

EXACT SUSTAINABLE AIRCRAFT CONCEPTS RESULTS AND COMPARISON

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Abstract

The project "Exploration of Electric Aircraft Concepts and Technologies" (EXACT) serves as a central integration initiative of DLR with the primary objective of exploring how the climate impact of aviation can be drastically reduced while maintaining economic competitiveness. The focus of the project was set on intra-continental transport, resulting in the development and assessment of various sustainable aircraft concepts for two distinct aircraft classes — a 70-seater regional class and a 250-seater short-range class. The paper describes the unified framework developed for the project, which enabled the consistent modelling and comparison of aircraft concepts with various propulsion system types, including synthetic-kerosene-driven, hydrogen-based, fuel-cell-powered, and plug-in hybrid-electric configurations. The employed methodological approach incorporates component models for structural load analysis, mass estimation, energy storage systems, aerodynamics, and mission performance. The models comply with the consistent integration of radically different technologies at the aircraft level and encompass interfaces for feeding global-fleet-assessment methods under identical boundary conditions. The paper also outlines the project results, which provide valuable insights into the trade-offs, synergies, and relative performance of the different technologies, while demonstrating the advanced modelling capabilities required to evaluate future sustainable aviation solutions.

Keywords

Overall Aircraft Design, Sustainable Aircraft, Energy Efficient Propulsion, Hydrogen, Fuel Cell, Battery-Electric, Hybrid-Electric Propulsion

NOMENCLATURE

Abbreviations

CPACS	Common Parametric Aircraft Configuration Schema
DLR	German Aerospace Center
EIS	Entry Into Service
EXACT	Exploration of Electric Aircraft Concepts and Technologies
LH2	Liquid Hydrogen
MHEP	Mild-Hybrid-Electric Propulsion
OAD	Overall Aircraft Design
PHEP	Plug-In-Hybrid-Electric Propulsion
TLAR	Top-Level Aircraft Requirement

1. INTRODUCTION

The aviation industry is confronted with a dual challenge: the need to address its significant contribution to global warming while maintaining economic competitiveness and meeting growing demands for air transport. Current propulsion technologies and aircraft architectures must evolve to comply with increasingly challenging climate goals, such as the Paris Agreement and the European Green Deal, which aim to achieve net-zero emissions by 2050. In response to these challenges, novel aircraft configurations and energy carriers — including synthetic kerosene, liquid hydrogen, and hybrid-electric solutions — offer promising pathways to drastically reduce emissions and improve environmental performance.

The project "Exploration of Electric Aircraft Concepts and Technologies" (EXACT) [1] was initiated as the central integration initiative of DLR to assess the potential of sustainable aircraft concepts. EXACT aimed to provide a holistic understanding of how various propulsion systems and energy carriers perform within the framework of future regional and short-range aircraft operations. In contrast to other studies that analyze individual technologies in isolation, EXACT evaluates multiple aircraft concepts systematically and quantitatively under unified boundary conditions. This methodological approach ensures the comparability of configurations that differ considerably in terms of design and operational implications for sustainable aviation. The obtained results enabled the identification of key technologies, trade-offs, and operational implications for sustainable aviation.

A critical challenge in this assessment is achieving consistent and reliable modelling of fundamentally different propulsion system types, ranging from synthetic-kerosene-driven turbofans to hydrogen-based, fuel-cell-powered propulsion, and plug-in hybrid-electric architectures. The employed solution was to develop an advanced overall aircraft design (OAD) framework that integrates various component models. These include tools for modelling key aircraft characteristics, such as aero-propulsive efficiency, component and structural masses, aerodynamic characteristics, and mission performance, enabling a thorough analysis of the aircraft concepts.

The present paper presents an overview of the EXACT project's aircraft modelling activities, with an emphasis on the direct comparison of sustainable concepts for regional and short-range aircraft. The study provides quantitative insights into the potential of these configurations to reduce

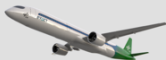
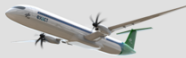
Aircraft Class	Short-Range (transonic)	Short-Range (subsonic)	Regional
Range	1500 nm		1000 nm
Capacity	250-seater		70-seater
Cruise Mach	0.78	0.6-0.7 (optimized)	0.55
Syn. Fuel-Powered Aircraft Concepts	Turbofan	Turboprop	Turboprop
			
LH2-Powered Propulsion	Turbofan Mild-Hybrid (MHEP)	Turboprop Mild-Hybrid (MHEP)	Fuel-Cell-Powered E-Propeller
			
	LH2 Direct Burn + Fuel Cell for On-Board Systems		
Hybrid-Electric-Powered Propulsion	Plug-In Hybrid-Electric Propulsion (PHEP)		
	 		
	Fully electric propulsion + Turfboshaft Range Extender		
All Concepts are Modelled for EIS (Entry-Into-Service) 2040 Technology Projections			

FIG 1. Propulsion system architectures and aircraft configurations in the scope of the EXACT project.

the climate impact of aviation by highlighting the average energy efficiency of each configuration at global-fleet level.

2. SCOPE AND BOUNDARY CONDITIONS

The project EXACT aimed to define viable aircraft concepts with the potential to enhance the sustainability of the global air-transport fleet in 2050. The target entry-into-service year of the concepts was set to 2040, allowing sufficient development time for the inclusion of more radical technologies and providing sufficient buffer time for fleet penetration.

Intra-continental transport, with operational distances up to 1500 nautical miles, was set as the primary exploration target. No propulsion technologies or energy storage systems were directly excluded at the start of the project. A discussion on the considered aircraft classes and configurations is provided in subsection 2.1. The implications of the future EIS of the concepts are discussed in subsection 2.2.

The aircraft modelling strategy of the project underwent a gradual shift from broad, qualitative studies used to down-select the most promising aircraft configurations and technologies, towards complex multidisciplinary models. These models included interfaces for global holistic analyses of climate impact, life cycle, and operating costs, which is detailed in subsection 2.3.

2.1. Target Aircraft Classes and Concept Configurations

The EXACT project focuses on two aircraft classes — regional and short-range — each with a distinct Top-Level-Aircraft-Requirements (TLARs) set. These two classes represent a significant portion of current and projected future air transport operations [2], making them ideal candidates for assessing novel energy carriers and propulsion technologies. The differences between seating capacity and cruise speed have a pronounced impact on the overall aircraft configuration and propulsion system architecture, increasing the diversity of the solution space. The short-range-class models were further divided into transonic and subsonic aircraft to explore the effect of design speed on overall efficiency, climate impact, and operating costs.

Aircraft models featuring different energy storage systems and propulsion types were developed and analysed within the framework of each of the defined classes. Initially, no limitations were defined for the selection of aircraft configurations or propulsion technologies; however, building up the knowledge base on energy carriers different than kerosene and on power providers alternative to gas turbines required significant resources. Hence, the broadness of the studies was limited to propulsion systems based on synthetic kerosene, liquid hydrogen, and batteries.

An overview of the energy carriers and propulsion configurations considered in the final results of the project is presented in Figure 1.

2.2. Technology Assumptions and Projections for Entry Into Service in 2040

The aircraft concepts analysed within the project assume a future entry into service (EIS) year of 2040. Therefore, technology development projections needed to be implemented in the modelling process:

- Incremental Advancements in Structures and Aerodynamics:**
Evolutionary improvements in structural materials and aerodynamic performance were assumed, based on input from disciplinary experts within the EXACT consortium. Implementing these projected advancements results in weight savings and drag reduction, enhancing the overall performance of the concepts.
- Integration of Novel Propulsion Technologies:**
Technologies such as fuel-cell-powered systems and battery-hybrid-electric propulsion architectures were modelled using projections from published studies, existing projects, and official technology roadmaps. For instance, hydrogen fuel cells and plug-in hybrid-electric systems were assumed to achieve significant efficiency and energy density improvements by 2040 compared to the state-of-the-art technology.
- Bleedless, Fully-Electric On-Board Systems:**
All aircraft concepts were modelled with fully-electric and bleedless on-board systems. This approach standardised the comparison by eliminating mechanical or bleed

air off-takes, which are present mainly in gas-turbine-based propulsion. For example, fuel-cell-powered systems and gas turbines were evaluated with similar on-board power demands, thereby improving comparability.

4) **Clean-Sheet Aircraft Designs:**

All concepts were assumed to be clean-sheet designs, optimized from scratch rather than retrofitted onto existing aircraft architectures. This ensured that each configuration fully leverages synergies with its respective propulsion system, such as optimized tank placement for liquid hydrogen or distributed propulsion for fuel-cell architectures.

The establishment of this modelling framework facilitated a consistent comparison of the various sustainable aircraft concepts developed in EXACT.

2.3. Concept Downselection Process

The final EXACT concepts, illustrated in Figure 1, are the result of an extensive downselection process carried out throughout the project, the details of which can be found in Figure 2.

Initial low-fidelity studies explored a broad range of aircraft configurations and propulsion technologies, effectively narrowing down the solution space while simultaneously developing the required capabilities to increase the quality of subsequent studies. During this phase, interfaces between the participating institutes were established, and critical knowledge gaps and development needs were identified.

A major part of the project efforts were focused on developing tools and methods to integrate higher-fidelity modelling results from the contributing institutes. This process enhanced the capabilities of the overall modelling framework, ensuring consistent and robust evaluation of the different aircraft concepts. The selection process was performed iteratively, utilizing the global assessment framework, which was developed in parallel with the concept modelling [3–7].

This systematic and iterative approach ensured that the concepts selected for the final assessment loop represented the best-performing and most viable sustainable aircraft solutions, balancing efficiency, environmental performance, and feasibility.

3. OVERALL AIRCRAFT MODELLING

The EXACT project employed a unified and systematic framework for modelling sustainable aircraft concepts, ensuring consistent evaluation across diverse propulsion systems and energy carriers. This section outlines the key methods and tools used for the modelling of aircraft components, aerodynamics, propulsion systems, on-board systems, and mission performance. The integration of these methods enabled a holistic assessment of aircraft performance under identical boundary conditions.

3.1. MDO Platform for Aircraft Design

The overall aircraft design methodology consists of disciplinary Level 0 and Level 1 tools comprising an aircraft sizing workflow based on the Common Parametric Aircraft Configuration Schema (CPACS) [8, 9]. The workflow is configured with the help of the remote component environment (RCE) [10], which allows for a fast and flexible tool-chain architecting.

The backbone for the design workflows is *openAD* — a DLR-internal tool for overall aircraft design [11], which has been developed at the Institute of System Architectures in Aero-

nautics. The sizing methodology follows a conceptual-level semi-empirical approach. It is used for providing an overall aircraft sizing based on input constraints and generates a 3D aircraft in *CPACS* as an output. *openAD* also generates a semi-empirical component mass breakdown, handbook-level aero polars, as well as turboprop and turboprop decks based on simplified engine cycle calculations.

A pivotal property of the aforementioned tool is its highly flexible input, which allows the feeding back of results from higher-fidelity tools into the aircraft sizing process, e.g., structural analysis, mission trajectories, aerodynamic polars, etc. Hence, the tool is utilised as a synthesizer for more complex design workflows.

3.2. Aircraft Component Masses and Structures

A combination of analytical methods and empirical correlations was utilised to calculate the structural masses of the aircraft [12–15]. *LOADzero* and *LGLOADzero* [13] were utilized for flight and ground load estimation, while fuselage and wing structural masses were derived using *CpacAnalyse* [14], *PreDocs* and *DELiS* [15]. Empirical corrections, based on calibration with reference aircraft, ensured consistency between analytically optimized primary structures and additional secondary components [12]. For advanced configurations, materials and technologies such as composite structures for wings were incorporated, providing insights into weight-saving potentials.

3.3. Aerodynamics

The aerodynamic models were derived using the handbook methods implemented in *openAD* [11]. A subset of the *openAD* output are aerodynamic decks, including different slat and flap settings, which can be used for the high-speed and low-speed mission trajectories calculation, see subsection subsection 3.6.

The tool *LIFTING LINE* [16, 17] was employed as an enhancement of the standard handbook methods in more unconventional cases. For example, a study on the 250-seater, short-range turboprop concept [18] includes a description of the utilisation of the tool for capturing the wing-propeller interaction effects, thereby avoiding an underestimation of the transonic drag. Furthermore, adjustments to aerodynamic performance were implemented to account for blown wing effects in distributed propulsion concepts.

3.4. Aircraft Balance and Handling Qualities

The centre of gravity and the static margin of the aircraft were determined in *openAD* for key states of aircraft loading, encompassing various cruise, take-off, and landing conditions. Additionally, an unpublished DLR-internal tool *WAB* (Weight And Balance) was used for determining the centre of gravity envelope of the aircraft.

The tool *CASCOT* (CPACS-based Aircraft Stability & Control Tool), developed in the LuFo project SynergIE [19], was used to ensure the sizing of the control surfaces is consistent with CS25 certification requirements.

3.5. Propulsion and On-Board Systems

As illustrated in Figure 1, the propulsion systems explored in EXACT encompass a range of technologies, including:

- gas-turbine-driven engines, i.e. turboprops or turboprops, powered by:
 - synthetic kerosene
 - liquid hydrogen

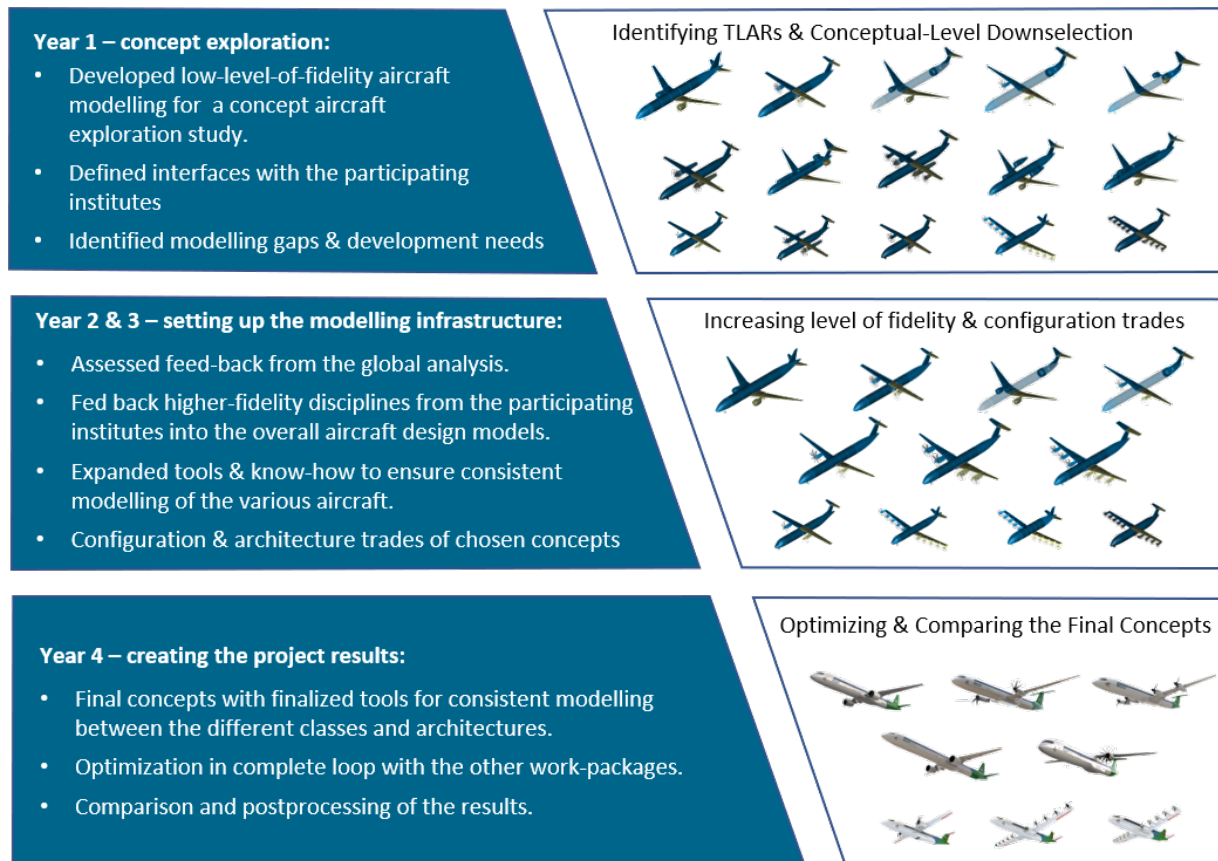


FIG 2. Concept downselection in the EXACT project.

- fuel-cell systems used for:
 - providing power to electric propellers
 - mild-hybrid propulsion system in combination with gas-turbine-driven engines, in which the fuel cells provide the power required for on-board systems and enhance the performance of the gas turbines during low-power operation, e.g., in taxi, descent, etc.

- battery packs powering electric propellers

The modelling of propulsion systems and the on-board systems was conducted in alignment with the high-fidelity models of the disciplinary experts from various institutes participating in EXACT. This included key characteristics, such as power and energy requirements for important aircraft operation profiles, component failure safety analysis, space allocation and structural integration, and subsystems bookkeeping.

A comprehensive description of the turbofan and turboprop modelling can be found in the study by Atanasov et al. [18]. The modelling of LH2 turbofans with mild hybrid propulsion is described in multiple presentations and publications [6,20,21]. The battery-electric and fuel-cell powered propulsion systems were presented in several public events [22–26].

3.6. Mission Analysis

Mission performance, including payload-range capabilities and fuel consumption, was analysed using the trajectory tools *AMC* (Aircraft Mission Calculator) for high-speed mission segments and *LSP* (Low-Speed Performance) [27] for low-speed operations such as take-off and landing. While there is no dedicated publication on *AMC* yet, it has already been utilized in numerous projects, including multiple published studies [28–30].

The trajectory calculation accounted for operational allowances, flap settings, and energy consumption during various phases of flight. Special attention was given to the performance of hydrogen-fueled aircraft, particularly in addressing center-of-gravity shifts during take-off and fuel consumption over short and medium-haul missions.

3.7. Liquid Hydrogen Storage Systems

The design and modelling of liquid hydrogen storage systems were critical for the hydrogen-powered concepts explored in EXACT. The storage system focused on two main challenges:

- 1) Cryogenic Storage Requirements:** Liquid hydrogen requires storage at extremely low temperatures (approximately 20 K). Insulation technologies, including multi-layer vacuum insulation, were considered to minimise boil-off losses during the mission.
- 2) Integration into Aircraft Geometry:** Tank placement and design were optimised for aerodynamic and structural efficiency. For regional aircraft, cylindrical cryogenic tanks were integrated into the rear fuselage. For short-range aircraft, more complex tank geometries were analysed to accommodate higher fuel requirements without compromising payload capacity.

The hydrogen storage systems were modelled with tools capable of assessing both thermal performance and structural integration [31,32]. Trade-off studies were performed to balance the tank mass, storage efficiency, and operational feasibility. The insights gained from these studies helped identify the best-performing configurations for hydrogen-fueled aircraft and minimise impact on overall aircraft performance [21,33].

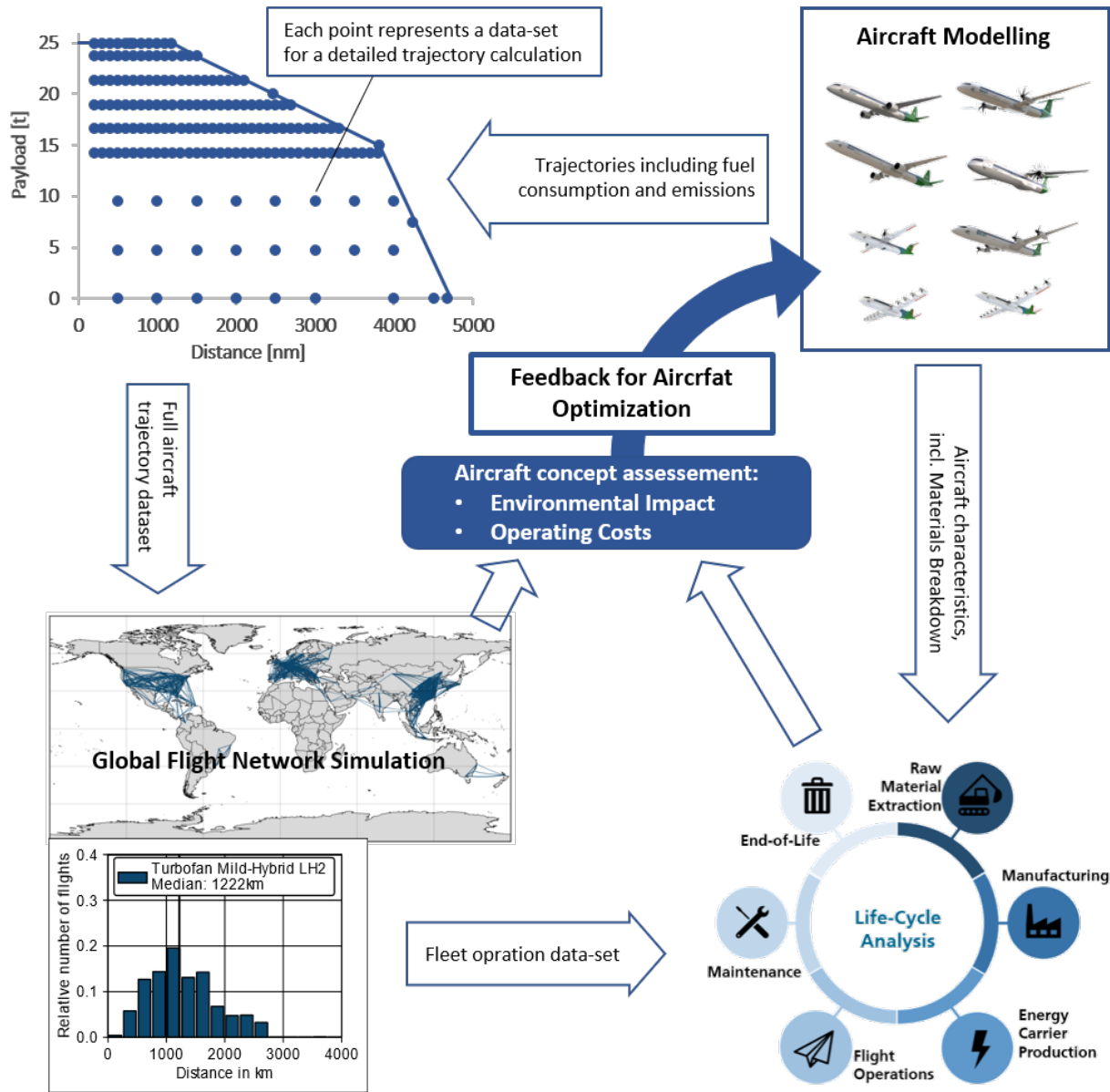


FIG 3. Global aircraft assessment and optimization loop schematic.

4. OVERALL AIRCRAFT DESIGN RESULTS

This section will provide a compact overview on the modelling results of the final aircraft concepts. The optimization strategy of the aircraft concepts is described in subsection 4.1. The final results and energy-efficiency comparison between the various concepts is provided in subsection 4.2, followed by a discussion of the results in subsections 4.3 and 4.4.

4.1. Aircraft Assessment and Optimization

The EXACT aircraft concepts were optimised through the utilisation of simulations that emulated global fleet operation (see Figure 3). This objective was accomplished by employing a model that replicated the operation of an entire fleet comprising 500 aircraft for each aircraft concept that was submitted for evaluation. The assessment of each concept was performed independently from each other. The following capabilities were used for the global-level assessment of each concept:

- **Global fleet operation simulation:** The operation of a fleet of 500 aircraft of the same type was simulated, describing the full aircraft life span of all 500 aircraft servicing existing airport pairs. The simulation incorporated details such as day-to-day flight schedules, overnight stays, maintenance and overhaul checks, and crew circulation. Several operating scenario simulations were created employing this approach. One such scenario simulated a fleet with a tendency to prioritise short-haul operation, facilitating the employment of slower-flying concepts. Conversely, another scenario simulated a fleet with a tendency to operate on longer routes, which are more suitable for faster aircraft concepts. The scenario variation permitted an investigation of the results sensitivities to different operational scenarios for each aircraft concept.
- **Fleet life cycle assessment:** Simulations calculated the life-cycle impact of a fleet comprised by 500 aircraft of a given aircraft concept, accounting for material extraction, manufacturing, energy-carrier production and logistics, operational energy use, and end-of-life effects. Special considerations included battery replacement for elec-

tric aircraft and hydrogen tank replacements for hydrogen-powered concepts.

- **Environmental impact simulation:** The fleet simulation of each aircraft concept was fed to the global climate simulation tool AirClim [34,35], which calculated the overall climate impact of the fleet over the entire aircraft life-span. The climate impact assessment included CO₂ and non-CO₂ effects, as well as life-cycle effects, such as material extraction, maintenance, and disposal.
- **Fleet cost model:** The detailed fleet simulation was used to calculate the operating costs of 500-airliners-sized global fleet for each aircraft concept separately, averaging the costs over the entire life-span. The model included costs for capital investment, energy consumption, maintenance and overhaul, crew, and fees. Different cost scenarios were created, varying the energy cost projections of each energy carrier - fossil kerosene, synthetic kerosene, liquid hydrogen, battery replacement costs and recharging electricity costs.

The concept down-selection described in Figure 2 was performed in-loop with these global assessment capabilities. A schematic of the overall loop from the modelling of the aircraft concepts to the assessment of the fleet operating costs and climate impact is presented in Figure 3. Examples of the utilisation of these capabilities are described in numerous published studies (see references [6, 7, 18, 21]).

The optimization of each aircraft concept configuration and characteristics aimed to minimize the calculated fleet-level direct operating costs. The performed trade-off studies varied key-parameters, such as wing geometry, engine characteristics (e.g. propeller or fan diameter, number of blades), cruise speed, cruise altitude, flap position for take-off, and many concept-specific parameters. A detailed example of a model optimization study is described in Atanasov et al. [18].

4.2. Energy-Efficiency Comparison between the EXACT Concepts

The final EXACT concepts resulted from extensive down-selection and optimization, as described in subsection 2.3 and 4.1. Figure 4 compares energy efficiency across concepts under two fleet operation scenarios [3]:

- **Scenario 1:** A baseline operation scenario typical for short-range single-aisle airliners, emphasizing longer intra-continental routes (mean distance 1400 km).
- **Scenario 2** A scenario focusing on short-haul routes, more suitable for slower concepts where speed penalties are less impactful (mean distance 800 km).

Comparing the concepts across two different operational scenarios provided valuable insights, emphasizing the dependency of results on the fleet operational profile, which reflects the needs of the targeted market. This comparison highlighted shifts in optimal design characteristics, such as cruise speed, flight altitude, and even propulsion system type, with respect to shifting market requirements. The following tendencies could be observed from the comparison of the EXACT concepts shown in Figure 4:

- 1) **Baseline aircraft:** The 250-seater turbofan model is a conventional kerosene-powered aircraft, representing the projected baseline evolutionary advancements. With a 20% increase in efficiency compared to a state-of-the-art reference airliner, it serves as the benchmark for the other concepts.
- 2) **Speed vs efficiency:** The turbofan concepts of the 250-seater class, powered by kerosene or liquid hydrogen, are designed for a cruise speed of Mach 0.78. Reducing the design speed to Mach 0.66 (15% reduction) im-

proves efficiency by approximately 25% on average. The results variations between Scenario 1 and Scenario 2 provide additional insights. Off-design operations, such as taxiing, take-off, descent, approach, and landing, are unavoidable components of every mission. While longer missions (predominant in Scenario 1) allow the aircraft to spend most of the flight time in cruise, shorter routes (predominant in Scenario 2) experience a higher relative impact from off-design phases. The off-design operation significantly decreases overall efficiency, which explains the tendency for higher energy consumption in Scenario 2 for most concepts. However, slower aircraft concepts, with smaller engines, consume less fuel during off-design operations, thereby reducing the efficiency penalty in Scenario 2. These effects are described in detail in the paper by Atanasov et al. [18].

- 3) **Hydrogen direct burn with Mild-Hybrid Architecture:** The LH₂-driven, 250-seater turbofan and turboprop concepts feature engines with direct-burn of hydrogen, enhanced by fuel-cell systems in a Mild-Hybrid-Electric Propulsion Architecture (MHEP). The fuel cells deliver electrical power for the on-board systems (offtake-less engine operation) and allow driving the main engines electrically in low-power phases like taxi and descent with turned-off gas turbines. As a result, the mild hybridization significantly improves the aircraft fuel efficiency in off-design operation. This reduces the overall performance penalties from the integration of the liquid hydrogen energy storage. Furthermore, as indicated in Figure 4, the highly efficient off-design operation due to the mild-hybrid propulsion system also decreases the average efficiency difference between Scenario 1 and Scenario 2. A comprehensive overview of these concepts and the described effects has been presented by Silberhorn in [20].
- 4) **Fuel-Cell Propulsion:** Fuel cell propulsion is significantly heavier than direct burn engines; however, it is capable of attaining levels of fuel efficiency in excess of 50% (power output relative to fuel energy consumption) already at small power classes [22]. These characteristics are synergetic with lower-power applications, such as mild-hybridization of direct burn engines of the 250-seater LH₂ concepts, where the efficiency gains overcome the mass penalties. The trade-off studies in EXACT determined that a fully-fuel-cell-powered propulsion is a suitable choice for the smaller, 70-seater aircraft class [18]. As demonstrated in Figure 4, the fuel-cell-driven regional concept (D70 Fuel-Cell-Electric) is approx. 25% more energy-efficient than a conventional turboprop at this aircraft class (D70 Turboprop).
- 5) **Plug-In-Hybrid Propulsion (PHEP):** The PHEP concepts developed in EXACT (D70 Plug-In Hybrid and D250 Plug-In Hybrid) are capable of serving distances up to 600 km fully electrically. Electric operation is extremely energy efficient, despite the high mass of the aircraft due to the heavy battery. When additional range is required, the PHEP concepts use kerosene, which is converted to electric energy by a range-extender generator powered by a gas turbine. In range-extender power mode, the PHEP concepts are the least efficient due to the heavy propulsion system mass. Therefore, the range extender usage is utilised only to the extent required to attain the additional range, thereby minimising kerosene consumption. For example, a 800 km mission would only consume fuel required for the 200 km additional range, in addition to the electric range of 600

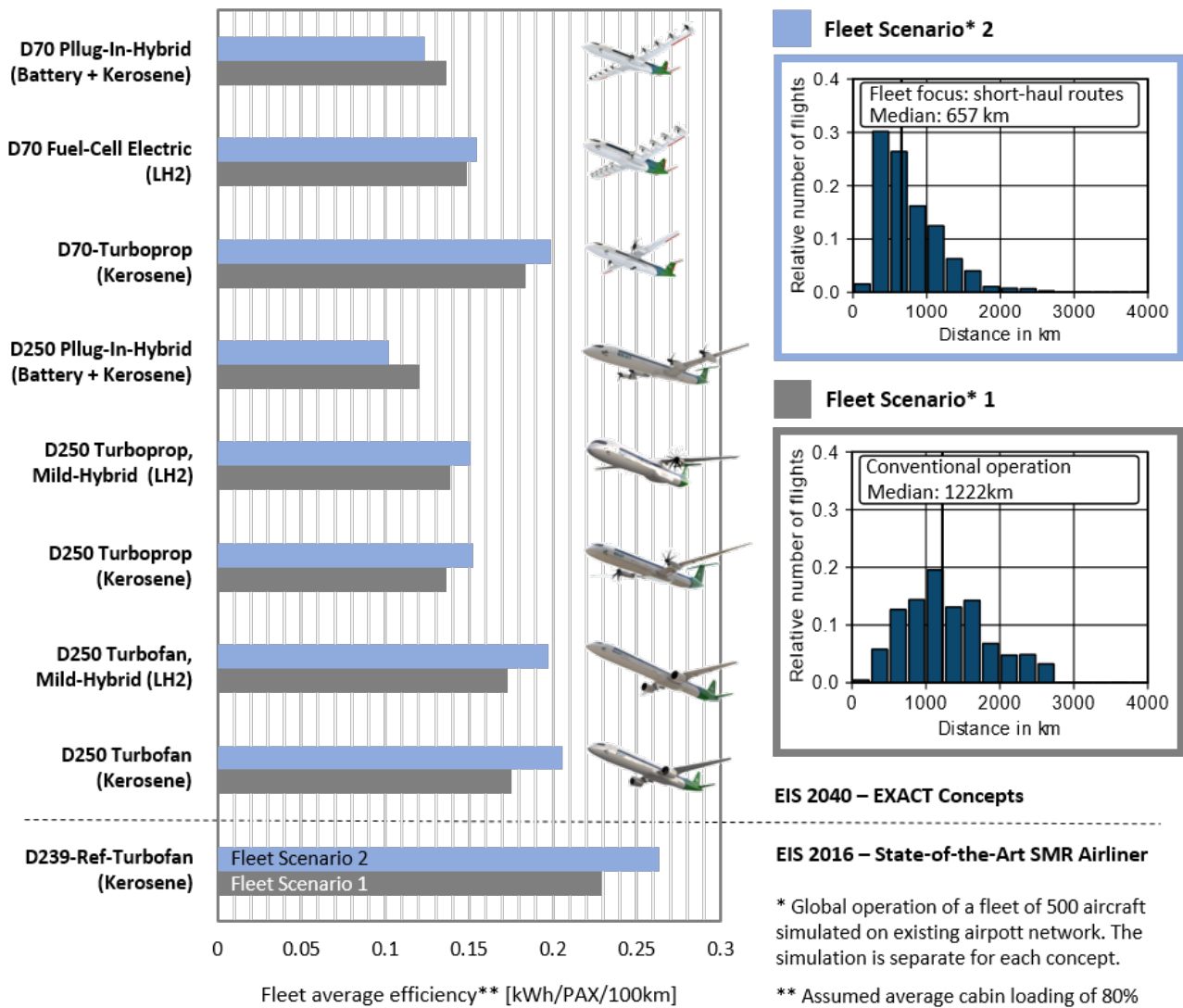


FIG 4. Fleet-level efficiency comparison between the EXACT concept aircraft.

km. Consequently, even routes of 1000-2000 km feature a significant portion of all-electric operation. As a result, the energy-efficiency of the PHEP concepts is the highest even up to distances of 1500-2000 km, leading to the lowest fleet-level energy consumption on both scenarios shown in Figure 4. The EXACT technology assumptions for the electric propulsion component modelling were presented on multiple public forums [22–24].

- 6) **Scaling Effects:** Comparing the achieved average efficiency of the 70-seater turboprop model with that of the 250-seater model reveals the significant impact of the "effects of scale". Larger components generally exhibit higher efficiency in key performance areas, including structural mass, aerodynamics, and engine efficiency. The relative efficiency differences attributed to scaling effects are also evident when comparing the 70-seater PHEP aircraft with the 250-seater PHEP aircraft. Interestingly, the impact of size is less pronounced in this case, as battery efficiency remains largely unaffected by size.

4.3. Results Discussion

The present paper has a clear focus on the vehicle-level results and does not delve into the holistic assessment capa-

bilities used in EXACT. An overview of the comparison between the different concepts with respect to global climate impact and operating costs was presented in multiple public events [36–39]. As would be anticipated, the final EXACT results conclude that concepts with higher energy efficiency tended to perform better in both key assessment aspects - climate impact and costs.

In the larger, short-range class, concepts employing open propeller propulsion (turboprop) exhibited a clear advantage in terms of operating costs when compared to their turbofan-driven counterparts, despite the cost penalties due to the design speed reduction of 10%-15% [18]. Within the framework of EXACT, the concepts assume entry into service of 2040 and are assessed for operation in 2050 with future energy costs projections significantly higher than current energy costs [6, 7]. As a result, the impact of increased energy efficiency on operating costs dominated the time-related penalties resulting from slower flight. The climate impact assessment also identified noteworthy non-linearities. Specifically, the reduced flight speeds naturally reduced the optimal flight altitudes of the open propeller concepts, leading to decreased non-CO₂ effects and thereby further reducing the overall environmental impact. As demonstrated in the presentation of the final EXACT results in [36], a fleet of future short-range turboprop-driven

airliners would have an approximately 35% lower climate impact than a fleet of future turbofan aircraft. Only a part of this effect comes directly from the 25% reduced fuel consumption (see Figure 4) and the remainder from additional reduction in non-CO₂ effects.

The implementation of electric propulsion systems, powered by batteries or fuel cells, has the potential to yield further efficiency enhancements. In the context of regional aircraft, the performance of fuel cell propulsion systems has been shown to significantly exceed that of conventional turboprop engines [22]. Within the larger aircraft class domain, fuel cells were advantageous mostly for enhancing hydrogen-driven gas turbines in mild-hybrid architectures [7, 20, 21].

As illustrated in Figure 4, the lowest energy consumption was achieved by the Plug-In-Hybrid (PHEP) concepts. The 250-seater PHEP concept demonstrated approximately 30% improved energy efficiency in comparison to the corresponding turboprop-powered concept and 50% energy efficiency improvement in comparison to the 250-seater turbofan concept. Consequently, the energy costs for the operation of the PHEP aircraft are substantially reduced, even including the replacement of the batteries each time at the end of their life with 3000 cycles assumed for the EXACT assessment [36]. The energy cost reduction potential was even more significant than the increased costs of a heavier airframe. The net result showed lower overall operating cost compared to the 250-seater turboprop and turbofan concepts, especially for higher-energy-costs scenarios.

As outlined in sub-section 4.2, the PHEP concepts are operated fully electrically on routes up to 600 km, thereby eliminating any direct emissions for such flights. For longer missions, the kerosene-fueled range extender is employed sparingly, solely to supply the additional energy required to increase the range. Consequently, a significant part of the operation of the PHEP concepts is without direct emissions, which significantly decreases the environmental impact. Even considering the effects of battery replacement and recycling, the PHEP concepts demonstrated a significant potential for climate impact reduction compared to future turboprop and turbofan propulsion [36].

4.4. Results Validity

The project uniquely offers a common framework for directly and consistently comparing multiple types of propulsion systems and energy carriers across two different aircraft classes. However, it should be noted that the final concepts were selected and optimised for the technology assumptions and costs projections defined in the project. Thus, the EXACT results should be regarded primarily as a baseline for comparison between the different propulsion systems, valid under the boundary conditions set in the project. For instance, should fuel-cell propulsion technology advance more rapidly than projected in EXACT, the optimal aircraft configurations and overall results could shift significantly.

Basic sensitivity analyses of key projections were conducted during the course of the project. Multiple energy cost scenarios, complemented by varying airline operational profiles, were included in the operating cost and climate impact assessment [7, 18], providing insights into how results vary under some alternative key assumptions. With a focus on transparency, many of the numerous EXACT publications, summarised in [1], present the project boundary conditions and modelling approaches.

The concept exploration in EXACT has established a robust foundation that can be used for qualitative analyses of vary-

ing boundary conditions or for identifying directions for future studies.

It is important to note that EXACT focused on short-range applications, limited to intra-continental operations. The scope of the holistic assessment capabilities is enhanced in the follow-up project EXACT2, where the modelling framework is further expanded to encompass mid- and long-range aircraft [1].

5. CONCLUSIONS AND OUTLOOK

This paper provided an overview of the framework developed in the DLR-internal project EXACT, with a focus on aircraft concept modelling, methods, tools, and the main boundary conditions. It described the aircraft concepts explored in the project and offered a direct and consistent comparison of multiple propulsion systems and energy carriers across two distinct aircraft classes — 70-seater regional class and 250-seater short-range class.

The results from EXACT highlight that aircraft concepts with higher energy efficiency consistently performed better in both climate impact and operating cost assessments. Several major levers for improving energy efficiency were identified during the concept down-selection process:

- **Reducing the design cruise speed** of a baseline turbofan-driven airliner from transonic to subsonic speeds (by 10%-15%) was shown to lower fuel consumption by 20-30%. This is achieved through structural and aerodynamic improvements enabled by the lower speed, combined with a switch to turboprop propulsion. This efficiency improvement is also applicable for hydrogen-powered airliners.
- **Using fuel cells** for enhancing hydrogen-powered direct-burn propulsion in a mild-hybrid propulsion architecture (**MHEP**) was shown to improve the fuel consumption of 250-seater hydrogen-powered airliners by approximately 5%. These benefits were observed for both turboprop and turbofan engines.
- **Employing fuel-cell-powered propulsion** for a 70-seater regional aircraft resulted in 25% energy consumption reduction compared to a turboprop baseline aircraft of this class.
- **Using batteries** as a primary power provider in a plug-in-hybrid-electric propulsion architecture (**PHEP**) increases the average energy efficiency by allowing fully electric operation on routes up to 500-600 km, complemented by a kerosene-fueled range extender to enhance operational flexibility. This approach is particularly advantageous for fleets operating on shorter routes. However, the hybrid operation also proved to be highly efficient for distances up to 1500-2000 km, due to the significant portion of electric energy used. The project fleet-level analyses on different operational networks, confirmed the following energy efficiency improvement possible with the PHEP architecture concepts (primary result dependence is on the average flight network distance):
 - **30-45%** for regional aircraft (70-seater class) compared to a baseline turboprop aircraft.
 - **10-30%** for short-range aircraft (250-seater class) compared to a kerosene-driven turboprop.
 - **25-50%** compared to the 250-seater kerosene-driven baseline turbofan airliner.

The EXACT framework has established a solid foundation for the evaluation of sustainable aircraft concepts, offering valuable insights into the trade-offs, synergies, and perfor-

mance implications of various configurations and propulsion systems.

Building on the success of EXACT, the follow-up project, EXACT2, will extend the modelling framework to include mid- and long-range aircraft. This next phase will address additional challenges, such as increased technological and operational uncertainties and advancements in modelling tools to better capture fleet-level interactions and global market dynamics. With a broader scope that includes a wider range of aircraft classes and operational scenarios, EXACT2 aims to deliver deeper insights into the feasibility and impact of sustainable aviation solutions, thereby paving the way for effective decarbonisation strategies across the aviation sector.

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