REASSESSMENT OF PARAMETRIC OPTIMIZATION AND PERFORMANCE ANALYSIS METHODOLOGY FOR MILD HYBRID AIRCRAFT PROPULSION SYSTEMS

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Abstract

In previous work published by the authors, a novel methodology for modeling and simulating a mild hybrid turbofan architecture was presented, along with a fully-integrated engine and vehicle optimization approach. The proposed parametric modeling and design approach was examined using an example optimized 2030 technology reference aircraft was developed based on the Airbus A320neo, and then an optimized mild hybrid electric turbofan and associated aircraft model was created based on that 2030-EIS optimized engine and aircraft. The present work seeks to readdress and refine these results by identifying the resulting impacts from the addition of several improved electrical component models such as cabling andt a new descent idle operability model, as well as improvements and modifications to hybrid electric operational mode models. The work here includes a revised hybrid electric engine-vehicle optimization study performed for Airbus A320neo vehicle model, yielding 2030-EIS mild hybrid turbofan engine and aircraft model. Resulting performance metrics, such as block fuel and energy use for the optimized conventional and mild hybrid aircraft and engine models are shown, in comparison to their baseline counterparts. Lastly, potential improvements in modeling fidelity, and recommendations for hybrid electric propulsion (HEP) systems and their operation to achieve improved fuel burn benefit, along with related areas of future research is discussed.

Keywords: hybrid electric propulsion, more electric aircraft engine, aircraft-engine optimization

1. Introduction

Recent years have seen studies seeking to pursue greater levels of electrification on civil passenger aircraft, in part, for the purposes of reducing fuel costs, as well as reducing aviation-related greenhouse gas emissions. Many different studies have been performed exploring the broad design space of electrified civil aircraft, from fully electric to more electric aircraft (MEA) concepts with conventional gas turbine propulsion. Electrified propulsion concepts from the published literature range from turboelectric distributed propulsion, as found in the NASA N3-X concept, to hybrid turbofan plants as seen in the BOEING SUGAR VOLT, each architecture presenting its own difficulties with regards to design and implementation [1] .

One potentially promising concept for electrification of single aisle class civil aircraft is the mild hybrid propulsion concept, which employs electric machines to provide power to supplement gas turbine cycles by acting as motor-generators. Working in conjunction with an energy storage system (ESS), these electric machines allow for power off-take and augmentation to the conventional gas turbine system which they modify. These concepts ultimately provide the nexus of near-term technology levels for electrified aircraft propulsion systems with proven and reliable engine architectures, potentially providing an interstitial solution on the pathway to higher levels of electrification and greater improvement with regards to energy consumption and emissions production.

While exploration of the mild hybrid turbofan design space is relatively new, notable progress has been made in understanding the potential benefits and limitations of several mild hybrid configurations. Previous work presented by the authors [2], [3] explored a dual-motor mild hybrid turbofan propulsion system and its resulting system-level impacts on a single aisle 150 passenger class vehicle, a 2030 technology reference aircraft based on the Airbus A320neo with PW1127G-JM turbofan. This updated study is being performed in part as the addition of updated fidelity in the integrated engine and aircraft modeling tools. Specifically, improvement of electrical component models, conventional operating mode improvements such as an improved descent idle, and electrical operating mode improvements, including electric taxi and electric power transfer. The results of the improved models are expected to provide greater understanding of how the mild hybrid propulsion architecture performs across vehicle platforms and engine types, and furthermore, how such concepts compare to conventional aviation engine counterparts.

1.1 Literature Review

In surveying the literature, the idea of the parallel hybrid turbofan originated in the SUGAR study[4]. The hybrid system used batteries to offset climb and cruise power with minimal engine changes. Battery specific energy requirements were significantly higher than the state-of-the-art (SOA) at the time and remain 2-3 times larger today. Although the system barely broke even in energy comparison to a conventional baseline, but it showed significant Jet-A fuel reductions. Gladin et. al. [5] proposed optimizing the power system for a fully variable power insertion with no battery needed for the design mission but a larger battery for shorter off-design missions. This required modular batteries for short range, made possible by weight reduction due to lower fuel load. This flexible system required high battery specific energies (400 W-hr/kg, double today's capability) to break even on energy for very short flights, and added operational complexity with battery swapping.

A parallel NASA-funded effort at the United Technologies Research Center (Raytheon) by Lents [6] suggested using the electric motor to reduce gas turbine core size, employing battery technology for energy storage. Engine cycle analysis showed cruise TSFC benefits, and significant fuel savings for short missions, but battery specific energy needs were high due to large power required to maintain climb rate. The design range was reduced by added weight, with a minimum specific energy of 1000 W-hr/kg for a 900 nmi mission. A subsequent study by the same authors proposed optimizing aircraft trajectories and engine ratings during climb to reduce energy storage needs and optimize mission fuel [7].

In contrast to large-scale battery electric hybrids, the *mild* hybrid system suggests fitting dual-purpose motor/generators on both engine shafts for power insertion or extraction, without necessarily reducing the core size or using power during cruise to reduce battery requirements for long range. Linked by a DC bus, the system can be powered by various energy storage types. NASA researchers demonstrated benefits for engine dynamics and control with a system called "TEEM" [8] [9], which could enhance engine component design, cycle efficiency, and weight. These ideas can potentially have design benefits, but research defining exact benefit values on the topic is somewhat sparse.

An additional feature of this architecture is that the electric machine on one shaft can be powered in part or fully by opposite shaft. This allows the fan and booster to be driven partially by the high pressure turbine and the core compressor to be powered in part by the low pressure turbine. Studies have shown that this capability can be used to reduce idle fuel consumption, which has benefits at low part power segments [10].

The machines, energy storage, and other features of the architecture can also be used to perform existing subsystem functions on the aircraft. These functions comprise engine start, power generation, emergency power, inert gas production, and fire suppression. This enables the removal of other existing redundant sub-systems and increases the benefit to cost trade-off by reducing the net weight added to the airplane. The particular functionality that is achievable of the powertrain architecture will depend on the type of energy storage and sizing of the electric machines. For example, high temperature fuel cells have a wide variety of functionality [11] that can be performed on the airplane, whereas batteries and capacitors have relatively fewer functional capabilities.

Finally, one additional potential benefit is the use of a more electric sub-systems architecture, which alleviates the engine of part or all of its bleed flow requirements, potentially producing a more efficient cycle. One research question, yet to be fully addressed by a complete set of research, is whether or not there is a synergy between the mild hybrid architecture and the more electric systems architecture.

The research conducted by the current authors seeks to quantify the potential benefits achievable by a mild hybrid turbofan architecture and explore the compounding effects these discrete benefits for a relevant single aisle aircraft mission. The work also seeks to identify necessary thresholds for component key performance parameters in order to achieve commercial viability. This paper explores the various modes of operation enabled by the HEP architecture, introduces a parametric modeling approach for each mode, and determines impacts and benefits associated with them individually and when they are stacked in a variety of combinations.

2. Baseline Aircraft

2.1 Modeling and Simulation Environment

The hybrid-electric aircraft modeling framework in this work is developed using the Environmental Design Space (EDS) from Georgia Tech's Aerospace Systems Design Laboratory (ASDL). EDS is a versatile tool capable of simulating various engine and airframe types and assessing the environmental impact of aviation. Built on the Numerical Propulsion System Simulation (NPSS) framework, EDS supports automated data exchange between modules, allowing for comprehensive analysis of engine architectures and airframe configurations, including multi-design point cycle designs. The comprehensive suite of software tools which comprise EDS are integrated and designed to enable a thorough assessment of the environmental impacts associated with aviation, as detailed in [12], [13] and [14].

2.2 2030 Reference Aircraft

To assess the impact of hybridization of future aircraft, two different 150-passenger Large Single Aisle (LSA) non electric advanced aircraft models were created using the methodology developed by Harish et al. (2022) [15]. The work presented here utilizes one advanced 2030 concepts using the Airbus A320neo with PW1133G-JM engine as baseline initial vehicles, 2018 Technology Reference Aircraft (TRA) vehicle. The 2018 TRA vehicle serves as the non-hybrid baseline vehicle benchmark which the electrified variants are compared.

To model the projected performance of advanced aircraft for 2030, improvements in aerodynamics, propulsion systems, and weights were integrated using k-factors for technologies expected to reach Technology Readiness Level (TRL) 9 by that year. A cruise climb schedule was implemented for both vehicle types to explore potential mission performance.

The optimization of the 2030 aircraft models was conducted using a Design of Experiment (DOE) approach. This involved varying multiple engine parameters, such as Burner Efficiency, Fan Pressure Ratio (FPR), Overall Pressure Ratio (OPR), and High Pressure Compressor Pressure Ratio (HPCPR), along with aircraft parameters like Thrust-to-Weight Ratio (TWR), Wing Loading (WSR), wing sweep angle, wing taper ratio, and wing thickness-to-chord ratio. Thousands of DOE cases were run through EDS, and the aggregate results were used to create surrogate models with neural networks to accurately predict aircraft and engine behavior. The optimal design was then determined by minimizing fuel burn while adhering to performance constraints such as takeoff field length, approach speed, and wing fuel volume capacity, as outlined in [15]. In addition to these constraints, new constraints are imposed, all of which are exhibited in Table 1.

Table 1 – Optimization constraints

Optimization Constraints	Value
Approach Speed	< 140 knots
Wingspan	< 122 ft
Core Size	> 2.9 lbm/s
T3 Limit	< 1760 R
Fan Diameter	< 81.3 in
Excess Fuel	$\sim$0
OEI 2nd seg climb thrust	> 0
All Engine TOFL	< 6,950 ft
One Engine Out TOFL	< 8,000 ft
Climb Time	< 20 min

The performance results comparison between the baseline aircraft model and the 2030 advanced model is presented in the following Table 2 which describes the results for the A320neo-based vehicles for both 2018 TRA reference and 2030 versions. The results of the 2030 optimized vehicle models remained consistent with previous study [3], except for enhancements in the modeling process and the overall framework. These models constitute the non-hybrid references against which the mild hybrid electric configuration systems-level impacts can be evaluated.

Table 2 – A320neo-based LSA Vehicle Results Summary

Vehicle parameters	Units	A320neo (2018 TRA)	2030 Optimized	% Change w.r.t. 2018 TRA
Block Fuel @ Design Range (3402 nmi)	lb	35,814	27,302	-23.77 %
Block Fuel @ Econ Range (500 nmi)	lb	5,886	4728.76	-19.66 %
MTOW	lb	172,186	162,606	-5.56 %
OEW	lb	96,487	96,679	0.20 %
Cruise SFC	$lbm/hr/lbf$	0.5263	0.4928	-6.37 %
Wing Area	ft^2	1,322	1,415	7.03 %
Sea Level Static BPR	–	12.42	16.12	29.79 %
Start of Cruise LoD	–	17.97	21.96	22.20 %
Fan Diameter	in	77.4	81.5	5.30 %

3. Mild Parallel-Hybrid Powertrain Architecture

3.1 General Architecture Definition

In previous work, a dual electric machine, parallel Hybrid Electric Propulsion (HEP) system was conceptualized, modeled, and analyzed, forming the foundational framework for the research presented in this paper. As depicted in Figure 1, the proposed parallel hybrid-electric powertrain is designed with two distinct, yet interconnected powertrains: one powered by a gas turbine and the other by electricity. Each electric machine is linked to a power converter, facilitating the conversion of power between AC and DC as needed. These power converters are then connected to a central node, forming a high-voltage DC bus, through battery cables. The central node is, in turn, linked to a battery pack which serves as the propulsion system's dedicated ESS. The battery pack accumulates energy when either the High-Speed (HS) or Low-Speed (LS) electric machine operates as a generator and releases stored energy when providing mechanical torque to the motor for shaft power augmentation during motor operation. This configuration is duplicated on both sides of the aircraft, with one propulsion system located beneath each wing. The synchronization of these powertrains enhances overall efficiency and redundancy in the hybrid-electric system.

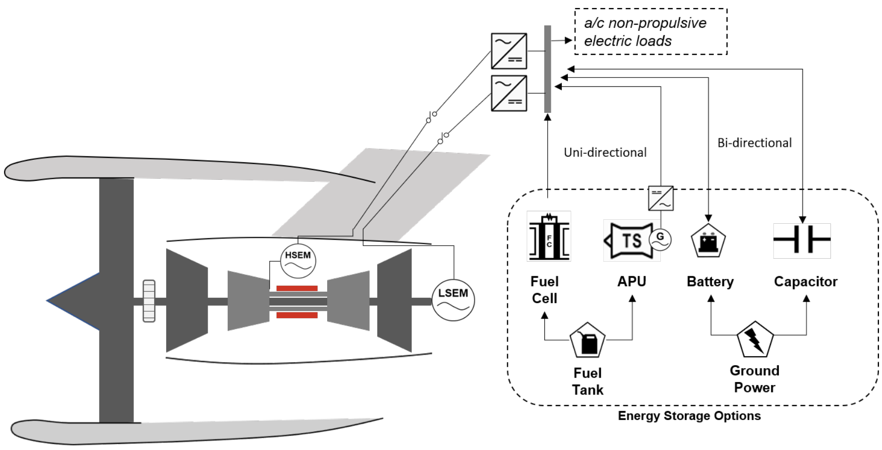


Figure 1 – Mild Hybrid Electric Generic Propulsion Architecture

3.2 Hybrid Operational Modes

In this section, the modes of operation which are proposed to control the hybrid electric propulsion system proposed in this work are described. Definition of operational modes which leverage the electrification of the engine architecture are critical to generating block fuel and energy reduction benefit.

3.2.1 Electric Taxi

eTaxi mode operates exclusively on the Low-Pressure (LP) electric motor and associated power systems while having the High-Pressure electric system offline and eliminating the need for the gas turbine engine. In this mode, electrical subsystem load can be sourced from the battery or Auxiliary Power Unit (APU). The operations modeled in this mode are vital for determining the electric machine size in the design loop as the acceleration requirements of taxi require a very large motor power.
Compared to previous years work, a new parametric standard eTaxi cycle has been developed, modifying straight-line distances with predefined stops before engine start for warm-up. The schematic depiction of this taxi configuration is presented in Figure 2. To execute this cycle, essential user-defined inputs include maximum taxi speed, acceleration rate, number of stops, and eTaxi ground distance. The thrust required for specific acceleration/velocity and distance is computed using established equations of motion, considering friction conditions from prior work [3] and [2]. Notably, the mission cycle has transitioned to a much more parametric form, distinguishing it from the non-parametric approach in other studies and previous work by the authors.

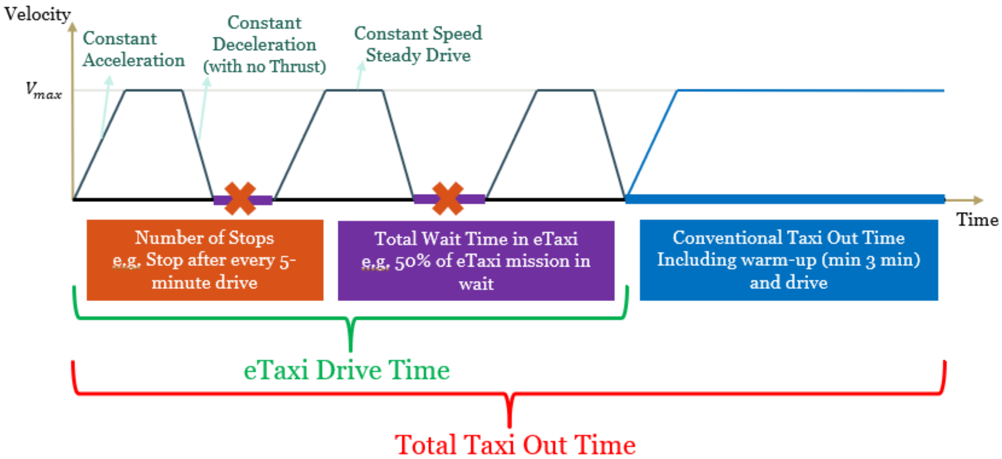


Figure 2 – Notional eTaxi Time vs Velocity Graph

3.2.2 Takeoff Boost and Core Downsizing

One potential benefit to the proposed mild hybrid electric propulsion architecture is the ability to downsize the gas turbine core, thereby reducing both fuel used for operation over the mission profile, as well as enabling a reduction in weight due to smaller turbomachinery and associated nacelle diameter. While this mode provides a potential cascade of benefits to the aircraft design, the reduced core size corresponds to a reduction in overall thrust able to be generated by the engine.
Consequently, the electric machines used in the mild hybrid propulsion system must be sized proportionally to augment the shrunken gas turbine to produce sufficient thrust as to meet the takeoff field length requirements as the non-hybrid TRA vehicles. Under the proposed hybrid engine sizing scheme, the engine core can be downsized up to cruise thrust at max continuous temperature. An important factor in sizing the hybrid propulsion system is that excessive core downsizing requires additional power from batteries during flight, resulting in considerable weight issues, notably for single-aisle missions.

3.2.3 Climb Boost

The use of electrical energy could be also used to enhance gas turbine performance during climb. Integration of climb boosting can be performed in conjunction with core downsizing, or independently, either selection resulting in an increased power demand from the hybrid propulsion system. This increased demand will require added power from the electric machines, and greater energy stored in the energy storage systems. Increases in both requirements correspond to increases in weight for the overall hybrid propulsion system. However, this weight increase can be offset by scaling down the engine core, such as employing takeoff boost or reducing the engine's capacity during climb, ultimately leading to a smaller fan or engine size. Two critical operational factors, the cutoff altitude and minimum climb rate requirement, influence the power management strategy. These factors aim to regulate the electric energy needed for the climb mission, aiming to avoid excessive energy storage that would increase aircraft weight. The higher the climb rate requirement, the greater the need for electric boosting, but excessive reliance on boosting throughout the climb segment would lead to a disproportionately large energy storage system, potentially negating fuel burn reductions relative to conventional aircraft. Thus, the cutoff altitude and minimum climb rate are introduced to mitigate this issue.

3.2.4 Sub-Idle Descent: Electric Power Transfer

The significance of descent-idle modeling in comprehending the Electric Power Transfer (EPT) mode's impact on fuel efficiency is essential. EPT's effectiveness primarily lies in optimizing the engine's low-speed phase, notably during descent, where excessive fuel consumption occurs due to by design inefficiencies. Sub-idle modeling was integrated to model to determine minimum available thrust during descent within the engine's physical constraints. Integration of an additional LPC bleed element with variable capability plays an essential role in managing Low-Pressure Compressor stall margin, dynamically manipulating the bleed valve to sustain a minimum LPC stall margin. This enhancement enables the engine model to operate at considerably lower thrusts. Nevertheless, operational constraints, including minimum shaft speeds, stable fuel-to-air ratio, and maintaining operational bleed above 7%, pose limitations. Altitude and speed directly influence the engine's minimum thrust operating point, primarily constrained by minimum High-Pressure (HP) shaft speed or fuel to air ratio.
Electric Power Transfer (EPT) operates independently within a mild hybrid system, exclusively utilizing electric motors without an energy storage system. EPT defines its ability to continuously transfer power between High-Pressure (HP) and Low-Pressure (LP) shafts through electric motor connections, effectively reconfiguring thermodynamic coupling to establish a new equilibrium, particularly beneficial during descent to address lower engine power settings' inefficiencies. During descent, EPT focuses on reducing LP speed and fuel flow while maintaining minimum HP speed. This positive EPT mode extracts power from the LP electric motor to sustain minimum HP shaft speed without extracting any energy from the battery and extracted power isn't redirected to the system except for powering aircraft subsystems.
The aircraft's power system is crucial for supplying electricity to its subsystems. Traditionally, electrical generators were located on the high-pressure (HP) engine spool because of its reliably high and steady operating speed [16]. However, with the introduction of the electric power transfer system, there's a shift in how these power loads are distributed, reducing the dependency on the HP spool. The EPT system enables effective distribution of electrical subsystem loads across both engine shafts, enhancing power allocation according to the engine's operational efficiency.
The implementation of electric power transfer with the sub idle descent module represents a novel approach, with more detailed information available within [17] for the same vehicles that descpried here.

3.2.5 Turbine Electrified Energy Management (TEEM)

TEEM, as a sustained operational mode, persists throughout the entirety of flight missions. Its principal function involves enhancing transient operability control through the utilization of electric machines on both shafts, thereby mitigating issues encountered during acceleration and deceleration phases. This strategic approach facilitates the adoption of narrower operability margins for the gas turbine's turbomachinery design, enabling the deployment of more efficient components. As a result, this electric operational mode contributes significantly to enhancing overall engine efficiency. In the process of motor sizing, an assessment is conducted for the motor requirements in various modes, followed by the utilization of a parametric curve from [9] to ascertain the power needs of the electric machines, ensuring effective transient control.

3.3 Aircraft Systems Architecture

3.3.1 Electrical Power Generation

IDGs (Integrated Drive Generators) serve as electrical generators supplying primary power during normal flight conditions on the aircraft, by a power offtake from the thrust-producing gas turbine system. Typically, one IDG is situated on each engine, linked to the High-Pressure (HP) shaft through a constant-speed gear (CSG) transmission. Simulating the replacement of IDGs involves eliminating the weights associated with each IDG system, including the connected CSG transmission. The HP shaft motor serves as the functional replacement for the IDG due to the fact that the IDGs operate at high input shaft speeds and demand low torque.

3.3.2 Emergency Power

The RAT (Ram Air Turbine) serves as an emergency power generation device present in most contemporary civil aircraft. The RAT typically deploys in emergency scenarios automatically, and uses freestream air to drive a turbine, providing electrical and hydraulic power to critical systems, such as control surfaces. In the context of the examined propulsion system, a battery pack up-sizing strategy was devised as an alternative to the RAT. In previous work by researchers, the required emergency energy to complete a safe landing in the single aisle segment is determined to be 20 kWh [18]. This energy requirement was incorporated as an additional capacity in the battery sizing process, simulating the replacement of the RAT. In the electrical system sizing scheme, multiple battery packs placed in parallel configuration were integrated to fulfill this supplemental power demand, ensuring that the necessary 20 kWh for RAT replacement was either met or exceeded.

3.3.3 Engine Start

Air turbine starters, small pneumatic starters situated on each engine, employ high-pressure air from ground start carts, APUs, or bleed air from an online engine to supply starting torque to an offline engine. Considering that air turbine starters deliver high torque at lower shaft speeds, the LS electric motor in the parallel HEP architecture is suggested as its functional replacement.

4. Electric Powertrain

4.1 Component Technology and Modeling

The electric powertrain serves as the linchpin of the hybrid electric turbofan concept. A basic schematic of the primary electric powertrain including all major components can be seen in Figure 3. A brief description of the electrical modeling approach and weight calculation used for each component, along with their assumed technology parameters and levels can be found in the following sections.

4.1.1 Energy Storage System

The electrical powertrain's energy storage system provides power to the electrical loads during discharge, and consists of a battery pack that can be both discharged and recharged during flight. A Simulink battery model built upon the research published by Tremblay and Dessaint [19] forms the core of the battery pack model used in the electrical powertrain. The battery pack design parameters are calculated based on battery cell design parameter inputs and mission requirements. The battery cell design parameters, as shown in Table 3, are based the Samsung INR18650-30Q lithium ion battery cell, a similar battery cell to the one selected for NASA's X-57 Maxwell [20].

The battery pack weight is calculated based upon its chemical and packaging weight, where the chemical weight is determined by the total battery pack energy (Wh) and battery cell specific energy (Wh/kg). The packaging weight of the battery pack is dictated by a weight build-up of the cooling, housing, battery management system, and intra-pack wiring weights.

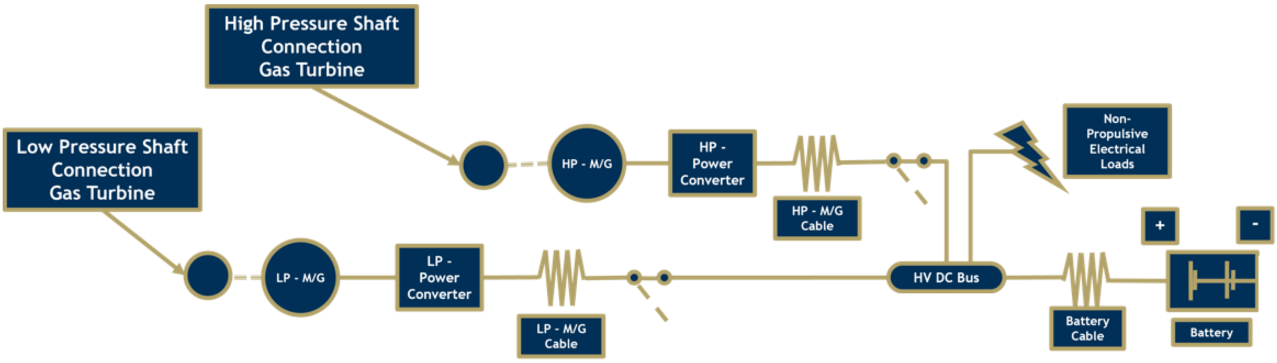


Figure 3 – Primary Electric Powertrain in Mild Parallel Hybrid Architecture

Table 3 – Reference Battery Cell Parameters

Battery Parameter	Value
Nominal Capacity [Ah]	3.0
Nominal Voltage [V]	3.6
Max Continuous Current [A]	15
Cell Specific Energy [Wh/kg]	225
Weight [g]	48

4.1.2 Electric Machines

The electric machine components are represented through a simplified model of a permanent synchronous machine with a constant back-EMF (electromagnetic field), which have the capability to function as either motors or generators. In motor mode, they contribute torque to the engine shafts by consuming energy stored in the ESS, thereby augmenting the gas turbine engine's performance, and reducing fuel flow required to meet a particular thrust target.

In generator mode, the electric machines convert mechanical shaft power into electrical power with an efficiency corresponding to the electric machine shaft's input corrected speed and power output. In this mode, the electric machines can either power the onboard subsystems, charge the ESS, or both.

For the parallel hybrid-electric propulsion system presented here, two electric machines are used– one for each shaft in the gas turbine. These machines can be controlled independently, and the selection of each machine's operational modes (motor or generator) is dictated by the segment-specific hybrid electric operational modes described in the previous sections, above.

Electric machine weights are determined by its maximum power rating and specific power (W/kg). Estimates for the specific powers of electric machines were derived from research conducted by Pastra et al. [21], where projected specific power and efficiency levels to year 2050 for electric machines are presented.

4.1.3 Power Converters

The inclusion of electric machines in the overall parallel hybrid architecture required to enable the conversion of AC to DC (rectifiers) power, or DC to AC (inverters), as well. This electrical component model also encompasses the DC to DC type, which performs the function of voltage step up or step down.

If the model is an inverter, the power converter is a three-phase type which takes teh DC power from the ESS and converts it to AC power. This power is then suitable to be used by the electric machines for shaft power augmentation. Operating as a rectifier, the opposite is true–the AC power is converted from three phase power to DC power, which is suitable to be stored in the hybrid ESS, battery. The DC-DC power converter facilitates power transfer between the HVDC bus and battery system, accommodating changes in their voltages during a mission. The process of power conversion, and thus the addition of each power converter component in the system constitutes a reduction in overall electrical system efficiency.

Power converter weights are determined as a function of each power converter's maximum power rating and specific power (W/kg). The estimates for power converter specific powers were derived from the research conducted by Hall et al. [22], where the authors projected power converter specific power and efficiency levels up to the year 2050.

4.1.4 Power Cables

The voltage drop in the power cables between electrical components are modeled using Ohm's law. Overall power cable weight is estimated based upon a build-up of the power cable component weights, which are calculated based upon the maximum power cable voltage/current seen during the design mission. The power cable component weights are determined based upon the thickness of the insulation, magnetic shielding, and cooling jacket, as well as conductor size and count. The conductor configuration is dictated by an overall resistance input or conductor ampacity as defined by the National Electric Code, NFPA 70.

4.1.5 Electric Bus and Electric Subsystems

A constant DC power draw on the DC bus of the electric powertrain is used to model the non-propulsive electrical loads. Here, the electric bus acts as an electric junction for the electric powertrain, balancing the currents of all connected source and load components.

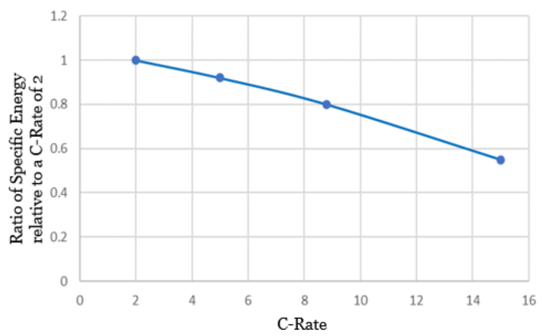
4.1.6 2030 Technology KPPs

Several studies were conducted by the current authors ([21], [22]) and NASA in order to project design parameter values for a future SOA electrical system for use in hybrid electric aircraft propulsion. The values of these projected electrical system parameters are provided in Table 4. Initially, a 1 C discharge battery specific energy value of 491 W-hr/kg was assumed for the 2030 time frame for use with the ESS model. However, based upon the high power draw and high discharge rate during during both takeoff eTaxi acceleration, it was decided that 8.75 C rate cell would be required for the electrical powertrain. After reviewing current state of the art EV and HEV cells, a 20% knock-down factor was applied to 1 C discharge battery specific energy value above–yielding a battery specific energy of 391 W-hr/kg.

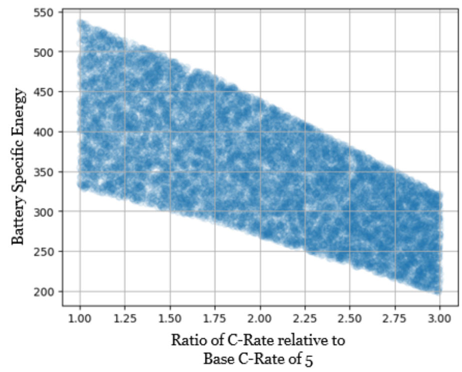
Table 4 – Technology Parameters

Variable	Value
Battery Cable Length	60
Battery Specific Energy	391
Battery Pack Factor	0.75
Battery Cell Capacity Scalar	1
Zero Load Voltage Factor	1
Max Continuous Current Scalar	1.75
Battery Cable Efficiency	0.996
Power Converter Efficiency	0.985
Power Converter Specific Power	13.8
Electric Machine Efficiency	0.968
Electric Machine Specific Power	13
Electric Machine Cable Efficiency	0.996
Bus Efficiency	1
HPC Efficiency Improvement	+1%
HPC Weight Scalar	-10%

In addition to the aforementioned analyses, further investigation was conducted to establish a correlation between the maximum C-Rate and specific energy. This additional study aimed to elucidate the relationship between these key parameters, recognizing the inherent correlation between battery specific energy and C-rate, which cannot be varied independently. Furthermore, the determination of effective battery specific energy from the base measure through the application of a knockdown factor was considered during this investigation, as illustrated in Figure 4 as the C-rate increases, there is a corresponding decrease in the effective battery specific energy.



(a) Evolution of the knockdown factor as a function of the battery c-rate



(b) C-rate increase vs the effective battery specific energy

Figure 4 – Correlation between C-Rate and specific energy

5. Integrated Aircraft Modeling

Section V will elaborate on the modeling and simulation (M&S) approach utilized to conduct the technical analysis of a parallel hybrid-electric powertrain featuring a dual electric machine setup.

5.1 Concept of Operations and Electrification Modes

The potential benefits of the mild hybrid system, as discussed earlier, offer a vast mission choice space due to the diverse array of modes possible. Each selected electrification mode imposes requirements on various aspects of the system, such as rated motor power and energy storage needs. Moreover, each mode necessitates the model to handle a multitude of power settings and possibilities regarding flight modes implementation, including timing and extent. In the mild hybrid system, the different operational modes outlined in section 3.2 can be applied to specific mission segments. The TEEM functionality is integrated throughout the flight envelope, while other modes are deployed in specific flight modes along the mission. The aircraft model is engineered to enable the activation or deactivation of each mode during the sizing process, facilitating the evaluation of specific designs incorporating various functionalities.

5.2 Hybrid-Electric Vehicle Sizing and Synthesis Approach

Figure 5 provides an overview of the hybrid-electric vehicle sizing and synthesis approach.After completing gas turbine analysis, the vehicle sizing and synthesis process moves to electric powertrain analysis, comprising electric mission and powertrain weight breakdown. The electric mission involves determining design parameters of electrical components and assessing overall powertrain performance throughout the flight envelope. Additionally, electric machine power schedules are generated for engine deck formation. Once the electric mission module is executed and design parameters are determined, powertrain weight is estimated based on individual component weights. The electric powertrain setup is integrated on both sides of the airplane for each engine, involving sizing electric machines and energy storage, and evaluating performance during cruise and descent.

The electric machine sizing process entails determining the maximum power rating and efficiency peak for each of the two machines, LS and HS. Three key design parameters—maximum power rating (HP), design torque (lbf-ft), and design speed (RPM)—are calculated for each machine. These parameters are interrelated, allowing the calculation of one based on the knowledge of the other two. The design point of the electric machines is determined based on the flight condition with the highest power requirements.

The energy storage system (battery pack) sizing mission encompasses sizing all remaining electrical components: the battery pack, power cables, power converters, and the bus. Initially, the battery pack and power converters are sized based on mission requirements, followed by sizing the power cables based on maximum operating conditions (voltage/current) each component will encounter during the electrified part of the flight envelope. The battery pack is sized according to mission segments requiring battery electric power. The objective is to determine the total capacity (Ah) and initial voltage of the battery pack (V) needed to complete the electrified portion of the mission, while meeting a user-defined discharged state of charge (SoC) at the mission's end. The battery capacity is iteratively determined for each flight segment until the resulting SoC at the end of the mission approximates 20%. Additionally, the sizing process is constrained by the maximum allowable current per cell determined by the battery's C-Rate. Throughout the process, the battery's operational status is updated before proceeding to the next flight segment, and the battery design parameters are stored upon completion of the sizing process.

The engine deck generation is crucial for the vehicle mission analysis, providing essential information for the propulsion system. For conventional gas turbines, the engine deck includes performance data at each flight point, facilitating performance identification during mission analysis. In the case of hybrid-electric propulsion (HEP) aircraft, two engine decks are required: one for non-electrified flight portions and the other for hybrid operation. This hybrid deck is based on thrust and fuel flow performance, calculated using power schedules for the electric machines.

Within EDS, aircraft sizing and mission analysis are conducted by FLOPS, considering various inputs like mission requirements and performance constraints. Aerodynamic drag polars are estimated, and engine cycle analysis, either within FLOPS or via external engine decks, is utilized. In the case of parallel hybrid-electric propulsion, both hybrid and non-hybrid engine decks are provided as inputs. FLOPS iterates through design loops, estimating component and system weights to determine the Operating Empty Weight (OEW) and fuel capacity for the design mission.

Following mission analysis, propulsion system and aircraft integration are assessed to ensure compliance with operational constraints. If the provided hybrid-electric propulsion system fails to meet mission requirements, scaling factors are generated for thrust targets at various flight points. During the feedback loop, climb/descent mission profiles and vehicle gross weight estimates are updated for use in electric mission phases and eTaxi power requirements calculation. Comparatively, no changes from previous papers are noted in these processes.

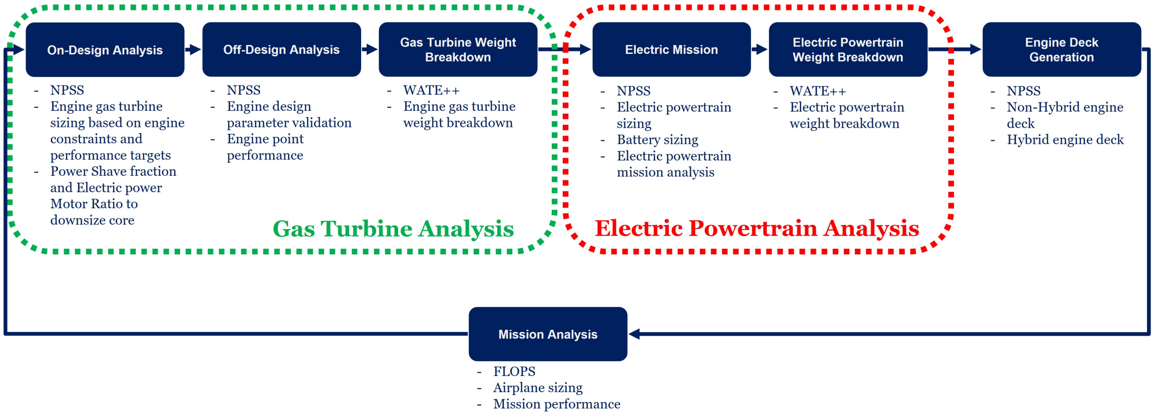


Figure 5 – Hybrid-Electric Vehicle Sizing and Synthesis [2]

6. Results

The results for the LSA 150-passenger vehicle are presented in two sections. The first section examines the individual electrical flight modes and their effects on key performance parameters, such as block fuel burn and weights. The second section outlines the probabilistic assessment and its results.

6.1 Flight Modes and Architectures Benefits Analysis

As discussed in Section 3.2 the parallel-hybrid electric propulsion system architecture can be operated using different flight modes. The impact of these modes on block fuel burn is illustrated for the design mission (3400 nmi) as well as shorter range economic off-design missions of 900 nmi and 500 nmi, as shown in Fig. 6. The results reveal an increase in block fuel burn for the design mission and a reduction of up to 6% for the 500 nmi short-range off-design mission with electrification. This increase can be attributed to the additional weight of the electrical system, leading to an overall increase in aircraft weight. Table 5 illustrates the weight distribution of the parallel-hybrid electric aircraft in comparison to the 2030 advanced non-electrified aircraft.

The implementation of eTaxi demonstrates considerable value in achieving block fuel benefits, particularly evident at off-design ranges. Furthermore, the TEEM operability management mode exhibits modest improvements in benefits. Notably, findings indicate that the clean sheet Parallel Hybrid (PLH) vehicle surpasses baseline and retrofit vehicles in terms of block fuel usage, suggesting a notable influence of the parallel hybrid system on aircraft design parameters. Additionally, analysis reveals that the inclusion of the parallel hybrid system results in an additional Electric Power Transfer (EPT) benefit, with a measured increase of 0.4% on 900 nautical miles (nmi) and 0.55% on 500 nmi in the optimized case.

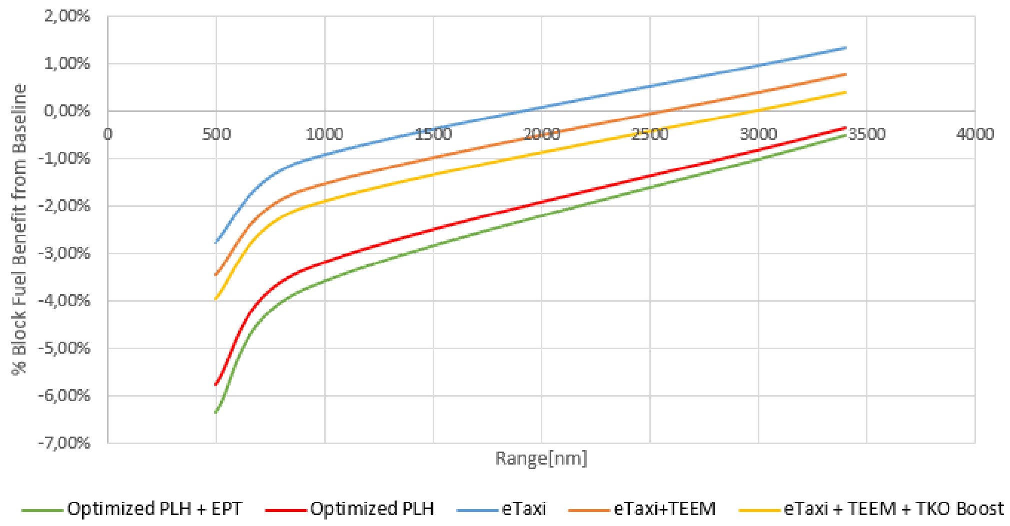


Figure 6 – Block fuel burn delta w.r.t. baseline at off-design mission ranges

However, it's important to acknowledge several caveats in analysis. Traditional sub-systems and Auxiliary Power Unit (APU) remain in use, potentially affecting the observed benefits. Additionally, while TEEM benefits are evident, they are currently measured at only 1%, suggesting the potential for achieving more significant benefits with further detailed efforts. Moreover, analysis highlights the need for updating Thermal Management System (TMS) impacts to provide a comprehensive understanding of their influence on overall system performance.

The optimization of the electrified vehicle employs the same methodology discussed in Section 2.2 . This methodology, detailed earlier, provides a systematic framework for achieving optimal performance and efficiency gains.

6.2 Parametric Design Optimization and Probabilistic Assessment

The variable inputs to the physics-based model are the following parameters found in table 6. A design of experiment was created based on the ranges specified for each inputs. After running the design of experiment through the physics based model of the parallel hybrid electric aircraft, surrogates models of the outputs of interest were created to achieve a faster computation time when performing the optimization process. The validation of those surrogate is presented in figure 7.

In previous work [23], the importance of using a systematic optimization process instead of a graphical, design space exploration (DSE)-based approach was highlighted. Therefore, in the process of conducting this research, the authors have developed a method to conduct systematic optimization of the design with a probabilistic analysis. This method is called Deterministic Design Optimization (D-DO). D-DO is a single objective optimization using a genetic algorithm with the only goal to minimize the block fuel for 900nm. The exact values for the inputs found with the D-DO method are in table 7.

Based on the design input results, the uncertainty in the technological variables presented in table 8 was propagated with a Monte Carlo sampler using the surrogate models of the outputs of interest. The resulting distribution is presented with the blue curve in figure 8. The mean of the distribution is

Table 5 – Aircraft Weight Distribution Comparison

		Baseline	Optimized PLH + EPT		
	Component	Weight (lbs)	Weight (lbs)	Weight difference(lbs)	% change w.r.t. baseline MTOW
Per Engine	LP Machine	0	149	149	0.09
	HP Machine	0	94	94	0.06
	LP Power Converter	0	150	150	0.09
	HP Power Converter	0	16	16	0.01
	Battery Packaging	0	116	116	0.07
	TMS	0	169	169	0.10
	ATS	68	0	-68	-0.04
	IDG	224	0	-224	-0.14
Aircraft Total	RAT + Associated Structure	184	0	-184	-0.11
	Battery Cells	0	900	900	0.55
	Battery Packaging	0	278	278	0.17
	Net EAP Weight	0	2797	2797	1.71
	Engines	16467	15335	-1132	-0.69
	Fuel Systems	649	645	-4	0.00
	Propulsion Total	17116	18777	1661	1.02
	Structure	45879	46548	669	0.41
	Systems	28526	28554	28	0.02
	MEW	91522	93879	2357	1.44
	Operating Items	5234	5236	2	0.00
	OEW	96756	99115	2359	1.45
	MZFW	130506	132865	2359	1.45
	Mission Fuel	32657	32409	-248	-0.15
	MTOW	163163	165274	2111	1.29

Table 6 – Physics-based model inputs

Input Name	Description	Units	Min	Max
TWR	Thrust-to-Weight Ratio	-	0.28	0.36
WSR	Wing Loading	lb/ft2.	115	140
TR	Taper Ratio	-	0.195	0.3132
TCA	Thickness-to-Chord Ratio	-	0.09	0.13
T4max	Turbine Inlet Temperature	°F	2900	3600
T4margin	Difference in turbine inlet temperature for max takeoff thrust and max continuous thrust	°F	-2.50	-125
SWEEP	Wing Sweep	°	19.5	29.93
FPR	Fan Pressure Ratio	-	1.35	1.55
OPRD_TOC	Overall Pressure Ratio at Top of Climb	-	45	65
HPCPR	Pressure Ratio of High Pressure Compressor	-	13	20
Ext_Ratio	Extraction ratio	-	0.9	1.35
Power Shave Fraction	Reduction of core size relative to baseline	%	0.05	1.0
Electric Voltage	Battery stack design voltage	V	500	1500
Climb Rate Floor	Floor climb rate for determining when boost is necessary	ft/min	500	3000
Battery_k8	Battery technology factor on the battery max continuous current	-	1	3

around -1.81% which represents a reduction of around 2% in fuel burn compared to the A320 2030 advanced non-hybrid aircraft. The standard deviation value of this distribution is 0.61. This number gives an insight into the spread around the mean and the robustness of the selected design point with the D-DO algorithm.

A Sobol analysis was also performed to understand which inputs have the most impact on the table 9. Relying on the D-DO optimum point, by order of importance the three most impactful uncertain variables are: high pressure compressor adiabatic efficiency, cell-specific energy, and pack factor. The sum of the first order effect decreases as the fuel benefits become more aggressive. The main observation is that to ensure the successful development of hybrid electric aircraft, resources and

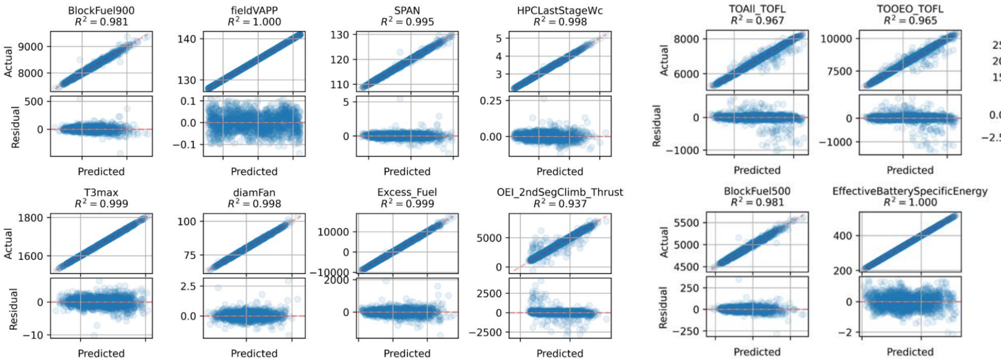


Figure 7 – Actual vs. predicted and residuals vs. predicted plots for the validation dataset of the surrogate models in this study

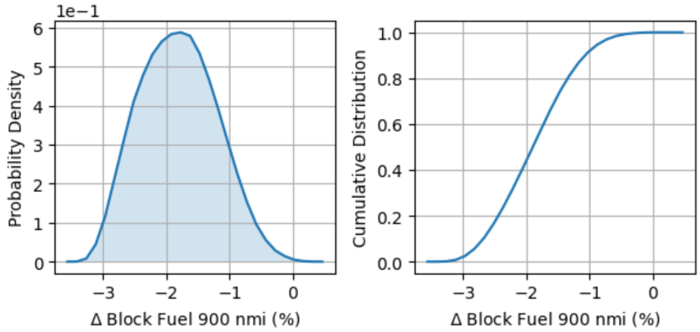
Table 7 – D-DO input variables results

Input Category	Input Name	DDO
Aircraft Design Variables	T4margin (℉)	-277
	Thrust-to-Weight Ratio	0.30
	Wing Loading	116
	Taper Ratio	0.20
	Thickness-to-Chord	0.09
	T4max (℉)	3180
	Wing Sweep	19.50
	Fan Pressure Ratio	1.40
	Operating Pressure Ratio at Top of Climb	55.3
	High Pressure Compressor Pressure Ratio	17.21
	Extraction Ratio	1.10
Hybridization Design Variables	Power Shave Fraction	0.26
	Electrical Voltage (V)	1154
	Battery k8	1.36
Operational Constraints	Climb Rate Floor (ft/min)	693

efforts should be put into improving the technological performance and decreasing the uncertainty of the high pressure compressor adiabatic efficiency, the cell-specific energy, and the pack factor.
When a minimum constraint of 2% fuel saving is applied, the scatter plot of the figure 9 shows an infeasible design space near the lower bound of the HPC Efficiency Delta. For the higher bound of the HPC Efficiency Delta, feasible space exists even for lower cell-specific energy than the 2030 projected nominal value of 490 Wh/kg. Regarding the pack factor that represents the battery packaging weight of the battery, an increase in the density of the feasible design space as the pack factor decreases and with increase in the cell-specific energy. The red arrow shows the direction that increases the density of the feasible design space which embodies the design that decreases the block fuel for 900nm by at least 2%. The red dotted line shows the boundary of the technology input space when a constraint is applied to the block fuel output.

Table 8 – Technological Input Uncertainty Modeling

Uncertain Input	Description	Min	Nominal	Max	Units	Distribution
Battery Cell-level Specific Energy	Energy capacity per unit mass of the battery	359	489	584	Wh/kg	Triangular
Inverter Efficiency	Power loss over the inverter	0.982	0.985	0.988	%	Triangular
Inverter Specific Power	Power-to-mass ratio of the inverter	9.6	13.8	17-3	kW/kg	Triangular
Electric Motor Efficiency	Efficiency at electrical design point	0.963	0.968	0.974	%	Triangular
Electric Motor Specific Power	Power-to-mass ratio of the electric motor	9.2	13.2	16.1	kW/kg	Triangular
HPC Efficiency Delta	High pressure compressor efficiency delta at aero design point	0.0028	-	0.0228	-	Uniform
Pack Factor	Factor accounting for packaging material weight of the battery	0.4	-	1.0	-	Uniform



	Mean	Std. Dev.	5th Perc.	Median	95th Perc.
DDO - 2030	-1.81	0.61	-2.77	-1.82	-0.79

Figure 8 – D-DO distribution probabilistic benefits analysis

Table 9 – Sobol analysis results with constraints on the block fuel savings for 900nm

Block Fuel 900 nmi Constraint	None	0%	-2%
Factor			
Cell Specific Energy	34.4	33.7	15.6
Electric Motor Specific Power	0.0	0.0	0.1
Electric Motor Efficiency	0.4	0.4	0.5
Inverter Specific Power	0.4	0.4	0.2
Inverter Efficiency	0.0	0.0	0.0
HPC Deff	49.7	49.3	25.4
Pack Factor	14.1	13.4	3.7
Total Ist-order effects	99.0	97.3	45.6

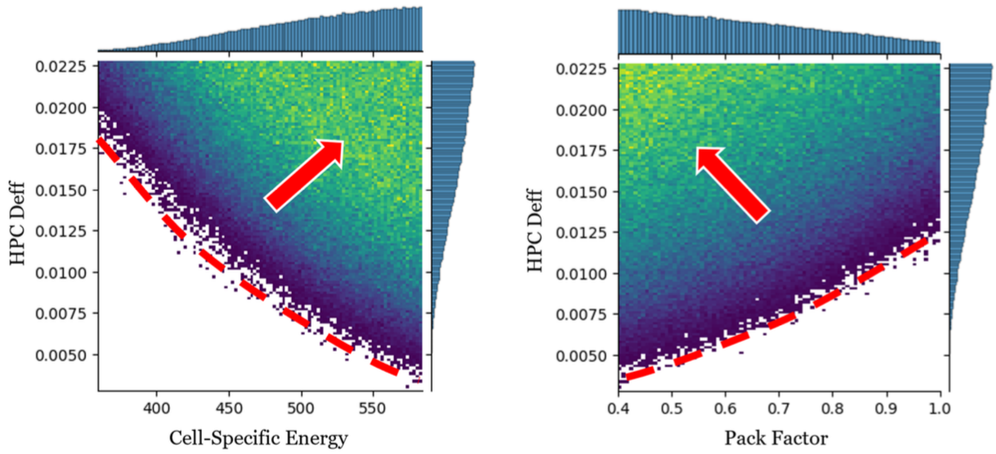


Figure 9 – Scatter plot showing the input variable design space with the constraint applied

7. Conclusion

This paper presents a detailed exploration of the mild hybrid propulsion system architecture, drawing insights from existing literature to define its key components, including operational modes. Through the integration of a parametric powertrain performance and sizing model into an established aircraft design framework, the study optimizes a design for a full-range 150-passenger single-aisle aircraft. The results demonstrate that significant benefits can be realized at Key Performance Parameter (KPP) values; moreover, the findings suggest that Electrified Aircraft Propulsion (EAP) holds promise for future single-aisle platforms, provided that appropriate technology goals are achieved.

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