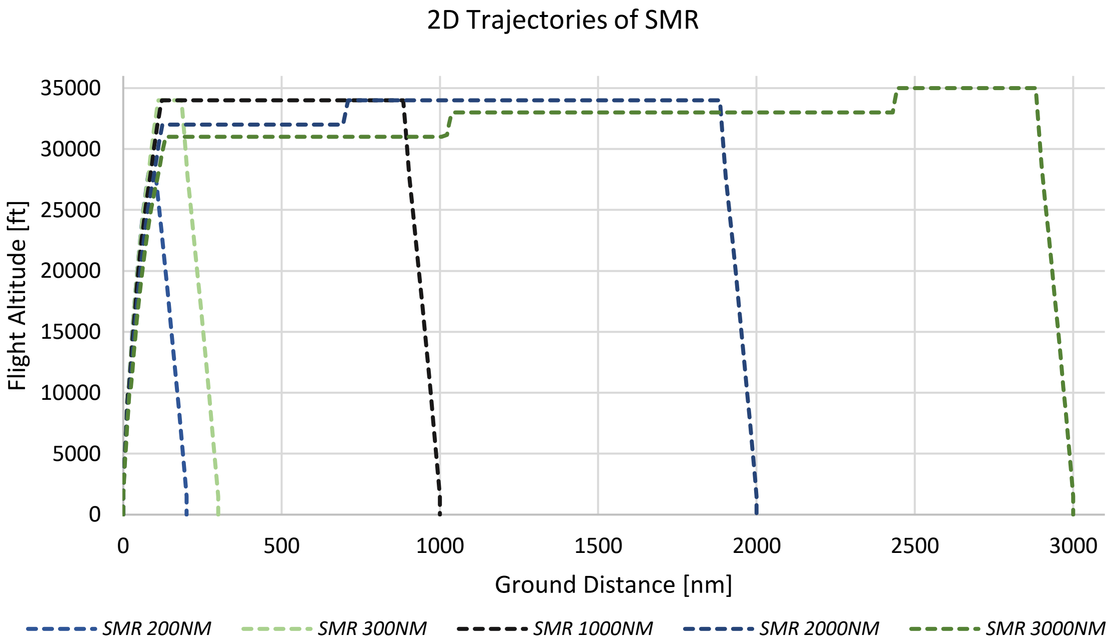


Figure 9: Generic mission profiles for regional (above) & short medium range (below) aircraft for SESS

For the generic trajectories, no Air Traffic Management (ATM) restrictions were considered. It was assumed that the aircraft could always climb out to its optimal cruise level, aiming to minimize fuel burn and perform step climbs as needed. Furthermore, standard atmospheric

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

conditions (ISA) without any wind vector were assumed throughout the mission. The 2D-mission profiles for HER & SMR baseline can be found in Figure 9.

Table 6: Emission Indices for SESS

Market Segment	EI CO_2 [kgH_2O/kg Fuel]	EI H_2O [kgH_2O/kg Fuel]	EI NO_x [kgH_2O/kg Fuel]
HER SMR	3.156	1.237	P_3 -T_3 Method for generation of Engine Deck

As the prediction of emissions represents a key input for the climate impact assessment, the underlying methods are briefly outlined here. In general, the well-known Emission Index (EI) is used to estimate the amount of a specific species emitted relative to the amount of fuel burned throughout the mission phases. The emission indices of CO_2 and H_2O depend solely on the fuel composition and assume of complete combustion, making them directly proportional to the fuel flow (see Table 6). In contrast, the prediction of NO_x emissions is more uncertain, as it depends not only on the fuel properties but also on the temperature and pressure conditions within the engine during operation. For the HER and SMR configurations in the SESS study, EI NO_x emissions are estimated using a P_3-T_3-based empirical approach. This method relates combustor inlet pressure and temperature to the NO_x emission index. It enables altitude-dependent NO_x predictions based on specific engine operating conditions. The conceptual engine design for SMR and HER is based on knowledge-based and semi-empirical methods, which are used to generate engine performance maps. These maps provide discrete operating points with detailed information on fuel flow and emission indices. They are subsequently used in the AMC tool to calculate, among other parameters, the emission flows along the full 2D mission trajectory. [17]

Assumptions

The other main input besides the emission trajectories for the AS4D tool is the so-called Assumption File, which characterizes the aircraft by Lower Heating Value (LHV) [MJ/kg], EI H_2O [kgH_2O/kg Fuel], CO_2 for fuel production [kgCO_2/kg Fuel], fraction of CO_2 neutral fuel [-], EI soot [-], aircraft size [pax], wing span [m]. The parameters LHV, EI H_2O and wing span from the assumption file, as well as the overall propulsion efficiency from the generic trajectories, are specifically used to calculate the potential for contrail formation using the Schmidt–Appleman criterion. The extent of contrail formation is primarily influenced by the aircrafts size, overall propulsive efficiency and the EI H_2O, which affect the total distance flown to meet demand, as well as by the EI soot, which determines the quantity of emitted particulates. The parameters CO_2 for fuel production and fraction of CO_2 neutral fuel have been mainly neglected. These Life cycle reductions, such as those achieved through the use of SAF, are not considered in this study, as the focus lies primarily on tank-to-wake aircraft implications. The assumptions used for the SESS are outlined in Table 7. [18–20]

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

Table 7: Assumptions for HER and SMR for SESS

Market Segment	LHV [MJ/kg]	EI H_2O [kgH_2O/kg Fuel]	CO_2 for fuel production [kgCO_2/kg Fuel]	fraction of CO_2 neutral fuel [-]	EI soot [-]	aircraft size [pax]	wing span [m]
HER	43.24	1.237	0	0	10^{15}	72	27
SMR						239	36

2.3.2 Next Generation Aircraft Performance Analysis (NGAPA)

In contrast to the first study, which applied a simplified sensitivity approach using modified emission flows within pre-computed generic trajectories, this analysis is based on a fully iterated aircraft concept from [15, 21]. The SMR-2035 and HER-2035, introduced in *2.3.2. Future Aircraft Technology Considerations*, represent an advanced regional & short- to medium-range aircraft design developed using multi-fidelity and multi-domain toolchain [15, 21, 22]. For this study, no parametric emission manipulation via a DoE was applied. Instead, the digitized HER-2035 & SMR-2035 aircraft models itself reflects the integrated effect of specific technological improvements on aerodynamic performance, propulsion efficiency, and structural characteristics. Using this digitized aircraft models, mission trajectories and associated emission flows were calculated and subsequently used to assess the climate impact, similar as outlined in *2.3.1 Simplified Emission Sensitivity Study (SESS)*. The overall workflow for both market segments is illustrated in Figure 10.

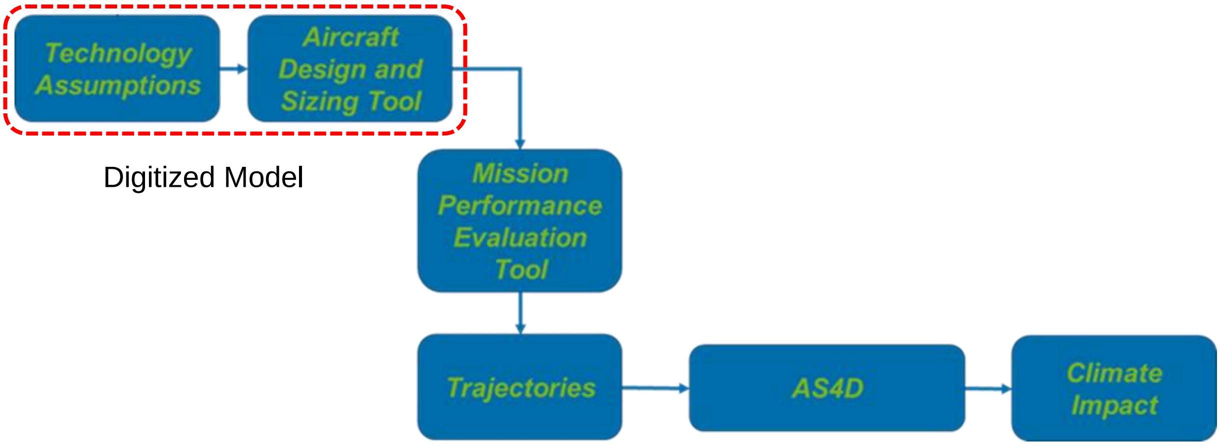


Figure 10: Workflow for the Simplified Technology Integration Study, with 2035 aircraft technology status

To better understand the results when comparing the baseline aircraft to the 2035 concepts, the underlying assumptions are discussed directly within the results sections. These include changes to key parameters in the assumptions file, such as wingspan, EI H_2O, and EI soot.

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

In addition, trajectory-related differences arise as a direct outcome of the different aircraft designs. All of these factors directly influence the resulting climate impact and are therefore examined alongside the climate impact results. This also allows for a consistent classification of the 2035 aircraft concepts within the DoE result space.

2.5 Climate Metrics for Technology Impact Assessment

As outlined in Deliverable 2.2, it is crucial to select the climate metric in alignment with the specific research questions being addressed. In this study, the primary aim is to assess the effect of technological improvements on an aircraft fleet operating over a sustained lifetime. The focus is on evaluating the impact of different technologies and, more specifically, the sensitivities to emission flows and later for a specific set of technologies. Therefore, in D2.2, a trade-off analysis was conducted through a series of workshops, incorporating input and feedback from external stakeholders across various domains of the aviation sector. Based on four defined requirements, ATR100 and EGWP100 were identified as the most suitable climate metrics for climate impact assessment of aviation technologies. [2]

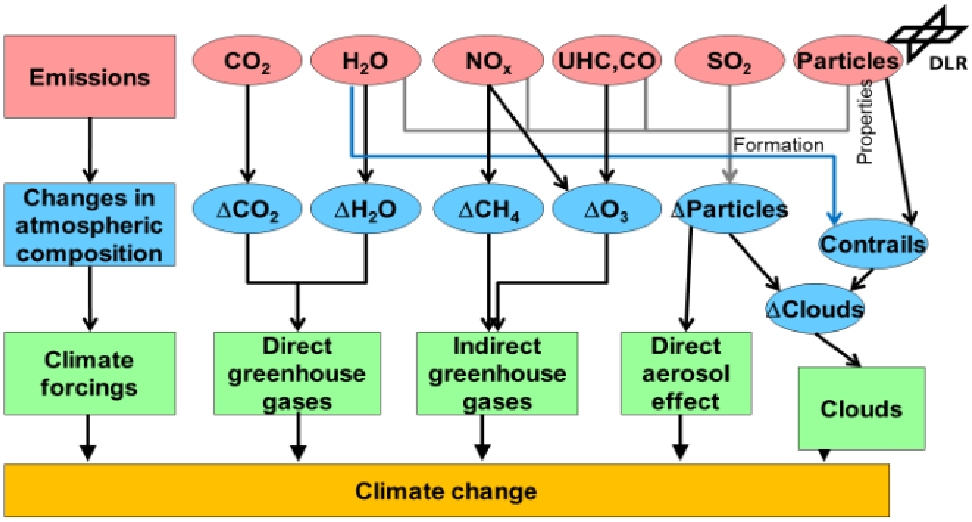


Figure 11: Overview on the process chain from aviation emissions to climate change from D2.2 [2]

ATR100 represents the Average Temperature Response over a 100-year time horizon, capturing the near-surface temperature change caused by aviation operational emissions. This metric is well-suited for the study's objectives as it provides a comprehensive assessment of both short-lived and long-lived climate forcers, enabling a robust evaluation of the long-term climatological impacts of various technological scenarios. In contrast, EGWP100 (Efficacy-weighted Global Warming Potential) is a modified form of GWP that adjusts for the varying climate efficacies of different forcers. Whilst ATR, as a temperature-based metric, offers more direct relevance to temperature targets by incorporating a broader range of climate processes, it also involves more assumptions and uncertainties. EGWP100 therefore serves as a practical compromise, providing improved accuracy in representing aviation's climate impact while maintaining methodological consistency with the widely used GWP framework. [2]

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

In this study, the AS4D tool, which incorporates the 4-layer approach, was used to calculate the environmental impact in terms of ATR. To additionally report results in EGWP, conversion factors from [23] were applied to estimate the fleet-level climate impact of the 2035 aircraft concepts only. Following this methodology, results are consistently expressed in terms of ATR100 and absolute emission masses, enabling a clear quantification of the contribution of individual emission species to the overall climate impact. It is worth noting that the impact of H_2O emissions are split into two components (see Figure 11). The first component is the direct greenhouse gas effect of H_2O, which occurs when atmospheric equilibrium is disturbed, leading to a warming effect. The second component is related to contrail formation, which results from the water vapor and particles present in the engine exhaust. In the analysis, both effects are presented separately: The H_2O Fleet Impact reflects the radiative imbalance caused by direct water vapor emissions, while the Contrail Fleet Impact captures the climate effect associated with the formation of contrails.

Climate Impact on global fleet-level from AS4D expressed in ATR:

- Total Environmental Fleet Impact [mK]
- CO_2 from fuel burn Fleet Impact [mK]
- CO_2 from Fuel Production Fleet Impact [mK]
- CO_2 from Production CO_2-neutral fuel Fleet Impact [mK]
- H_2O Fleet Impact [mK]
- NO_x Fleet Impact [mK]
- Contrails Fleet Impact [mK]

Climate Impact on global fleet-level from AS4D expressed in emission mass:

- Fleet CO_2 Emissions [kg]
- Fleet H_2O Emissions [kg]
- Fleet NO_x Emissions [kg]

Furthermore, we used the results from AS4D to conduct a more detailed analysis and post-processed the outputs to express the data in terms of CO_2e factors for each specific contributor. To recap, CO_2e is potentially a more tangible metric for some stakeholders, allowing for easier assessment of the impact of different technologies. By comparing the ATR contributions of all emission species to the ATR contribution of CO_2, the climate impact of each species in CO_2-equivalent terms can be expressed. This ultimately enables the derivation of a non-CO_2 emission factor (also called CO_2 equivalent factors or 'multipliers'), which can be used to quantify the additional climate impact beyond that of CO_2 alone.

Climate Impact on global fleet-level from AS4D expressed relatively to CO_2:

- CO_2e: CO_2 =1, H_2O, NO_x, Contrails, CO_2 from Fuel Production & CO_2-neutral fuel
- CO_2e and non-CO_2e

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

Furthermore, the aim of this study, and the specific objective of the AS4D tool, is not to predict the absolute climate impact of aircraft technologies, but rather to benchmark different technological options against one another. A more detailed explanation is provided in Section *3.4. Limitations*. To support this benchmarking approach, the total values expressed in ATR and emission masses are normalized to our baseline aircraft for which no DoE manipulation factors have been applied. In this context, the D239 and HER baseline represents 100% climate impact and emission mass. Any potential technological alterations, applied through the DoE manipulation factors, are then expressed as relative variations compared to this 100% baseline.

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

3. RESULTS

This chapter presents the results of the two-step assessment approach applied to evaluate the climate impact of future aircraft technologies. To recall, a broad sensitivity analysis is conducted using the *Simplified Emission Sensitivity Study (SESS)*, which explores a wide solution space based on systematically varied emission reductions derived from technological improvements. Building on these insights, the second part of this chapter focuses on the *Next Generation Aircraft Performance Analysis (NGAPA)*, where fully iterated aircraft concepts for the 2035 entry-into-service timeframe are assessed. This sequential approach allows for a structured investigation of technology sensitivities, followed by an initial assessment of the climate impact of specific future aircraft configurations.

3.1. Simplified Emission Sensitivity Study (SESS)

We will now conduct a more detailed assessment of the results obtained from the solution space generated and spanned by the DoE setup. We begin with a broad analysis of the entire solution space in relation to the key areas of improvement defined within the DoE framework (see Table 5). Based on this overview, we will explore the results in more depth, focusing on correlations between reductions in emission flows and their implications for climate impact and total emission mass. Next, we provide a high-level comparison of the two market segments in terms of total climate impact, emission mass, and CO_2-equivalent factors. Building on this, we will revisit the Clean Aviation objectives and identify specific areas of improvement that align with our reframed objective, interpreting Clean Aviation's goal of a 30% reduction in greenhouse gas emissions as an equivalent reduction in overall climate impact. The outcome of this analysis will help us identify potential high-level technology packages capable of meeting this goal.

Overview of main results for HER and SMR

Figure 12 illustrates the normalized Fleet Environmental Impact (FEI) for the regional market segment, grouped by the four Areas of Improvement alongside the Baseline. As previously mentioned, the Baseline represents the reference value, set to 1 or 100% of the fleet's climate impact or FEI. The remaining data points reflect the FEI values based on the corresponding DoE factor assumptions from Table 5, which result in an alteration of climate impact compared to the Baseline.

It is evident that the proposed reductions lead to a lower FEIs (see Figure 12). For the suggested Areas of Improvement, increasingly ambitious improvement factors have been applied, progressing from Aerodynamics to Propulsion, then to a combination of both, and finally to SAF. Among these, the SAF assumptions result in the greatest reduction in FEI compared to both the other improvement areas and the baseline. The degree of overlap between the improvement zones is directly influenced by the assumed ranges of improvement factors, which partially overlap, particularly as the level of ambition increases across the Areas of Improvement.

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

Overall, the data point representing the highest combination of improvement factors in the DoE achieves the greatest reduction in FEI, with approximately 43 percent reduction compared to the baseline, resulting in a remaining FEI of only 57 percent for Regional Market Segment.

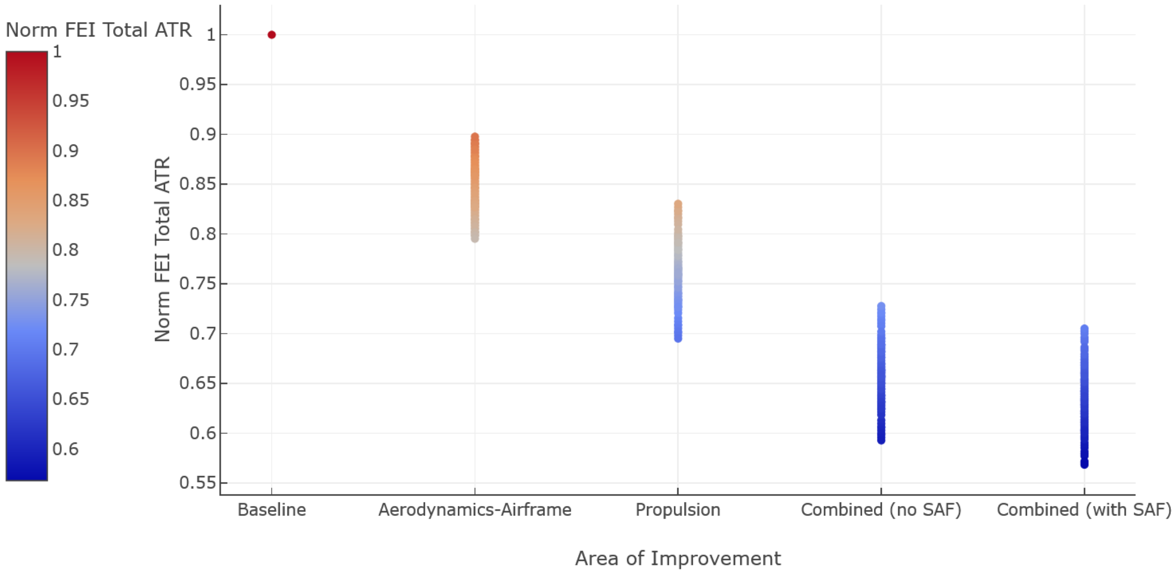


Figure 12: HER overall results scatter presentation for areas of improvement and normalized Fleet Environmental Impact

For the Short-Medium Market Segment, a similar behaviour is evident (see Figure 13). Here as well, the FEI can be reduced based on the defined Areas of Improvement and the corresponding higher improvement factors. As in the regional segment, the highest combination of DoE factors yields the greatest potential reduction in FEI. In the case of the SMR, the highest reduction of around 49% is achieved, resulting in a FEI of approximately 51% compared to the baseline for the Area of Improvement "Combined (with SAF)".

Although not presented in the figures, additional remarks are provided to clarify the relative magnitude of HER and SMR contributions. A comparison of the two market segments indicates clear discrepancies in both total and normalized FEI (see Figure 13 & Figure 12). values. The lower absolute FEI of the regional segment is explained by its smaller market share, characterized by fewer flights and shorter average distances. These operational characteristics inherently limit its overall contribution to climate impact when compared with the SMR segment. In addition to total values, differences are also reflected in the normalized FEI results, suggesting that not only the absolute scale but also the relative sensitivity of emission impact to climate impact differs between the two segments. This pattern points to the importance of network effects.

A closer analysis of the data shows that the reduction potential attributed to aerodynamic and airframe improvements results in a similar FEI across both segments, ultimately lowering it by about 20%. Recalling the applied DoE assumptions, it becomes clear that the reductions were

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

uniformly leveraged across the relevant emission species, primarily reflecting improvements related to fuel burn. These improvements directly contribute to a lower FEI.

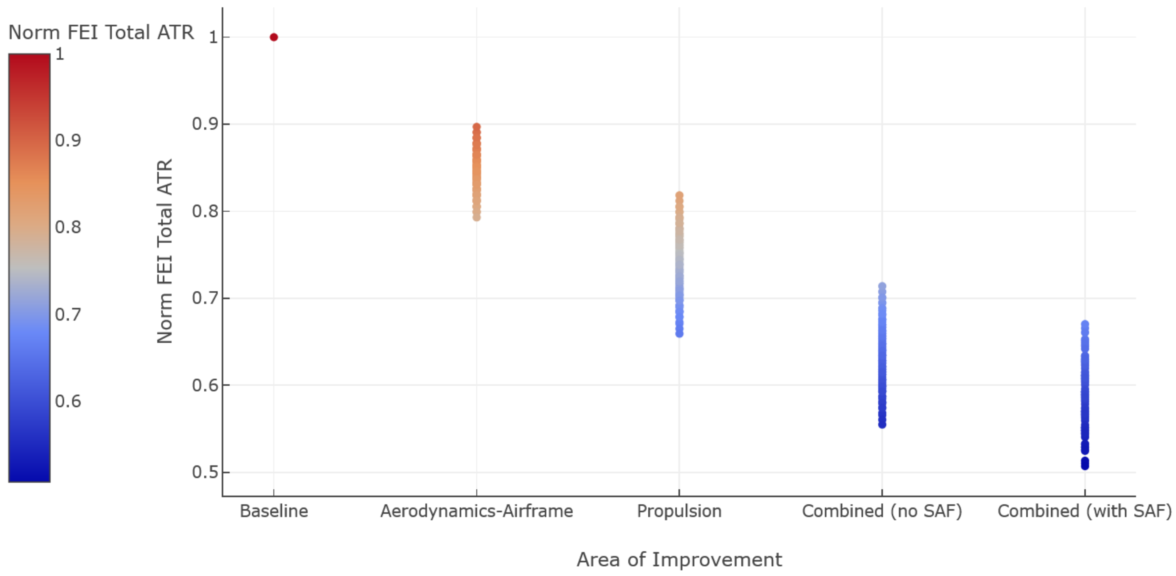


Figure 13: SMR overall results scatter presentation for areas of improvement and normalized Fleet Environmental Impact

In contrast, when looking at the impact of propulsion improvements, larger discrepancies become evident. For the regional segment, the FEI reduction ranges from approximately 16% to 21%, whereas for the SMR, significantly higher reduction potentials between 18% and 33% are observe, despite applying the same DoE factor improvement assumptions.

To recall what was applied in the propulsion DoE setup: the improvements generally lead to better fuel efficiency, thereby reducing fuel burn. Additionally, it was assumed that future engines would feature advanced combustion chambers, potentially enabling leaner combustion and further reducing non-carbon emissions [17]. We observe that, under the same applied reduction factors, the short- to medium-range segment achieves a more significant reduction in FEI compared to the regional segment. Previously, we saw that for moderate reductions, primarily driven by improvements in fuel burn, both segments demonstrated comparable reduction potentials. However, in this case, the propulsion improvements specifically target non-CO_2 emissions, such as NO_x and soot, through the application of lean combustion technologies.

To understand the reason for this observed behaviour, we need to examine the operational profiles of the HER and SMR segments more closely. Regional aircraft typically cruise at lower altitudes than SMR aircraft, due to differences in aircraft architecture and shorter mission ranges, which make lower cruise altitudes and speeds more cost-efficient. In contrast, SMR aircraft operate at higher altitudes, which not only benefits fuel efficiency over longer distances but also exposes them more directly to conditions conducive to non-CO_2 climate effects (see Figure 13).

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

As outlined in Deliverable D2.2, NO_x emissions at higher altitudes have a greater climate impact mainly due to increased formation of ozone [2]. Additionally, contrail formation is highly sensitive to flight altitude and geographic location. Generally, lower temperatures at higher altitudes increase the likelihood of contrail formation. Additionally, the altitude of the tropopause strongly affects contrail occurrence, as contrails tend to form under cold and moist conditions near or just below the tropopause [24]. Since the height of the tropopause varies geographically, being higher at the equator and lower at the poles, this also influences the regional distribution and persistence of contrails.

Regional aircraft, which typically operate at lower cruising altitudes and avoid high-latitude regions and are therefore less affected by contrail and NO_x-related effects. In contrast, aircraft in the short- to medium-range segment often cruise at higher altitudes and may fly through polar regions, where the tropopause is lower and conditions for both ozone formation and persistent contrails are more favourable. As a result, measures to reduce soot and NO_x emissions have a stronger climate mitigation effect in the SMR segment compared to the regional segment (see Figure 13). The same trend is also evident across the other Areas of Improvement, where the FEI mitigation potential becomes even more pronounced for the SMR segment compared to the HER segment as the assumed reduction factors increase. This becomes particularly clear when comparing the combined case to the combined including SAF-case, in which relatively high improvement factors were applied under the DoE assumptions. [24, 25]

While the impact of soot reduction in the HER segment remains relatively small, reflecting its operation at lower altitudes and under less favourable conditions for non-CO_2 effects, the SMR segment shows a notably larger effect. This is consistent with the previously discussed altitude-dependent sensitivity of soot emissions and corresponding contrail formation, further highlighting the greater climate impact reduction potential of advanced propulsion and fuel technologies when applied to the SMR market segment.

To further investigate this, we assessed the normalized FEI for the individual climate agents and used this, along with the total FEI, to calculate the corresponding CO_2e values, which are visualized in the form of a CO_2e contribution pie chart. Figure 14 illustrates the relative contributions of the different climate agents to the total climate impact, expressed in CO_2 equivalents (CO_2e). Since CO_2e represents the effect of each agent translated into an equivalent amount of CO_2 the conversion factor for CO_2 itself is 1 across all use cases.

As shown in Figure 14, CO_2 remains the dominant contributor to the total climate impact for both the HER and SMR segments. Moreover, the relative importance of CO_2 increases further as reductions in non-CO_2 emissions are applied to both market segments. Generally, NO_x ranks as the second-largest contributor, followed by contrails in third place, and H_2O as the smallest contributor. In particular the shares and contribution of the different agents to FEI are different. In general, we observe that for the baseline, CO_2 has the largest effect on the total FEI for the HER segment, followed by NO_x. In contrast, for the SMR segment, NO_x contributes most significantly, with CO_2 being the second-largest contributor. However, the impact of contrails is notably higher in the SMR segment. These differences can be attributed to the distinct operational profiles and regional characteristics of the two market segments.

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

Figure 14: CO_2e breakdown in comparison of HER (above) & SMR (below) for Baseline and Combined Technology with SAF

In contrast, HER aircraft typically cruise at lower altitudes and operate on shorter routes, thereby reducing their exposure to such non-CO_2 climate effects.

When analysing the SAF Combined scenario, we observe that both segments show their highest mitigation potential in the reduction of contrail formation, though to different extents. In the HER segment, the relative contribution of contrails to total FEI is reduced by approximately 6%, whereas in the SMR segment, the reduction reaches around 10%, nearly twice as much. This difference reflects the greater sensitivity of the SMR segment to contrail-related effects, due to its operations at higher altitudes and in regions more prone to contrail

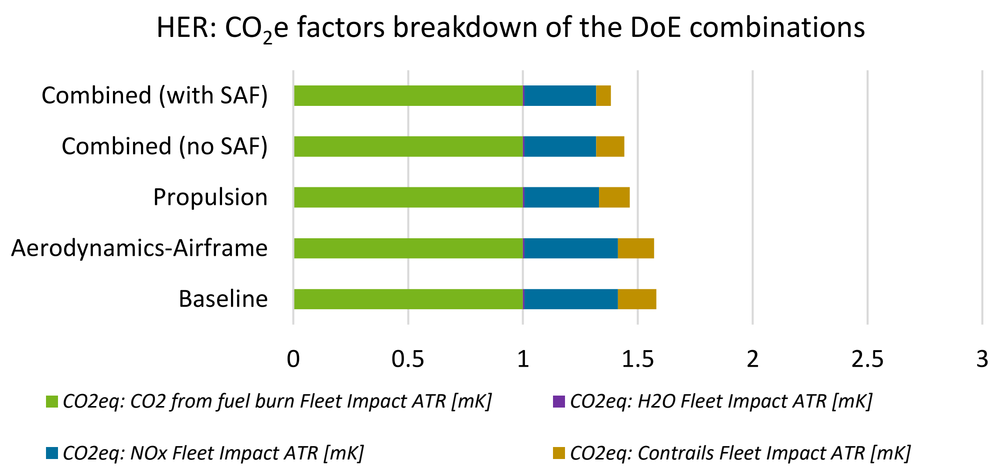
The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

formation. Consequently, a higher mitigation potential is achieved for SMR compared to HER under the same technological assumptions.

When comparing the NO_x contributions for SMR and HER with CO_2e (Figure 14), we observe distinct behaviours. The HER achieves a reduction of around 3% in total relative CO_2e impact from the Baseline to the Combined with SAF scenario, whereas the SMR shows a reduction of only about 1%. This clearly indicates one key insight: for SMR, the reduction in contrail effects plays a significantly more dominant role compared to NO_x reductions. The stronger mitigation effect of contrails in SMR outweighs the contribution of NO_x improvements, resulting in a comparatively smaller total impact reduction attributed to NO_x when examining the contributor-level results. The reason for this is the high reduction assumptions of up to 80% soot reduction in the Combined SAF scenario. Nevertheless, it remains evident that NO_x plays a crucial role in the overall climate impact, contributing approximately 41%.



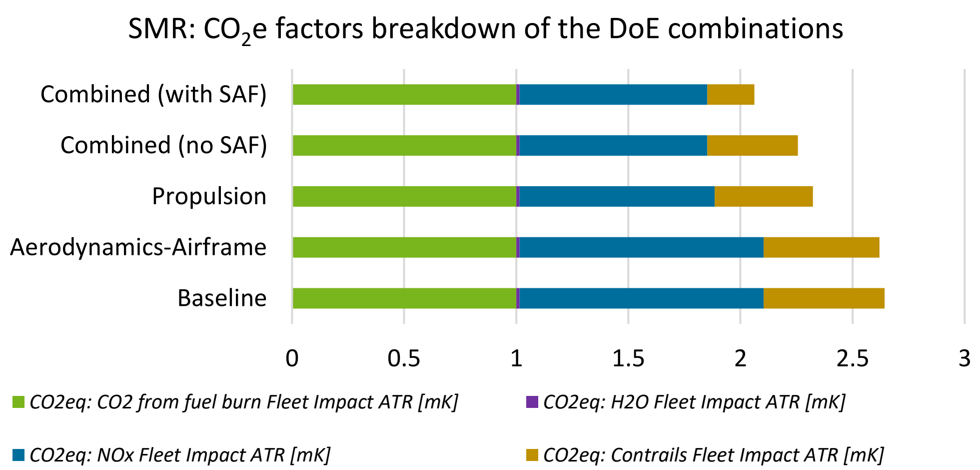


Figure 15: CO_2e breakdown for HER (above) & SMR (below) for best DoE combinations for each Area of Improvement

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

The same trend is visible in Figure 15, where CO_2 remains the largest contributor to the total FEI for both SMR and HER segments, followed by NO_x, contrails, and H_2O. For SMR, across aerodynamics, structures, and baseline cases, NO_x constitutes the largest contribution, followed by CO_2, contrails, and H_2O. Notably, contrails represent a larger share of the total FEI in SMR compared to HER.

Despite these relative shares, we can also observe that the overall CO_{2e} factor is comparatively smaller for HER. This highlights that the non-CO_2-related emissions have a significantly lower impact in HER compared to SMR. This difference is primarily driven by regional and operational characteristics of the respective network segments. In contrast, HER aircraft operate at lower altitudes and over shorter distances, reducing exposure to such effects. As a result, the non-CO_{2e} factor in SMR exceeds the value 1, indicating that technologies targeting non-CO_2 emissions offer a greater potential for reducing the FEI in this segment. Their impact is more substantial compared to measures focusing solely on CO_2 or fuel burn reduction.

In the HER segment, the situation is reversed: CO_2 emissions remain the dominant contributor, while the combined impact of non-CO_2 contributors is only about half the size of the CO_2 component.

Beyond the comparison between market segments, we can also assess how the DoE-specific reduction factors influence the relative leverage of individual contributors compared to CO_2, in terms of their impact on the overall FEI. This becomes particularly evident when examining the Aerodynamic–Airframe improvements, which primarily result in a reduction in fuel burn. Since the CO_{2e} factor remains unchanged between the Baseline and Aerodynamic–Airframe scenarios, the resulting reduction in FEI is applied uniformly across CO_2 and non-CO_2 contributors, reflecting a balanced impact. In contrast, Propulsion technologies tend to more directly target non-CO_2 emissions, particularly NO_x, leading to a more pronounced reduction in the non-CO_{2e} factor relative to CO_2. This demonstrates a shift in the leverage effect, where propulsion improvements disproportionately reduce non-CO_2 climate impacts.

When examining the Combined Technologies scenario, only moderate changes are observed. This suggests that both CO_2 and non-CO_2 contributors are reduced to a similar extent, with only a slight additional reduction in non-CO_{2e}, primarily attributed to residual NO_x improvements. The most significant shift in non-CO_2 occurs in the Combined with SAF scenario, where a notable reduction in contrail formation is observed. This leads to a further decline in the non-CO_{2e} factor. Once again, network and operational effects become apparent: due to differences in cruise altitudes and regional routing, contrail mitigation is more effective in the SMR segment, further emphasizing the role of operational context in determining the climate impact reduction potential.

To further assess the effect of soot and NOx, the DoE was used to inform sensitivity studies. Figure 16 shows the sensitivity plot for a specific part of the DoE design space. It should be noted that the results of this sensitivity analysis are highly dependent on the choice of reference aircraft, engine type, technology assumptions, network scenario and coverage, as well as the temporal evolution scenario. Therefore, they cannot be directly extrapolated to other scenario setups. This area was selected as it represents where most overlap between the areas of improvement occurs, providing a wide range of variations and the corresponding impact. Therefore, the DoE space for CO_2 and H_2O with the input improvement factors set to

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

0.2 was selected. Soot as well as NOx were varied, ranging from 0.1 up to 0.4. First, we take a look at the general sensitivity behaviour of these two climate impact contributors.

It becomes evident that the NOx sensitivity curve is steeper compared to the soot curve for both HER and SMR. This shows that, for an equal reduction (e.g., 0.1 equals 10%), a stronger reduction in climate impact can be achieved with NOx compared to soot. This leads to a higher reduction potential for NOx.

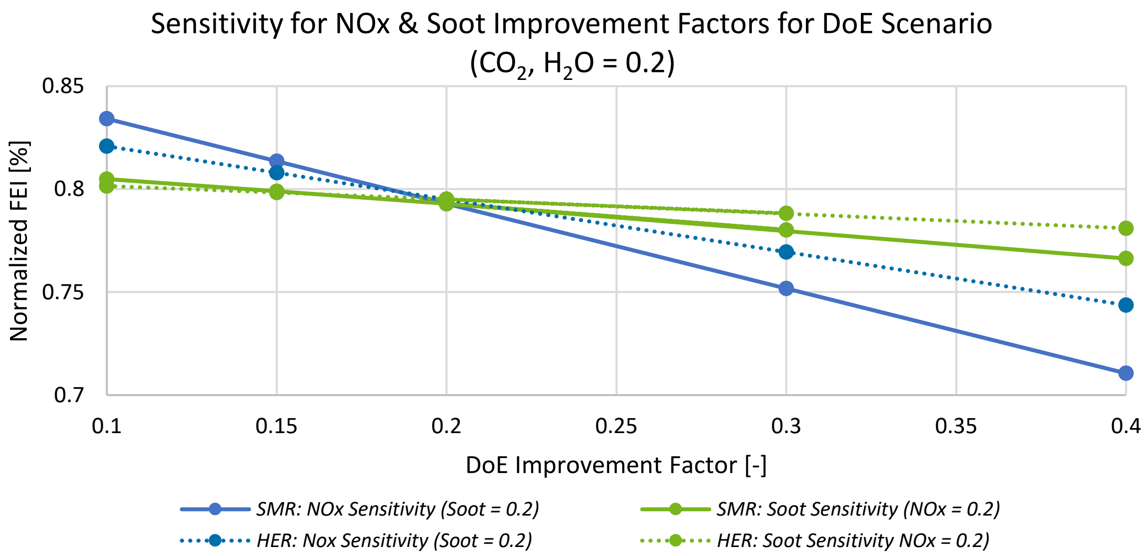


Figure 16: Sensitivity plot of soot vs NOx for the const. values of CO_2 and H_2O =0.2 for SMR & HER

When examining the results in detail, it becomes evident that initially the NO_x curve shows a lower reduction potential and a higher fleet-level climate impact compared to the soot curve. This is caused by the underlying DoE assumptions for this initial point: at a DoE improvement factor of 0.1, the NO_x curve corresponds to a soot reduction of 0.2 (const.), while for the soot curve, the NO_x reduction is set to 0.2 (const.). As a result, the higher NO_x reduction in the soot curve leads to a lower initial fleet-level FEI compared to the NO_x curve. However, this advantage diminishes with increasing DoE improvement factors. At a factor of 0.2, all assumptions and reductions for NO_x and soot are identical, resulting in the intersection point of both curves.

Another noticeable effect can be observed across the market segments. Initially, the HER configuration shows a lower FEI compared to the SMR. With increasing DoE improvement factors, this difference diminishes, and at a factor of 0.2, both configurations assume identical emission reductions. As a result, the influence of individual species becomes negligible, and the overall reduction is uniform across all climate-relevant contributors. Consequently, the higher leverage of CO_2 compared to non-CO_2 species, which initially benefits the HER configuration, is neutralized.

At lower improvement factors, the HER configuration consistently shows a lower FEI for both the NO_x and soot curves, with this effect being more pronounced for NO_x. This is due to the higher relative contribution of CO_2 to the total FEI for HER compared to non-CO_2 species. As

CLEAN AVIATION
The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

a result, reductions in non-CO_2 species have less influence on the total FEI, leading to a smaller overall reduction potential. When only soot and NO_x are varied, the reduction potential for HER is therefore lower than for SMR, as the operational characteristics of HER reduce the sensitivity of the total FEI to soot and NO_x reductions.

Recall of Clean Aviation Objectives in regards to Areas of Technology Improvements

We now aim to assess the gathered results in the context of the Clean Aviation (CA) high-level objectives. Clean Aviation aims to develop, integrate, and demonstrate technological innovations into new aircraft concepts by 2035, with the goal of reducing aircraft greenhouse gas (GHG) emissions by no less than 30% compared to 2020 state-of-the-art technology [1]. To evaluate our results against these targets, we first recall the distinction between GHG mass emissions and their climate impact. While the total mass of emitted species, such as CO_2, H_2O, NO_x, and soot, provides a direct measure of emissions, their climate impact varies significantly due to atmospheric conditions and processes, which are in turn influenced by operational and regional dependencies. Therefore, we will now compare both the mass breakdown and the climate impact contribution of each species, for the SMR baseline case (see Figure 17).

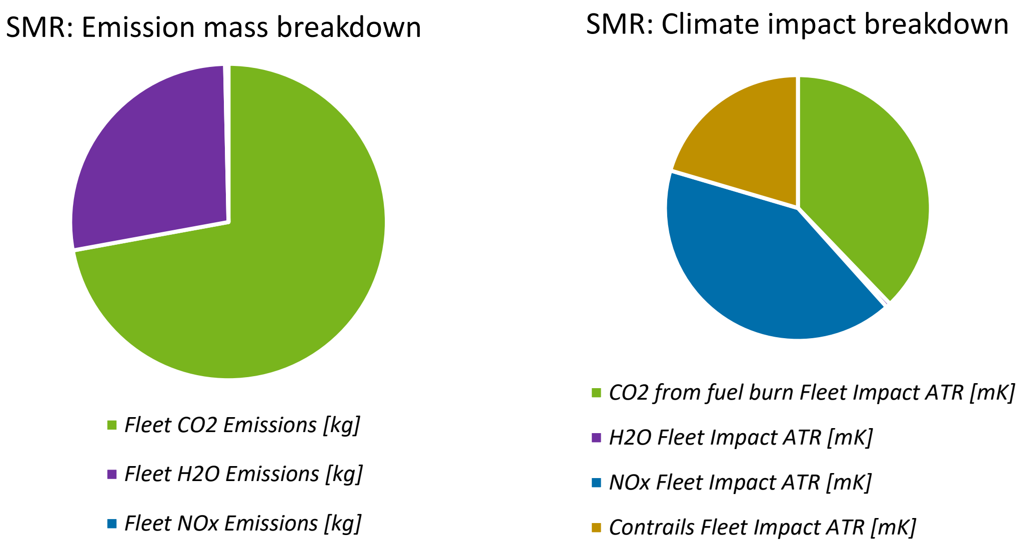


Figure 17: SMR-Baseline total emission mass (left) and total climate agent breakdown (right)

The emission mass is therefore expressed in kg and the total FEI in mK computed by using the ATR100 metric. Now let us take a first look at the emission mass breakdown: approximately 72% of the total emissions consist of CO_2, followed by H_2O with around 28%. In contrast, NO_x emissions account for less than 1% of the total emission mass. However, when we shift our focus from emission mass to climate impact (expressed with the climate metric ATR100 in mK), a very different distribution becomes apparent. CO_2 contributes around 38% to the total FEI, while NO_x contributes approximately 41%. Contrails, which are mainly driven by soot particle emissions, account for about 20%, and H_2O contributes only 1% to the

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

overall impact. This clearly illustrates that emission mass does not linearly correlate with climate impact. Species with low mass emissions, such as NO_x and soot, can still have a disproportionately high climate effect due to their complex interactions in the atmosphere. Therefore, we reframed the Clean Aviation objectives in a way that is more meaningful for this study. Ideally, a targeted 30% reduction in greenhouse gas emissions should also result in a 30% reduction in total climate impact (FEI). We use this benchmark to identify the potential emission reductions per species required to meet this goal, acknowledging that a balanced and impact-driven mitigation strategy is essential.

Figure 18 presents the revised Clean Aviation targets, highlighted in red, for the HER and SMR market segments. Both segments can meet these targets with propulsion-only technologies as well as with combined solutions that pair propulsion advances with airframe-aerodynamic improvements. Although a thirty-percent reduction is theoretically achievable for both segments using propulsion-only measures, the HER segment can reach this level only under the most optimistic reduction scenario. The data points achieving these reductions were derived under the following assumptions:

- *FEI reduction: -30.3%*
    - DoE values:
        - CO_2 =-25%
        - H_2O= -15%
        - NO_x = -40%
        - soot = -40%
- *FEI reduction: -30.5%*
    - DoE values:
        - CO_2 =-25%
        - H_2O= -25%,
        - NO_x = -40%,
        - soot = -40%

For the short and medium range (SMR) segment, the situation is different: a larger share of propulsion-only data points meets the target. The specific range intervals that achieve this goal are outlined below.

- *FEI reduction: -30.2% up to -34.1*
    - DoE values:
        - CO_2 =-15% up to -25%
        - H_2O= -15% up to -25%,
        - NO_x = -40%
        - soot =-20 up to -40%

CLEAN AVIATION

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

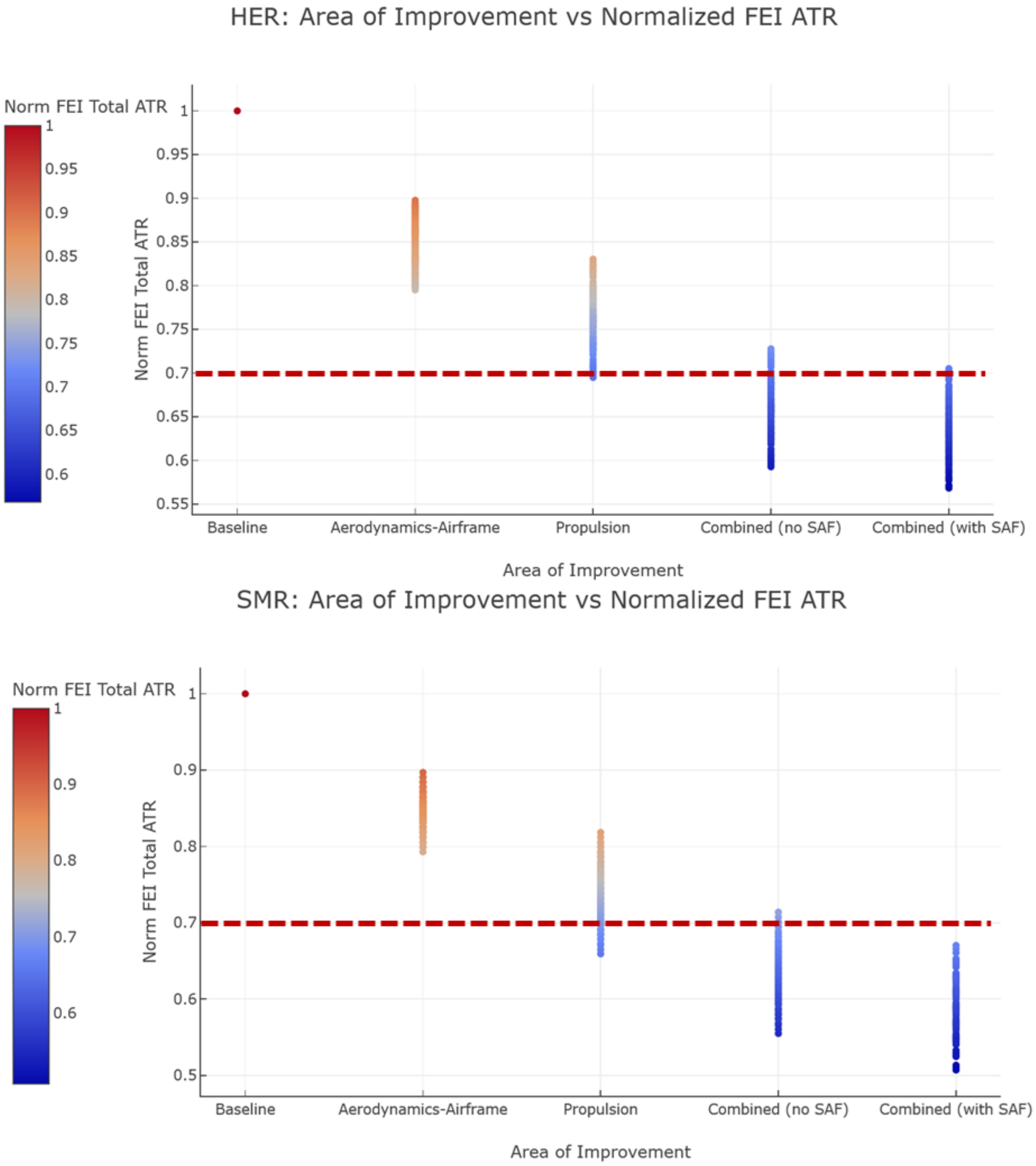


Figure 18: Interpretation of Clean Aviation Target (red-framed) translated into Fleet Environmental Impact (FEI) in ATR100 Target for HER (above) & SMR (below)

The SMR segment therefore appears to be more sensitive and responsive to reductions, particularly in non-CO_2 effects, due to the aforementioned operational and regional differences compared to the regional segment.

In conclusion, technologies specifically targeting non-CO_2 effects have a greater impact in the SMR segment compared to the HER segment. Which leads to a higher climate impact contribution of non-CO_2 emissions in the SMR segment, as reflected in the (normalized) FEI values used in this study.

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

In contrast, the HER segment shows lower mitigation potential in the area of non-CO_2 emissions, since these aircraft typically operate at lower altitudes where such effects are less pronounced. As a result, technologies that reduce CO_2 or fuel burn, thereby uniformly lowering all emission species, tend to have a stronger effect in HER.

3.2. Next Generation Aircraft Performance Analysis (NGAPA)

In contrast to the preceding sensitivity study, which relied on parametric emission modifications, this assessment is based on aircraft concepts that were developed using dedicated multi-fidelity toolchains. These pre-existing designs are used in this study to assess the associated emissions and resulting climate impact. Two representative concepts are considered: HER-2035 and SMR-2035. The respective design backgrounds and key assumptions are briefly recalled, followed by the emission estimates and the resulting climate impact assessment.

3.2.1 Regional EIS 2035

As introduced in Chapter *2.3.2 Future Aircraft Technology Selection*, the D70 Plug-in Hybrid Electric Aircraft (PHEA) was selected as the HER-2035 representative for the aircraft environmental performance assessment. A digitized model of the D70 PHEA was used, and its mission performance characteristics were calculated using AS4D, as described in Chapter *2.3.2 Next Generation Aircraft Performance Analysis (NGAPA)*.

It should be noted that a modified branch of the AMC tool was used for the calculation of generic trajectories for the analysis of HER-2035. While the core objective of AS4D remains the optimization of fuel usage, this modified version was adapted to incorporate operational strategies specific to hybrid-electric flight operations. To briefly recall, the D70 PHEA employs a plug-in hybrid electric configuration. For flight ranges up to 300 NM, the aircraft operates fully electric, powered entirely by its onboard battery system (plugged-in battery). For extended missions such as 1000 NM, the operational strategy changes: after the initial climb phase, the gas turbine takes over to propel the aircraft until the reserve and contingency fuel thresholds are reached. Beyond that point, the battery system resumes propulsion for the final segments of the flight.

Based on this operational logic, generic mission trajectories were derived and subsequently used as the main input for AS4D to calculate the Fleet Environmental Impact (FEI) in Average Temperature Response for 100 years (ATR100). Additional required inputs include aircraft- and scenario-specific assumptions, which are outlined in Table 8. For both the HER and SMR studies, a SAF scenario setup was defined, following a structure similar to the DoE approach. In both cases, the potential impact of SAF was modeled by adjusting the emission index for soot. Specifically, a 50% reduction in soot emissions for the low soot scenario and an 80% reduction for the high soot scenario was assumed. As this study focuses solely on a tank-to-wake assessment, life-cycle savings have been excluded.

Moreover, the use of SAF results in altered fuel properties compared to conventional Jet A-1, notably due to a higher hydrogen content in the chemical composition. This leads to increased water vapor emissions, covered by the emission index for water vapor for SAF fuels [16].

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

Table 8: Scenario Assumptions & Key Parameters for the HER-2035 Study Case

Scenarios	EI H_2O [kgH_2O/kg Fuel]	EI Soot [kgH_2O/kg Fuel]	Wingspan [m]
D70-Baseline, without SAF	1.237	10^{15}	27.0
HER-2035, without SAF	1.237	10^{15}	30.3
SAF: low soot reduction scenario	1.367	$5*10^{14}$	-
SAF: high soot reduction scenario	1.367	$2*10^{14}$	-

To correctly assess the implications of the 2035 aircraft compared to the baseline, the operational differences between them needed to be examined as a first step. Therefore, the vertical mission profiles of the generic trajectories were analyzed based on Figure 19.

It is evident that for the 100 NM and 300 NM missions, both aircraft operate at similar cruising altitudes. However, for the 1000 NM mission, the HER-2035 initially flies at a lower altitude before performing a significant step climb to higher flight levels. This behavior results from the optimized hybrid-electric operational strategy, as previously described. This strategy is implemented within the modified branch of the AMC tool to support hybrid-electric mission planning and performance evaluation.

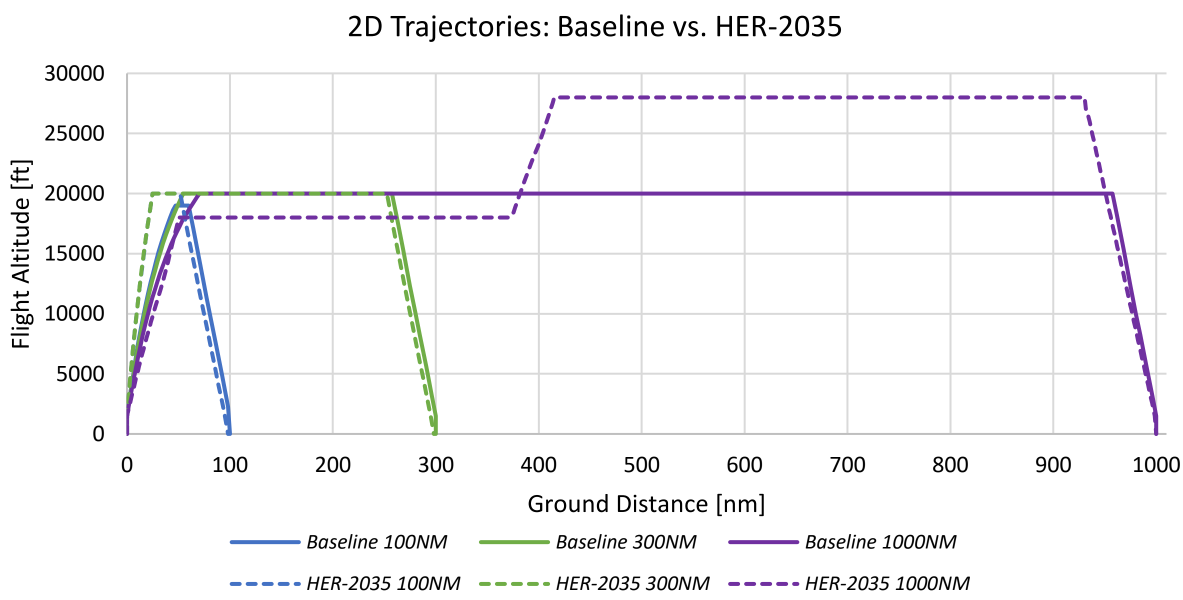


Figure 19: Comparison of the generic mission profiles for HER-baseline (dashed-line) & HER-2035 (solid-line)

As a next step before assessing the fleet-wide environmental impact of the concept Figure 20 presents a comparison of fleet-level emissions relative to the baseline concept. Specifically,

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

the figure compares the emission masses of CO_2, H_2O, and NO_x for conventional fuel use in the HER-2035 concept, as well as for SAF scenarios applied to both the baseline and HER-2035.

When comparing the baseline with its SAF counterpart, the influence of differing fuel properties becomes evident, particularly the higher emission index of water for SAF, which results in increased water vapor emissions. In contrast, the HER-2035 concept shows significant reductions in all emission masses. Since the HER-2035 can operate fully electric on missions up to 300 nm, these flights are essentially zero-emission, achieving a 100% reduction in emissions. Beyond 300 nm, the HER-2035 relies on a kerosene-fuelled gas turbine to extend its range. At a mission range of 1000 nm, the HER-2035 achieves a block fuel reduction of approximately 52% compared to the baseline aircraft, primarily due to the integration of novel technologies and a more efficient powertrain architecture outlined in *Chapter 2.3.2. Future Aircraft Technology Considerations*.

On the fleet level, even greater reductions are observed of around 87% for CO_2 and H_2O, and 80% for NO_x. These substantial savings are attributed to the operational characteristics of the regional network, where most flights are under 300 NM and can thus be operated fully electric as zero-emission flights. As a result, the hybrid-electric ranges that rely on the gas turbine contribute less significantly to the overall fleet emissions, leading to higher total emission reductions. As only generic trajectories were used to model aircraft performance across a range of flight distances within the network, it is worth noting that some modelling limitations may exist. Specifically, the interpolation between fully electric zero-emission flights (up to 300 NM) and hybrid-electric operations (up to 1000NM) may not accurately reflect the non-linear relationship between battery and gas turbine usage. Fuel or emission consumption in missions where both systems are active is likely not linearly dependent on the two interpolation grid points 300 NM & 1000 NM, which may affect the precision of the results in this transition range.

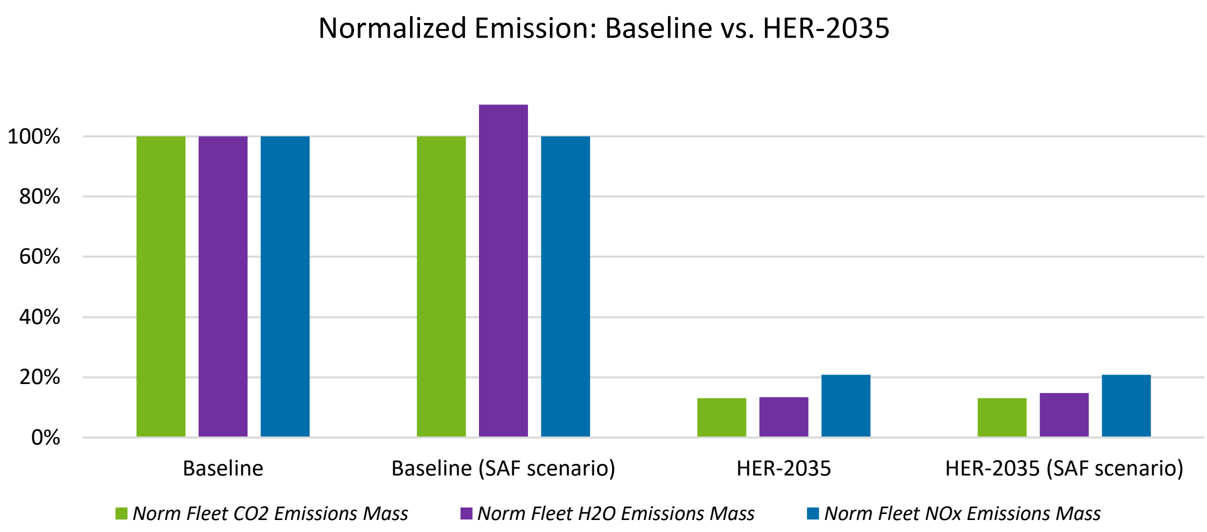


Figure 20: Normalized overall network emissions baseline vs. HER-2035

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

For the SAF scenario, an increase in H_2O emission mass is also evident due to the fuel properties of SAF, leading to an increase of approximately 10% compared to the conventional fuel scenario for the HER-2035.

After evaluating the normalized total emission masses for the regional network, the normalized Fleet Environmental Impact (FEI) can be analysed, as shown in Figure 21. On the far left, the overall FEI is presented for the different concepts/scenarios in comparison to the baseline. To provide a clearer understanding of the results, the individual contributors to the total FEI, CO_2, H_2O, NO_x, and contrails, are also plotted. The following section begins with an analysis of the normalized total FEI. In general, it is evident that the HER-2035 concept demonstrates the highest FEI mitigation potential ranging from 75% up to 82%, primarily due to its fully electric or hybrid-electric operations. When operated with SAF, even greater reductions can be achieved, mainly attributed to the lower soot number, which significantly reduces the climate impact from contrail formation.

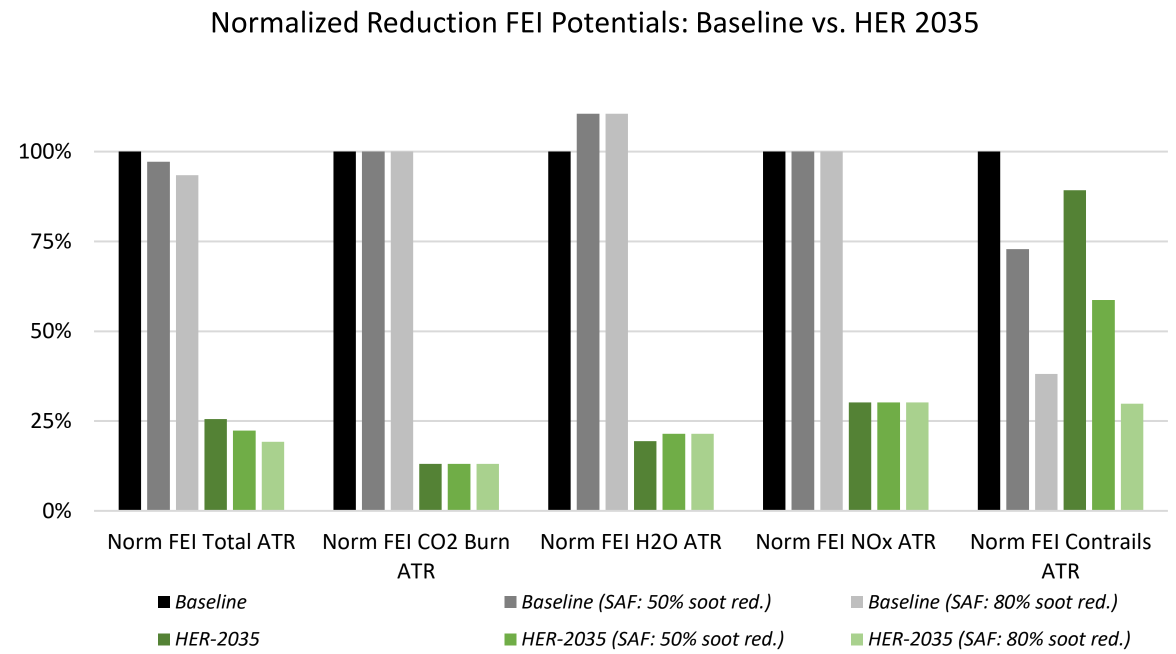


Figure 21: Normalized breakdown of climate impact contributors for baseline vs. HER-2035

When comparing these results to the baseline scenario, the general effect of SAF can be assessed. In terms of total reduction potential, the SAF scenario results in a modest overall FEI reduction, approximately 2.9% for a 50% reduction in soot number, and 6.5% for an 80% reduction. The increased water vapor emissions associated with SAF, due to its fuel properties, contribute to a higher direct warming effect from H_2O. At the same time, the lower soot number reduces contrail formation. Notably, contrail formation differs between the baseline and HER-2035 under SAF scenarios. This is primarily due to the generally lower emission masses of the HER-2035, which, through fully electric or hybrid-electric operation, lead to reduced contrail formation.

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

In general, as outlined in Chapter *3.1. Simplified Emission Sensitivity Study (SESS)*, non-CO_2 effects have relatively low leverage in the regional market segment due to its specific operational and network characteristics. As a result, the mitigation potential for non-CO_2 species such as H_2O, contrails, and NO_x contributes less significantly to the overall Fleet Environmental Impact (FEI) compared to CO_2. This explains why the relatively small reductions in these components have only a minor effect on the total FEI.

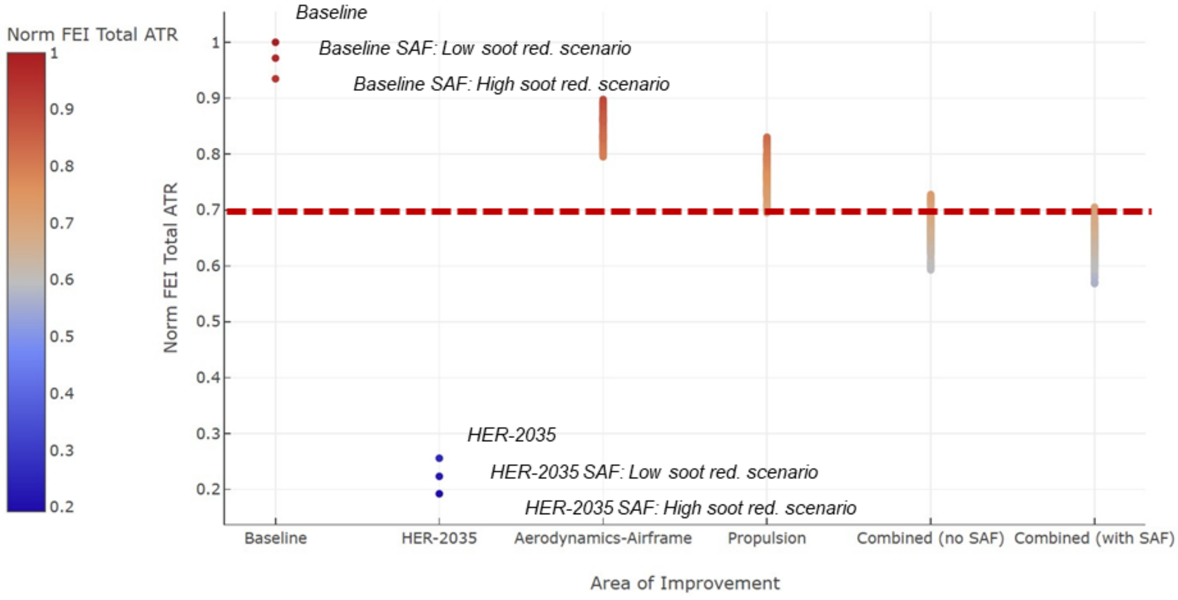


Figure 22: Total Fleet Environmental Impact in ATR-100 for HER-baseline, DoE points and HER-2035

To classify the results of the HER-2035 within the DoE design space, the total Fleet Environmental Impact (FEI) values have been compared and are illustrated in Figure 22. As previously mentioned, for the baseline HER, soot reduction alone leads to only minor mitigation in total FEI. In contrast, the HER-2035 demonstrates notable reductions due to its zero-emission and hybrid-electric operations throughout the network.

As the regional segment operates over shorter ranges, it offers a more technologically tangible application for hybrid-electric propulsion, due to inherently lower power and energy requirements. These, in turn, lead to smaller mass penalties compared to other market segments such as SMR. Therefore, hybrid-electric technologies, when combined with optimized operational strategies as applied in the HER-2035 (D70-PHEA), can result in significant reductions in the regional leet-level climate impact. Consequently, the HER-2035 performs considerably better than the simplified modelled designs explored within the DoE space, which do not account for such advanced concepts.

It should also be noted that regional aircraft typically operate on shorter routes with lower passenger demand in comparison to the SMR segment. As a result, the overall flight volumes and consequently the climate impact of the regional market are generally lower. This is not only due to fewer flights but also because of shorter mission lengths and the associated lower cruise altitudes.

CLEAN AVIATION

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

3.2.2 Short-Medium EIS 2035

For this study, the F25 -- SMR-2035 has been selected, as described in Section 2.*3.2 Future Aircraft Technology Considerations – Short-Medium EIS 2035*. The F25 serves as a technology integration platform, combining several advanced features aimed at improving aerodynamic and propulsion efficiency.

To assess its climate impact, a similar approach to that outlined in *Section 4.1 Simplified Emission Sensitivity Study (SESS)* has been applied. The analysis began with the calculation of generic mission performance using a digitized model of the F25 for mission ranges of 200, 300, 1000, 2000, and 3000 nautical miles. These generic trajectories, along with defined assumptions, were then used to calculate the Fleet Environmental Impact (FEI) in Average Temperature Response for 100 years (ATR100) using the AS4D tool.

Table 9: Scenario Assumptions & Key Parameters for the SMR-2035 Study Case

Scenarios	EI H_2O [kg H_2O/kg Fuel]	EI Soot [kg H_2O/kg Fuel]	Wingspan [m]
Baseline– without SAF	1.237	$1*10^{15}$	36
SMR 2035 – without SAF	1.237	$1*10^{15}$	45
SAF: low soot reduction scenario	1.367	$5*10^{14}$	-
SAF: high soot reduction scenario	1.367	$2*10^{14}$	-

In this study, we assessed the normalized climate impact of the SMR-2035 (F25) in comparison to the baseline (D239) using conventional kerosene as well as SAF, assuming soot reductions of 50% and 80% [26, 27]. The assumptions and key parameters, apart from fuel burn reduction, for the two concepts are summarized in Table 9. Due to the chemical properties of sustainable aviation fuel, which contains a higher proportion of hydrogen that is converted into water vapor during combustion, a higher water vapor emission index has been selected (Table 4). Additionally, the wingspan has been increased from 36 to 45 meters under in-flight conditions, as part of the design evolution from the baseline reference aircraft to the SMR-2035 concept.

To interpret the results of this analysis, it is essential to first assess the operational differences between the aircraft concepts, as flight altitude plays a critical role in understanding the normalized FEI results. Figure 23 illustrates the two-dimensional trajectories for the generic flight profiles of the baseline and SMR-2035 configurations. As previously mentioned, both the initial cruise altitude and step climbs throughout the mission were calculated with the primary objective of minimizing mission fuel burn. It is evident that the SMR-2035 generally operates at higher flight levels compared to the baseline due to design changes.

CLEAN AVIATION

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

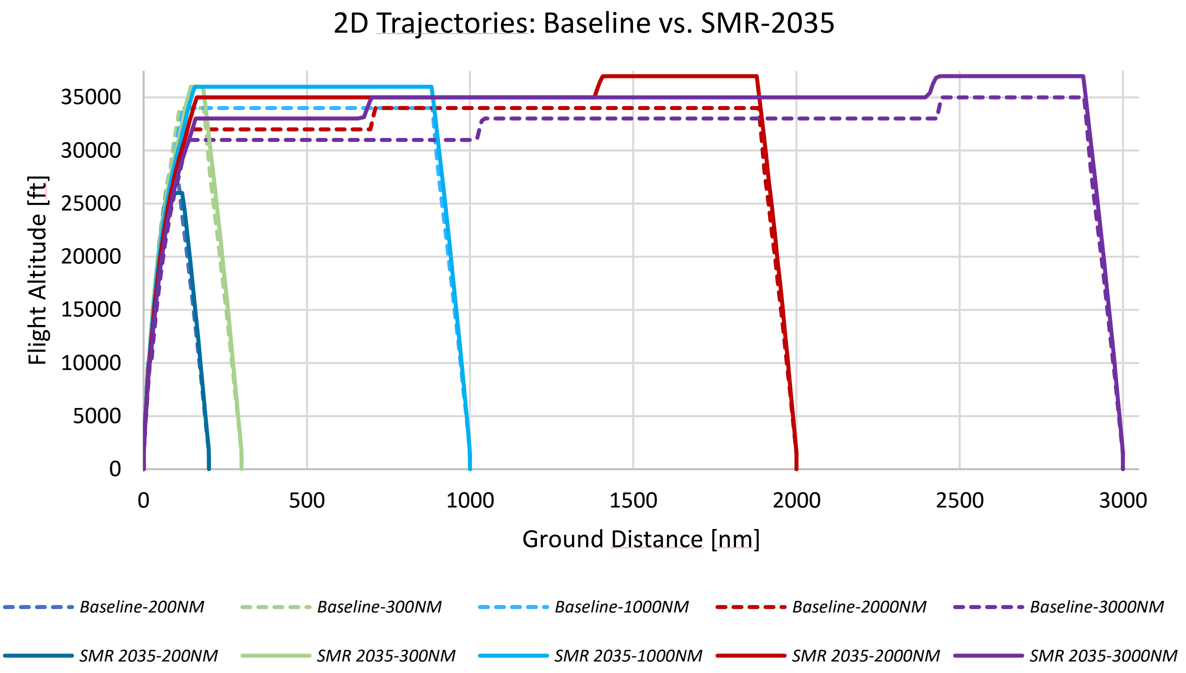


Figure 23: Comparison of the generic mission profiles for baseline (dashed-line) & SMR-2035 aircraft (solid-line)

As these operational changes directly affect fuel burn and, consequently, emissions, the resulting emissions for the different scenarios are analyzed in Figure 24. The figure specifically illustrates the normalized total emission mass reductions for the various species across the operated network for the baseline and SMR-2035 concepts using conational fuel as well as for the SAF scenario.

For conventional fuel, the SMR-2035 achieves a CO_2 and H_2O reduction of approximately 18%, while NO_x emissions are reduced by around 35% compared to the baseline. As CO_2 emissions and fuel burn are linearly correlated through the EI CO2 of 3.16 kg CO_2 per kg of fuel, the average CO_2 reduction of approximately 18% compared to the baseline is consistent with the reported fuel burn savings on the 800 NM mission, where the F25 (SMR-2035) achieves a comparable reduction [15].

It is also evident that the emission reductions across the conventional and SAF scenario for the F25 are nearly identical for most species. An exception is water vapor, where a slight increase in total emission mass is observed for both baseline and SMR-2035 for the SAF scenarios due to the higher assumed emission index resulting from the use of SAF.

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

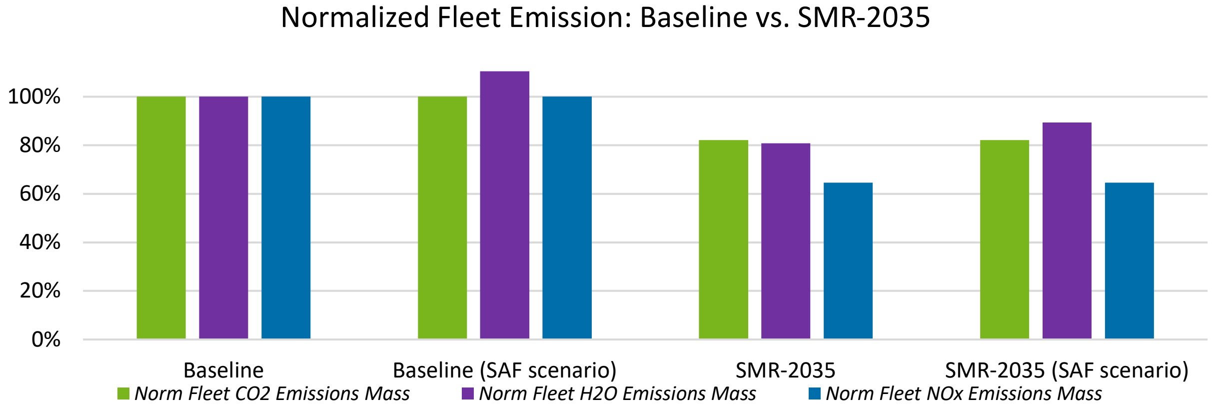


Figure 24: Normalized overall network emission reduction baseline vs. SMR-2035

Following the analysis of emission reduction effects across the overall route network, normalized Fleet Environmental Impact (FEI) in ATR100 will now be analyzed. Figure 25 presents the normalized total FEI results on the far left, representing the global fleet impact of the different concepts relative to the baseline, followed by the breakdown of climate contributors for both the baseline and SMR-2035 configurations to support a more detailed understanding of the underlying effects. The baseline is depicted in shades of black to grey, with grey tones representing the two SAF scenarios featuring different soot reduction levels. Similarly, the SMR-2035 is shown in green tones, where the dark green indicates the conventional fuel case, and lighter shades represent the SAF scenarios with varying soot reductions.

Among the SMR-2035 and baseline scenarios, the configuration using conventional kerosene shows the smallest reduction in total FEI, while the SAF-based scenarios exhibit a higher mitigation potential. Within the baseline configuration, the greatest overall FEI reduction of approximately 15% is achieved in the SAF scenario with an 80% soot reduction. In contrast, a soot reduction of 50% results in only an 8% decrease in total FEI. As only SAF is varied and no additional technological changes are considered, the mitigation potential in both SAF scenarios is primarily driven by the reduction in soot emissions. However, due to the altered fuel properties of SAF, water vapor emissions increase, leading to a stronger direct greenhouse effect. This results in an approximately 10% higher climate impact from water vapor, despite the aircraft operating under the same mission characteristics.

The SMR-2035, which integrates novel technologies, achieves the highest overall reduction in total climate impact at around 34% compared to the baseline. This result is observed in the SAF scenario featuring an 80% soot reduction and falls within the range of our interpretation of the Clean Aviation target, which aims for a 30% reduction in climate impact for this segment. To better understand this outcome, the individual contributors to the FEI have been additionally plotted as aforementioned.

The CO_2 emission reduction, previously discussed at around 18%, translates directly into a similar reduction in the climate impact contribution of CO_2. The same applies to NO_x across all cases, as no additional assumptions were made in between the SMR-2035 scenarios similar to the baseline setup.

CLEAN AVIATION

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

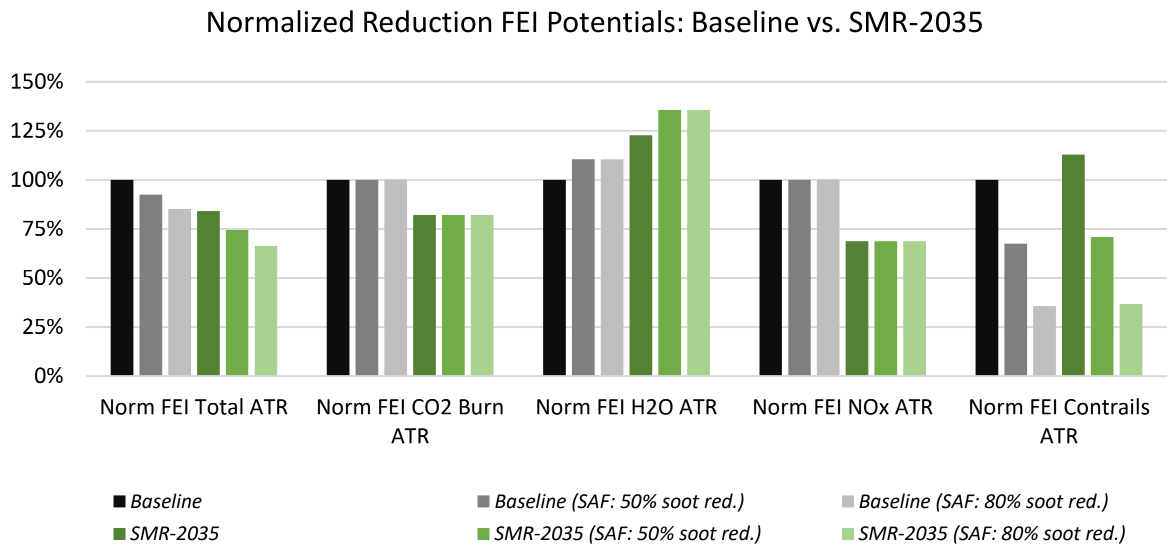


Figure 25: Normalized breakdown of climate impact contributors for baseline vs. SMR-2035

For water vapor, however, a different pattern emerges. All SMR-2035 scenarios show an increase in FEI contribution from H_2O, with the SAF scenarios exhibiting a consistent rise of approximately 35% compared to the baseline water vapor FEI. This increase can be directly attributed to the higher H_2O emission mass resulting from the use of SAF, consistent to what was observed in the baseline SAF scenario. Interestingly, even the SMR-2035 scenario using conventional fuel—assuming the same H_2O emission index and water vapor emission characteristics as the baseline—shows an increase in the H_2O-related contribution to FEI. In this case, the absolute H_2O emission mass is actually lower than that of the baseline as presented in Figure 24, suggesting that the higher FEI contribution is not driven by emission mass alone. Instead, this increase must be attributed to operational factors, particularly the higher operating cruise altitudes of the SMR-2035. At these altitudes, the altitude-dependent impact of water vapor becomes more pronounced, ultimately leading to a higher FEI despite similar fuel properties. Even so, the direct contribution of H_2O as a greenhouse gas to the FEI remains relatively small, as previously outlined in Figure 17.

For the contribution of NO_x, the reduction potential in FEI is approximately 32% and remains similar across all configurations, as no differentiation between the various F25 scenarios was made with respect to NO_x emissions.

For the contribution of contrails, interesting implications are observed. For the SMR-2035 aircraft powered by conventional fuel, an increase in contrail formation potential is visible in comparison to the baseline, even though the EI H_2O and EI soot remain identical. This increase is primarily attributed to improvements in overall propulsive efficiency of approximately 4%, resulting from the higher bypass ratio (BPR) of the engines.

Higher overall propulsive efficiency implies that the engines release a smaller fraction of combustion heat into the exhaust plume during cruise. As a result, the exhaust plume reaches higher relative humidity during the mixing process for a given ambient temperature. This enables contrail formation at higher ambient temperatures, increasing the probability of

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

contrail occurrence. Thus, paradoxically, aircraft with more fuel-efficient engines may form contrails more frequently under the same atmospheric conditions. [18, 19]

Additionally, the aircraft also exhibits a higher wingspan and aspect ratio. In the current model, wingspan dependencies are incorporated based on statistical correlations. An increase in wingspan (historically associated with higher aircraft mass) leads to the generation of stronger wake vortices. These more intense vortices exhibit higher descent rates, causing them to penetrate into warmer atmospheric layers more rapidly. As a result, the warming of the vortex core occurs earlier compared to aircraft with smaller wingspans. This inhibits ice crystal formation and consequently reduces the likelihood of persistent contrail formation. In this case, the increase in wingspan from 36 m to 45 m alone results in a reduction of approximately 10% in the FEI contrail contribution. It should be noted that in our case, the aircraft uses a high aspect ratio wing and also has a lower MTOM and wing loading compared to the baseline. This would lead to reduced wake vortices, which could, in turn, have the same or even a lower effect on contrails, depending on whether the generated vortices descend more slowly compared to those from the baseline. [25]

For the SMR-2035 scenarios with SAF, the increased EI H_2O values and higher overall propulsive efficiency tend to favor contrail formation. However, the significant reduction in EI soot and resulting ice crystal formation which leads to contrails with a lower optical thickness and climate impact outweighs these effects.

Even with all the aforementioned counteracting effects, the reductions in CO_2, NO_x, and soot have a greater influence on the total FEI, thereby reducing the overall climate impact of the SMR-2035 in all study cases compared to the baseline (see Figure 25).

Table 10: Overall Fleet-Level Emission Reductions & Normalized FEI for Baseline & SMR-2035 scenarios

Scenarios	Normalized Total FEI	CO_2 reduction	H_2O reduction	NO_x reduction	Soot reduction
Baseline – without SAF	1.00	0	0	0	0
Baseline SAF: low soot reduction scenario	0.93	0	0	0	0.5
Baseline SAF: high soot reduction scenario	0.85	0	0	0	0.8
F25 – without SAF	0.84	0.18	0.18	0.35	0
SMR-2035 SAF: low soot reduction scenario	0.74	0.18	0.11	0.35	0.5
SMR-2035 SAF: high soot reduction scenario	0.66	0.18	0.11	0.35	0.8

To conclude this assessment, the SMR-2035 and baseline configurations, including their respective SAF scenarios, are positioned within the DoE result space, as illustrated in Figure 26. To further provide context and enable a better comparison between the applied inputs and the emission reductions derived from the DoE study, the fleet level emission reductions and

CLEAN AVIATION
The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

the normalized total FEI across the operated network are outlined above (see Table 10). These can be directly compared to the input assumptions used in the DoE study. As previously mentioned, Figure 26 illustrates the FEI impact of the SMR-2035 and baseline with SAF only considerations within the DoE design space. The results are consistent with those discussed earlier: the conventional kerosene F25 configuration achieves the lowest total FEI reduction at approximately 16%, while the SAF scenarios show greater reductions of around 26% with an additional 50% soot reduction and approximately 34% with an additional 80% soot reduction. In particular, the use of SAF significantly influences the resulting climate impact.

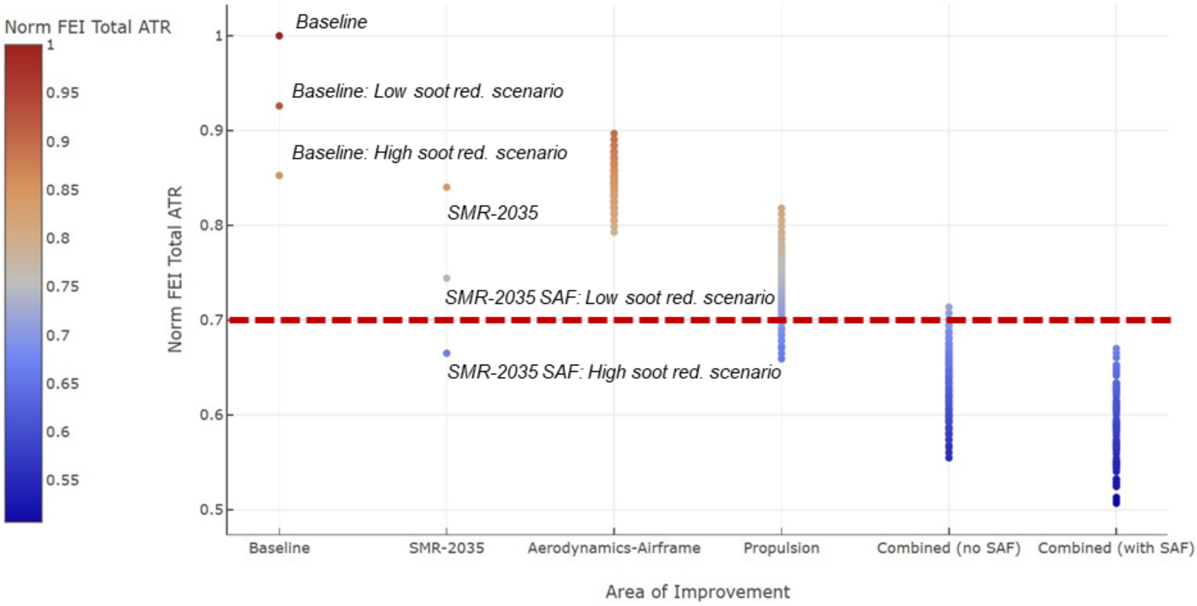


Figure 26: Total Fleet Environmental Impact in ATR-100 for Baseline, DoE results and SMR-2035

Although the reduction factors for CO_2, H_2O, and soot in the SMR-2035 are comparable to those assumed in the DoE study for the propulsion-only and combined Areas of Improvement, the overall FEI mitigation potential remains in the mid to lower range of the DoE results. This is primarily due to the relatively modest reductions in CO_2, H_2O, and NO_x achieved by the SMR-2035 compared to the more optimistic assumptions in the DoE. It should be noted that the DoE study is based on a simplified modelling-assessment approach, which limits its accuracy. In contrast, the use of digitized models incorporating multi-fidelity design tools as used in this study provides a more realistic estimate of achievable emission reductions and, consequently, the potential climate impact.

3.3. Influence of Climate Metric Selection on 2035 Aircraft Concepts

To conclude this study, a comparison of the Average Temperature Response (ATR100) and the efficacy-weighted Global Warming Potential (EGWP100), both based on a 100-year time horizon, was conducted. As discussed in Chapter 2.2, one limitation of the AS4D tool is that it only provides results for ATR100. Therefore, EGWP100 values were derived in a post-processing step using conversion factors provided by Dahlmann et al. [23]. These conversion

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

factors were applied to the climate agents assessed by AS4D to translate their respective ATR100 responses into EGWP100 values. Specifically, agent-specific weighting factors were used to estimate the climate response for specific agents based on equation 3 from [23] :

$$EAGWP_{100,i} = \frac{ATR_{100,i}}{factor_{ATR100,i}} * factor_{EAGWP100,i} \qquad (1.1)$$

The overall climate impact in terms of EGWP can then be calculated as the sum of all individual climate agents, each derived using the above-described conversion relation. It is worth noting that in the referenced paper, the NO_x-related climate effects were further disaggregated into the contributions from O_3, CH_4, and PMO (Primary Mode Ozone). Since AS4D provides a combined effect for NO_x emissions, the average of these three factor components was used to approximate the NO_x-related EGWP climate impact.

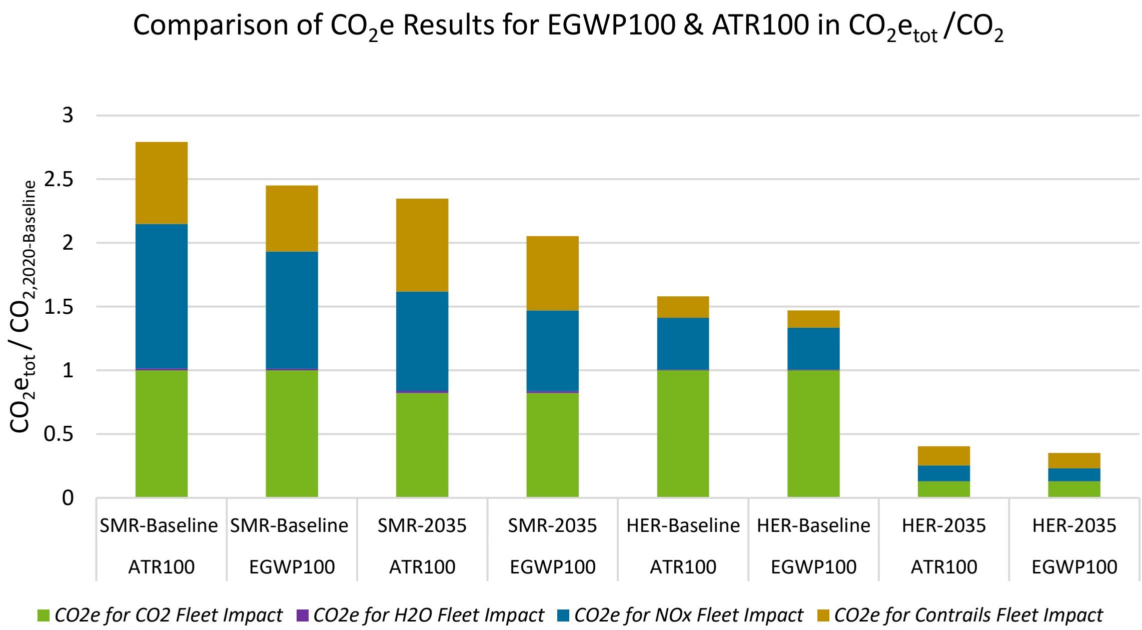


Figure 27: Comparison of CO_2e factors for the climate metrics ATR100 and EGWP100

Figure 27 illustrates the comparison of CO_2e factors derived using the ATR100 and EGWP100 climate metrics for the Baseline, SMR-2035, and HER-2035 aircraft concepts all operating on conventional fuel. For comparative analysis across different aircraft designs, results have been normalized using the ratio CO_2e_{tot} / CO_2. Since the CO_2e factors are normalized to the CO_2 emissions of the baseline, the impact of each new aircraft design on all climate agents can be directly compared to the baseline. As previously mentioned, the differences between the SMR and HER concepts are evident across various metrics, with the HER generally exhibiting lower CO_2e factors due to its distinct operational characteristics. Additionally, the use of hybrid-electric propulsion significantly reduces the contributions of CO_2 and NO_x. In

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

contrast, the SMR-2035 shows higher reduction potential for CO_2 and NO_x, while increases in H_2O and CiC emissions are observed, as concluded in the preceding chapters.

For both metrics, the relative contributions of H_2O, and NO_x to the total CO_2e are generally comparable. However, small variations are evident, with non-CO_2 agents tending to show slightly lower contributions under EGWP100 than under ATR100. As this study constitutes an academic benchmarking exercise, the implications of applying these two metrics will therefore be investigated in the following.

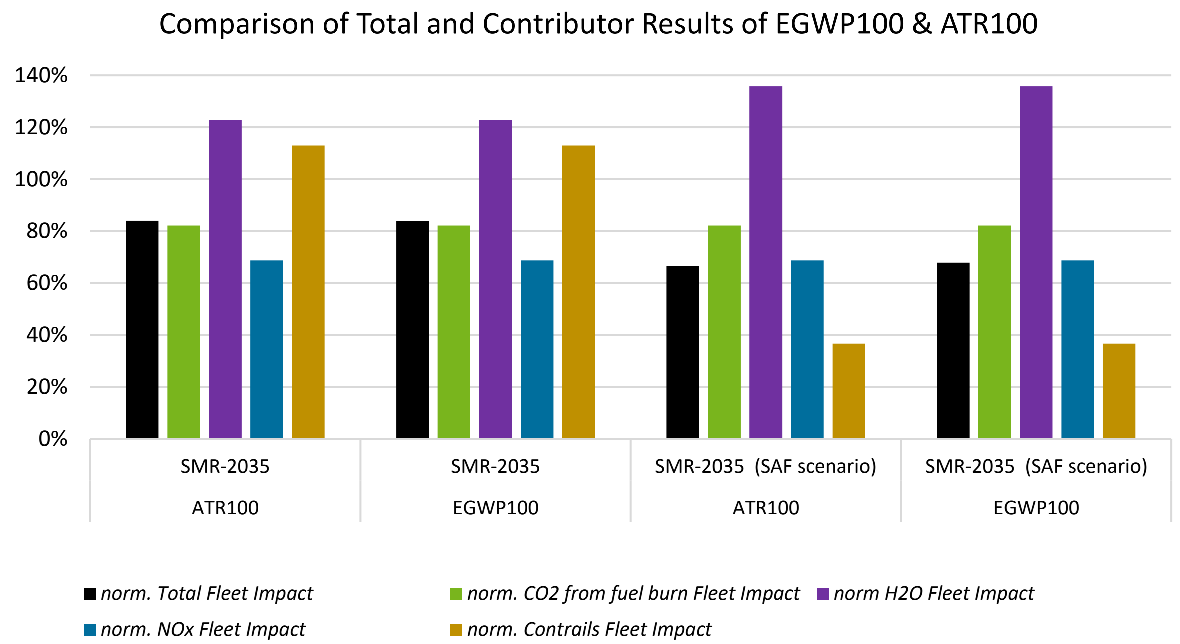


Figure 28: Comparison of total results for SMR-2035 use case

To further evaluate the impact of advanced technologies and fuel options, total reductions in climate impact metrics relative to the baseline have been assessed for the SMR use case. Figure 28 presents the normalized mitigation potential for the SMR-2035 concept operating on conventional fuel, as well as under a SAF scenario assuming an 80% reduction in soot emissions. Results are shown for both ATR100 and EGWP100 metrics. Additionally, to better understand the contributing effects, the percentage mitigation for individual climate agents has been plotted alongside the total values.

Overall, the relative mitigation within individual contributors (e.g., CO_2, H_2O, NO_x, CiC) is consistent across both climate metrics, showing the same reduction levels per agent for the same scenarios. The comparison of the total climate impact relative to the baseline also reveals a similar trend for both metrics. Across all scenarios, a comparable total climate impact reduction is visible, with only small variations <1%. Therefore, both climate metrics demonstrate very similar overall trends.

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

CLEAN AVIATION

Co-funded by the European Union

3.4. Limitations

Limitations in the proposed studies

This simplified assessment models technological advancements in a basic manner, reducing workflow complexity and enabling extensive sensitivity analyses. Technological improvements are represented through simple technology factors or emission flow adjustments throughout the mission. Consequently, aircraft sizing is simplified and snowball effects are excluded, as the study focuses on the sensitivity of technological variations and their impact on climate.

Limitations in the AS4D tool

The AS4D model has limitations in representing processes with low levels of understanding (e.g., natural cloud changes due to aircraft aerosol emissions) or low overall impact (e.g., direct soot and sulphate climate effects). Contrail formation and properties for non-kerosene aircraft are not well researched. The AS4D model adapts kerosene-based criteria with adjustments for EI H_2O, LHV, and propulsion efficiency, but further investigation is needed to refine these assumptions. Additionally, the workflow in its current setup relies on underlying static assumptions for market forecasts, including EIS, ramp-up, fleet renewal, and passenger demand predictions. To ensure comparability, the same market conditions are assumed for all runs. Absolute climate impact values may differ from higher-fidelity climate impact models and forecast scenarios; however, the AS4D model's sensitivity representation is well-suited for its purpose of comparing different aircraft concepts against each other.

Another important modelling constraint arises from the use of generic trajectories to simulate aircraft performance across a range of mission distances within the network. In particular, the interpolation between fully electric, zero-emission flights and hybrid-electric may oversimplify the nonlinear dynamics of battery and gas turbine interaction. Fuel and emission characteristics in missions where both systems are active are unlikely to scale linearly between these two points, potentially reducing the precision of results in this transitional mission range.

A further limitation is that aerodynamic effects, such as the reduction of wake vortex strength due to increased wing span or higher aspect ratio, are not explicitly implemented when comparing aircraft variants with the same configuration but modified geometries. As a result, potential aerodynamic benefits that could (negatively) influence contrail formation or dispersion are not captured within the current AS4D setup.

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

4. Summary and Conclusions

This report presented an approach for evaluating the climate impact of advanced aircraft technologies, inspired by Clean Aviation research, at both the mission and fleet levels. The assessment applies the four-layer approach developed in WP2 "Climate Impact Assessment". Using a two-step methodology, the study combines mission-based emission inventories with technology-driven design modifications to quantify the potential of innovative aircraft concepts.

In the first step, the impact of technological improvements was evaluated by applying DoE improvement factors directly to generic aircraft trajectories. Emissions were adjusted proportionally to investigate their effects on climate impact.

The second step refined this analysis by integrating these improvements into a full aircraft design process. This demonstrated how technology-specific factors, such as aerodynamic performance or propulsion system characteristics, influence emissions and climate impact at the aircraft level, enabling a deeper understanding of how advanced technologies can contribute to overall climate mitigation.

The results clearly show that the climate impact of future aircraft concepts, such as the SMR-2035 and HER-2035, cannot be assessed in isolation based on individual technologies or emissions alone. Instead, their effects are highly interdependent and reveal clear trade-offs between different design objectives. For example, while improvements in overall propulsive efficiency reduce CO_2 emissions, they can increase the likelihood of contrail formation. Similarly, a larger wingspan improves aerodynamic efficiency but alters wake vortex characteristics, which may influence contrail dynamics. The use of SAF reduces soot emissions, contributing to contrail mitigation, but may also increase water vapor emissions. These findings underline the inherently multi-objective nature of future aircraft design and technology integration for the goal of climate compatible aviation.

A key insight from the DoE sensitivity studies is the importance of emission species-specific mitigation strategies. While NO_x reductions contribute meaningfully to overall climate impact mitigation, their technological feasibility for the SMR-2035 remains more uncertain compared to other areas of improvement, such as fuel burn or soot reductions. However, it is important to note that these outcomes are highly dependent on the specific study setup, including the choice of reference and baseline aircraft, engine type, network configuration, and operational assumptions. Variations in these parameters can significantly influence the relative importance and effectiveness of individual mitigation strategies.

These technological effects are further amplified or diminished by operational factors at the network level. As demonstrated, the distribution of short- and long-haul routes, as well as typical operating altitudes, significantly influence the actual climate impact, particularly for non-CO_2 effects, which are highly dependent on atmospheric conditions and geographic location. Consequently, simplified approaches based on static CO_2-equivalent factors are insufficient to capture the full picture, especially in scenarios where evolving route networks or technological improvements alter specific emission contributors in different ways.

In addition to technology and operational interdependencies, the study assessed the effect of individual emission species on total climate impact. The sensitivity analysis comparing soot and NO_x in terms of their influence on fleet-level climate impact reduction revealed that, when

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

applying linear scaling factors, NO_x generally offers a greater mitigation potential than soot. However, this effect differs between market segments:

- For HER aircraft, operational characteristics such as lower cruise altitudes and shorter ranges result in a lower overall contribution of non-CO_2 emissions to total fleet climate impact. Consequently, while the trend of NO_x reductions having a higher mitigation potential than soot remains observable, the absolute magnitude of these effects is reduced compared to the short- to medium-range (SMR) segment.

- For SMR aircraft, with higher cruise altitudes and greater exposure to atmospheric regions favourable for contrail formation and ozone generation, non-CO_2 effects play a substantially larger role, and NO_x and soot mitigation measures show greater sensitivity and overall climate benefit.

This suggests that, for HER, priority should be given to CO_2 / fuel burn reduction technologies, as they provide the most leverage for lowering the overall climate impact. Hybrid-electric concepts could be a promising option for shorter ranges, as these aircraft could potentially lead to significant CO_2 reductions or even zero-emission operation, ultimately lowering total climate impact. For SMR, the different operational characteristics, such as operating at higher flight levels and on longer routes, amplify the relative influence of non-CO_2 effects. In this context, reductions in soot and NO_x have a greater impact on overall climate impact, compared to the regional market segment.

At the very end, both proposed climate metrics, namely the Averaged Temperature Response (ATR) and the efficacy-weighted Global Warming Potential (EGWP), have been assessed regarding their outcomes. Since both metrics differ only by small variations in climate agent weightings, the resulting differences in total mitigation potential were minor, and both metrics showed similar trends and behaviours across scenarios, confirming their robustness for technology climate impact assessments.

To adequately account for these complex technological and operational interactions, a comprehensive, dynamic assessment framework is essential. The applied 4-layer approach addresses this need by integrating technological, operational, and temporal aspects [28]. It enables a consistent evaluation of future aircraft and market segments, considering evolving route networks, technological advancements, and changing operational patterns. By coupling a 4D emission inventory with region- and altitude-dependent climate impact calculations, this approach ensures that all relevant contributors and their interactions are captured in a scientifically robust and operationally realistic manner.

Furthermore, the results highlight that optimizing technology alone is insufficient. Operational strategies, such as cruise altitude selection also has the potential to significantly reduce climate impact.

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

REFERENCES

[1] Clean Aviation, *Strategic Research and Innovation Agenda (SRIA) 2024.* [Online]. Available: https://clean-aviation.eu/sites/default/files/2024-09/2024-Clean-Aviation-SRIA.pdf

[2] K. Dahlmann, V. Grewe, S. Matthes, S. Zhukovska, *D2.2 – Climate Metrics, Differences Between Simplified and Advanced Methods, and Recommendations.* [Online]. Available: https://www.claim-project.eu/_files/ugd/6c904e_900b65024f66441e829a42dd982bb605.pdf

[3] S. Wöhler, G. Atanasov, D. Silberhorn, B. Fröhler, T. Zill, *Preliminary Aircraft Design Within A Multidisciplinary And Multifidelity Design Environment.* [Online]. Available: https://elib.dlr.de/185515/1/AE2020_032_woehler.pdf

[4] C. Davide, S. Delbecq, S. Defoort, P. Schmollgruber, E. Benard, and V. Pommier-Budinger, "From FAST to FAST-OAD: An open source framework for rapid Overall Aircraft Design," *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 1024, no. 1, p. 12062, 2021, doi: 10.1088/1757-899x/1024/1/012062.

[5] V. Palladino,, A. Jordan, N. Bartoli, P. Schmollgruber, V. Pommier-Budinger, E. Benard, "Preliminary studies of a regional aircraft with hydrogen-based hybrid propulsion," in *AIAA AVIATION 2021 FORUM*, VIRTUAL EVENT, 08022021.

[6] L. Weber, *An Approach to Aircraft Technology Roadmapping by Mission-Level Assessment.* [Online]. Available: https://elib.dlr.de/196263/1/An Approach to Aircraft Technology Roadmapping by Mission-Level Assessment_Weber_DLR_intern.pdf

[7] German Aerospace Center (DLR - Institute of Atmospheric Physics & Institute of Air Transport) in cooperation with Airbus, "The AirClim Surrogate Model for Aircraft Design AS4D V1.0: internal documentation,"

[8] German Aerospace Center, *RCE – The Remote Component Environment.* [Online]. Available: https://rcenvironment.de/

[9] ATR, *ATR 72-600 Aircraft Characteristics for Airport Planning Manual.* [Online]. Available: https://www.atr-aircraft.com/airport-and-maintenance-planning

[10] Clean Aviation HERA-Project, *HERA Project.* [Online]. Available: https://project-hera.eu/home

[11] M. C. Gelhausen, W. Grimme, A. Junior, C. Lois, P. Berster, "Clean Sky 2 Technology Evaluator—Results of the First Air Transport System Level Assessments," *Aerospace*, vol. 9, no. 4, p. 204, 2022, doi: 10.3390/aerospace9040204.

[12] FlightGlobal, *Orders for A321neo overtake those for A320neo.* [Online]. Available: https://www.flightglobal.com/air-transport/orders-for-a321neo-overtake-those-for-a320neo/146768.article

[13] Airbus, *Aircraft Characteristics for Airport Planning Manual.* [Online]. Available: https://www.airbus.com/en/services/support/aircraft-characteristics

[14] G. Atanasov, *Concept Introduction: 70 PAX Plug-In Hybrid-Electric Aircraft (D70 PHEA).* [Online]. Available: https://elib.dlr.de/193116/1/EXACT-MTR-D70PHEA-Introduction.pdf

[15] S. Wöhler, J. Häßy, V. Kriewall, *Establishing the DLR-F25 as a Research Baseline Aircraft for the Short-Medium Range Market in 2035.* [Online]. Available: https://elib.dlr.de/208272/1/ICAS2024_0399-Woehler_Sebastian.pdf

[16] S. Wöhler, *A Parametric Aircraft Design Framework for Novel Aircraft Concepts*.

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

[17] J. Häßy and B. Fröhler, "The Virtual Propulsion Expert: Application of a Hybrid Surrogate-Based Rubber Engine Model in Aircraft Design," in *AIAA AVIATION 2023 Forum*, San Diego, CA and Online, 06122023.
[18] U. Schumann, "Influence of propulsion efficiency on contrail formation," *Aerospace Science and Technology*, vol. 4, no. 6, pp. 391–401, 2000, doi: 10.1016/S1270-9638(00)01062-2.
[19] S. Unterstrasser, "Properties of young contrails – a parametrisation based on large-eddy simulations," *Atmos. Chem. Phys.*, vol. 16, no. 4, pp. 2059–2082, 2016, doi: 10.5194/acp-16-2059-2016.
[20] L. Megill, K. Deck, and V. Grewe, "Alternative climate metrics to the Global Warming Potential are more suitable for assessing aviation non-CO2 effects," *Commun Earth Environ*, vol. 5, no. 1, pp. 1–9, 2024, doi: 10.1038/s43247-024-01423-6.
[21] D. Brousset-Matheu, E. Nguyen Van, S. Defoort, X. Roboam and B. Sareni, "Exploring coupling effect between airframe and propulsion in parametric models for electric regional aircraft with range extender," AeroBest 2025, 2025.
[22] A. Sgueglia, "Methodology for sizing and optimising a Blended Wing-Body with distributed electric ducted fans," ISAE - Institut Supérieur de l'Aéronautique et de l'Espace, 2020. [Online]. Available: https://hal.science/tel-02487044/document
[23] K. Dahlmann, S. Matthes, and V. Grewe, "Conversion of climate metrics for policy applications," Preprint, 2025.
[24] U. Burkhardt, L. Bock, and A. Bier, "Mitigating the contrail cirrus climate impact by reducing aircraft soot number emissions," *npj Clim Atmos Sci*, vol. 1, no. 1, pp. 1–7, 2018, doi: 10.1038/s41612-018-0046-4.
[25] B. Kärcher, "Formation and radiative forcing of contrail cirrus," *Nat Commun*, vol. 9, no. 1, p. 1824, 2018, doi: 10.1038/s41467-018-04068-0.
[26] R. H. Moore. *et al.,* "Biofuel blending reduces particle emissions from aircraft engines at cruise conditions," *Nature*, vol. 543, no. 7645, pp. 411–415, 2017, doi: 10.1038/nature21420.
[27] R. Dischl *et al.,* "Measurements of particle emissions of an A350-941 burning 100 % sustainable aviation fuels in cruise," *Atmos. Chem. Phys.*, vol. 24, no. 19, pp. 11255–11273, 2024, doi: 10.5194/acp-24-11255-2024.
[28] B. Kärcher, "Formation and radiative forcing of contrail cirrus," *Nat Commun*, vol. 9, no. 1, p. 1824, 2018, doi: 10.1038/s41467-018-04068-0.

The project is supported by the Clean Aviation Joint Undertaking and its members

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union