

EXPLORATION OF ALTERNATIVE PROPULSION ARCHITECTURES FOR BUSINESS AVIATION

Mathieu Bouchard[1], Musavir Bashir[2], David Rancourt[1], Susan Liscouët-Hanke[2], Frédéric Sirois[3], Shannon Lloyd[2], Ali Tfaily[4], Michael Mark[4], Richard Freer[5] & Jérémy Moriot[6]

[1]Createk Innovation Group, Interdisciplinary Institute for Technological Innovation (3IT), Université de Sherbrooke, Sherbrooke, Québec, Canada
[2]Concordia University, Montréal, Québec, Canada
[3]Polytechnique Montréal, Montréal, Québec, Canada
[4]Bombardier, Montréal, Québec, Canada
[5]Pratt & Whitney Canada, Longueuil, Québec, Canada
[6]Calogy Solutions, Sherbrooke, Québec, Canada

Abstract

The business aviation sector faces distinct decarbonization challenges due to its unique operational profile, which requires the flexibility to perform frequent short-haul flights alongside occasional long-range missions from geographically diverse airports. This paper presents the outcomes of Project EAP, a comprehensive four-year academia-industry collaboration that investigated the feasibility of alternative propulsion architectures tailored for super-midsize business jets. By first establishing the operational realities of the fleet through extensive flight data analysis, the study evaluated several propulsion concepts against realistic mission constraints. The research identifies electrically-assisted turbofans and dual-fuel hydrogen-kerosene combustion as the most operationally compatible architectures, offering pathways to reduce environmental impact while preserving essential payload-range capabilities and airport flexibility. Furthermore, to capture the complex interdependencies of disruptive configurations like hydrogen-electric systems, a distributed Multidisciplinary Design Analysis and Optimization (MDAO) framework was deployed. This approach specifically addresses the realities of industrial settings by treating socio-technical coordination as a primary design constraint. By formalizing data governance, organizational autonomy, and intellectual property protection, the methodology enabled the secure integration of proprietary models across a heterogeneous network of partners. Ultimately, this work not only provides a foundational assessment of viable propulsion technologies but also delivers a robust, practically deployable methodology for collaborative aerospace design.

Keywords: Business Jets, Alternative Propulsion Systems, MDAO, Hybrid-Electric, Hydrogen, Cryogenics

1. Introduction

Business aviation has experienced steady growth over the past few years, driven by the need for flexible, point-to-point air transportation and increasing demand for premium travel solutions [1]. While the sector represents only a small fraction of global aviation activity in absolute terms, its environmental impact is significant when considered on a per-passenger or per-flight basis [2]. This relatively high carbon intensity has brought business aviation under growing scrutiny [3], particularly as society, regulators, and industry stakeholders intensify their focus on climate change [4, 5, 6]. In response, the business aviation sector has adopted ambitious net-zero carbon targets of their own [7].

Much of the current effort on alternative propulsion concepts, such as battery-electric, hybrid-electric, and hydrogen-based systems, has focused on commercial and regional aviation [8]. Although these proposed solutions exhibit promise for mitigating in-flight greenhouse gas (GHG) emissions, they

impose considerable penalties on range capability, payload capacity, airport accessibility, or some combination thereof [9]. Such trade-offs may be tolerable on well-established routes where existing performance margins exceed operational requirements, but they largely eliminate the operational flexibility that characterizes business aviation. One key explanation for the comparatively limited research on alternative propulsion systems tailored to business aviation [10] is the inherent complexity of business aircraft operations, encompassing both the wide distribution of mission lengths and the diverse categories of airports routinely served. Thus, there remains a need to better understand how these technologies can be effectively applied to business aviation, with its specific operational profiles, performance requirements, and market characteristics.

This paper presents the main outcomes of project EAP, a four-year collaboration between academia and industry that investigated the feasibility of alternative propulsion concepts for business aviation. The investigated concepts range from incremental enhancements to turbofans, such as electric assistance during transient phases of operation [11] and dual-fuel hydrogen–kerosene combustion [12, 13], to more disruptive configurations like hydrogen-electric propulsion.

1.1 Project EAP: Exploration of Alternative Propulsion technologies for business jets

Project EAP is a collaborative project involving three universities (Université de Sherbrooke, Concordia University, and Polytechnique Montréal), a business jet manufacturer (Bombardier), an engine manufacturer (Pratt & Whitney Canada), and a supplier of thermal management and battery systems (Calogy Solutions).

Funded jointly by CRIAQ and NSERC, the project was organized into eight work packages covering the full breadth of disciplines relevant to alternative propulsion for business jets, from aircraft-level performance (WP1), thermal management (WP2) and multidisciplinary optimization (WP3) to component-level technologies such as hydrogen storage (WP4), electrically-assisted turbofans (WP5), battery systems (WP6), and superconducting electrical components (WP7), and Life-cycle analysis (WP8) as illustrated in Figure 1.

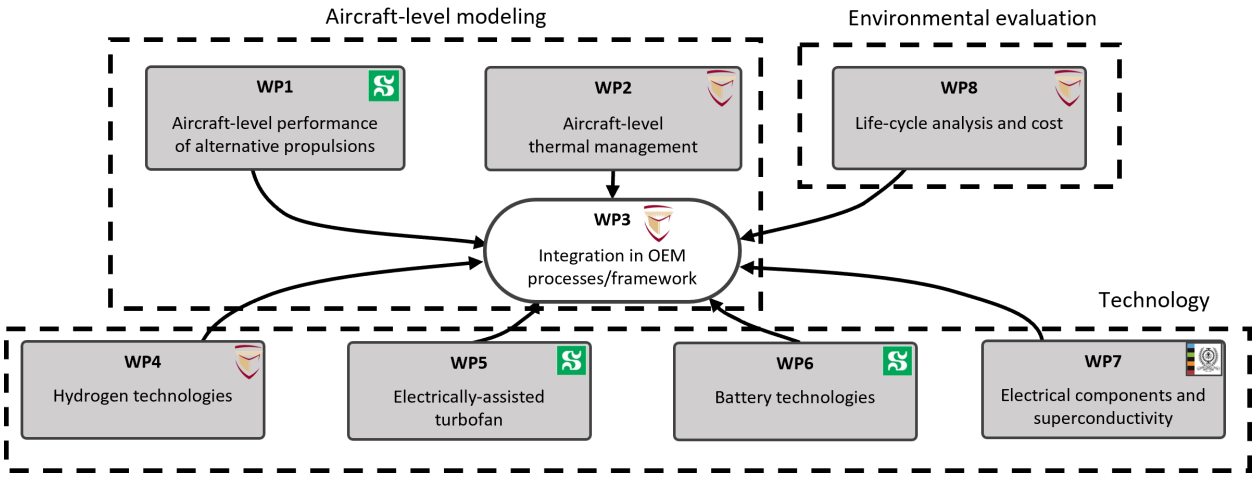


Figure 1 – Work breakdown structure of project EAP.

Battery thermal runaway characterization, a requirement for any architecture relying on batteries for energy storage, was also investigated experimentally [14] and is reported on separately [15].

1.2 Operational Reality of Business Jets

A major roadblock to exploring technological solutions that lower the environmental impact of business aviation is the sector's highly complex and distinctive operating patterns. While regional and commercial airlines generally fly between established city pairs and can use aircraft tailored to those specific routes, business aviation serves a wide spectrum of missions, from very short trips to long-haul transoceanic flights, and frequently operates out of smaller airports commonly associated with

general aviation (GA), typically served by Fixed-Based Operators (FBO). Moreover, to preserve the anonimity of business jet users, most of flight data is removed from the FAA database, rendering flight data analysis of these aircraft much more complex. To understand the operational needs of this category of aircraft, Automatic Dependent Surveillance-Broadcast (ADS-B) data from 9500 unique aircraft for the entire year of 2022 was purchased from ADS-B Exchange (JETNET) [16]. This dataset offers rare insight into the complex operations of these aircraft and enables a more judicious exploration of alternative propulsion technologies, as summarized below for a subset of 1,995 super-midsize business jets from three manufacturers [17].

The flight distance distribution of super-midsize business jets reveals a sharp dichotomy between typical and occasional operations. Over 80% of flights cover less than 1,000 nautical miles, well under one-third of the aircraft's range capability, with the most common missions falling between 200 and 500 nautical miles. Yet despite this concentration in short-haul operations, 51% of the fleet has flown at least one leg exceeding 2,000 nautical miles within the same year. This coexistence of frequent short trips and occasional long-range flights is a defining feature of business aviation: the aircraft must be sized for the extremes rather than the median, which significantly constrains the feasibility of propulsion architectures optimised for a single design point.

Business jets also operate across a remarkably broad and fragmented airport network. The number of distinct airports visited by individual aircraft in a year typically ranges from a handful to over 50, with 34% of the fleet accessing at least 50 different airfields. Operations are strongly biased toward smaller, less-congested airports: Teterboro Airport leads U.S. business jet traffic with close to 10,000 arrivals, and only four major commercial hubs appear among the 20 most frequented airports in Europe. This geographic spread makes the rollout of any alternative-fuel ground infrastructure, whether electric charging or hydrogen storage, a substantial logistical challenge, as no single airport captures enough traffic to anchor a viable network.

Actual flight profiles also deviate considerably from idealised trajectories for two compounding reasons. On shorter missions, the aircraft simply does not have sufficient range to reach an efficient cruise altitude before beginning its descent, meaning a significant share of the fleet's operations are flown in a continuous climb-descent profile with no meaningful cruise phase. On top of this, air traffic control constraints and airspace management further degrade the achievable flight profile on longer legs, where business jets are routinely assigned sub-optimal cruise altitudes or vectored around congested corridors. Both effects inflate fuel burn relative to nominal mission analyses based on clean climb-cruise-descent profiles, and they complicate the energy sizing of alternative propulsion systems that are sensitive to off-design operating conditions. Taken together, these three factors underscore why business aviation presents a particularly difficult environment for the introduction of low-emission propulsion technologies.

Also, from an environmental impact assessment perspective, alternative aircraft propulsion architectures pose a significant challenge, as they not only affect aircraft operations but also depend heavily on a global supply chain, with significant diversity and uncertainty in fuel production scenarios.

2. Methodology

The particular requirements of business aviation, as summarized by section 1.2, constrain the viable design space in terms of potential for reducing GHG emissions, particularly for solutions which could be considered feasible in the short- to mid-term. Due to the wide scope of the project, design space exploration was mostly limited to the aircraft level with some key powertrain subsystems modeled in more detail when necessary. The results therefore rely on some key assumptions with respect to powertrain technology, such as the feasibility of a combustion chamber for both hydrogen and jet fuel, or the mechanical integration of electric motors to a turbofan's spool.

2.1 Reference Aircraft and Mission

The reference aircraft used for project EAP is the Bombardier Research Aircraft Configuration (BRAC), shown in figure 2, which is a Challenger 300-sized aircraft and is thus representative of a super-midsize business jet [18]. The reference turbofan engine is the Honeywell HTF7000, a two-spool mixed-flow turbofan representative of the engines used in super-midsize business jets [19]. The characteristics listed in table 1 are representative values for an aircraft of this size.

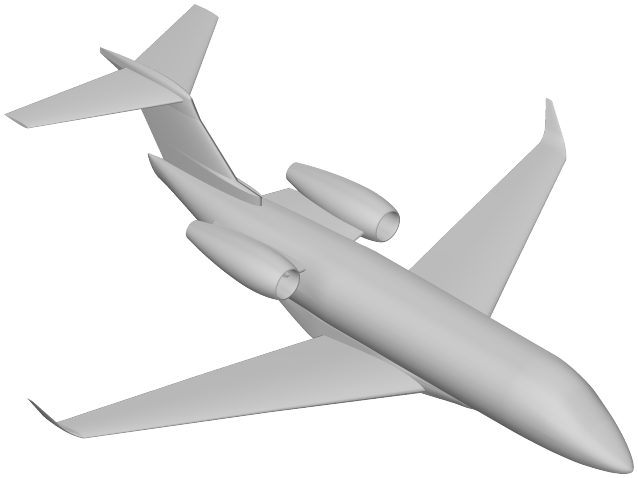


Figure 2 – BRAC geometry

Reference aircraft	**Value**	**Unit**
Typical mission range	600	nmi
Ferry range	3,500	nmi
Cruise speed	Ma 0.80	-
Initial cruise altitude	41,000	ft
Operating Empty Weight	24,000	lb
Maximum Take-Off Weight	40,000	lb
Reference turbofan		
Static sea level thrust	2x 6,826	lbf
Cruise thrust	2x 1,910	lbf
Cruise TSFC	0.642	lb/(h·lbf)

Table 1 – Baseline specifications

The reference mission, depicted in Figure 3, follows the jet aircraft mission profile specified by the National Business Aviation Association (NBAA) [20], which incorporates fuel reserves for a first approach, a go-around and climb to 5,000 ft followed by five-minute hold, a diversion to an alternate airport 200 nmi away, and 30 minutes reserve at loitering speed. Ground operations are represented as an equivalent fuel burn corresponding to 10 minutes at ground-idle power, and take-off as one minute at maximum take-off thrust. The climb is flown at the best rate of climb, with airspeed limited to 250 KCAS below 10,000 ft in accordance with standard airspace regulations. Cruise is flown at the aircraft's best cruise altitude and may incorporate up to three step-climbs. Descent is completed at flight idle, followed by a standard instrument approach approximated as a five-minute loiter segment at 5,000 ft.

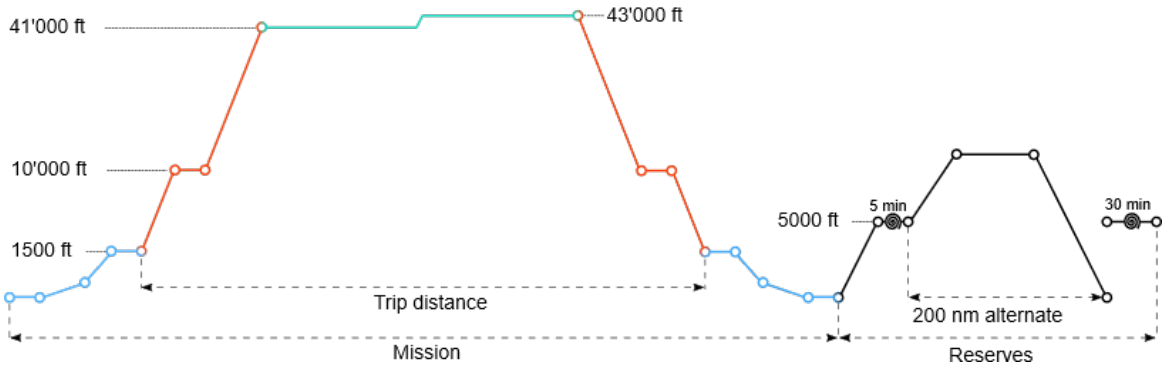


Figure 3 – Reference mission with step-climb and flight reserves.

2.2 Aircraft and Propulsion Performance

Feasibility is assessed using the in-house ELDORADO framework, specifically created to investigate alternative propulsion architectures for business jets. This framework incorporates a graph-based propulsion model, allowing complex propulsion architectures to be represented through power flows among sinks (thrust and off-takes), powertrain components (such as electric motors and turbofans), and energy sources (such as Jet A-1 and LH_2). Powertrain component modeling complexity ranges

from constant maximum power and efficiency values, to parametric models, and up to full engine decks. Where required, such as with liquid hydrogen tanks or cryogenic thermal management systems, detailed models can be coupled to ELDORADO through the multidisciplinary design analysis and optimization (MDAO) environment described below (section 2.4).

2.3 Subsystem Models

This section presents an overview of the detailed subsystem models used to investigate specific propulsion architectures when simplified models did not provide sufficient accuracy to evaluate their feasibility.

2.3.1 Hydrogen Technologies

As liquid hydrogen storage in aircraft is a major change, a parametric hydrogen tank model has been developed [21] to assess the feasibility of hydrogen-based propulsion architectures. The model is used to define the required space for hydrogen storage in the aircraft fuselage, providing an optimal tank geometry and weight for a given amount of hydrogen, accounting for tank pressure, dormancy requirements, and installation constraints stemming from aircraft geometry. A variety of geometric, insulation type, and material-related parameters can be used to explore various tank options [22]. In addition, a parametric, dynamic simulation model of a proton exchange membrane (PEM) fuel cell has been developed [23] to explore architectures featuring fuel cells.

2.3.2 Thermal Management System (TMS)

Thermal management is a key driver of alternative propulsion architectures. As one of the key components, a parametric model for heat exchanger sizing has been developed [24], that can be used for a variety of fluids, including cryogenic hydrogen, and is suitable for phase-phase conditions [25]. The heat exchanger was selected as a key component due to the potential volume penalty.

2.3.3 Superconducting Electric Powertrain

A sizing framework for superconducting propulsion components was developed to assess the feasibility of cryogenic-electric powertrains in LH_2-powered aircraft. The tool enabled consistent definition of superconducting motor and cable geometry, mass, operating limits and efficiency as a function of power demand, superconducting materials properties, and cryogenic temperature fluctuations and constraints. The framework was designed to be fully compatible with the cryogenic thermal-management system described above. This ensured that the strong interdependence between the electrical performance and the cryogenic heat load was captured during the early stages of evaluation of superconducting machine and cable concepts. Details are still unpublished.

2.3.4 Electrically-assisted Turbofan

The electrically-assisted turbofan concept, introduced in section 3.1, was modeled on a thermodynamic cycle basis using pyCycle, a computational framework specifically developed for the thermodynamic cycle analysis of gas turbine engines [26]. In this project, the framework was further extended to enable both steady-state and transient simulations [11].

2.3.5 Life-cycle Assessment

An anticipatory LCA framework [27] was developed to explore reasonable and extreme-case future environmental burdens from baseline and alternative aircraft architectures. This approach acknowledges significant uncertainty related to the future, e.g., uncertainty related to regulatory environments, airport infrastructure, and supply chains. The LCA model scope focuses on scenarios for a kerosene baseline and a hydrogen-kerosene dual-fuel concept, to capture the particular challenges of hydrogen production. The model leverages existing LCA models for aircraft and fuel life cycles [28], electricity and hydrogen production mixes projections [29, 30], and life cycle inventory data from various sources. Future versions should incorporate the perspectives of stakeholders in the broader aviation ecosystem to enable more informed future scenarios [31], particularly related to fuel logistics and management.

2.4 Collaborative Design Environment

In industrial aerospace development, MDAO frameworks are used to manage interactions between coupled disciplines. However, their implementation in collaborative environments remains challenging due to the distributed nature of real-world programs across universities, research centers, aircraft, engine and system manufacturers, and regulatory bodies, each operating under different computational infrastructures, intellectual property restrictions, cybersecurity requirements, and governance structures; as a result, the choice of an MDAO architecture must consider not only numerical performance but also organizational autonomy, secure data exchange, and interoperability. Classical architecture formulations provide structured approaches for decomposition and consistency, but their implementation in MDAO generally assume centralized access and unrestricted data sharing, which is not consistent with industrial settings where models are proprietary and integrated as black boxes. To address this, the Holistic Collaborative MDAO Selection (HCMS) methodology [32] formulates architecture selection as a coordination problem that accounts for coupling, organizational partitioning, communication, and governance constraints, extending existing distributed initiatives by focusing on practical deployment conditions rather than predefined workflows. Based on these criteria, HCMS evaluates and filters candidate formulations to identify architectures that are feasible under the given MDAO setting and design problem, providing a shortlist of viable solutions rather than a single purely optimal formulation. The implementation then follows an input/output-based integration approach using CPACS [33] and RCE [34], where disciplinary models remain locally hosted and only selected coupling variables are exchanged through standardized interfaces, ensuring controlled information sharing while preserving model confidentiality.

The initial application of the collaborative framework focused on steady-state multidisciplinary analyses, where aircraft sizing, mission performance, and LH_2 tank sizing were integrated within a distributed workflow to evaluate dual-fuel aircraft configurations. In this context, coupling variables such as tank mass, fuel requirements, and aerodynamic penalties were exchanged between disciplinary tools until a consistent system-level solution was obtained. Recognizing that many hydrogen-related phenomena are inherently time-dependent, a subsequent proof-of-concept study extended the framework to transient multidisciplinary coupling by incorporating a dynamic LH_2 tank model capable of predicting boil-off generation and pressure evolution throughout a mission. This demonstrated the ability of the collaborative environment to support not only steady-state MDAO workflows but also time-dependent multidisciplinary analyses involving transient thermal and storage-system behavior [35].

3. Results

This section presents the two main architectures found to be of interest for further study: the electrically-assisted turbofan (fig. 4a) and dual-fuel combustion (fig. 4b). The reader is directed to the original publications for more details. The hydrogen-electric architecture (fig. 4c) was not found to be compatible with the operational requirements of business aviation established in section 1.2, but proved well suited to explore the complex multidisciplinary interactions that exist between subsystems and their respective stakeholders.

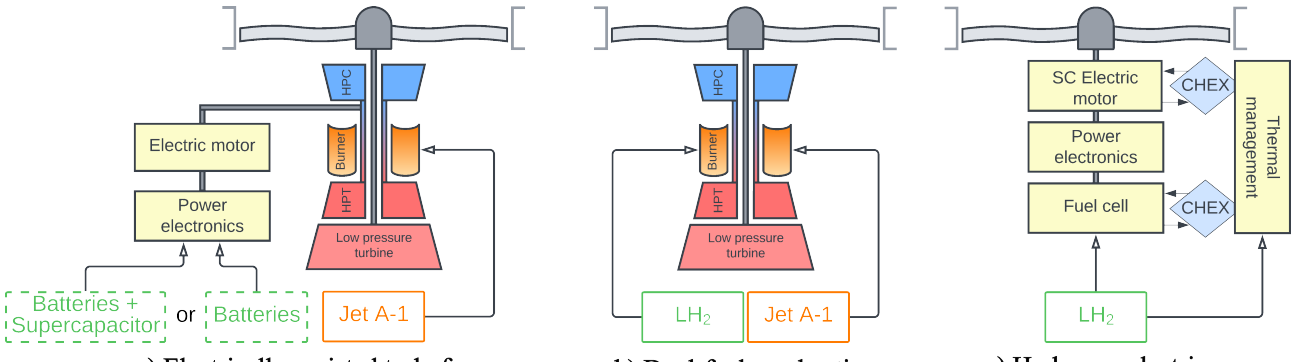


Figure 4 – Conceptual representations of the propulsion architectures of interest.

3.1 Electrically-assisted Turbofan

A conventional turbofan's steady-state efficiency is fundamentally constrained by the operability margins required to perform transient operations. Certification mandates that engines accelerate from 15% to 95% of rated thrust within five seconds [36], forcing compressor designs to operate with conservative stall margins that leave performance potential untapped during steady-state flight. The electrically-assisted turbofan concept exploits this observation: by supplying mechanical power directly to the high-pressure spool during rapid acceleration events, the compressor stability constraint is relaxed, enabling a turbomachinery redesign that shifts the high-pressure compressor (HPC) operating line closer to its stall boundary and into a more efficient region of the compressor map. This architecture remains relatively lightweight compared to other hybrid-electric configurations and does not depend on electric charging infrastructure at airports. Two electric powertrain variants are considered: (1) an electric motor supplied by an aerospace-grade battery pack, and (2) an electric motor supplied by supercapacitors in turn recharged by a battery pack.

The concept was evaluated using the thermodynamic cycle model described in section 2.3.4. Baseline analyses identified the HPC as the critical component during spool-up. Optimization of the redesigned HPC, constrained by burner exit temperature, overall pressure ratio, and the baseline stall margin during acceleration, yielded a 0.78% reduction in cruise thrust-specific fuel consumption (TSFC). Improvements were observed across the entire flight envelope and were generally larger outside of cruise, reaching 1.46% at sea level static and 3.03% at flight idle. Critically, this redesign requires only 339 Wh (i.e., 0.339 kWh) of electrical energy and a peak shaft power of 451 kW per acceleration event, far below the megawatt-class power and energy levels associated with typical parallel hybrid-electric architectures.

At the aircraft level, analysis of the typical mission (600 nmi) show that the battery-supercapacitor architecture achieves block fuel savings approaching 0.5% (see figure 6) under optimistic technology projections [37, 38, 39, 40], albeit with an associated increase in powertrain weight (see figure 5). In contrast, the conventional battery architecture not only erodes most of the underlying turbofan-level benefits in fuel burn, but also incurs an additional powertrain weight penalty that can result in a net fuel burn increase, even on this relatively short-range mission, where TSFC improvements are largest due to the higher proportion of non-cruise flight segments.

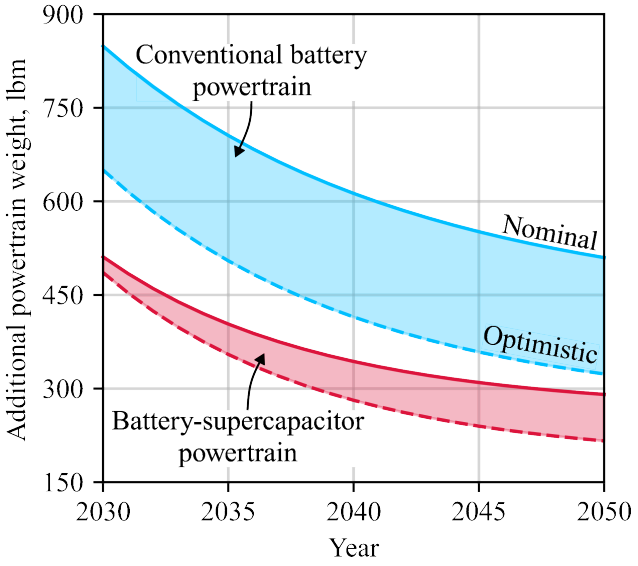


Figure 5 – Additional weight due to electric powertrain, for both engines.

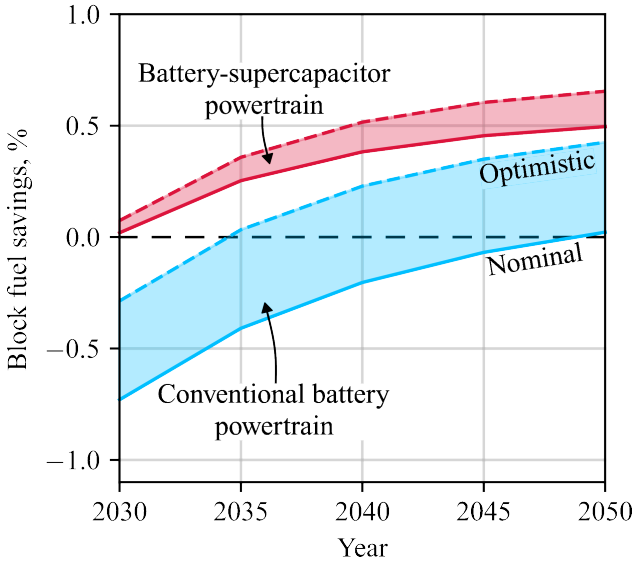


Figure 6 – Block fuel savings for a typical mission of 600 nmi.

The concept is therefore technically sound at the turbofan level, but its aircraft-level viability depends critically on powertrain integration strategy. A standalone architecture dedicated solely to transient as-

sistance carries an inherent weight penalty that substantially dilutes the engine-level gains. More synergistic approaches, such as inter-spool power transfer or shared electrical storage within a broader More Electric Aircraft (MEA) architecture, represent the most promising paths to capturing the full efficiency potential of the concept [11].

3.2 Dual-fuel Combustion

As established in section 1.2, business aviation's operational profile presents a fundamental tension for decarbonization: while most flights are short-haul, operators require the flexibility to cover occasional very long distances, often from small airports with limited infrastructure. Pure battery-electric or hydrogen-only propulsion cannot satisfy these constraints simultaneously. The hydrogen-kerosene dual-fuel concept addresses this by burning hydrogen for the most frequent short-distance flights, thereby reducing GHG emissions for the most frequent flights, while retaining full Jet A-1 capability for long-range operations, when hydrogen is unavailable, and for flight reserves [12, 13].

The dual-fuel concept was evaluated by assuming that the turbofans are capable of burning both hydrogen and jet fuel while maintaining the same performance and weight as the baseline engines. A fuselage plug aft of the cabin houses the liquid hydrogen tank and related systems, sized for a 600 nmi mission, as illustrated in figure 7. As illustrated in figure 8, the added weight and aerodynamic drag reduce the four-passenger range by 21%, from 3,408 nmi to 2,687 nmi, in kerosene-only mode, and by 11% to 3,044 nmi when both fuels are available, rendering only 0.03% of all Challenger 300 flights in our dataset infeasible for 2022. By contrast, a hydrogen-only conversion would fail to complete the 600 nmi design mission as reserves would also be flown on hydrogen, confirming that the dual-fuel approach imposes a substantially smaller penalty on overall operational flexibility.

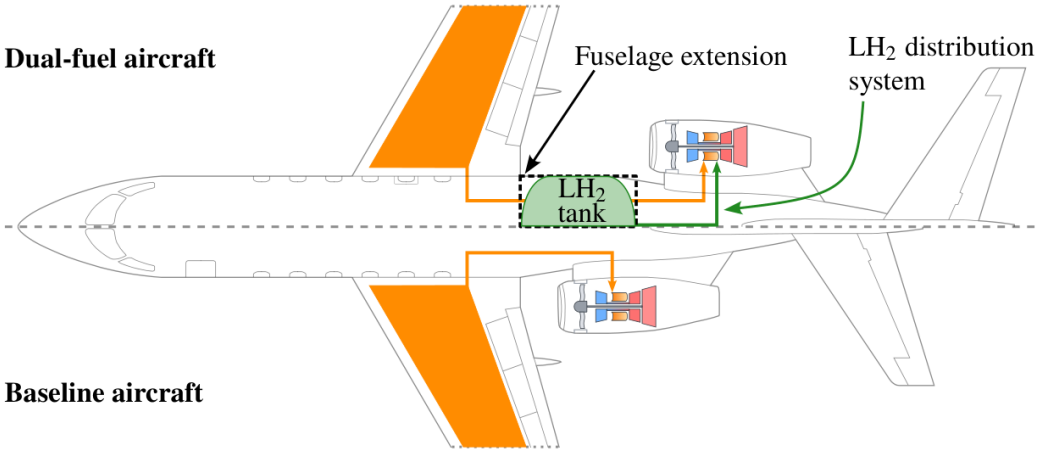


Figure 7 – Comparison of dual-fuel aircraft (top) and reference aircraft (bottom) showing fuselage extension to accommodate liquid hydrogen storage.

The impact of hydrogen infrastructure availability was evaluated by assuming that hydrogen will initially be available at large commercial hubs, from which it is then transported to small airports within a given radius. In-flight emissions from combustion were evaluated for all flights from Challenger 300 jets in the dataset discussed in section 1.2 (i.e., 762 aircraft totalling 171,553 flights), which are representative of the BRAC, while increasing the hydrogen availability until full coverage is achieved. Figure 9 showcases the achievable reduction in fleet-level in-flight combustion emissions over a year compared to the baseline aircraft.

A minimum hydrogen distribution radius around large commercial hubs is required before the weight and drag penalties of the dual-fuel aircraft reach break-even in terms of in-flight combustion emissions. At the fleet level, this break-even occurs at a supply radius of approximately 10 miles. Beyond this threshold, fleet-level $CO_{2,eq}$ reductions become significant, reaching 31.4% at a 130-mile radius. Conversely, if hydrogen remains available only at the large hubs themselves, fleet-wide emis-

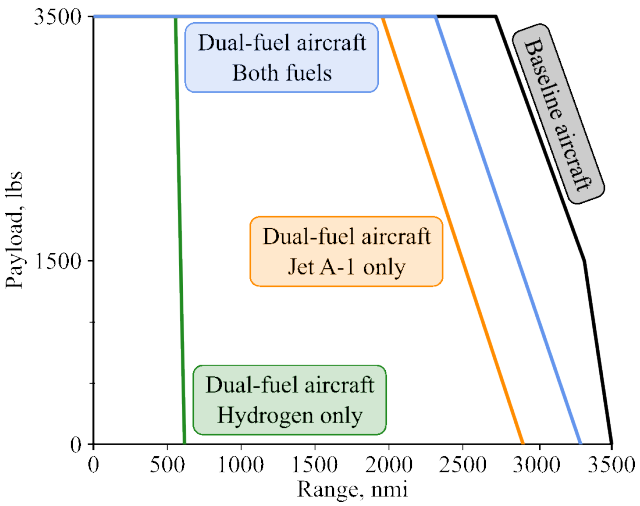


Figure 8 – Payload-range capability of the Dual-Fuel and baseline aircraft.

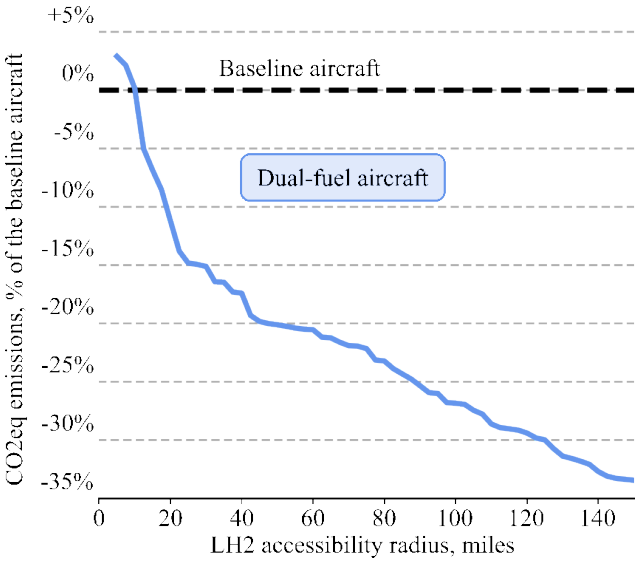


Figure 9 – Impact of LH_2 accessibility radius on Dual-Fuel architecture CO2eq emissions.

sions increase by approximately 3% due to the aircraft's added weight and drag. Even beyond the break-even radius, the dual-fuel fleet consumes approximately 8.8% more energy than the reference aircraft, meaning the concept's net environmental benefit remains sensitive to the carbon intensity of the hydrogen production pathway.

3.3 Hydrogen-Electric

As noted earlier, although it does not yet satisfy the operational requirements of business aviation, the hydrogen-electric architecture provides a valuable example for examining the potentially complex interactions that may arise when stakeholders collaborate on a novel propulsion architecture.

To evaluate the implementation of the hydrogen-electric propulsion architecture within a collaborative multidisciplinary design environment, the workflow was structured to capture the major disciplinary interactions associated with hydrogen storage, power generation, propulsion, thermal management, and aircraft-level performance assessment while enabling distributed execution across heterogeneous analysis tools. Figure 10 presents the finalized XDSM-based MDAO workflow adopted for the hydrogen-electric propulsion architecture within the distributed CPACS–RCE environment. The workflow decomposes the integrated propulsion system into five tightly coupled disciplinary work packages corresponding to aircraft performance and sizing, LH_2 tank sizing, superconducting propulsion components, fuel cell sizing, and thermal management. The XDSM formalism explicitly captures the dominant multidisciplinary coupling pathways governing the architecture, including mass–energy interactions, cryogenic cooling requirements, propulsion-efficiency feedback, and thermal-rejection dependencies. In particular, the workflow highlights the central role of the thermal-management subsystem, which acts as the primary coupling bridge between the superconducting propulsion chain and the hydrogen fuel-cell system through both cryogenic and non-cryogenic heat-management loops. It has to be noted that this workflow also demonstrates the successful integration of different tools: Matlab/Simulink for the superconducting propulsion and Python code for the remaining work packages.

Given the complexity of this architecture and the large number of interdependent parameters, considerable work remains before we can approach a feasible design, but it is already clear that, given current technology, the weight of the fuel cells prevents achieving any reasonable design. Therefore, no quantitative example could be provided at the time of writing this paper. However, having put in place a complete and working MDAO framework to perform this type of analysis is a significant achievement in itself.

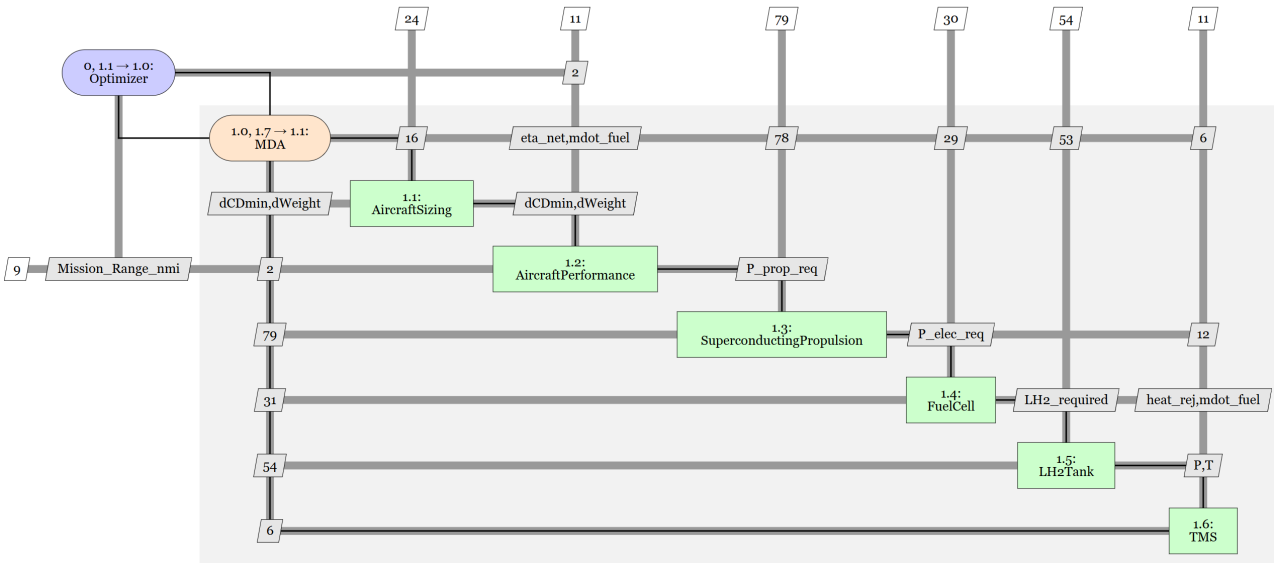


Figure 10 – Extended Design Structure Matrix (XDSM) representation of the distributed MDAO workflow adopted for the hydrogen-electric propulsion architecture.

4. Key Takeaways and Lessons Learned

This section synthesizes the key takeaways and lessons learned from Project EAP, organized into four categories: (1) the practical realities of business aviation operations, (2) the feasibility of alternative propulsion architectures for business jets, (3) individual subsystem analysis modelling and analysis, and (4) collaborative MDAO in an industrial context.

Operational reality of business jets

- ADS-B data analysis confirms that business aviation's operational profile is fundamentally bi-modal: while the majority of flights are relatively short, most business jets fly long-distances occasionally, meaning that range capability cannot be traded away entirely even for aircraft primarily used on short missions.
- The diversity of airports served, predominantly smaller, less-congested facilities far from major commercial hubs, makes ground infrastructure availability (electric charging, hydrogen supply) a critical constraint on any alternative propulsion concept, independent of aircraft performance considerations.

Alternative propulsion architectures

- The electrically-assisted turbofan concept demonstrates that meaningful efficiency gains are achievable with modest electrical energy requirements, but aircraft-level viability hinges on powertrain integration strategy; a standalone transient-assist architecture carries an inherent weight penalty that largely offsets engine-level gains.
- The dual-fuel hydrogen-kerosene concept is the most operationally compatible architecture identified for business aviation, as it preserves long-range capability and airport flexibility while enabling fleet-level in-flight $CO_{2,eq}$ reductions as hydrogen infrastructure matures. However, the concept's environmental benefit is contingent on both hydrogen availability at smaller airports and the carbon intensity of the production pathway.
- In the hydrogen-electric architecture, if we set aside that most of the underlying technologies are still at a low but steadily improving TRL, the weight and thermal management needs of the fuel cells remain a well-known bottleneck that currently prevents suggesting any viable propulsion architecture. It is still unclear if the weight of the thermal management system could be kept

within acceptable limits. By contrast, the mass and performance of all other components is not an issue a priori.

Individual Subsystem Analysis Aspects

- A flexible, parametric LH_2 tank sizing model enables the identification of the optimal tank configuration within the sizing constraints of the aircraft, considering safety-related aspects such as minimum number of tanks, dormancy and venting; allowing fuselage cross-sectional modification would allow optimizing the tank weight.
- Heat exchanger sizing is important for the overall system performance, but the heat exchanger dimensions have been shown as less critical than the sizing of the fuel cell.
- Environmental Impact Assessment using an LCA approach is very complex and includes significant uncertainty, which has to be addressed properly.

Collaborative MDAO in an industrial setting

- The use of the open-source integration platform RCE allowed the implementation of a distributed collaborative workflow, using tools developed by different partners with different software. Defining clear interfaces (using standards like CPACS) and conceptualizing the workflow early is a key success factor; the remote execution introduces significant coordination overhead, however, it allows for collaborative work, promoting sharing of expertise rather than a siloed, simplified analysis.
- Collaborative MDAO deployment in industrial environments is governed not only by numerical coupling complexity but also by socio-technical constraints, including organizational autonomy, intellectual-property protection, cybersecurity policies, and the use of distributed black-box disciplinary tools. The developed Holistic Collaborative MDAO Selection (HCMS) framework helps to consider these aspects.

5. Conclusion

This paper summarized key results of project EAP, a four-year university-industry collaboration investigating the feasibility of alternative propulsion concepts for business aviation. The project combined statistical analysis of flight data, aircraft-level trade studies, and a distributed design-environment perspective to narrow the propulsion design space to solutions that preserve the defining flexibility and performance of business jets.

Operationally, ADS-B data showed that business-jet usage is dominated by short missions but still includes infrequent long-range legs and a highly fragmented airport network, which together make both range retention and scalable ground infrastructure key feasibility constraints. Within this context, two propulsion concepts were found to merit continued attention. Electrically-assisted turbofans can unlock small but measurable efficiency gains by using limited electrical energy during transient events to relax operability-driven design margins, though aircraft-level benefit depends strongly on the mass and integration of the electric powertrain. Dual-fuel hydrogen-kerosene combustion offers a pragmatic pathway to reduce in-flight $CO_{2,eq}$ on the most common missions while retaining Jet A-1 capability for long-range operations and reserve requirements; however, its net benefit remains coupled to hydrogen availability beyond major airport hubs and to the upstream carbon intensity of hydrogen. The hydrogen-electric architecture is not ready to be quantified yet, but the weight and heat management of fuel cells is a real (and known) bottleneck at this time.

Finally, the Holistic Collaborative MDAO Selection methodology highlighted that deploying multidisciplinary workflows across industry-academia partnerships requires treating IP, cybersecurity, governance, and heterogeneous tooling as first-order constraints alongside numerical coupling. Future

work should refine subsystem fidelity and integration assumptions, extend environmental assessments to full life-cycle impacts, and mature secure collaborative MDAO implementations to accelerate concept down-selection under realistic program constraints.

6. Contact Author Email Address

Please direct any questions or comments to Prof. David Rancourt at David.Rancourt2@USherbrooke.ca.

7. Copyright Statement

The authors confirm that they, and/or their company or organization, hold copyright on all of the original material included in this paper. The authors also confirm that they have obtained permission, from the copyright holder of any third party material included in this paper, to publish it as part of their paper. The authors confirm that they give permission, or have obtained permission from the copyright holder of this paper, for the publication and distribution of this paper as part of the ICAS proceedings or as individual off-prints from the proceedings.

References

[1] Honeywell International Inc. 2024 Global Business Aviation Outlook. Market report, Honeywell Aerospace, October 2024.

[2] Andrew Murphy and Valentin Simon. Private jets: can the super-rich supercharge zero-emission aviation? Technical report, Transport & Environment, April 2021.

[3] Thierry Dubois. Climate protestors storm static display at EBACE. *Aviation Week Network*, 23 May 2023.

[4] International Civil Aviation Organization. States Adopt Net-Zero 2050 Global Aspirational Goal for International Flight Operations, October 2022.

[5] European Commission. Flightpath 2050 Europe's Vision for Aviation, Maintaining global leadership and serving society's needs, Report of the High-Level Group on Aviation Research. Technical report, 2011.

[6] FAA. United States, 2021 Aviation Climate Action Plan. Technical report, Federal Aviation Administratio, 9 November 2021.

[7] Dan Hubbard. Business Aviation Pledges Net-Zero Carbon By 2050 and Increasing Fuel Efficiency as Part of Renewed Climate Commitments. *National Business Aviation Association*, 12 october 2021.

[8] Eytan J. Adler and Joaquim R.R.A. Martins. Energy demand comparison for carbon-neutral flight. *Progress in Aerospace Sciences*, 152:101051, January 2025.

[9] Jennifer Ramm, Antonia Rahn, Daniel Silberhorn, Kai Wicke, Gerko Wende, Veatriki Papantoni, Florian Linke, Markus Kühlen, and Katrin Dahlmann. Assessing the feasibility of hydrogen-powered aircraft: A comparative economic and environmental analysis. *Journal of Aircraft*, 61(5):1337–1353, 2024.

[10] Khaled Alsamri, Jessica J. De la Cruz, Melody Emmanouilidi, Jacqueline L. Huynh, and Jacob Brouwer. Methodology to Assess Emissions and Performance Trade-Offs for a Retrofitted Solid Oxide Fuel Cell Hybrid and Hydrogen Powered Aircraft. In *AIAA SCITECH 2023 Forum*, National Harbor, MD & Online, January 2023. American Institute of Aeronautics and Astronautics.

[11] Jacob Cadrin-Aubin, Mathieu Bouchard, and David Rancourt. Business Aviation Turbofan Efficiency Improvement by Electrical Assistance During Transient Operations. In *AIAA AVIATION FORUM AND ASCEND 2025*, Las Vegas, Nevada, July 2025. American Institute of Aeronautics and Astronautics.

[12] Louvel, Nathan, Bouchard, Mathieu, and Rancourt, David. Preliminary Exploration of a Kerosene-Hydrogen Propulsion System Applied to a Business Aicraft. *Canadian Aeronautics and Space Institute AERO, Ottawa, Canada*, 14-16 November 2023.

[13] Nathan Louvel, Mathieu Bouchard, and David Rancourt. Impact of Hydrogen Availability at Airports on the Potential Environmental Benefits of Hydrogen-Kerosene Dual-Fuel Business Jets Using ADS-B Data. In *AIAA AVIATION FORUM AND ASCEND 2025*, Las Vegas, Nevada, July 2025. American Institute of Aeronautics and Astronautics.

[14] Xavier Arcand, William Mooney, Dany Francoeur, Hassan Azarkish, Mathieu Bouchard, and David Rancourt. Evaluation of Thermal Runaway Venting Characteristics for High-Energy Density and High-Power Density 21700-Format Li-ion NMC Cells. In *AIAA AVIATION FORUM AND ASCEND 2025*, Las Vegas, Nevada, July 2025. American Institute of Aeronautics and Astronautics.

[15] William Mooney, Mathieu Gendron, Xavier Arcand, Dany Francoeur, and David Rancourt. Design and Operation of Low-Cost Multi-Scale Test Beds for Battery Thermal Runaway Initiation and Propagation. In *35th Congress of the International Council of the Aeronautical Sciences (ICAS)*, Sydney, Australia, September 2026.

[16] ADS-B Exchange. ADS-B Exchange - track aircraft live, 2024.

[17] Nathan Louvel, Mathieu Bouchard, and David Rancourt. Statistical Analysis of Super-Midsize Business Jet Operations Using ADS-B Data. In *Toward Sustainable Aviation Summit 2025*, Toulouse, France, January 2025.

[18] Ali Tfaily. *Bayesian optimization and transfer learning for aircraft conceptual design*. PhD thesis, 2025.

[19] David K. Winstanley. HTF7000 Engine Design, Development and Uses. *SAE International Journal of Aerospace*, 6(2):545–554, September 2013. Number: 2013-01-2228.

[20] National Business Aviation Association. NBAA Management Guide. Management guide, 2025.

[21] Gala Licheva. Parametric hydrogen tank sizing model for aircraft conceptual design. Master's thesis, Concordia University, Montreal, Canada, December 2024.

[22] Gala Licheva and Susan Liscouët-Hanke. Cryogenic Tank Sizing Model for the Conceptual Design of Hydrogen-Powered Aircraft. In *ICAS 2024*, Florence, Italy, September 2024.

[23] Leonardo Cavini, Susan Liscouët-Hanke, and Nicole Viola. Acausal fuel cell simulation model for system integration analysis in early design phases. *Modelling*, 5(4):1435–1453, 2024.

[24] Eyrn Scarlet Sagala. Parametric heat exchanger sizing model for early aircraft design phases. Master's thesis, Concordia University, Montreal, Canada, August 2025.

[25] Eyrn Scarlet Sagala and Susan Liscouët-Hanke. Parametric Sizing Model for Cryogenic Heat Exchangers for Early Aircraft Design. *Aerospace*, 13(2):142, February 2026.

[26] Eric S. Hendricks and Justin S. Gray. pyCycle: A Tool for Efficient Optimization of Gas Turbine Engine Cycles. *Aerospace*, 6(8), August 2019.

[27] Ben A. Wender, Rider W. Foley, Troy A. Hottle, Jathan Sadowski, Valentina Prado-Lopez, Daniel A. Eisenberg, Lise Laurin, and Thomas P. Seager. Anticipatory life-cycle assessment for responsible research and innovation. *Journal of Responsible Innovation*, 1(2):200–207, 2014.

[28] Argonne National Laboratory. GREET Model (R&D Version 2023), 2023. R&D Version 2023.

[29] International Energy Agency. World Energy Outlook 2025, 2025. Accessed 2026-06-09.

[30] U.S. Energy Information Administration. Annual Energy Outlook 2025, 2025. Accessed 2026-06-09.

[31] Zeynab Yousefzadeh and Shannon M. Lloyd. Prospective life cycle assessment as a tool for environmentally responsible innovation. In *2021 IEEE International Symposium on Technology and Society (ISTAS)*, pages 1–9, 2021.

[32] Musavir Bashir, Susan Liscouët-Hanke, Nathan Louvel, Mathieu Bouchard, David Rancourt, and Antoine De Blois. An integrated collaborative framework for distributed multidisciplinary design optimization: Application to alternative aircraft propulsion systems. *Aerospace*, 13(5), 2026.

[33] Marko Alder, Erwin Moerland, Jonas Jepsen, and Björn Nagel. Recent Advances in Establishing a Common Language for Aircraft Design with CPACS. In *Aerospace Europe Conference 2020*, 2020.

[34] Brigitte Boden, Jan Flink, Niklas Först, Robert Mischke, Kathrin Schaffert, Alexander Weinert, Annika Wohlan, and Andreas Schreiber. RCE: An Integration Environment for Engineering and Science. *SoftwareX*, 15:100759, July 2021.

[35] Musavir Bashir, Gala Licheva, and Susan Liscouét Hanke. Transient boil-off and pressure dynamics analysis in aircraft liquid hydrogen tanks. *Aerospace Science and Technology*, page 111887, 2026.

[36] Federal Aviation Administration. 14 CFR §33.73 — Power or Thrust Response, 1971.

[37] Chrysoula L. Pastra, Christopher Hall, Gokcin Cinar, Jon Gladin, and Dimitri N. Mavris. Specific Power and Efficiency Projections of Electric Machines and Circuit Protection Exploration for Aircraft Applications. In *2022 IEEE/AIAA Transportation Electrification Conference and Electric Aircraft Technologies Symposium (ITEC+EATS)*, pages 766–771, Anaheim, CA, USA, June 2022.

[38] Christopher Hall, Chrysoula L. Pastra, Andrew Burrell, Jonathan Gladin, and Dimitri N. Mavris. Projecting Power Converter Specific Power Through 2050 for Aerospace Applications. In *2022 IEEE/AIAA Transportation Electrification Conference and Electric Aircraft Technologies Symposium (ITEC+EATS)*, pages 760–765, Anaheim, CA, USA, June 2022.

[39] Blake Tiede, Cody O'Meara, and Ralph Jansen. Battery Key Performance Projections based on Historical Trends and Chemistries. In *2022 IEEE/AIAA Transportation Electrification Conference and Electric Aircraft Technologies Symposium (ITEC+EATS)*, pages 754–759, Anaheim, CA, USA, June 2022.

[40] Chrysoula L. Pastra, Neri Ganzarski, Jonathan C. Gladin, and Dimitri N. Mavris. Projecting Key Performance Parameters for Electric Powertrain Components through 2050 for Aerospace Applications. In *AIAA AVIATION 2023 Forum*, San Diego, CA, USA, June 2023. AIAA 2023-4341.