

A MULTI-RANGE HYBRID-ELECTRIC OPEN-ROTOR AIRCRAFT CONCEPT FOR THE WIDE-BODY PASSENGER CLASS

Georgi Atanasov[1], Daniel Silberhorn[1] & Vincenzo Nugnes[1]

[1]German Aerospace Center (DLR), Institute of System Architectures in Aeronautics, Hamburg, Germany

Abstract

This paper presents the HMR (Hybrid Multi-Range) aircraft concept for the wide-body passenger class designed to achieve high efficiency across both long-range and people-mover operations. This capability is enabled by a configurable plug-in hybrid-electric propulsion system combined with an airframe and open-propeller propulsion architecture optimised for sub-sonic cruise speed of Mach 0.7. In its battery-hybrid-electric people-mover configuration, the aircraft enables fully electric operation below 400 NM and highly efficient hybrid-electric operation on longer distances, resulting in energy consumption reduction of 40-60% compared to conventional aircraft on ranges below 1,000 NM. By replacing the baseline battery system with additional fuel tanks, the same aircraft can be operated in a long-range configuration, where modelling results indicate fuel efficiency improvements of approximately 20% relative to turbofan-powered aircraft of comparable technology level. Thus, the study demonstrates the potential of configurable hybrid-electric propulsion systems to improve transport efficiency across a wide range of mission profiles while reducing dependence on future battery technology advances.

Keywords: Aircraft Design, Multi-Range Aircraft, Plug-In Hybrid-Electric Propulsion, Open-Rotor, Partially Turbo-Electric Powertrain

1. Introduction

The German Aerospace Center (German Aerospace Center, DLR) project EXACT 2 (Exploration of Electric Aircraft Concepts and Technologies [1]) investigates technological solutions capable of substantially reducing the energy consumption and emissions of air transport while preserving its economic and operational viability. To address the broad spectrum of future air transport demand, the project considers a wide range of aircraft classes, spanning from short- and medium-range applications to long-range airliners. In addition, people-mover aircraft featuring high-density wide-body cabin layouts are included in the scope, as future trend analyses performed within the project indicate that such aircraft could play a relevant role in future air transport systems.

Within this framework, a multi-range hybrid-electric aircraft concept was developed to investigate whether a single configurable aircraft platform could efficiently address both long-range and people-mover market segments. The central design approach consists of a configurable hybrid-electric propulsion system with a variable hybridisation ratio, enabling the aircraft to adapt its onboard energy storage between battery-dominated and fuel-dominated configurations depending on the targeted operational role. The primary focus of the initial concept exploration was the achievable reduction in energy consumption and associated climate impact. For this reason, the aircraft described in this paper was designed for a reduced cruise speed of Mach 0.7, enabling the combination of a highly efficient subsonic airframe featuring an unswept wing with open-rotor propulsion. Within EXACT, further studies will investigate whether the potentially substantial reduction in operating costs enabled by the resulting fuel-efficiency improvements can compensate for the speed-related cost increase associated with lower cruise speed in both target markets.

The resulting aircraft concept developed within EXACT 2 is designated HMR (Hybrid Multi-Range aircraft). In its battery-hybrid-electric people-mover configuration, its propulsion concept enables fully electric operation on very short routes below 400 NM and highly efficient hybrid-electric operation on mission ranges up to approximately 2,000 NM, covering the dominant share of typical people-mover operations. In this configuration, modelling results obtained within EXACT 2 indicate energy efficiency improvements of 40–60% relative to conventional long-range aircraft on mission ranges below 1,000 NM.

A key enabling characteristic of the HMR concept is the similarity between the battery-to-gross-aircraft mass ratio of plug-in hybrid-electric aircraft and the fuel mass fractions typical of long-range aircraft. This characteristic enables the heavy battery system of the people-mover configuration to be replaced by additional fuel tanks without requiring major changes to the airframe or propulsion system layout. In this long-range configuration, the same aircraft achieves fuel efficiency improvements of approximately 20% relative to turbofan-powered aircraft of comparable technology level on long-range missions.

Such a design philosophy represents a novel contribution to the research landscape. Previous studies on people-mover aircraft have predominantly focused on turbofan-powered configurations, largely due to their commonality with conventional long-range aircraft architectures. A similar multi-range hybrid-electric concept was previously explored in [2]; however, that study focused exclusively on the short- and medium-range market. In contrast, the present paper describes a concept specifically designed to compete in two distinct market segments and compares it against two dedicated reference aircraft: a long-range turbofan-powered configuration and a turbofan-powered people-mover aircraft optimised for short- and medium-range operations.

Overall, the HMR concept highlights the substantial potential of combining hybrid-electric propulsion with moderate flight speed reduction to significantly improve the fuel efficiency of wide-body aircraft across multiple operational markets. Such solutions are of particular interest given the high relevance of the long-range aircraft segment to the total climate impact of global aviation [3].

2. Aircraft Concept Description

The HMR aircraft employs a hybrid-electric propulsion architecture with a modular energy-storage system, allowing the physical volume allocated to fuel tanks and batteries to be reconfigured based on mission requirements. The propulsion system combines the capability to safely operate exclusively on gas turbines without battery support with the capability for fully electric and hybrid-electric flight. This enables a configurable aircraft concept in which the onboard battery mass can be adapted to the requirements of a given mission, allowing the same aircraft platform to address different market segments.

In the present study, this flexibility is exploited to define two configurations of the same aircraft that can efficiently serve two fundamentally different markets, as shown in Figure 1:

- The long-range configuration HMR-LR carries no batteries, thereby avoiding the associated mass penalty during long-range operations. Instead, the propulsion system is equipped with additional fuel tanks, increasing its payload-range flexibility and enabling efficient long-range transport missions.
- The people-mover configuration HMR-PM is equipped with large battery packs that enable fully electric operation on short routes and highly efficient hybrid-electric operation on missions up to 2,000 NM. The high battery mass is traded against payload-range capability, making this configuration particularly suitable for short-range operations, where the efficiency benefits of electric propulsion can be applied most effectively.

2.1 Propulsion Architecture and Integration

The propulsion architecture of the HMR concept is shown in Figure 2. The powertrain comprises four electrically driven propellers and two gas turbines integrated into the outer nacelles. Each gas turbine is mechanically connected to the corresponding outer propeller shaft in parallel to the electric

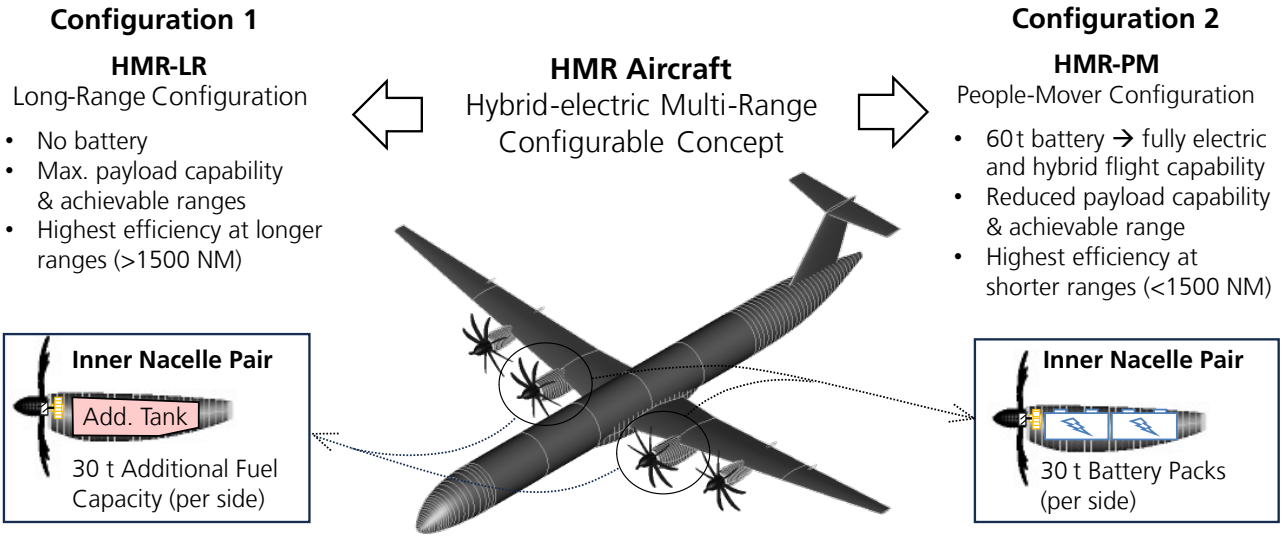


Figure 1 – Overview of the propulsion system configurability of the HMR concept.

motor through a one-way bearing. This arrangement allows mechanical power to be transferred from the gas turbine to the propeller while preventing torque transfer from the electric motor to the gas turbine. Consequently, the propulsion system can operate in a fully electric mode without rotating or otherwise affecting the inactive gas turbines.

The inner nacelles contain dedicated compartments that can be equipped either with battery systems or with additional fuel tanks, depending on the selected aircraft configuration. As illustrated in Figure 1, these compartments are occupied by batteries in the people-mover configuration HMR-PM and by additional fuel tanks in the long-range configuration HMR-LR. The compartments are positioned close to the aircraft centre of gravity, mitigating excessive centre-of-gravity travel when configuring the large battery masses and fuel volumes required by the different operating concepts. The four electric motors are interconnected through a power management and distribution system integrated into the wing structure, enabling electrical power transfer between all propulsion units and onboard energy sources.

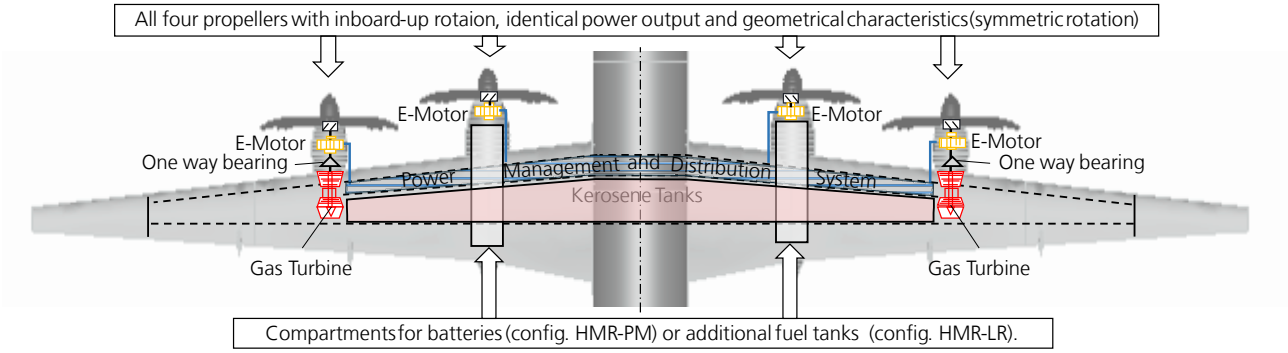


Figure 2 – Overview of the HMR propulsion system architecture and its integration into the airframe.

The selected four-propeller arrangement provides several advantages compared with a conventional twin-propeller configuration. The increased number of propulsion units improves overall system redundancy and provides additional integration volume within the nacelles for propulsion-system components and energy storage. Furthermore, distributing the required thrust over four propellers significantly increases the total propeller disc area. As a consequence, propeller thrust loading is reduced, enabling higher propulsive efficiency and improving the overall energy efficiency of the aircraft, which is detailed in Section 4..

The principal operating modes of the propulsion system are illustrated in Figure 3. In the HMR-PM configuration, the battery systems located in the inner nacelles can supply electrical power to all four propellers through the power management and distribution system, enabling fully electric flight.

During this operating mode, the gas turbines remain inactive and mechanically decoupled from the rotating propeller shafts by the one-way bearings.

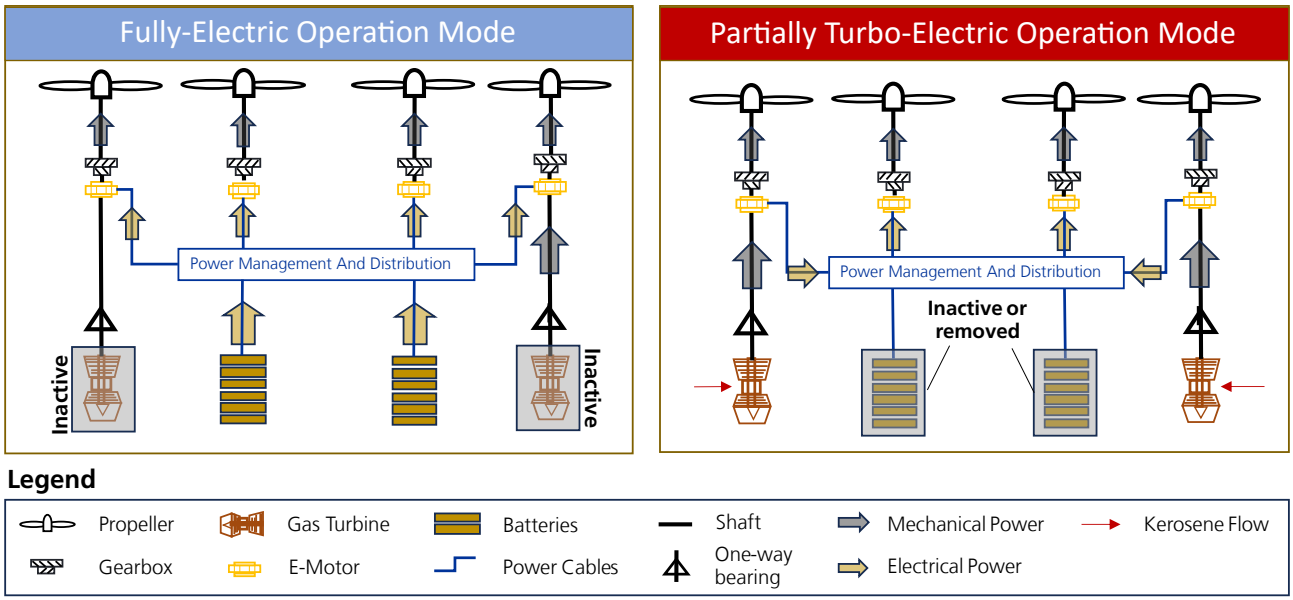


Figure 3 – Fully-electric operation mode (left) and partially turbo-electric operation model (right) of the HMR-PM configuration.

When the batteries are inactive or omitted entirely, as in the HMR-LR configuration, the propulsion system operates in a partially turbo-electric mode. In this case, the two gas turbines directly drive the outer propeller pair through the mechanical shafts while the electric motors connected to the same shafts operate as generators and transfer half of the turbine power through the power management and distribution system to the inner propeller pair. This arrangement allows all four propellers to remain active while requiring only two gas turbines, thereby combining the efficiency benefits of distributed propulsive power with a relatively simple and lightweight propulsion architecture.

2.2 Safety Aspects

The propulsion architecture of the HMR concept incorporates redundancy across all power providers and operational modes. In the HMR-PM configuration, all four propellers can be powered by multiple battery systems through the power management and distribution system. In the HMR-LR configuration, propulsion power is provided by two independent gas turbines, each capable of supplying power to both the corresponding outer propeller and one inner propeller through the partially turbo-electric architecture. However, in case of failure of a gas turbine, the remaining gas turbine can still power all four propellers. For the purpose of the present study, the power management and distribution system is assumed to be designed without common failure modes that could affect multiple propulsion units simultaneously. A detailed investigation of system redundancy, failure propagation, and certification aspects is planned as part of the continuation of the EXACT studies in 2027.

The aircraft sizing and performance assessment explicitly account for propulsion system failures during take-off. For the HMR-PM configuration, balanced field length calculations include the loss of half of the battery system (one side). The remaining batteries are assumed to be able to provide 10% higher power than their maximum power rated for take-off to power all four propellers. For the HMR-LR configuration, a gearbox failure of an outer propulsion unit is considered as the critical take-off failure case. As the gearbox connects the gas turbine with the corresponding outer propeller, such a failure effectively renders an entire outer nacelle inoperative. The balanced field length calculations therefore account for the resulting asymmetric thrust condition and reduced total power output capability. These aspects are also included in the propulsion system performance overview shown in Table 1.

2.3 Operation Strategy

The HMR concept is designed to enable operation in both the long-range (LR) and people-mover (PM) configurations throughout its service life. Reconfiguration between the two variants is assumed to be performed during extended ground periods, for example overnight, by replacing the battery modules of the HMR-PM configuration with additional fuel tanks or vice versa.

The HMR-LR configuration represents the baseline configuration of the aircraft. Owing to the absence of batteries, it provides the highest payload-range flexibility and can efficiently serve a broad range of long-range transport missions. In this configuration, the aircraft is operated exclusively on kerosene and behaves similarly to a conventional transport aircraft. As described in Subsection 2.1, the two gas turbines drive all four propellers through the partially turbo-electric propulsion architecture.

For missions below 2,000 NM, the aircraft can be operated in the HMR-PM configuration by replacing part of the fuel storage with battery energy storage. In this configuration, the aircraft operates as a plug-in hybrid-electric vehicle, enabling substantially higher energy efficiency on short- and medium-range missions. The battery system and onboard systems are designed to support fully electric operation on very short routes of up to approximately 400 NM. The gas turbines are utilised as range extenders on longer missions. They are also used to perform the reserve mission, as kerosene is more weight-efficient than batteries, allowing the batteries to be reserved fully for the main mission.

The power management strategy for fully electric and range-extender operation of the HMR-PM configuration is summarised in Figure 4.

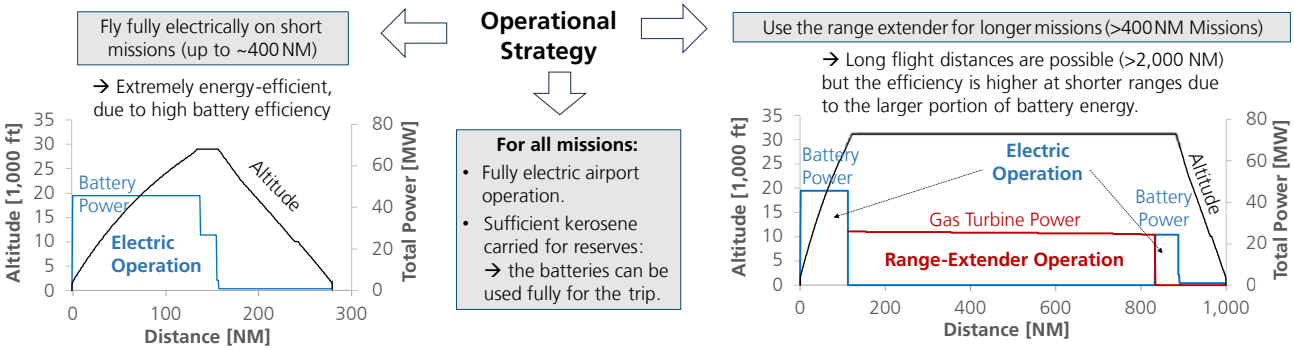


Figure 4 – The plug-in-hybrid-electric propulsion system power management strategy for fully electric and range-extender operation of the HMR-PM configuration.

3. Framework

The overall aircraft design and assessment framework developed within EXACT provides a consistent methodology for modelling aircraft concepts across multiple aircraft classes and conducting trade-off and optimisation studies [4]. In the present study, this capability is utilised to consistently compare the novel multi-range concept described in Section 2. with conventional aircraft of the same passenger class and technology level, as outlined in the following subsections.

3.1 Methodology

The aircraft concepts described in this paper were generated using the multi-disciplinary and multi-fidelity workflow, shown in Figure 5. RCE (Remote Component Environment) [5] was used as the workflow platform, where each tool communicates via the Common Parametric Aircraft Configuration Schema (CPACS) [6].

The workflow can be separated in three sections, the pre-processing, the main aircraft convergence loop, and the post-processing. The pre-processing part consists of a Design Of Experiments (DOE) component providing the chosen additional input to the main CPACS input file in case a DOE is conducted. The main part of the workflow is responsible for the overall aircraft sizing and is able to handle different propulsion system types, including turbofans and turboprops, powered by kerosene, or hydrogen, as well as hybrid-electric and fuel-cell based propulsion systems. The utilised tool chain includes capabilities for aircraft geometry generation, airframe structural sizing (supported by aircraft loads definition methodologies), low- and high-speed aerodynamic performance calculation,

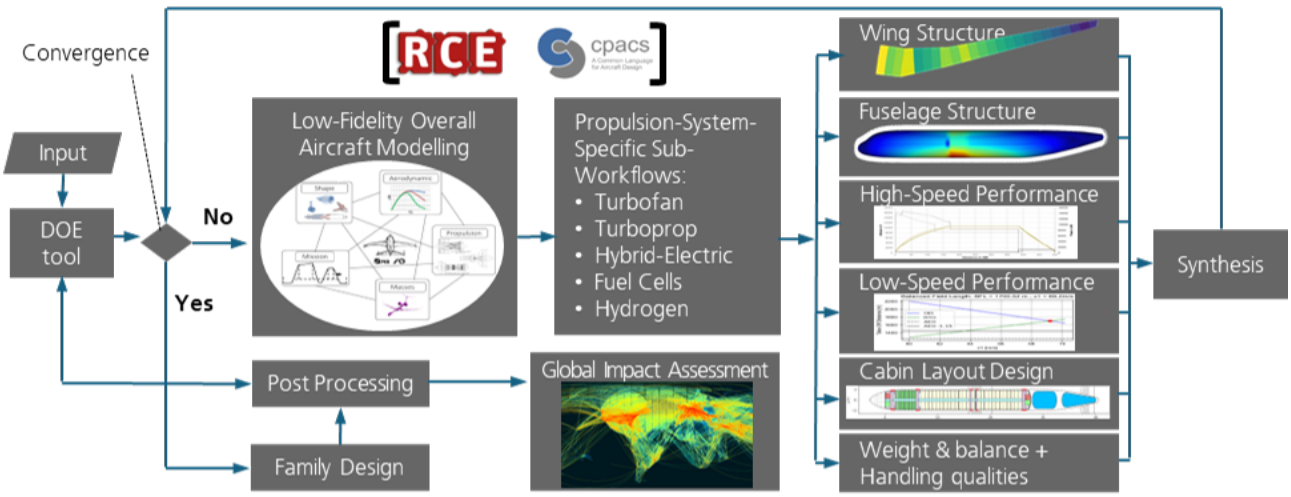


Figure 5 – Visualization of the applied workflow with main tools and sub-workflows.

propulsion system performance modelling, weight and balance assessment, low-speed and mission trajectory generation, and cabin sizing and layout generation. These capabilities are described in detail in [7].

Cabin layout generation is performed using the DLR Cabin Layout Generator [8], which automatically derives overall cabin geometries based on aircraft TLARs and the specified cabin-class distribution. As a preliminary design tool, it provides an estimate of the general cabin dimensions and a graphical representation of the seating arrangement. Consequently, the layouts presented in this paper are to be regarded as conceptual rather than fully optimized geometries. Nonetheless, the tool remains highly valuable for conducting trade-off studies across various interior configurations, as it validates the consistency between the class distribution and the available cabin volume while accounting for regulatory conformity. Given that the cabin configuration is central to the definition of the investigated aircraft concepts, additional details on the design strategy are provided in Section 3.3.

3.2 Boundary Conditions

The reference aircraft selected for this study (REF) is a DLR interpretation of the Airbus A350-1000. The geometry, mass properties, and performance characteristics of the REF model, generated using the above-mentioned workflow, closely match publicly available reference data for the A350-1000 [9]. Based on this reference aircraft, a baseline turbofan-powered aircraft denoted BAS and fuelled with synthetic kerosene was designed for an entry into service (EIS) of 2050. The concept incorporates technological advancements relative to the REF aircraft summarised in Figure 6, which are applied consistently across the design methods. BAS retains the same top-level aircraft requirements (TLARs) as the reference aircraft, with the exception of an increased design passenger capacity of 449 seats and a corresponding increase in maximum payload capability. The aircraft features an extended wing with foldable wingtips, enabling a larger wingspan while remaining within the same airport gate category as the REF aircraft. In addition, the design incorporates an advanced high-bypass-ratio bleedless turbofan engine. Several key airframe components are furthermore assumed to benefit from improved materials and manufacturing techniques, resulting in moderate reductions in structural mass and aerodynamic drag.

Starting from the BAS model, a short- to medium-range people-mover configuration denoted PMT (People-Mover Turbofan aircraft) was derived by reducing the design range and adapting the TLARs to typical short- and medium-range operational requirements. This concept serves as a benchmark for the efficiency achievable within the wide-body people-mover aircraft class using conventional turbofan propulsion.

As depicted in Figure 6, the configurable hybrid-electric multi-range concept HMR was developed for the same overall technology level and designed to comply, in its respective configurations, with both the long-range-class TLARs of the BAS model and the people-mover TLARs of the PMT aircraft. The only major exception is the cruise speed, which was reduced to Mach 0.70 in order to enable efficient

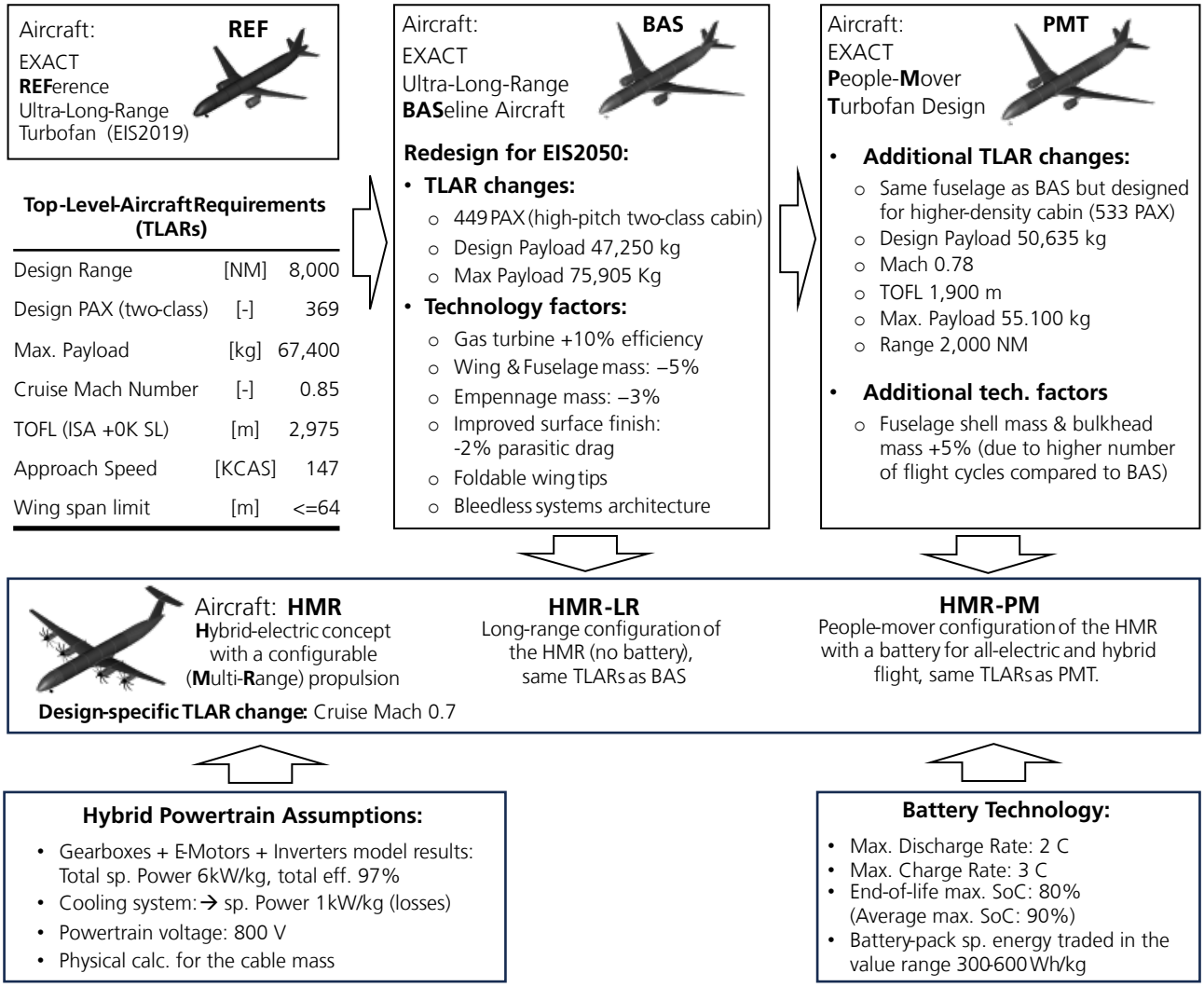


Figure 6 – TLARs and technology assumptions of the aircraft models designed for the study.

integration of open-rotor propulsion and explore the possible energy savings from reducing the aircraft speed. The partially turbo-electric propulsion architecture of the HMR furthermore assumes gas turbines and propellers of comparable technology level to the turbofan engines of the reference configurations. The key top-level powertrain components characteristics that resulted from the modelling within the EXACT framework are also summarized in Figure 6.

The BAS and the PMT model share the same fuselage geometry. This fuselage geometry is mostly applied on the HMR model as well but with slight deviation at the tail-cone section because of the different empennage arrangement. However, all three models feature the same overall cabin dimensions. Thus all of them can use the same cabin configurations.

3.3 Cabin Layout Options and Aircraft Model Designations

The BAS and PMT aircraft models share the same fuselage geometry, as described in Subsection 3.2. The same fuselage concept is also applied to the HMR aircraft, with only minor deviations in the tail-cone region resulting from the different empennage arrangement. Consequently, all three aircraft concepts feature identical cabin dimensions and can accommodate the same cabin configurations. However, the cabin layout that maximises the economic performance of a given aircraft depends on the market segment it is intended to serve.

The cabin geometry was initially derived for the long-range baseline aircraft BAS. The design objective was to maintain an overall aircraft length comparable to that of the REF aircraft while preserving a similar level of passenger comfort. To this end, the exit configuration of the Airbus A350-1000 was adopted, constraining the maximum cabin length through regulatory exit-spacing requirements. In

order to accommodate the increased passenger capacity within these constraints, the fuselage diameter was enlarged, allowing the addition of one seat per row. The resulting low-density long-range cabin layout is shown in Figure 7a).

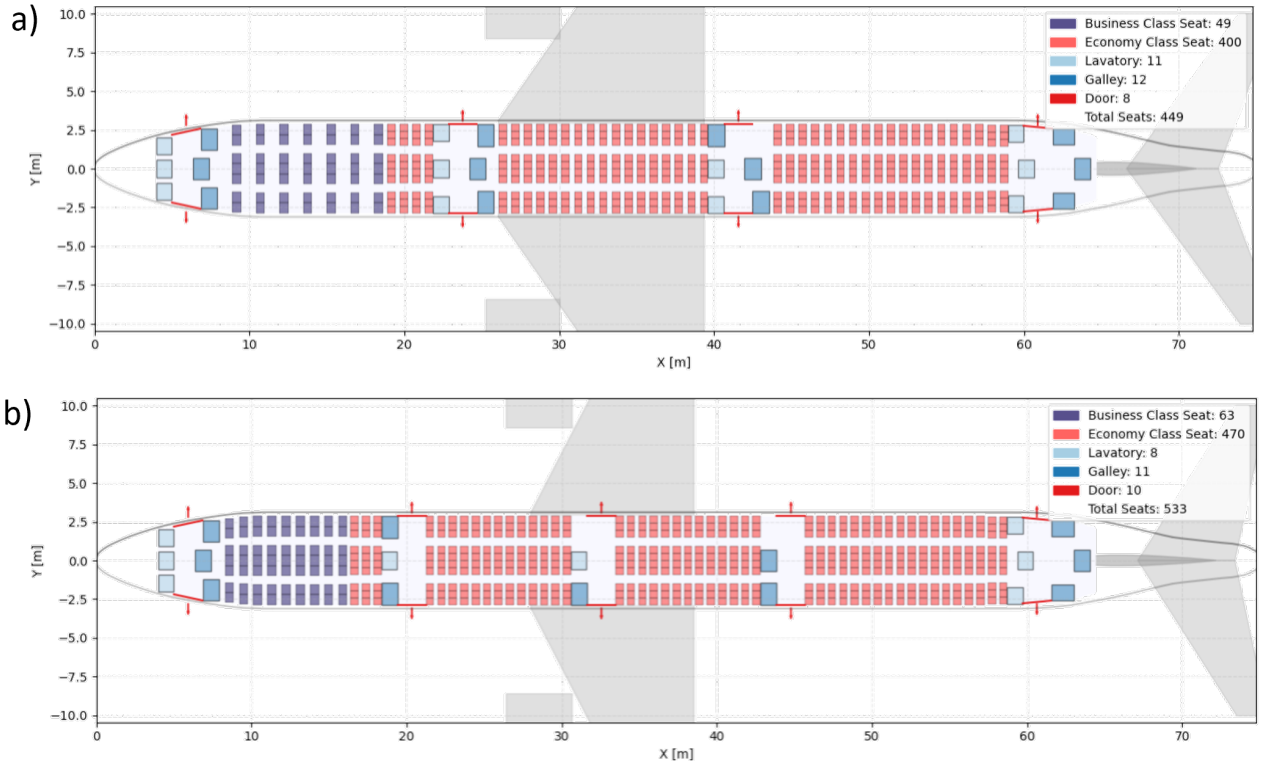


Figure 7 – Two cabin layouts for the aircraft models in the study, which feature the same overall cabin geometry. Layout a) features a low-density seat arrangement suitable for long-range operation. Layout b) features a high-density seat arrangement suitable for short-range operation.

The PMT aircraft was subsequently developed using the same fuselage geometry and cabin length as the BAS. However, the cabin arrangement was adapted to reflect the operational requirements of short-range people-mover service. The layout follows typical market practice, comprising a moderate business-class section corresponding to approximately 12% of total seats and a higher-density economy-class arrangement. This results in a design capacity of 533 passengers. To support the increased passenger count, an additional overwing exit was introduced. Similar to the main-deck arrangement of the Airbus A380, this consists of a dual-lane overwing exit, enabling high-density configurations of up to approximately 580 passengers, ultimately limited by the available cabin length. The resulting layout is shown in Figure 7b). Despite the increased seating capacity, the number of floor elements is reduced compared to the long-range baseline, reflecting the less demanding comfort and service requirements of short-range operation. Consequently, this layout is not considered suitable for long-range missions.

Since the HMR concept is intended to address both the long-range and people-mover markets, both cabin layouts represent viable configuration options. The low-density layout provides a natural match for long-range operation, whereas the high-density layout may be attractive for operators primarily targeting short-range people-mover missions. The selection of cabin layout and propulsion-system configuration can therefore be adapted to the intended utilisation strategy of the aircraft.

This configurability introduces the need for a designation system capable of distinguishing between the various cabin and propulsion-system configurations considered in the present study. The nomenclature adopted for this purpose is introduced in Subsection 3.4.

3.4 Aircraft Configuration Options

As described in the previous subsection, two cabin layouts are applicable to the BAS, PMT, and HMR aircraft concepts. While the selected cabin layout does alter the aircraft geometry or its primary top-

level characteristics, it directly affects the maximum passenger capacity, the mass of operator items, and the achievable passenger comfort level. These factors are particularly relevant for the intended operating range of the aircraft. The low-density 449-seat layout is suitable for long-range operation, whereas the higher-density 533-seat layout provides improved fuel efficiency per passenger but is only considered suitable for short-range missions due to its reduced comfort level. Consequently, it is important to distinguish between the cabin configuration options of the different aircraft concepts when analysing the results. The aircraft designation system adopted in this paper therefore incorporates both the cabin-layout identifier and, in the case of the HMR concept, the propulsion-configuration identifier, as summarised in Figure 8.

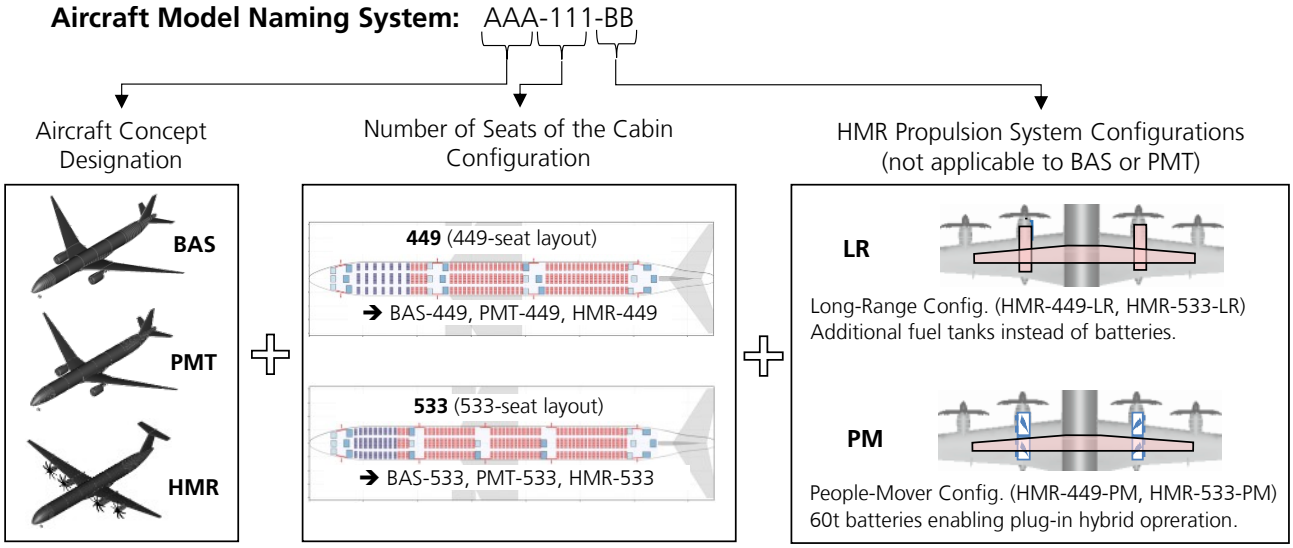


Figure 8 – Aircraft designation logic of the different cabin and propulsion-system configurations considered in the study. All aircraft concepts share the same cabin geometry and can optionally be configured to either cabin layout. The HMR concept additionally supports both long-range (LR) and people-mover (PM) propulsion configurations.

Although cabin layouts can generally be modified throughout an aircraft's service life, the available configuration options are constrained by the number and placement of emergency exits. The layout shown in Figure 7b) is designed for a two-class 533-passenger arrangement but may also be configured as a single-class layout accommodating up to approximately 580 passengers. However, once the aircraft is built with the corresponding ten-exit arrangement, it cannot be converted into the eight-exit layout shown in Figure 7a). Likewise, the 449-seat configuration can be adapted to different seating-class distributions but cannot accommodate 580 passengers because of its lower emergency-exit capacity. For the purposes of this study, the two layouts shown in Figure 7 are therefore treated as distinct aircraft configurations that remain fixed throughout the aircraft's service life. Nevertheless, an airline could theoretically operate a mixed fleet of aircraft equipped with different cabin layouts, thereby addressing a broader range of market requirements.
The configurability of the HMR concept is independent of the cabin-layout selection. Each cabin-layout option can be combined with both the long-range (LR) and people-mover (PM) propulsion configurations described in Section 2.. Consequently, an aircraft configured with either the 449-seat or the 533-seat cabin can alternate between LR and PM operation throughout its service life, for example during extended ground periods.
Based on these considerations, the following concept variants are analysed in the present study:

- **BAS-449** – Reference cabin configuration of the long-range baseline aircraft. The layout is optimised for long-range operation and provides a passenger comfort level comparable to that of the REF aircraft.
- **BAS-533** – High-density cabin option of the baseline aircraft. This configuration improves fuel efficiency per passenger but it is primarily suitable for short-range operation because of the

reduced passenger comfort level.

- **PMT-533** – Reference cabin configuration of the people-mover turbofan aircraft. The layout is specifically designed for high-capacity short-range operation.
- **PMT-449** – Reduced-density (higher comfort) cabin option of the people-mover aircraft. This configuration is of limited relevance to the present study because the resulting reduction in passenger capacity decreases fuel efficiency on a per-passenger basis.
- **HMR-449** – HMR configuration equipped with the long-range cabin layout. This option is most naturally combined with the HMR-449-LR propulsion configuration (see Figure 1; however, it can also be operated in the HMR-449-PM configuration to improve efficiency on shorter routes.
- **HMR-533** – HMR configuration equipped with the high-density cabin layout tailored for short-range operation. This option is primarily intended for operation in the HMR-533-PM configuration, while the HMR-533-LR configuration plays a secondary role because the cabin layout is not considered suitable for long-range missions.

4. Results

Figure 9 compares the payload-range capabilities of the investigated aircraft concepts and illustrates the different operational markets they are intended to address. The BAS and PMT aircraft were designed and optimised for dedicated mission requirements, resulting in two separate aircraft concepts that share a common fuselage geometry but target fundamentally different operational ranges. The BAS concept is optimised for long-range operation, whereas the PMT concept is tailored to the short-range people-mover market.

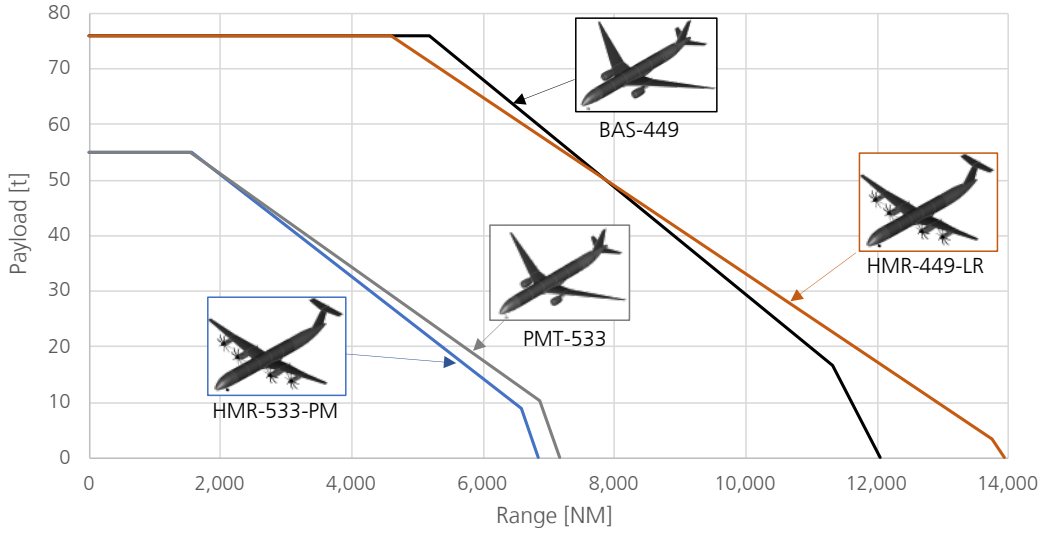


Figure 9 – Payload-range diagram comparison between the BAS-449, PMT-533, and two representative configurations of the HMR aircraft - HMR-449-LR and HMR-533-PM.

In contrast, the HMR concept was specifically developed to efficiently address both market segments. In its HMR-533-PM configuration, the aircraft operates as a highly efficient plug-in hybrid-electric people mover, whereas the HMR-449-LR configuration enables competitive long-range operation through the replacement of battery storage with additional fuel tanks.
The implications of these design objectives on the resulting aircraft characteristics are discussed in Subsection 4.1. Subsequently, Subsection 4.2 evaluates the resulting energy-efficiency benefits and highlights the advantages of the configurable multi-range design approach.

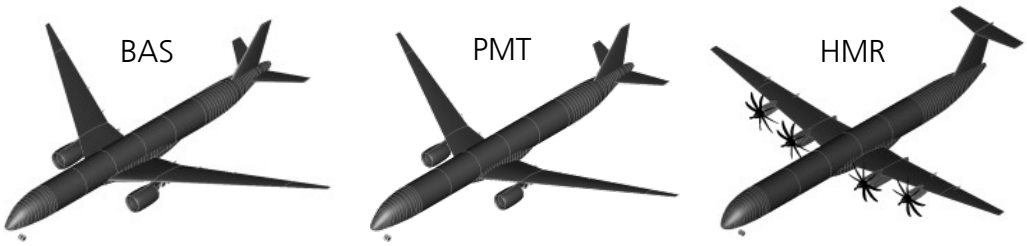
4.1 Comparison of Key Aircraft Characteristics

The overall characteristics of the investigated aircraft concepts are compared in Figure 10, Figure 11, Figure 12, and Table 1. Together, these figures provide insight into the geometric differences between

the aircraft, their resulting aerodynamic and propulsion performance, and the implications for aircraft mass.

4.1.1 Geometry

The geometry comparison shown in Figure 10 highlights the common design philosophy shared by the three aircraft concepts as well as the key differences resulting from their intended missions. All aircraft feature a wingspan of 80 m, which can be reduced to 65 m through foldable wing tips in order to remain compatible with the same airport gate category as the reference aircraft (see Figure 6). Likewise, the fuselage cross-section is identical for all concepts, enabling the use of the common cabin layouts described in Section 3.4. The HMR fuselage is slightly shorter than those of the BAS and PMT concepts due to a more aggressive tail-cone tapering. This is enabled both by the significantly lower design cruise speed of Mach 0.7 and by the T-tail arrangement, which reduces empennage-related constraints on the rear-fuselage shaping.



Wing span	80 m (foldable to 65m)		
Fuselage Crossection	6.23m x 6.39 m (width x height)		
Fuselage length	74.8 m		73m
Wing ¼-chord sweep	31.6°	25.1°	4.1°
Propulsor Diameter	4.1 m (Nacelle)	3.7 m (Nacelle)	9 m (Propeller)
Wing Ref. Area	515 m^2	420 m^2	430 m^2
Tot. Wetted Area	2690 m^2	2490 m^2	2540 m^2

Figure 10 – Geometry overview and comparison between the study aircraft BAS, PMT, and HMR.

More pronounced differences can be observed in the wing design. The large variation in wing sweep between the concepts directly reflects their significantly different design cruise speeds. The BAS aircraft features the largest wing area because its design is constrained by the large fuel volume required for long-range operation. In contrast, the PMT aircraft benefits from a significantly lower design range, while the HMR-LR concept stores a substantial fraction of its fuel within nacelle-integrated tanks. Consequently, neither the PMT nor the HMR concepts are constrained by wing fuel volume, allowing their wing designs to be optimised for aerodynamic performance resulting in smaller wing planforms, as will be detailed in the next subsections.

4.1.2 Aerodynamics

Figure 11 provides an overview of the aerodynamic performance of the reference, baseline, and study aircraft. The reference aircraft REF has a substantially lower span of 65 m compared to the 80 m span of the future aircraft models, which is the main driver for the substantial shift in aerodynamic efficiency. The comparison further highlights the aerodynamic benefits of reduced cruise speed, as the PMT and HMR achieve progressively higher lift-over-drag ratios compared to the BAS model. Particularly noteworthy is the comparison between the PMT and HMR concepts, which feature similar wing reference areas, total wetted areas, and aspect ratios (see also Figure 10) and therefore comparable parasitic drag and induced drag characteristics.
Indeed, as can be seen in Figure 11, the aerodynamic polars of the PMT and HMR concepts are closely matched up to a lift coefficient of approximately 0.55, corresponding to the design cruise lift coefficient of the PMT. Beyond this point, however, the aerodynamic performance of the PMT deteriorates rapidly as transonic wave-drag penalties become increasingly significant. Since both aircraft employ wings with similarly high aspect ratios, the theoretical aerodynamic optimum of such wings

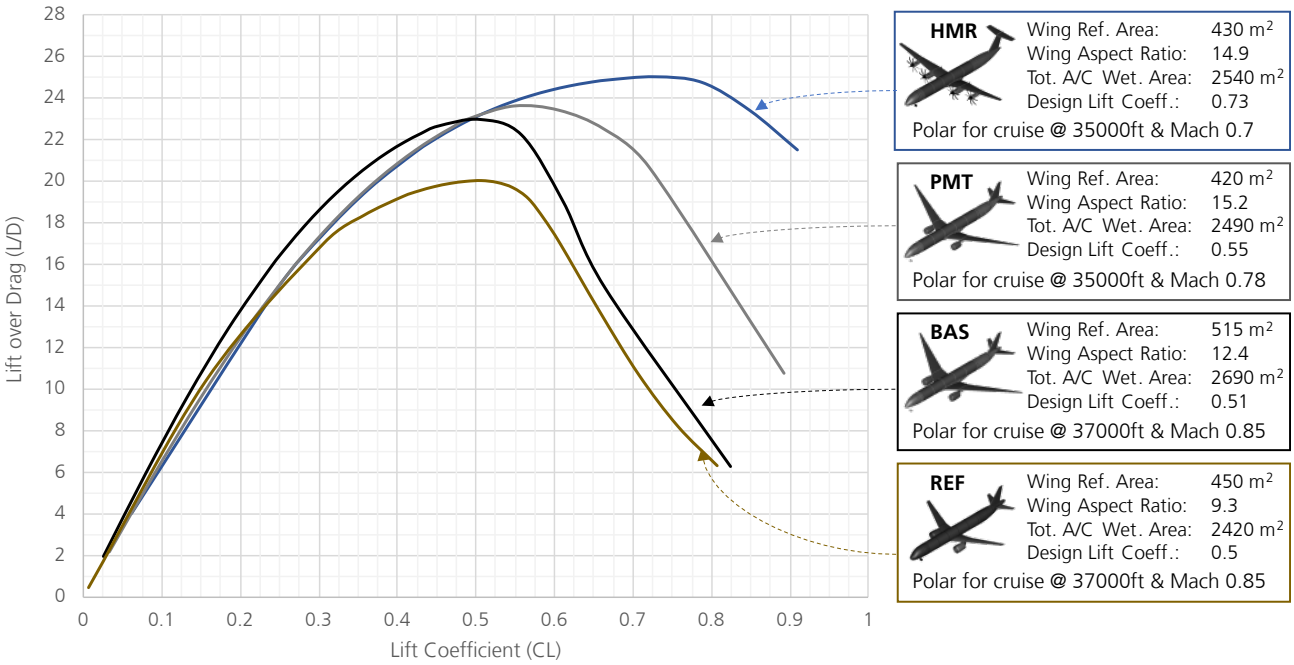


Figure 11 – Cruise aerodynamic polar comparison of the study aircraft.

occurs at considerably higher lift coefficients. This characteristic is exploited much more effectively by the HMR concept, which was designed for a cruise lift coefficient of approximately 0.73. As a result, the aircraft operates much closer to the optimum of its aerodynamic polar and achieves substantially higher lift-to-drag ratios during cruise.

The PMT could theoretically be redesigned for higher cruise lift coefficients by modifying the airfoil characteristics to delay the onset of transonic drag rise. However, the current PMT represents the overall aircraft design optimum resulting from a compromise between cruise efficiency, take-off performance, and propulsion-system sizing. For example, increasing the cruise altitude would reduce the dynamic pressure and thereby increase the required cruise lift coefficient. However, the lower ambient air density would simultaneously require larger engines to provide the necessary thrust, offsetting the aerodynamic benefit through increased engine mass and drag. Alternatively, the wing reference area could be reduced to increase the cruise lift coefficient. This approach, however, would increase the required take-off lift coefficient and consequently the take-off thrust requirement, again leading to larger and heavier propulsion systems.

The HMR concept largely avoids these compromises owing to its fundamentally different propulsion architecture. As discussed in Subsection 4.1.3, the large open-rotor propulsion system requires considerably less shaft power during take-off than an equivalent turbofan-powered aircraft. Consequently, the gas turbines are sized primarily by the top-of-climb and cruise power requirements rather than by take-off thrust. This provides substantially greater freedom to increase the cruise lift coefficient without incurring the penalty of oversized engines.

Furthermore, the lower design cruise speed of Mach 0.7 enables the HMR to combine high cruise lift coefficients with comparatively low cruise altitudes. This further reduces the required gas turbine size while also offering potential benefits with respect to non-CO_2 climate impact, although these aspects are outside the scope of the present study. To maximise the cruise lift coefficient, the wing reference area was minimised by including an aggressive high-lift-system design into the wing modelling employing double-slotted Fowler flaps together with slotted trailing-edge flaps. In combination with the unswept wing planform, this configuration was estimated to yield a maximum lift coefficient of approximately 3.25. Although this value has not yet been validated by CFD analysis, it has been reviewed within the EXACT consortium and is considered a realistic preliminary-design assumption. Further enhancement of the high-lift system may enable even smaller wing areas and consequently additional improvements in cruise aerodynamic efficiency in future iterations of the HMR concept.

One of the remaining uncertainties in the aerodynamic assessment of the HMR concept is the aero-

propulsive interaction between the propellers and the wing. Several research projects have investigated such effects in detail, including the LuFo project SynergIE [10] and the Horizon 2020 project IMOTHEP [11]. Although both studies considered considerably smaller and slower aircraft configurations, they consistently demonstrated that wing-mounted propellers can provide a net positive aero-propulsive benefit when appropriately integrated into the airframe. In particular, nacelle integration under the wing, positioning the propeller rotation axis below the wing leading edge, and maintaining sufficient spacing between the propeller disc and the wing were identified as key integration features for achieving favourable aero-propulsive characteristics [12, 13, 14]. In addition, the aerodynamic shaping of the nacelles, together with an appropriate aerofoil selection and wing twist distribution, was shown to have a significant influence on the overall outcome.
The transonic turbofan design study in [15] further demonstrated negligible transonic drag impact of the propeller-wing interaction of an aircraft with a similar design speed (Mach 0.7) and with even higher propeller loading compared to the HMR aircraft. The principal integration guidelines identified in these studies were therefore adopted for the HMR configuration. Based on the currently available evidence, the present study conservatively assumes an overall neutral aero-propulsive impact of the propeller-wing integration.

4.1.3 Propulsion

The propulsion-system characteristics of the investigated aircraft concepts are compared in Table 1. A particularly relevant performance indicator is the *total propulsion efficiency*, which quantifies the overall efficiency with which the energy stored in the onboard energy source is converted into useful propulsive power. In other words, it represents the fraction of the fuel lower-heating-value energy (or stored battery energy) that is ultimately transformed into the useful work required to propel the aircraft (thrust integrated over the flown distance). Together with the aerodynamic efficiency and the aircraft mass, the total engine efficiency therefore constitutes one of the three principal parameters governing the overall mission fuel efficiency of the aircraft.
During cruise, the HMR concept achieves a considerably higher total propulsion efficiency than the turbofan-powered aircraft models. This improvement is primarily a consequence of the substantially higher propulsor efficiency of the large open propellers. Despite the additional transmission losses introduced by the partially turbo-electric powertrain and the somewhat lower thermodynamic efficiency of the smaller gas turbines, the HMR-449-LR configuration achieves the highest overall propulsion efficiency of all kerosene-powered models. When operated in its people-mover configuration, the efficiency is shifted to an even higher level owing to the high efficiency of the battery-electric powertrain. As shown in Table 1, the total engine efficiency of the HMR-533-PM configuration during fully electric cruise is almost twice that of the turbofan-powered aircraft.
The advantages of the HMR propulsion architecture are even more apparent during low-speed operation. The large total propeller area leads to substantially reduced power requirements. For comparable static and end-of-field thrust levels, the HMR propulsion system requires approximately one third of the power demand relative to the turbofan-powered concepts. Furthermore, the aircraft retains considerably higher available thrust levels during a component failure event due to the improved redundancy of the hybrid propulsion architecture. Thus, the reduced take-off power requirements allow employing significantly smaller gas turbines, optimally sized for the cruise and top-of-climb operational requirements.
The combination of high propulsive efficiency under both cruise and take-off conditions is a key enabler of the HMR concept. It allows the propulsion system to satisfy the demanding performance requirements resulting from both the long-range and people-mover TLARs (see Figure 6) without incurring significant penalties from propulsion-system oversizing.

4.1.4 Mass Breakdown

The mass breakdown comparison is provided in Figure 12. A large fraction of the take-off mass of the long-range REF and BAS aircraft is fuel. Thus, fuel efficiency improvements also significantly impact the total aircraft mass. Consequently, the more efficient BAS aircraft has a similar maximum take-off mass (MTOM) level to the REF aircraft despite being designed for a significantly larger fuselage and payload capacity. Similarly, the aerodynamic and propulsive efficiency advantages of the HMR-LR

Table 1 – Propulsion system performance comparison between the study aircraft.

		REF-369	BAS-449	PMT-533	HMR-449-LR	HMR-533-PM[1]
Engine Type		Turbofan	Turbofan	Turbofan	Hybrid	Hybrid
Bypass Ratio		10	14	14	(propellers)	(propellers)
Operation Mode		-	-	-	PTE[2]	Electric[1]
Mid-Cruise at a Representative Mission [3]						
Altitude	[ft]	37000	37000	35000	35000	33000
Mach	[-]	0.85	0.85	0.78	0.7	0.7
Thrust (All Engines)	[kN]	125	122	98	107	116
Propulsor Efficiency[4]	[-]	0.75	0.76	0.76	0.89	0.89
Equiv. Power Output (All Engines)[5]	[MW]	46	41	30	25	27
Eqiv. Tot. Systems Offtakes[6]	[MW]	0.6	0.5	0.5	0.5	0.5
Power Provider Eff.[7]	[-]	0.55	0.6	0.59	0.55[9]	0.94[10]
Total Propulsion Efficiency[8]	[-]	0.41	0.45	0.44	0.48	0.82
Top-of-Climb (ISA+10K)						
Flight Level & Mach	[ft]	33000	35000	33000	33000	31000
Mach	[-]	0.83	0.83	0.76	0.68	0.68
Thrust (All Engines)	[kN]	180	154	139	134	205
Propulsor Efficiency[4]	[-]	0.73	0.75	0.73	0.88	0.87
Equiv. Power Output (All Engines)[5]	[MW]	64	52	44	31	48
Eqiv. Tot. Systems Offtakes[6]	[MW]	0.6	0.5	0.5	0.5	0.5
Power Provider Eff.[7]	[-]	0.54	0.59	0.59	0.55[9]	0.94[10]
Total Propulsion Efficiency[8]	[-]	0.38	0.44	0.43	0.48	0.81
Sea-Level Static (ISA)						
Thrust (All Engines)	[kN]	870	900	700	940	900
Equiv. Power Output (All Engines)[5]	[MW]	160	155	117	50	48
End-of-Field @ Sea-level, ISA, Mach 0.25						
Thrust (All Engines)	[kN]	683	680	530	461	451
Propulsor Efficiency[4]	[-]	0.37	0.38	0.4	0.8	0.8
Equiv. Power Output (All Engines)[5]	[MW]	159	152	114	49	48
Eqiv. Tot. Systems Offtakes[6]	[MW]	0.4	0.4	0.4	0.4	0.4
Power Provider Eff.[7]	[-]	0.49	0.55	0.55	0.52[9]	0.94[10]
Total Propulsion Efficiency[8]	[-]	0.18	0.21	0.22	0.41	0.75
Most Critical Engine Component Failure @ 400ft, ISA+25K						
Failed Components		1 Turbofan	1 Turbofan	1 Turbofan	1 Gearbox [11]	1 Battery [12]
Mach	[-]	0.24	0.26	0.22	0.23	0.23
Thrust (All Remaining Engines)	[kN]	264	256	208	289	251
Propulsor Efficiency[4]	[-]	0.37	0.41	0.38	0.82	0.83
Equiv. Power (Remaining Engines)[5]	[MW]	61	58	44	30	26
Eqiv. Tot. Systems Offtakes[6]	[MW]	0.1	0.15	0.15	0.15	0.15
Power Provider Eff.[7]	[-]	0.46	0.52	0.52	0.50[9]	0.93[10]
Total Propulsion Efficiency [8]	[-]	0.17	0.21	0.20	0.41	0.77

[1] The PM (People-Mover) configuration is capable of both fully-electric and gas-turbine-powered flight (with the partial turbo-electric operation mode); however, the focus is set only on its electric operation mode in the table.
[2] PTE - Partial Turbo-Electric operation mode.
[3] 8000 NM mission for the REF-369, BAS-449, and HMR-449-LR aircraft, 2000 NM mission for the PMT-533, 300 NM fully-electric mission for the HMR-533-PM.
[4] The efficiency at which the power provider (gas turbines or batteries) power output (excluding offtakes and after the transmission losses) is converted into propulsive power (efficiency = thrust * velocity / power), including exhaust thrust.
[5] The shaft power of the power provider after the transmission losses + the exhaust equivalent power.
[6] The offtake shaft power + the equivalent power needed for bleed compression.
[7] The efficiency at which the energy from the energy storage system (low-heating-value energy of burned kerosene for gas turbines and stored electric energy for batteries) is converted into power output (for both propulsive needs and offtakes), including the transmission losses.
[8] The total engine efficiency at which the energy from the energy storage system (low-heating-value energy of burned kerosene for gas turbines and stored electric energy for batteries) is converted into propulsive power output (thrust * velocity). This value includes the negative impact of offtakes.
[9] The value includes approx. 96% partial turbo-electric chain efficiency (50% direct drive & 50% turbo-electirc transm.).
[10] The value includes geared e-motor efficiency & battery discharge losses.
[11] The loss of a gearbox at the outer nacelle renders one gas turbine + one propeller inoperative.
[12] The loss of a one battery pack leaves only one battery as a power provider during electric take-off.

concept, which were described in the previous subsections, ensure a lower MTOM level than the BAS model. This effect is most pronounced for the PMT aircraft because of its significantly lower design range. The reduction in design fuel mass leads to favourable snowball effects throughout the aircraft design (most pronounced on the landing gear structural mass) contributing to a reduction in airframe mass.

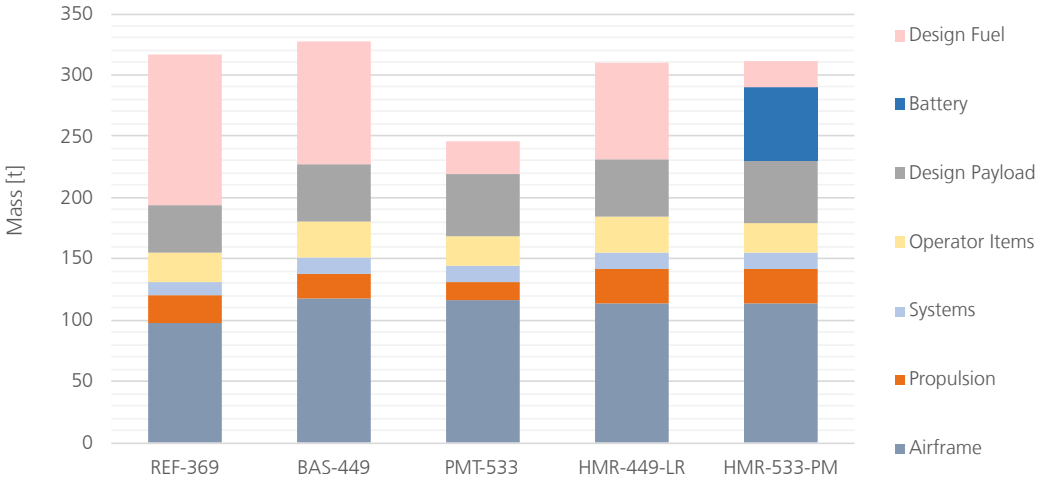


Figure 12 – Mass breakdown comparison between the BAS-449, PMT-533, and two representative configurations of the HMR aircraft - HMR-449-LR and HMR-533-PM. The design fuel shown for the aircraft with a long-range 450-seats layout (BAS-449 & HMR-449-LR) is for a 8,000 NM mission. The design fuel shown for the aircraft configurations with a people-mover-suitable 533-seats layout is for a 2,000 NM mission.

In addition to the comparably low fuel mass fraction, the airframe mass of the HMR concept further benefits from the structural advantages of the unswept wing and the lower cruise altitude, which reduces fuselage pressurisation loads. The propulsion systems also benefits from the lower MTOM, as can be seen in the comparison between the BAS and the PMT models. However, the hybrid propulsion system of the HMR is inherently heavier than the conventional turbofan propulsion, even with the reduced power requirements (see also Subsection subsubsection 4.1.3), which penalises aircraft empty mass. Furthermore, the HMR airframe is sized to accommodate the loads associated with both the LR and PM configurations, further offsetting some of the potential structural mass benefits.
In the HMR-533-PM configuration, a large portion of the long-range fuel mass is replaced by battery energy storage, enabling highly efficient short-range operation. It is also noteworthy that the operator-items mass is lower for the short-range cabin configurations, allowing a larger battery mass to be accommodated within the same MTOM.

4.2 Aircraft Concept Energy-Efficiency Comparison

The aircraft characteristics discussed in the previous subsection ultimately translate into different mission-level energy efficiencies. This effect is illustrated in Figure 13 and Figure 14, which compare the specific block energy of the investigated aircraft concepts. The specific block energy is defined as the total mission energy consumption normalised by the transported passenger count and the mission distance.
The specific block energy curves of the REF-369 and BAS-449 aircraft shown in Figure 13 illustrate a characteristic behaviour of conventional long-range aircraft. The lowest specific block energy is achieved at mission distances of approximately 3,000–4,000 NM. At these distances, the highly efficient cruise phase dominates the mission profile, while the energy penalties associated with climb, descent, and airport operations become comparatively small. On shorter missions, these fixed less efficient mission segments represent a larger fraction of the total flight distance and therefore lead to a noticeable degradation in transport efficiency. Conversely, on very long missions, an increasing portion of the take-off mass consists of fuel that must be carried over substantial distances before

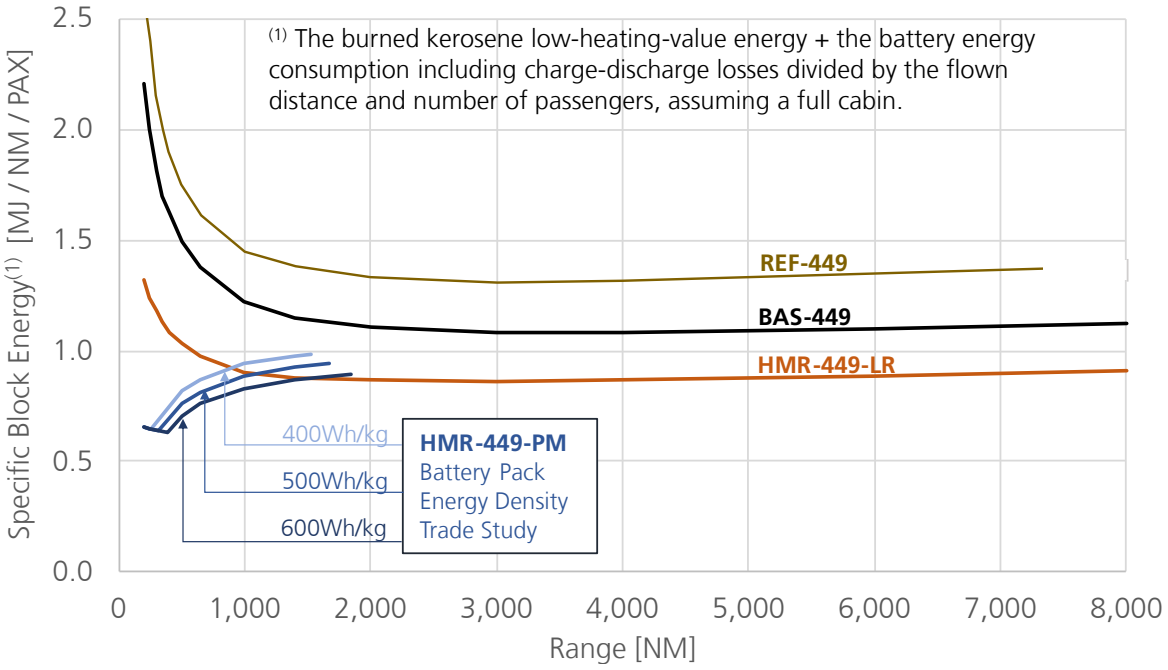


Figure 13 – Comparison between the specific block energy (energy consumed for a flown mission per passenger and per unit of distance) of the REF-369, BAS-449, and the HMR-449 in both its HMR-449-LR and HMR-449-PM configurations. The specific block energy of the HMR-449-PM configuration is plotted for different battery pack energy densities.

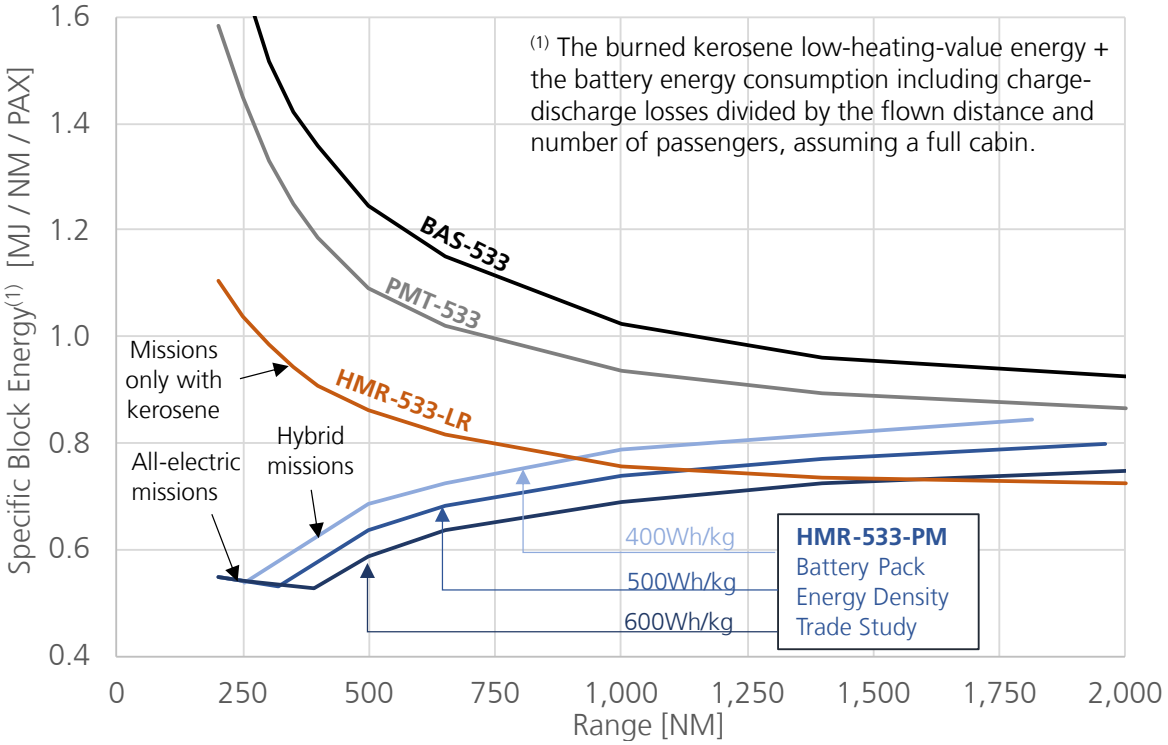


Figure 14 – Comparison between the specific block energy (energy consumed for a flown mission per passenger and per unit of distance) of the BAS-533, PMT-533, and the HMR-533 in both its HMR-533-LR and HMR-533-PM configurations. The specific block energy of the HMR-533-PM configuration is plotted for different battery pack energy densities.

being consumed, which lowers the overall energy-efficiency of the aircraft.
The BAS-449 aircraft consistently outperforms the REF-369 across the entire mission range, achieving an efficiency improvement of approximately 20%. This improvement is a direct consequence of the future technology assumptions adopted in the study, including advances in aerodynamic performance, propulsion-system efficiency, and structural technologies.
The benefits of tailoring an aircraft specifically to the people-mover market can be observed in Figure 14. The PMT-533 concept achieves an additional efficiency improvement of approximately 10–20% compared with the BAS-533 aircraft on missions below 2,000 NM. This improvement results from the reduced design range and cruise speed, and the associated reduction in aircraft mass, which allows the aircraft to operate more efficiently within its intended mission domain.
The most significant efficiency improvements are achieved by the HMR concept. In its long-range configuration, HMR-449-LR is approximately 20% more energy-efficient than the BAS-449 aircraft on long-range missions. This improvement is a direct consequence of the superior aerodynamic and propulsion efficiency discussed in Subsections 4.1.2 and 4.1.3. The configurable propulsion architecture of the HMR concept enables an additional optimisation mechanism. When deployed on shorter routes, the aircraft can switch to the HMR-449-PM configuration by replacing a portion of the fuel storage with battery energy storage. In this configuration, the aircraft exploits the high efficiency of battery-electric propulsion to substantially reduce mission energy consumption. However, the large battery mass introduces a performance penalty that increases with mission range. Consequently, a range exists at which the battery-efficiency advantage is balanced by the penalty of carrying the battery throughout the mission. As shown in Figure 13, this efficiency cross-over distance depends strongly on the battery specific energy. A battery pack with a specific energy of 400 Wh/kg enables efficiency improvements up to approximately 900 NM, whereas a 600 Wh/kg battery extends the efficiency-parity distance to approximately 1,600 NM.
The benefits of the HMR concept on short-range missions are illustrated more clearly in Figure 14. Even without batteries, the HMR-533-LR configuration achieves an efficiency advantage of approximately 15% relative to the PMT-533 aircraft, reflecting the superior aerodynamic and propulsive efficiency of the concept, which were described in Subsections 4.1.2 and 4.1.3. When operated in the HMR-533-PM configuration, however, substantially larger improvements become possible. On fully electric missions, corresponding to mission ranges of approximately 250–400 NM depending on battery specific energy, the aircraft achieves an energy-efficiency improvement of approximately 50–60% compared with the PMT-533 concept. At longer distances, the HMR-533-PM transitions to hybrid-electric operation, gradually reducing the efficiency advantage as the battery utilisation decreases.
Overall, the results demonstrate that the configurable HMR architecture enables the aircraft to exploit two complementary approaches for increasing efficiency. On long-range missions, the concept benefits primarily from its superior aerodynamic and propulsive characteristics due to the lower design Mach Number. On short-range missions, the addition of battery energy storage enables the aircraft to utilise the substantially higher efficiency of electric propulsion. The combination of these capabilities allows the same aircraft platform to achieve high transport efficiency across a significantly wider range of mission profiles than dedicated conventional aircraft concepts.

5. Discussion

This paper presented the HMR (Hybrid Multi-Range) aircraft concept, a configurable hybrid-electric open-rotor aircraft designed to efficiently address both long-range and people-mover operations within the wide-body passenger class. The concept was developed within the DLR project EXACT 2 and combines a partially turbo-electric propulsion architecture with a modular energy-storage system that allows reconfiguration between a long-range configuration (HMR-LR) without batteries and a battery-hybrid-electric people-mover configuration (HMR-PM). A comprehensive aircraft-design study was conducted using the multidisciplinary EXACT framework, and the resulting aircraft was compared against dedicated conventional aircraft concepts optimised separately for long-range and people-mover operation.

5.1 Key Findings of the Study

The results demonstrate that the HMR concept can successfully combine the efficiency advantages of two different operational domains within a single aircraft platform. In its long-range configuration, the concept achieves approximately 20% lower energy consumption than a turbofan-powered aircraft of comparable technology level. This improvement is primarily enabled by the combination of a highly efficient open-rotor propulsion system and a low-speed airframe optimised for a cruise Mach number of 0.7. In its people-mover configuration, the concept exploits the high efficiency of battery-electric propulsion, enabling fully electric operation on short routes and hybrid-electric operation on longer missions (up to 2,000 NM). Depending on mission range and battery technology level, energy-efficiency improvements of 20–60% relative to conventional aircraft are achieved.

It was further shown that the viability of the HMR concept does not depend on the availability of highly advanced batteries. The batteryless long-range configuration HMR-LR remains highly competitive due to its aerodynamic and propulsive efficiency. As future battery technology progresses, the battery-hybrid-electric people-mover configuration becomes more competitive over increasingly broader mission range spectrum. Consequently, the concept provides a robust pathway towards future hybrid-electric aviation, allowing operators to benefit from efficiency improvements immediately while retaining the option to exploit future battery advancements as they become available.

Overall, the results of the present study indicate that configurable hybrid-electric propulsion systems represent a promising approach for extending the benefits of hybrid-electric aviation beyond the traditional short- and medium-range market and towards the highly climate-relevant long-range aircraft segment.

5.2 Open Points for Future Work

The presented study focuses on one fixed propulsion architecture and integration into the airframe of the configurable multi-range concept. Further studies within EXACT will explore alternative integration strategies for the battery system and fuel storage, for example concepts with batteries integrated into the wing-fuselage fairing instead of the inner nacelles.

Furthermore, additional configurations with different hybridisation ratios will be studied. A mild-hybrid configuration with a minimal amount of batteries on board can be one interesting additional configuration that targets performance improvement of highly inefficient low-power mission phases, for example taxi, descent, approach and landing. Compared to the full plug-in hybrid propulsion system of the HMR-PM, a mild-hybrid configuration would more effectively leverage the long-range performance penalties from the added battery mass for achievable short-distance efficiency. As demonstrated in [2], its achievable energy-efficiency at shorter ranges will be lower than a plug-in hybrid configuration; however, it is considerably less sensitive to battery technology assumptions and may extend the range at which battery-supported operation remains beneficial, potentially making it particularly attractive for the medium-range market segment. Overall, a systematic study of different configuration combinations in the context of the entire aircraft family needs to be performed to fully explore the potential of the hybrid multi-range propulsion concept.

Another important topic is the influence of cruise speed on the overall aircraft assessment. The present study intentionally focused on a Mach 0.7 design point, which allows an unswept wing design with a high aerodynamic and propulsive efficiency. Future investigations should assess a broader range of cruise speeds and evaluate whether alternative open-fan or open-rotor propulsion concepts can retain a significant portion of the efficiency benefits at higher cruise Mach numbers.

Finally, the current work focused primarily on aircraft-level energy efficiency. Future studies within EXACT will therefore extend the assessment towards the project's primary evaluation metrics, namely operating economics and climate impact. This will allow determination of how the efficiency improvements demonstrated in the present study translate into competitive operating costs and meaningful reductions in the overall environmental impact of future air transport, especially given the significant trade-off with the lower design cruise speed of the described HMR concept.

6. Acronyms

The following aircraft designations and acronyms were used in the paper.

Acronym	Meaning
BAS	Baseline Aircraft
CPACS	Common Parametric Aircraft Configuration Schema
DLR	German Aerospace Center
DOE	Design of Experiments
EIS	Entry Into Service
EXACT	Exploration of Electric Aircraft Concepts and Technologies
HMR	Hybrid Multi-Range Aircraft
LR	Long Range
MTOM	Maximum Take-Off Mass
NM	Nautical Mile
PAX	Passengers
PM	People Mover
PMT	People-Mover Turbofan Aircraft
PTE	Partially Turbo-Electric
RCE	Remote Component Environment
REF	Reference Aircraft
SAF	Sustainable Aviation Fuel
TLAR	Top-Level Aircraft Requirement

7. Contact Author Email Address

Georgi Atanasov
German Aerospace Center (DLR)
Institute of System Architectures in Aeronautics, Hamburg, Germany
georgi.atanasov@dlr.de

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