System-Level Energy Pack Requirements for Sustainable Commercial Aviation

Arnson, Maxfield ; Cinar, Gokcin ; Waddington, Elias ; Ansell, Phillip J. ; Clarke, Matthew A. ; de Vries, R.; Salucci, F.; Prabhakar, Nirmit ; Gladin, Jonathan ; More Authors

DOI
10.2514/6.2024-3828

Publication date
2024

Document Version
Final published version

Published in
AIAA Aviation Forum and ASCEND, 2024

AIAA Aviation Forum and ASCEND co-located Conference Proceedings
29 July - 2 August 2024, Las Vegas, Nevada
AIAA AVIATION FORUM AND ASCEND 2024

10.2514/6.2024-3828

System-Level Energy Pack Requirements for Sustainable Commercial Aviation

Maxfield Arnson [1] and Gokcin Cinar [2]
University of Michigan, Ann Arbor, Michigan, 48109, United States

Elias Waddington [3], Phillip J. Ansell [4], and Matthew A. Clarke [5]
University of Illinois at Urbana-Champaign, Urbana, Illinois, 61801, United States

Reynard de Vries [6]
Delft University of Technology, 2629 HS Delft, The Netherlands

Francesco Salucci[7] and Nirmit Prabhakar [7]
Argonne National Laboratory, Lemont, IL 60439, United States

Jonathan Gladin[8]
Georgia Institute of Technology, Atlanta, Georgia, 30332-0150, United States

Mingxuan Shi [9]
The Boeing Company, Boeing Research & Technology, Everett, Washington, 98275, United States

Edward Lovelace [10]
Ampaire, Long Beach, California, 90808, United States

Peter de Bock [11]
Advanced Research Projects Agency – Energy (ARPA-E), Department of Energy
Washington, District of Columbia, 20585, United States

This paper presents comprehensive guidelines for the design of alternative energy aircraft, with a focus on battery-electric and hydrogen fuel cell powertrains. Traditional first-order models like the Breguet Range Equation are found to be inadequate for predicting the performance of electric aircraft due to their inability to account for varying power requirements and thermal management complexities. To address these limitations, the study utilizes advanced aircraft sizing methods following the guidelines provided. The methodology incorporates conceptual design stage analyses of wing and powertrain sizing, energy source sizing, weight predictions, thermal management, and power off-takes. Practical examples of electric aircraft design are provided to demonstrate the application of these guidelines. The results, which are repeatable using the information and open-source software provided, highlight the potential for different assumptions to lead to more optimized solutions. This paper provides crucial metrics and insights beyond common specific energy or power-to-weight ratios, offering detailed information that both aircraft designers and component technologists can use to develop technology solutions and optimize aircraft designs for sustainable aviation by 2050.

[1] Ph.D. Candidate, Department of Aerospace Engineering, University of Michigan, Ann Arbor, Michigan 48109, AIAA Student Member.
[2] Assistant Professor, Department of Aerospace Engineering, University of Michigan, Ann Arbor, Michigan 48109, AIAA Senior Member.
[3] Graduate Research Assistant, Department of Aerospace Engineering, AIAA Senior Member.
[4] Associate Professor, Department of Aerospace Engineering, AIAA Associate Fellow.
[5] Assistant Professor, Department of Aerospace Engineering, AIAA Member.
[6] Guest Researcher, Faculty of Aerospace Engineering, AIAA Senior Member.
[7] Aerospace Research Engineer, Vehicle and Mobility Systems, AIAA Member.
[8] Senior Research Engineer, Aerospace Systems Design Laboratory, School of Aerospace Engineering, AIAA Member
[9] Propulsion Engineer, Boeing Research and Technology, AIAA Member.
[10] Chief Technology Officer, Ampaire, AIAA Member.
[11] Program Director, Advanced Research Projects Agency-Energy, Department of Energy, AIAA Member.

Nomenclature

BRE	=	Breguet Range Equation
EAP	=	Electrified Aircraft Propulsion
EIS	=	Entry-into-Service
EPFD	=	Electrified Powertrain Flight Demonstration
FAST	=	Future Aircraft Sizing Tool
MTOW	=	Maximum Takeoff Weight
OEW	=	Operational Empty Weight
SLS	=	Sea-Level Static
TLAR	=	Top-Level Aircraft Requirements
TOGW	=	Takeoff Gross Weight
R	=	Range
C	=	Thrust-specific Fuel Consumption
E	=	Energy Density
L/D	=	Lift-to-Drag Ratio
$m_{\{\cdot\}}$	=	Mass
g	=	Gravitational Acceleration
$\eta_o p$	=	Overall Efficiency
η_p	=	Propulsive Efficiency
η_{maxpax}	=	Maximum number of passengers
η_{th}	=	Thermal Efficiency of Turbine Engine
η_{elec}	=	Electrical Efficiency of Electric Drive System
W_i	=	Initial Weight
W_f	=	Final Weight
V	=	Cruise Speed
ξ	=	Electrical Propulson Fraction fraction of total aircraft thrust at thrust to electrically driven propulsors

I. Introduction

In 2018, the aviation sector produced approximately 2.4% of global carbon dioxide emissions, a significant contributor to environmental concerns [1]. The overall impact on radiative forcing was even more substantial, estimated around 3.5% in 2011, considering additional effects from contrails and other emissions, such as NOx [1, 2]. The 2015 Paris Agreement created some of the most ambitious goals for reducing human impact on the climate to date [3]. In recent years, governing bodies have laid out climate action plans in accordance with the Paris Agreement. In 2019, the European Union presented the European Green Deal which briefly mentions aviation emissions and suggests ending fossil fuel subsidies for both aviation and maritime transport [4]. Since its inception, it has evolved to include more specific goals and regulations for the aviation sector. In 2022, the EU Council and Parliament have reached an agreement on a proposal specifying action plans for the aviation sector under the “ReFuelEU” initiative as part of the Green Deal, which was adopted in late 2023. This includes accelerating sustainable aviation fuel (SAF) usage and promoting alternative energy sources such as hydrogen [5].

In the United States, the Federal Aviation Administration (FAA) outlined its climate action plan with a net-zero by 2050 goal in 2021 [6]. In 2022, Congress passed the Inflation Reduction Act which allocated $300 million for research towards SAFs and sustainable aircraft technology. 80% of this funding is for SAF research [7]. Increased attention, regulation, funding, and research in the field of sustainable aviation allows faster progress towards the 2050 goals. Other efforts include ASCEND, REEACH, and PROPEL-1K programs at the Department of Energy’s Advanced Research Projects Agency – Energy (ARPA-E) that focus on electrified powertrains, power generation and energy storage respectively for the elusive future objectives of hybrid and fully electric flight.

While there has been heightened focus, achieving net zero aviation yet remains a distant goal, projected to be several decades away [8]. To meet the 2050 goals, it is essential to strategically coordinate current research efforts. For example, it would be an inefficient use of resources if a battery with the specific energy of jet fuel is developed, but with a limitation of 100 charge-discharge cycles. This example of the prioritization of specific energy over lifecycle capability exemplifies a potential misalignment in technical development that may undermine future sustainable aviation goals. To prevent such misalignments, it is imperative to foster collaboration between aircraft designers and technology experts immediately.

The integration of electric and hybrid-electric aircraft into the aviation industry necessitates a collaborative effort across aerospace, electrical, and mechanical engineering disciplines. Traditional structures of engineering society conferences and academic departments often segregate these disciplines, hindering interdisciplinary coordination. Aerospace designs and mission simulation expertise resides primarily with the aerospace community, jet engine and propulsion systems reside with the mechanical and combustion communities, and electric powertrain, battery and power electronics expertise resides with the electrical engineering community. The future of sustainable aircraft requires collaborative efforts and potentially realignment to work towards hybrid and electric flight. Forums such as the AIAA/IEEE Electric Aircraft Technologies Symposium (EATS) and the recent joint NASA-DOE Battery Workshop held in 2023 provide a pivotal platform for bridging these disciplinary divides.

In the NASA-DOE Battery Workshop, multidisciplinary experts convened to align their efforts, focusing on common mission parameters and aircraft reference designs. Several authors of this paper attended the workshop, where a significant communication gap between system designers and component researchers became apparent. This gap was most noticeable during discussions between aircraft designers and battery technologists. While the aircraft designers focused on how batteries could enable specific missions, they often overlooked the need to articulate detailed, battery-level technical requirements. On the other hand, battery technologists were prepared to offer solutions that met specific energy criteria, yet they regularly struggled to adapt these solutions to other mission-critical aspects, such as the high-power requirements essential for efficient aircraft operation. This scenario highlighted the pressing need for a more integrated communication framework, one that effectively bridges the divide between broad design objectives and the precise technical specifications required at the component level.

Consequently, the AIAA Electrified Aircraft Technologies Technical Committee formed a discussion group of experts from the industry, academia, and government, to identify and document the common misconceptions and important nuances in designing an electric aircraft. This paper is the resulting outcome of this effort, aiming to address the aforementioned communication gap, illustrated by the incident where a proposed battery solution met specific energy requirements but not the power requirements for aircraft operation. To address such challenges, the study proposes a universal communication framework, not limited to batteries but encompassing various types of energy storage systems in an energy-storage-agnostic manner. This framework aims to translate overarching aircraft requirements into specific energy storage subsystem criteria, providing clear and actionable goals for technologists. This approach is pivotal in bridging the divide and advancing technologies crucial for sustainable aviation.

The importance of collaborative initiatives like the AIAA/IEEE EATS and the NASA-DOE Battery Workshop in advancing hybrid and fully electric flight technologies is paramount. Yet, the success of these collaborations depends on clear, detailed, and effective communication across disciplinary boundaries. This paper contributes to this vital preparatory phase, establishing a method of communication that facilitates the development of hybrid and fully electric flight technologies.

A. Literature Review

The following literature review will examine existing research on aircraft design and component development in the context of electric and sustainable aviation, identifying gaps and areas where communication between aircraft designers and technologists can be improved.

The Breguet Range Equation (BRE), presented in Eq. 1, is a fundamental equation for estimating aircraft performance. It relies on key high-level performance parameters: aerodynamic efficiency (via L/D), propulsion efficiency (via $TSFC$, or C), and structural design (via W_i/W_f). Historically, this equation has been highly effective in calculating aircraft range using only a few key performance parameters (KPPs) within conventional propulsion systems.

$$R = \frac{V}{C}\frac{L}{D}\ln\left(\frac{W_i}{W_f}\right) \quad (1)$$

However, with the aerospace industry's shift towards unconventional aircraft, such as electrified models, the traditional BRE comes short in estimating the range due to the characteristics of these new propulsion systems. This is because, in its conventional form, BRE relies on the assumption that the difference between the initial and final weight of the aircraft is a direct indicator to how much energy is available for flight. To overcome this limitation, various modifications to BRE have been derived, generally tailored to a specific propulsion architecture of interest.

An approach to develop preliminary equations for unconventional aircraft came in 2012 when Hepperle derived an instance of a modified-BRE assuming constant aircraft mass [9]. This equation was used to show the drawbacks of constant mass aircraft as design range increases and to estimate the required energy density of batteries before they became a suitable replacement for jet fuel, although notes that specific energy density would have to increase from 750 to 1,500 Wh/kg to attract commercial interest for regional flights if they were to fly similar missions.

Jansen et. al derived range equations for more specific turboelectric propulsion systems, conducting break-even analysis for specific power and electric drive efficiency [10]. The analysis concluded by outlining the minimum required specific power and drive efficiency required by turboelectric aircraft to fly the same range as their conventional counterparts. The analysis noted that advanced aircraft technologies enabled by turboelectric aircraft, such as boundary layer ingestion, increased bypass ratio, and increased lift-to-drag ratio, could relax the breakeven requirements for specific power and drive efficiency. Duffy and Jansen furthered this research by expanding the efficiency terms depending on the selected turboelectric or hybrid electric architectures [11]. This work posed an additional performance parameter, electrical propulsion fraction, to consider, as given in Eq. 2. The efficiency term in this equation depends on the aircraft type (in terms of its propulsion architecture), and are given in Table 1.

$$R = \frac{L}{D}\frac{Se_{\text{fuel}}}{g}\ln\left(\frac{W_f}{W_i}\right)\left(\frac{\eta_p\eta_{\text{th}}\eta_{\text{elec}}}{(1-\xi)\eta_{\text{elec}}+\xi}\right) \tag{2}$$

Table 1 Overall efficiency for different aircraft types for use in Eq. 2 from Ref. [11].

Aircraft Type	Overall Efficiency
Conventional Aircraft (AC)	$\eta_{0AC} = \eta_{\text{pAC}}\eta_{\text{thAC}}$
Fully Turboelectric Aircraft (TE)	$\eta_{0TE} = \eta_{\text{pTE}}\eta_{\text{thTE}}\eta_{\text{elecTE}}$
Partially Turboelectric Aircraft (PE)	$\eta_{0PE} = \frac{\eta_{\text{pPE}}\eta_{\text{thPE}}\eta_{\text{elecPE}}}{(1-\xi)\eta_{\text{elecPE}}+\xi}$
Parallel Hybrid Electric Aircraft (HE)	$\eta_{0HE} = \frac{\eta_{\text{pHE}}\eta_{\text{thHE}}\eta_{\text{elecHE}}}{(1-\xi)\eta_{\text{elecHE}}+\xi\eta_{\text{theHE}}}$

de Vries et. al derived an equation similar to Duffy and Jansen, defining the power split slightly differently, however it can be shown that the two forms are equivalent [12].

Numerous studies have investigated beyond predesign and looked at the conceptual design of unconventional aircraft configurations. Gnadt et. al studied the effects of varying battery energy density for fully electric aircraft and considered which existing battery chemistries are most likely to be used in aircraft design [13]. This study optimized fully electric aircraft designs and compares weight penalties to that of a conventional reference, the Airbus A320neo. It was concluded that current battery technology does not enable practical fully electric flights at the Airbus A320neo scale and missions. Although it was noted that improvements in battery technology and reducing mission range could lower CO2 emissions (depending on electrical grid improvements), despite an increase in total energy consumption relative to the reference aircraft.

Cinar et. al explored the design space of hybrid electric regional aircraft [14]. The research demonstrated that both thin-haul and regional class turboprops, when employing a parallel hybrid electric architecture, achieved notable fuel savings compared to their advanced technology conventional counterparts, when the energy and power management of the hybrid system was optimized during the aircraft sizing process. This study explored various operational modes of a parallel hybrid electric system during the aircraft sizing process. This exploration included scenarios like fully electric taxi operations, takeoff assist, and climb assist, with variations in power levels, altitudes, and durations, encompassing a range of hybridization strategies, as well as the impact of battery charging during different flight stages. A critical finding of the paper was the significant influence of the energy and power management strategy on the sizing of the battery and, consequently, the fuel reduction benefits of new aircraft designs. For instance, in scenarios where the hybrid electric powertrain was utilized for takeoff assistance, the dimensioning of the battery was governed more by the peak discharge rate (i.e. the battery power requirement) rather than the total energy required (i.e. the battery specific energy requirement).

De Bock and Tew evaluated how hybrid electric aircraft using range extenders and electric propulsion could potentially be competitive with commercial flight by increasing overall propulsion efficiency to compensate for potentially increased cost of sustainable aviation fuels (SAF) [15].

The Center for High Efficiency Electrical Technologies for Aircraft (CHEETA) developed a concept for a liquid-hydrogen fuel-cell electric transport-category aircraft [16]. The aircraft was developed to match the range, speed, and payload capacity of the Boeing 737-800 but with no NO_x or CO_2 emissions in-flight. A study by Waddington et. al demonstrated the differences between fuel cell and conventional turbine performance at the mission level, the importance of integration of fuel cell thermal management, and the net impacts of fuel cell degradation throughout the aircraft lifecycle [17]. A key difference highlighted in the study was the use of inlet compression to the fuel cell to provide more power at higher altitudes than an equally sized combustion system.

The current literature is focused on a design perspective and lacks information essential to practical component development. The focus is on breakeven requirements for energy or power density and overall efficiency. Other papers focus on the design of a specific sustainable aircraft and outline any component assumptions made. This gives technologists a window into the thought process, although there may be implicit assumptions that would not be apparent to researchers with no aircraft design experience. A high-level approach to bridging this gap is required to create a shared language between researchers. Conceptual design analyses often reveal the sensitivity of aircraft performance to parameters not addressed in the BRE, corroborating the need for high-level relationships between top level aircraft requirements (TLAR) and component design.

This paper incorporates perspectives on novel aircraft design from academia, the electric aircraft industry, and the Department of Energy. A balance of inputs at the system level encourages practical aircraft design and technological improvement goals that would be absent in a purely academic exercise. This paper aims to demonstrate that direct and cross disciplinary collaboration is a necessity if the existing sustainability timeline is to be met. Moreover, it will serve as an open letter to the technologist community promoting a shared language between the levels of research.

II. Guidelines for Alternative Energy Aircraft Design

This section provides detailed guidelines for designing aircraft powered by alternative energy sources, addressing the communication gap between aircraft designers and technologists highlighted in the introduction section. By focusing on key areas such as wing and powertrain sizing, energy source sizing, weight predictions, thermal management, regulatory impacts, and practical considerations for conceptual design, these guidelines aim to align technical development with overall aircraft design goals.

A. Wing and Powertrain Sizing: Point Performance Equations

A fundamental step in the aircraft design process is to determine how much wing area is required, and how much thrust (generally used for turbojet or turbofan aircraft) or power (generally used for propeller aircraft) is required from the propulsion system. Since at the beginning of the design process the weight of the aircraft is unknown, this is often done with normalized parameters such as wing loading (W/S, i.e. how much weight of aircraft does each unit of wing area carry) and power loading (W/P, i.e. the inverse of how much (shaft) power is required from the powertrain per unit weight of the aircraft) or thrust-to-weight ratio (T/W, i.e. how much thrust is required from the powertrain per unit weight of the aircraft). In other words, the designer must select the wing loading and power loading (to be used interchangeably with "thrust-to-weight ratio" in the rest of this section) of the aircraft. This can be assumed based on existing aircraft data, or calculated using a performance constraint diagram—also known as a matching diagram or wing-loading/power-loading diagram.

There are several reasons why the power loading of novel aircraft configurations that use battery-electric or hydrogen fuel-cell propulsion can be substantially different from conventional aircraft configurations. First, these aircraft often present a higher number of engines, meaning that "one engine inoperative" scenarios are less stringent for the maximum power requirements. Second, these engines are often placed in way to exploit beneficial aero-propulsive interaction effects (“distributed propulsion”), reducing or increasing the power required for a given flight condition. Third, electric motors and fuel cells present very different power lapses with altitude than conventional combustion engines, meaning that for a same power requirement at altitude, the power required from the powertrain at sea level is different. And finally, while for conventional aircraft the shaft power loading of the aircraft directly indicates how much power is required from the “engine” (in that case, a gas turbine or reciprocating engine), in the case of hybrid aircraft combining batteries, combustion engines, and/or fuel cells, the shaft power requirements must be split into requirements for each of the powertrain elements. For this reason, it is generally recommended to calculate the actual power loading required, rather than assuming a value based on existing aircraft. Example methodologies of how to do this can be found in Refs. [18, 19].

1. Energy Source Sizing: A Special Case for Batteries

A common misconception regarding battery-powered aircraft is that they are always limited by their low gravimetric energy density (specific energy) compared to jet fuel. While there is some truth to this assertion, it is not universally applicable. Battery design must also consider the power required from the energy source, which is the energy per unit time.

Traditionally, maximum power requirements have been the primary sizing condition for engines, whether electric or gas turbine. The multi-design point approach for engines considers extreme conditions where maximum power is necessary. This approach should also be applied to battery sizing criteria.

For all-electric aircraft, the total energy required often determines the size (weight and volume) characteristics of the energy source. An energy pack of this size can typically provide the necessary power for the design mission, such as takeoff or reaching the top of the climb. However, this is not always the case, particularly in short-range and hybrid electric missions. For instance, Cinar et al. [14] illustrates that in a parallel hybrid electric aircraft that hybridizes the takeoff and/or climb segments, the battery is sized based on power requirements regardless of the power split between the engine and the electric motor, system voltage, or other component-technology-related assumptions. This is because the power required for takeoff and climb is so high that even a small percentage of it can be substantial. Moreover, in these hybrid operations, the cruise segment is not hybridized, so the battery is not used for an extended period, making the energy requirement a secondary, albeit important, factor in battery sizing compared to power requirements. Note that the power and energy requirements also dictate the number of cells connected in series and parallel, given specific cell characteristics. This configuration determines the pack voltage and current. An example of this sizing methodology is provided in Refs. [20, 21].

Consequently, aircraft and battery designers must consider both the most stringent power and energy conditions for alternative energy sources. This is particularly crucial for batteries, as their capacity depends on the power being extracted (i.e., current). Additionally, battery performance degrades over time, and the most demanding power and energy conditions may occur at a low state of charge or toward the end of the battery's life. For example, the power required for a missed approach after an initial takeoff at less than 100% state of charge (SOC) could become the critical sizing factor, rather than the power needed for a fully charged battery at the initial takeoff. Similarly, a battery at the end of its lifecycle will not provide the same energy and power capabilities as it did during its initial cycles.

B. Weight Predictions

Estimating the weight of novel aircraft configurations with batteries and fuel cells is different from conventional aircraft for two reasons. On one hand, there are new components that are traditionally not included in the aircraft weight breakdown, such as batteries, electric motors, cables, or hydrogen tanks. The weight of these components must be estimated using dedicated methods or statistics, which can be found in literature with various levels of fidelity and accuracy. A common approach taken in the early phases of the conceptual aircraft design is to characterize components using a single parameter that scales the weight of the component with the power it has to produce or the energy it has to provide. For example, one can assume a specific power "kW/kg" for electric motors, or a specific energy "Wh/kg" for batteries.

On the other hand, the introduction of new components may affect the weight of components that are encountered in conventional aircraft and for which established weight prediction methods already exist in handbooks such as Torenbeek [22] or Roskam [23]. For example, the use of electric propulsion often comes hand-in-hand with an electrification of other aircraft subsystems, leading to an increase in electrical system weight and a reduction in pneumatic system weight, compared to what handbook methods would predict. Or if a hydrogen tank is installed in the fuselage, the increase in volume required and change in weight distribution is likely to affect the fuselage structural mass.

One effect that has been described in older handbooks [24] and that has recently been found to be particularly relevant for electric aircraft [25], is the fact that many aircraft weight components do not scale with the maximum take-off weight (MTOW) of the aircraft—as is often assumed in e.g. empty weight correlations—but with other parameters such as the energy weight or payload weight. For example, if a battery is installed in or on the wing of an aircraft, some components' weight increases proportionally to the increase in MTOW (e.g. the landing gear), other components' weight increases only slightly (e.g. the wing structural mass, since the battery also contributes to bending-moment relief if installed in the wing), and other components' weight is not affected (e.g. the weight of the chairs in the cabin or the avionics in the cockpit). As a result, in this case the overall empty mass of the aircraft scales less than linearly with the battery mass, and the empty weight *fraction* of the aircraft is much lower than simple MTOW-based statistics would suggest. This effect is reflected studies where bottom-up weight build-ups are calculated, such as Refs. [13, 26]. It is therefore of vital importance to carefully perform the weight estimation of aircraft configurations with substantially different propulsive and non-propulsive systems.

C. Thermal Management Considerations

1. Changes of Thermal Management Systems for Alternative Energy Sources

The thermal management system (TMS) of an airplane which utilizes alternative energy sources can be much different from the one that is in an airplane with conventional jet fuel. The TMS in a conventional jet-fuel airplane includes environmental control system (ECS), anti-icing system, electronics cooling, and passive cooling mechanism by ram air or engine fan air [27, 28]. Such systems are used to ensure proper temperature and pressure for pilots, crews, passengers, cargo, equipment, as well as preventing icing conditions. However, for an airplane with alternative energy sources, new heat loads or new heat sinks may be introduced, leading to new required functionalities of the TMS. For example, hybrid electric propulsion systems will add new generators or electric motors to the propulsion system, which can be significant heat loads with even lower temperature (low-quality heat) considering the amount of required propulsive power and the operational temperature. Specific thermal management mechanism needs to be designed to handle such heat loads, since the existing TMS is not capable of handling such low-quality heat effectively. In addition, the energy sources themselves can be heat loads too, such as batteries, because heat is generated during both the discharging and charging processes. On the other hand, alternative energy sources such as cryogenic fuels (liquid hydrogen, liquid natural gas, etc.) may be used as new heat sinks too, which can mitigate the heating problem but need new TMS designs to utilize its cooling potential. Thus, proper design changes of the TMS are needed to enable the new functionalities to handle new thermal management challenges.

To solve these emerging thermal management issues caused by utilizing alternative energy sources, one solution is to use existing TMS with new cooling/heating interfaces to the new heat loads. For example, the conventional ECS is used for battery cooling after cooling the cabin [29–31]. Upsizing the conventional TMS to reach higher cooling/heating capability is also an alternative solution compared to using the existing ones. For other cases, novel TMS designs will be needed. However, it is impossible to enumerate all feasible candidate TMS solutions for a given set of thermal management requirements. By noting that all TMS designs follow the basic heat transfer physics, and most of the TMSs are fundamentally heat pumps, Shi [27, 32] came up with a behavior-based methodology to systematically generate candidate TMS architectures. Heat transfer behaviors are used to guide the TMS architecture space exploration, and a machine learning-based method is used to filter out infeasible designs. Such method has shown that novel configurations can be generated to handle new thermal management needs, with consideration of new types of heat sinks.

2. Capturing Impacts of Thermal Management System Changes

As shown in previous work by Chakraborty [33] and Shi [34, 35], subsystems influence the airplane-level performance mainly through four ways: 1) change of weight; 2) change of zero-lift drag; 3) extraction of engine bleed power; and 4) extraction of engine shaft-power. Such impacts will further influence both the aerodynamic performance and propulsion performance of the airplane, and then further lead to differences in fuel burn or energy consumption for missions. Such impacts are illustrated in Fig. 1 [35].

For thermal management systems for alternative energy sources, a similar concept still applies. Adding new components for the new TMS functions will incur additional weight penalties. Using ram air as a heat sink will increase the zero-lift drag. Ram air is also only an effective means of cooling when the aircraft reaches high speeds to facilitate sufficient heat transfer – at lower speeds, a puller fan may be required. Heat pumps or pumping the cooling/heating fluid requires power. However, in such alternative propulsion systems, this power might not only come from the propulsor, but also from the energy pack. Therefore, the updated impacts can be shown by Fig. 2.

D. Impacts of Regulations On Energy Pack Weight Sizing Constraints

Many aviation regulations regarding safety have originated and evolved over decades of learnings from safety incidents. The lack of historical data on aircraft with electrified propulsion systems poses not only a problem for sizing (as discussed in section II.B), but for regulators as well. While the same problem may have existed at the beginning of the jet age, the challenge is that the electrified aviation market may grow much quicker, and regulators need to quickly develop methods to manage reliability and fault mechanism uncertainties. For the alternative aircraft designer, the complexity of the potential fault paths and the accommodations will have an impact on weight to establish sufficient

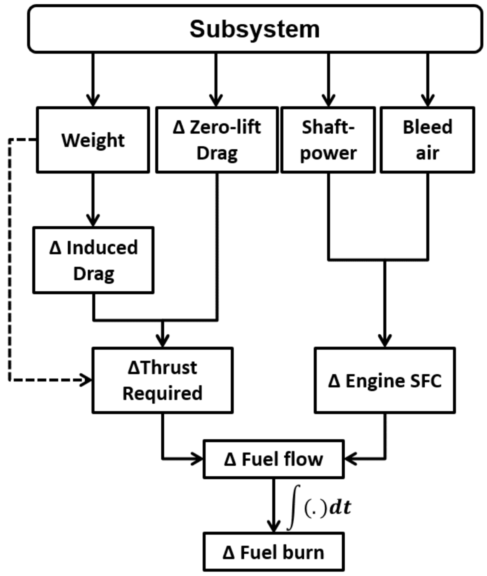


Fig. 1 Impacts of subsystems on airplane and mission-level performances [35]

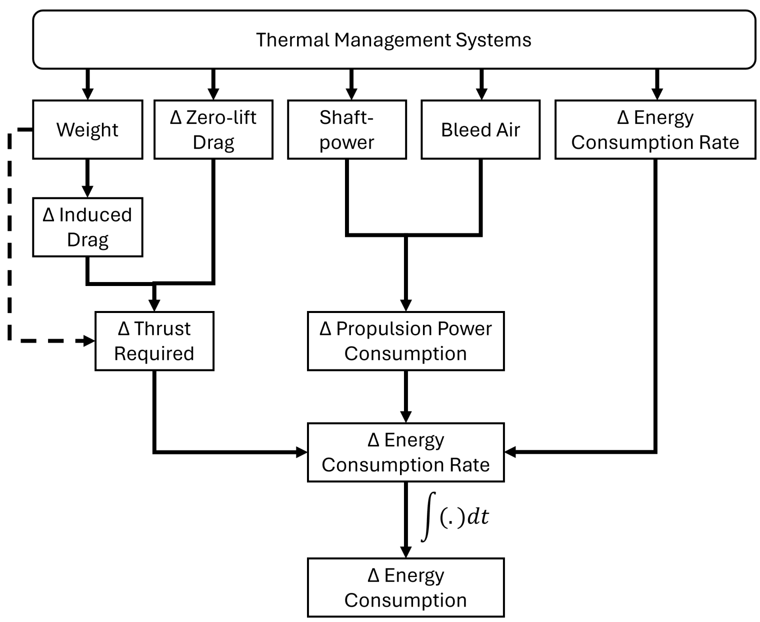


Fig. 2 Impacts of thermal management systems with alternative energy sources.

fault tolerance for the safety continuum requirements. While this paper is primarily focused on all-electric (battery or fuel cell) powertrains, this is one of the potentially interesting practical attributes of hybrid electric aircraft. Some of the key opportunities with hybrid electric are to 1) meet all reserve fuel requirements with liquid fuel with a delivered energy density factor of at least 12x lithium battery system reserves, and 2) fault accommodation potentially being met by a liquid fuel powerplant technology with decades of system safety history to reduce uncertainty.

It should be noted that not only do performance requirements (e.g., payload, range, fuel consumption, etc.) influence the alternative energy pack weight constraints, but the fuel jettison-related regulations also have great impacts. Based 14 CFR Part 25 [36], "*A fuel jettisoning system must be installed on each airplane unless it is shown that the airplane meets the climb requirements of §§ 25.119 and 25.121(d) at maximum takeoff weight, less the actual or computed weight of fuel necessary for a 15-minute flight comprised of a takeoff, go-around, and landing at the airport of departure with the* *airplane configuration, speed, power, and thrust the same as that used in meeting the applicable takeoff, approach, and landing climb performance requirements of this part.(§§ 25.1001)*" §§ 25.119 and and 25.121(d) refer to Landing climb: All-engines-operating condition and Approach regulations. When the battery is used as the alternative energy source of the airplane, special attention should be paid to these regulations because it would be natural to assume that the "fuel" or energy storage cannot be jettisoned. To ensure the corresponding compliance without having a jettison system, the low-speed aerodynamic performance needs to be analyzed if high credibility is desired. However, most existing publicly available conceptual design approaches/tools do not have the capability to do such low-speed aerodynamic analysis or, more specifically, to generate the drag polar associated with low-speed configuration. Therefore, there is a need to add such capability to address the alternative energy pack sizing challenge.

E. Practical Considerations for Conceptual Design

1. Electrified Subsystem Requirements

Aircraft requirements flow down to the electrified subsystem requirements and reflect, at the highest requirements level, the stakeholder mission for the aircraft. For the user stakeholder, the passengers buying tickets or shipping cargo, it is usually a matter of convenience and cost. Convenience attributes include availability from location to location, travel time, and other elements of logistical complexity. What is the price for different levels of convenience? For the provider stakeholders, including the airline operator and aircraft OEM, the primary measures are usually return on investment and scale of revenue. While these requirements seem abstract to the detailed electrified subsystem requirements, they are not, as will be described for some key electrified subsystems. The SAE Standard AIR 8678, *Architecture Examples for Electrified Propulsion Aircraft*, presents an organized and generalized decomposition of subsystem elements that may be present in electrified propulsion aircraft and the other subsystems that they typically interact with, shown in Figure 3 [37]. The following paragraphs under this section are practical implications for some of these key subsystems beyond the basic technical metrics of weight and SOC.

2. Energy Storage Systems (ESS)

The growing interest in reducing tailpipe emissions and the advances in battery technology have seen energy densities increase tenfold over the past decade. The aviation industry has shown increasing interest in adopting batteries as an alternate ESS in electrified aircraft systems [38]. If we track aircraft over the years, there has been a notable adoption of battery-electric systems in airplanes, with various battery types being utilized, including Nickel-Cadmium (Ni-Cd) [39], Sealed Lead-Acid [40], and Lithium-ion (Li-ion) batteries [41], each possessing distinct capacities. However, significant challenges prevent the widespread adoption of batteries as the primary energy carrier.

While battery-electric aircraft demonstrate superior end-to-end efficiency compared to Brayton-cycle engines, battery systems' energy and power densities, cyclability, safety, and abuse tolerance remain significant limitations [42]. As a consequence, numerous efforts, such as ARPA-E's Propel 1K [43], are underway to improve these performance metrics. The standout of the various battery systems are those using Li-ion batteries. Li-ion batteries have already been extensively integrated into various modes of ground transportation and manufacturing industries due to their superior properties when compared to other battery types. Being the third lightest element, the use of lithium allows us to pack as many charged particles as possible per unit volume for the same weight of battery. The focus of this paper will, therefore, be on lithium-ion battery technology, which has been the choice of battery packs on most electrified aircraft under development today. The most basic attributes of interest are as usual energy capacity, or when normalized by weight, gravimetric energy density (Wh/kg), and State of Charge (SOC), which indicates the ratio of the remaining usable energy (i.e., amount of 'charge') to the total usable energy capacity.

Beyond weight and SOC, other key attributes include gravimectric power density (W/kg), usable energy, cycle life, and installed cost. The usable energy is typically defined as the percentage of stored energy in a new pack that can be used in normal operation at the end of life when the pack is replaced. If a high energy density battery technology exhibits a relatively small usable energy fraction, the overall value of the technology may be diminished, potentially rendering it less advantageous compared to more mature lithium battery technologies. One way to capture this is to define the usable gravimetric density, still in Wh/kg, but where the Wh is only an end-of-life usable fraction of the ESS total stored energy. In this way, different technologies can be compared on a more level field. The next two attributes, cycle life and cost, are coupled from a practical stakeholder requirement perspective. Consider one technology that is capable of 1000 cycles before replacement and costs $100/kWh installed new, and then a second battery technology capable of 2000 cycles but at a cost of $200/kWh installed new. If the cost of initial installation and maintenance

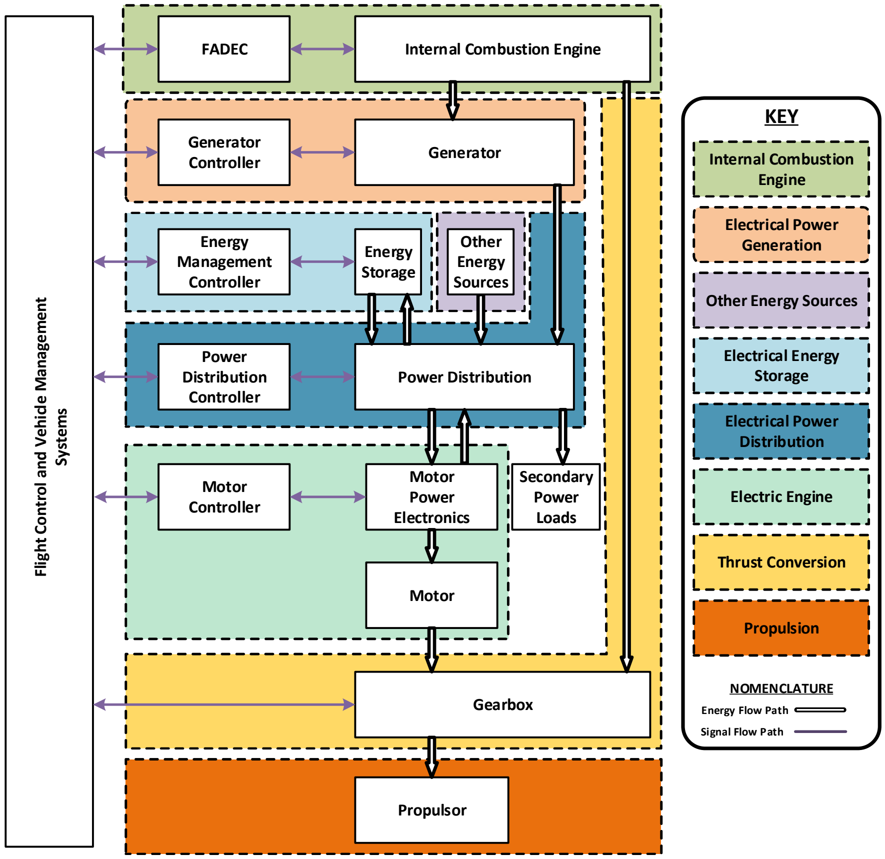


Fig. 3 SAE Standard Air 8678 [37].

replacements for these two solutions is calculated, the net lifecycle cost is the same to first order. In utility power projects, they are typically evaluated on a levelized cost of energy basis. The same can be done here. Both of these technologies have a basic levelized cost of $0.10/kWh/cycle, and within limits can be traded off evenly when designing an e-aircraft with a focus on other attributes such as inherent thermal runaway fault tolerance.

3. Electric Powertrains (Motor/Generators and Power Electronics)

Much of the focus in propulsion electric machinery for aviation is on weight, but weight should be traded off against efficiency with respect to its impact on other subsystems. The design point of a well optimized PM machine that delivers a given torque and speed, the weight of this machine is typically linearly proportional to the rated torque in first order analysis. Machine designers think about this as a constant shear stress at the machine airgap. To double the torque rating at constant shear stress, shaft speed, and efficiency then the surface area at the airgap needs to double, which might be as simple as doubling the stack length in a radial gap machine roughly doubling the weight of the machine as a result. Machines for a given shaft speed application (e.g. propeller shaft rpm) will typically be compared by their rated torque density (Nm/kg). For low-speed machines operating at propeller speeds typically around 1800 to 2200 rpm (or perhaps up to 4000 rpm for small distributed props) as opposed to gas turbine high spool speeds of 20k to 50krpm, the efficiency of the machine is typically dominated by the stator winding losses. The stator losses in turn are dominated by the weight of copper wire in the stators. Double the amount of copper and the first order the losses are cut roughly half. The weight of the machine goes up but so does the efficiency. This has direct implications on the amount of battery energy needed to deliver a propeller torque vs. time mission for the aircraft. In this way the weight of the propulsion motor impacts the weight of the battery for a given application and should be weighed in system analyses. The tradeoff weighting towards improving efficiency becomes stronger for longer mission applications. Each percent of efficiency improvement has twice as much weight impact on a battery sized for two hours vs. a battery sized for one hour of operation. A similar consideration is relevant for the power electronics used to condition electric power to/from the electric propulsion machine. For a given DC voltage distribution level, power electronics are typically compared by their current density (ADC/kg). Efficiency improvements in the power converters have a similar impact on battery sizing and weight. The weight implications for efficiency improvements in the power converters is typically more complex than in the electric machines though overrating the power devices and bus bars and changing switching frequencies are relevant design levers to consider.

4. High Voltage Distribution

The Boeing 787 Dreamliner, considered a 'more electric' aircraft, has 100 kilometers of wiring with over 3,500 connectors and 40,000 cable segments [44]. While much of this is low voltage and signal wire, in electrified propulsion aircraft applications for larger aircraft the weight of high voltage distribution between electric propulsion units in the wings and ESS supplies will be a considerable factor. Weight and balance traded off against high voltage distribution weight will be a considerable factor to evaluate in positioning the ESS subsystems within the aircraft structure. To reduce weight to transmit a given power level, voltage levels will be raised to the highest safe levels accounting for partial discharge effects and associated insulation and spacing requirements. Again, overrating of the cable ampacity and trading off copper for aluminum conductor will impact efficiency and battery weight.

III. Methodology for Electrifying Aircraft: Conceptual Approach and Preliminary Models

This section demonstrates a conceptual approach and presents preliminary models using publicly accessible tools. While not all elements from the guidelines are modeled in full detail, this approach offers practical examples for electrifying different classes of aircraft.

A. Supplemental Models

The work performed in this study used an open source software, Future Aircraft Sizing Tool (FAST) [45], developed with funding from the NASA Electrified Powertrain Flight Demonstration (EPFD) project, modified with the additional capabilities. The unmodified version of FAST is able to size conventional, hybrid electric, and fully electric aircraft concepts. The software utilizes a novel approach introduced by Cinar et. al. [46, 47] to describe various propulsion system architectures using "energy sources", "power sources", and "thrust sources", connected through "interdependency matrices." The matrices act as binary maps which connect the flow of power through propulsive components, allowing for modular use of conventional and unconventional energy sources, power producers, and thrust producers. Once a powertrain architecture is defined, FAST iteratively sizes an aircraft at a fixed design point. In other words, wing loading and thrust (or power) to weight ratio, along with several other parameters, are held constant and assumed feasible. The sizing iteration requires models, physics-based or data driven, to estimate component weights and energy consumption during power production. For the study conducted in this paper, additional models were required to address concerns raised in section II, which are described in the following subsections.

1. Battery Model

The battery model used for this study was developed using the method described in Tremblay and Dessaint [48]. The method is further adapted and the modeling parameters are tuned by as described in Ref. [21]. The battery model is a standard feature of FAST, which is well documented in the public repository. Therefore, only a high level overview is provided here.

Batteries are assumed to be Lithium-Ion, and their voltage drops according to the physics models described in the aforementioned sources. FAST stores several types of energy sources, and the battery model is called when an aircraft is flagged as having any type of battery as an energy source. An initial guess for battery weight is set by a user, as well as a number of battery cells in series, which sets a system voltage.

FAST communicates with the battery model by time-stepping through a mission profile and requesting power from the battery over a discretized time step. The voltage decreases as state of charge is depleted. At the end of the mission, FAST decides whether to resize the battery or not depending on the state of charge. If it is below 20%, the threshold for preserving battery life, the battery is made larger. If the SOC is above 23%, it is considered too large and downsized. Between these percentages the battery is considered suitable and is not resized. To resize the battery pack, FAST adds additional batteries wired in parallel (at the same voltage as set by the user) until the capacity of the new battery meets the required energy for the desired mission.

The capacity of a cell is set by the battery specific energy, which is parameterized by a user input. FAST cannot predict battery degradation over time, and requires a user to set an equivalent to end-of-life specific energy if degradation effects are to be considered.

2. *Fuel Cell Model*

The fuel cell model utilized in this study was adapted from previous work developed for CHEETA. This fuel cell is a high-temperature proton-exchange membrane fuel cell (HTPEMFC) with input air compression provided by a pump independent of the primary propulsion system. The fuel cell was estimated as a single 1-MW stack with the properties as listed in previous work [49]. This was then discretized at a specific power of 2.7 kW/kg, with the weight of the fuel cell being determined by the peak power requirement. Fuel tanks were estimated to weigh 65% of the weight of the fuel, as was estimated for the CHEETA aircraft. However, hydrogen fuel tanks are significantly more voluminous than conventional jet fuel tanks. Integrating these fuel tanks causes a significant structural weight increase due to the additional structure required to integrate [50]. To estimate the increased structural weight in this study, the ratio of CHEETA fuselage weight to the Boeing 737-800 fuselage weight was calculated and the estimated structural weight of this study's aircraft were increased to account for the increased fuel tank volume.

Fuel cell thermal management was performed using isolated heat exchangers as used in CHEETA [49]. These utilize the waste heat to generate thrust using the Meredith effect. The size of isolated heat exchangers was held constant from the CHEETA project.

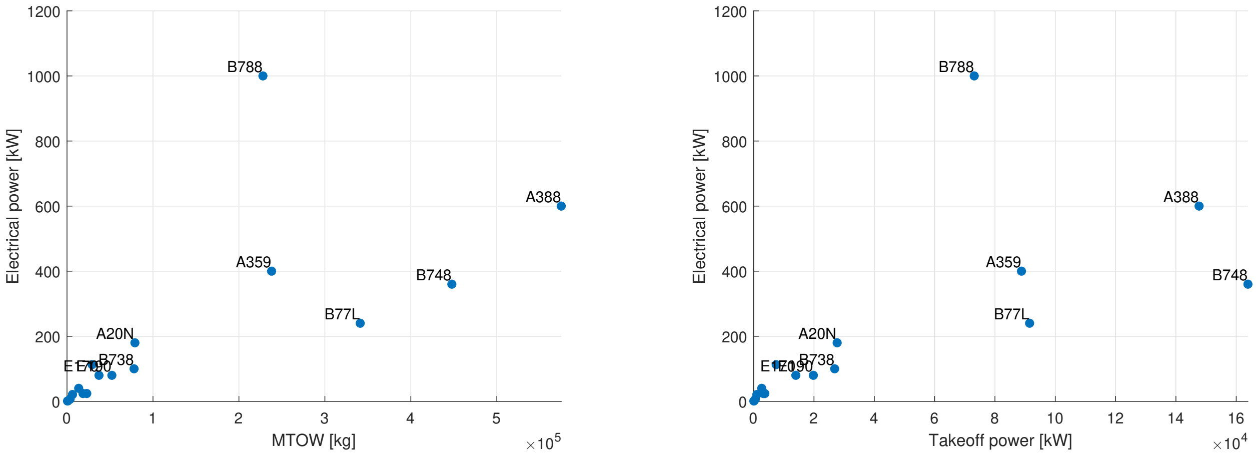
3. *Electrified Subsystems*

With a focus on aircraft electrification, the subsystems essential to aircraft operation also require an in-depth review. Traditionally, a mix of electrical, hydraulic, and pneumatic systems have been used to operate these various subsystems. However, with the move towards total electrification, many of these systems will also need to be electrified. Therefore, designing an all-electric aircraft will require sizing the power sources to accommodate these newly electrified systems. In this section, a preliminary methodology to size these systems and calculate the installed and continuous power loading required for electrifying the subsystems is established. The subsystems considered for this study are:

- Flight control actuation system: typically uses hydraulic power to actuate aerodynamic surfaces required to control the aircraft. Some smaller, regional turboprop aircraft might still make use of mechanical actuation [51].
- Landing gear system: has been hydraulically powered in most conventional aircraft. B787 and A220 use electrically actuated landing gear extension and retraction systems [51].
- Ice protection system: pneumatic power is used to inflate and deflate de-icing boots to mechanically remove ice from the wings, stabilizers, and engine inlets. Meanwhile, propeller blades, sensors, and flight deck windows are electrically heated to prevent the build-up of ice.
- Environmental Control System (ECS): conventionally high pressure engine bleed-air is treated within the environmental control unit (ECU), which removes excess moisture and determines the airflow rate, temperature, and pressure necessary to regulate cabin heating/cooling and pressurization. On the other hand, the ECS for the B787 is electrified and uses ram air taken from outside the aircraft, then compressed using electric cabin air compressors before being cooled and distributed to the cabin [52].
- Fuel system: each engine has its own mechanical pump, and each wing tank has an electric boost fuel pump and electrical transfer pumps to "cross-feed" the other engine while operating in single engine mode or to move fuel between tanks to offset unbalanced weight. This whole system will most likely disappear on all-electric aircraft.
- Avionics: are essential during flight for safe aircraft control and navigation. They must always remain operational. The power requirements for modern avionics systems are estimated to be in the order of tens of kW [53].
- Passenger services: considered non-essential, but most modern aircraft consist of in-flight entertainment. This system operates at peak power throughout the whole flight regime.
- Lighting: serves to illuminate the interior and exterior of the aircraft and is fully electrified.

In the initial phases of aircraft design, the scarcity of data makes quantitative analysis of electrified subsystems challenging. Therefore, for this study, a qualitative analysis is conducted to address the additional power requirements that arise when traditionally non-electrified subsystems—-such as the flight control actuation system, ice protection system, and ECS—are electrified. In doing so, the total electrical power generation capabilities of existing aircraft across various categories are surveyed.

Figures 4a and 4b show the total electrical power output for various aircraft based on their MTOW and takeoff power.



(a) **(b)**

Fig. 4 Electrical power generation for some aircraft as function of MTOW (a) and takeoff power (b).

Aircraft in the graph are labeled according to their ICAO code. The Boeing 787 is observed as the outlier, producing 1,000 kW of electric power to run its systems. No direct correlation is observed between the total installed electric power and the MTOW or the takeoff power of the aircraft. This is most likely a consequence of the different electrical power needs of each aircraft. The B787, for instance, is the only aircraft with bleedless engines and a dedicated ECS fully independent from the engine air [54]. In contrast, other modern airplanes, even more recent than the B787, do not feature such a system, but include other electrified equipment, such as the Electric Backup Hydraulic Actuators (EBHA) on the A380 and A350 [55].

To account for this heterogeneity of electrical power needs across different aircraft, a weight factor was introduced to compare the different electrical power values. Each subsystem is assigned a *qualitative load intensity* w_i, as shown in Table 2, which indicates how power-intensive a particular load is. These weights should be informed by real data points or more advanced aircraft design studies that focus on sizing each individual subsystem, such as [56] and [51]. Nevertheless, the application of those methods within the present work is out of scope as it would require much more detailed design data.

Table 2 Qualitative load intensity

Qualitative Load Intensity	w_i
Extremely high	10-9
Very high	8-7
High	6-5
Moderate	4-3
Low	2-1

For each aircraft, it is stated if a particular subsystem is already electrically powered using the following notation:

$$x_i = \begin{cases} 0 & \text{the system is not electrically powered} \\ 0.5 & \text{the system is partially electrically powered} \\ 1 & \text{the system is already electrically powered} \end{cases} \tag{3}$$

The total Weighted Installed Electrical Power (WIEP) is calculated to be:

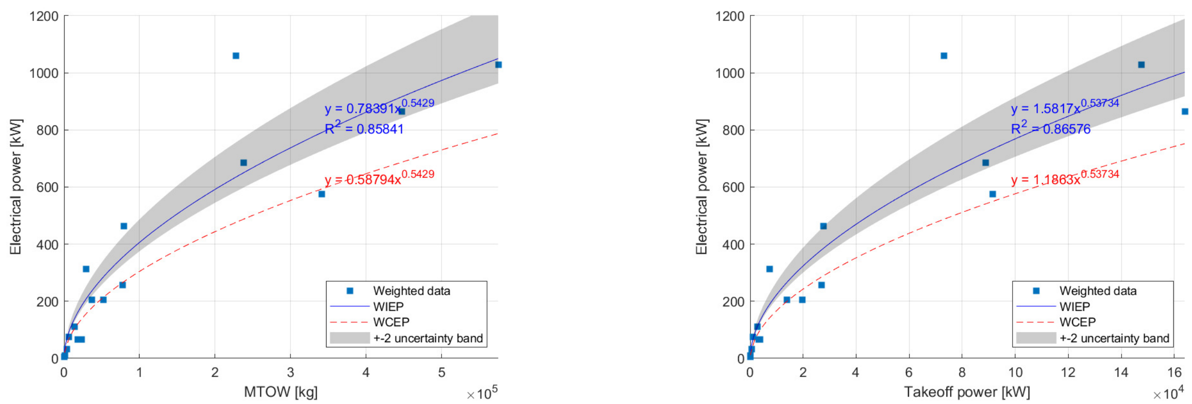
$$P_{\text{wiep}} = \frac{P_{\text{el}} \sum_{i=1}^{N} x_i w_i}{\sum_{i=1}^{N} w_i} \tag{4}$$

where N is the number of subsystems, and P_{el} is the original maximum electrical power generated by the aircraft.

Table 3 Chosen qualitative load intensity values for each subsystem

Subsystem	Qualitative Load Intensity	Is load continuous?
Flight Control Actuation System	6	Yes
Landing Gear System	2	No
Ice Protection System	6	No
Environmental Control System	10	Yes
Avionics	4	Yes
Fuel System	2	Yes
Pax Service	2	Yes
Lighting	3	Yes

This new weighting formulation helps find a better regression to correlate the total electrical power required to sustain aircraft subsystems with MTOW and takeoff power, as shown in Figure 5a and Figure 5b respectively. The grey bands around the regression lines are obtained by changing the w_i by ±2.



(a) **(b)**

Fig. 5 Predicted electrical power needs as function of MTOW (a) and takeoff power (b).

Some of the sub-systems are not required to be operational during the whole flight, like ice protection, landing gear, etc. Therefore, to distinguish the continuous power required from the total power required that will be used to size the aircraft powerplant, a continuous power factor is also considered when accounting for the power drawn during different phases of flight. This power is shown in red in the same in Figure 5a and Figure 5b.

Checking the correctness of these values is challenging because there is no real data for direct comparison. However, applying the regression to an A320-like aircraft (180 pax, MTOW 79,000 kg), yields an average installed power value of 2.15 kW/pax of installed power (or 1.87 kW/pax continuous) or 0.5 kW/N (or 0.43 W/N continuous). Comparatively, for the all-electric A320 designed in [13] the authors assumed a power off-take of 1 kW/occupant or 0.5 W/N of maximum takeoff weight.

4. Point Performance Requirements

Constructing a detailed point-performance diagram to determine the wing and power loading of the aircraft, as suggested in Sec. II.A can be a tedious task, where different flight conditions have to be included depending on the mission, the certification category of the aircraft, and type of powertrain employed. However, especially for electrically-driven aircraft, the most critical condition in terms of powered required is generally take-off, and the wing area is determined by the stall speed [18, 19]. This is not necessarily the case for conventional turbofan aircraft, where the power lapse of the combustion engine with altitude may lead other flight conditions, such as the power required at top-of-climb, to be the limiting case.

Therefore, in this exploratory study, a simplified approach is taken instead, where only four flight conditions are assessed. First, the wing loading is calculated based on the stall speed ($W/S = q_\infty C_{L,\max}$). Then, for that wing loading, three flight maneuvers are evaluated: take-off, a one-engine inoperative balked landing (which may be limiting for aircraft with a two engines and long runways), and a top-of-climb climb rate (which may be limiting for aircraft with combustion engines and high cruise altitudes). The last two are calculated by applying the point performance equations (in essence, the force equilibrium equations "$F = m \cdot a$" in horizontal and vertical direction) assuming a steady climb. The take-off maneuver is calculated using the equation for balanced field length developed by Torenbeek [24]. Once the three conditions are evaluated, the powers are corrected to sea level and the most restrictive W/P case is taken as sizing condition for the powertrain.

5. OEW Regressions

To predict weight the OEW of unconventional aircraft, traditional weight regressions cannot be used. There are inherent assumptions made in the weight regressions presented in canonical sources such as Torenbeek [24], Raymer [57], or Roskam [23]. These assumptions, such as fuel tank weights, fuel tank location, tube and weight considerations, and expected fuel weight fractions may be valid for traditional fuel burning aircraft but will not apply to battery electric or hydrogen fuel cell powered aircraft. This reasoning does not, however, entirely prevent the use of conventional historical data for OEW prediction when designing alternative aircraft. In FAST, hybrid electric aircraft OEWs are predicted by defining a new weight, "W_{Airframe}" such that:

$$W_{\text{Airframe}} = W_{\text{MTO}} - W_{\text{Crew}} - W_{\text{Payload}} - W_{\text{Fuel}} - W_{\text{Battery}} - W_{\text{Engines}} - W_{\text{Motors}} - W_{\text{Fuel Cells}} \quad (5)$$

This airframe weight parameter should act as a replacement for a full component weight buildup. It serves as a universal (energy-source agnostic) estimate for the purely structural weight which is required to hold together a payload, energy source(s), and a power source(s). Additionally, This weight parameter can typically be calculated with relative ease from information that is available in aircraft databases, such as the one built into FAST. The regressions embedded into FAST are utilized in this study to predict the airframe weight parameter based on not only MTOW but with additional considerations on range and energy mass as discussed in II.B. Separate physics-based models are used to size power and energy sources within FAST, discussed in previous sections of this work.

B. Model Integration

After the models discussed in previous subsections have been developed, they are integrated into FAST, with the exception of the battery model discussed in Section III.A.1, as it already exists in the stock version of FAST. Fuel cells and hydrogen fuel, however, must be integrated on their own. In addition to the weight estimation modifications mentioned in Section III.A.5, a new power producer was defined, which set a flag to call the fuel cell sizing and performance models from Section III.A.2 during the aircraft sizing iteration. Hydrogen as an energy storage device can be defined through the fuel's specific energy value, which is already parameterized in FAST. Updated point performance requirements, outlined in Section III.A.4, replace conventional values as inputs to the sizing code. The regressions developed in Section III.A.3 output power off-takes which are added to the required propulsive power when sizing the propulsors and estimating their energy consumption.

IV. Reference Aircraft Identification, Modeling, and Calibration

A. Reference Aircraft and Mission Selection

This work builds on previous studies by considering the same conventional turboprop reference aircraft presented in Ref. [58]. This reference serves as the reference vehicles for regional market in the NASA Electrified Powertrain Flight Demonstration study. The goal of these papers was to provide the electrification community with a common starting point for comparing future concepts in an apples-to-apples fashion. Consequently, the reference missions flown by the aircraft in this study are identical to those described in these sources. The selection process and detailed mission profiles for each aircraft are thoroughly justified in their work. An overview of the aircraft parameters is provided in Table 4.

Table 4 FAST Input Specifications for Conventional Reference Aircraft

Parameter	Units	Regional Turboprop
Reference Aircraft	–	ATR 42-600
Range	km	1,326
Payload	kg	4,560
Maximum Rate of Climb	m/s	7.49
L/D (Climb)	–	10
L/D (Cruise)	–	12
Cruise Speed	Mach	0.4
Cruise Altitude	m	7,620
Wing Loading	kg/m^2	342
Power-to-weight (SLS)	kW/kg	0.1731
Powerplant x2	–	P&W 127-M

B. Conventional Reference Aircraft Validation

The aircraft are modeled using a conventional propulsion system architecture and the aforementioned reference missions. The outputs from FAST are then compared to literature values for MTOW, OEW, and block fuel weight. The conventional reference aircraft validation data is shown in Tables 5, and 7.

Table 5 ATR42-600 Validation

Parameter	Units	Reference [59]	Model	Error
MTOW	kg	18,600	18,758	+0.847 %
OEW	kg	11,750	11,422	-2.792 %
370.4 km Block Fuel	kg	577	582.43	+0.940 %
555.6 km Block Fuel	kg	786	790.13	+0.526 %
740.8 km Block Fuel	kg	1019	1001.9	-1.677 %

For the purpose of validating the ATR model, the reference [59] does not report design mission block fuel. For this validation, the design mission was used the size the aircraft and each of the 200, 300, and 400 nmi mission block fuel values were used to validate the ATR 42-600 model.

C. Validation of Enhancements to FAST

Validating the supplemental models discussed in Section III.A is not possible using certification sheets or airport planning manuals as entirely battery-electric or fuel cell powered aircraft are not currently commercially available. However, there have been several studies conducted on conceptual fuel cell and battery electric aircraft of comparable size to the A320. The CHEETA Aircraft [16] and the All Electric Aircraft (AEA) as described in Gnadt et. al [13] were selected as reference aircraft for fuel cell and battery electric architectures respectively. Tuning factors on OEW, fuel burn, etc. calculations are empirically tuned to minimize errors relative to the reference aircraft. Then these factors are held constant when performing further studies. The inputs to FAST for the CHEETA and AEA-800 models are shown in the Appendix.

Table 6 Validation of Supplemental Models Against CHEETA Aircraft Concept

Parameter	Units	Reference [17]	Model	Error
MTOW	kg	81,923	82,496	+0.700 %
OEW	kg	58,900	59,517	+1.048 %
LH_2 Weight	kg	7,147	7,103	-0.612%
Fuel Cell Weight	kg	7,128	7,367	+3.346 %
Fuel Tank Weight	kg	4,646	4,613	-0.710 %
Electric Motor Weight	kg	838.0	867.5	+3.514 %

Table 7 Validation of Supplemental Models Against the AEA-800 Concept

Parameter	Units	Reference [13]	Model	Error
MTOW	kg	109,500	109,560	+0.054 %
Battery Weight	kg	36,000	38,128	+5.91 %
Design Mission Energy Expenditure	MWh	28.80	28.98	+0.612 %
Non-dimensional Energy per Payload per Distance	–	0.649	0.653	+0.612 %

V. Well-to-Wake Emissions and Cost Modeling

When assessing the sustainability outcomes of new electric aircraft configurations, it is important to consider the emissions and costs associated with the entire energy production process, not just the operational phase. This comprehensive approach, often referred to as well-to-wake emissions analysis, ensures that the environmental impact of energy production, distribution, and consumption is fully accounted for. For this reason, forecasts were used to project the CO_2 equivalent (CO_2e) emissions and cost per kWh (in 2024 USD) of electricity and liquid hydrogen for aviation applications. The resulting forecasts are provided in Table 8. The forecast for CO_2e produced across future global electricity grids was determined based on the IEA 2022 World Energy Outlook [60] report, which outlines a roadmap for net-zero electricity production by 2050. It should be noted that this forecast is highly optimistic and aggressive in its zero-emission goals for electricity production, as it provides a strategy that could successfully result in a net-zero emissions grid. Other agencies have proposed less aggressive forecasts for the adoption of renewable or carbon-free electricity production, but the IEA roadmap was selected as it aligns well with the vision of the current work. The delivery cost for energy across future electrical grids was forecast using projections produced by the US EIA [61]. While these costs focus specifically on the US market, they were deemed to be representative for the future scenarios of interest.

For hydrogen, the emission impacts of production, liquefaction, and distribution were assumed to vary significantly with the production method. The well-to-tank emissions were modeled using the Argonne GREET [62] tool, incorporating representative electrical grids and future market technologies. Currently, steam methane reformation, often referred to as "gray" hydrogen, is the predominant method for hydrogen production. Therefore, a standard production pathway for liquid hydrogen was modeled in GREET using steam methane reformation with a 2024 US grid. For 2035 markets, it was assumed that steam methane reformation would remain prevalent, but be coupled with carbon capture and sequestration technologies to reduce the overall production greenhouse gas emissions. This approach is often referred to as "blue" hydrogen. A representative pathway for this approach was configured in GREET, with simulations performed for forecast 2035 US electrical grids. Finally, a fully renewable hydrogen production process was modeled assuming the use of water electrolysis with electricity provided by a grid comprised exclusively of 50% wind power and 50% solar power. This pathway, often referred to as "green" hydrogen, results in zero CO_2e impacts, but requires significant increases in renewable electricity adoption. While these three pathways were presumed to be coupled to current (2024), mid-term future (2035), and far-term future (2050) markets, results that include mixes of production methods across gray, blue, green, or other pathways can be used across any forecast date. The cost for hydrogen started with \$10/kg LH_2 (\$0.300/kWh), which is representative of current values. For the mid-term 2035 scenario, a rate of \$5/kg (\$0.150/kWh) was assumed judiciously, but was further reinforced by cost forecasts from the Hydrogen Council [63], which optimistically forecast LH_2 costs at $4.30 by the year 2030. LH_2 costs for 2050 markets were assumed to be $3/kg ($0.090/kWh), based on ultimate values anticipated by the US DOE.

Table 8 Electricity, LH_2, and Jet A CO_2e and cost forecasts for 2024, 2035, and 2050.

Year	Electricity		LH_2		Jet A	
	gCO_2e/kWh	$/kWh	gCO_2e/kWh	$/kWh	gCO_2e/kWh	$/kWh
2024	460	0.122	429.8	0.300	306.3	0.067
2035	48	0.107	127.9	0.150	-	-
2050	0	0.11	0	0.090	-	-

Jet fuel prices can vary significantly based on location, time, and market conditions. The IATA fuel price monitor is generally considered a reliable source for industry-wide averages [64]. At the time of this study (June 2024), the global average jet fuel price was approximately $800 per metric ton, which was used in the results. However, future projections for such a volatile metric cannot be made confidently. Therefore, future price values were not included in Table 8 for jet fuel. For consistency, $800 per metric ton of jet fuel is assumed as the comparison point for future technologies.

According to a study by Jing et al. [65], the US-level volume-weighted average well-to-wake carbon intensity for jet fuel ranges from 81.1 to 94.8 gCO_2e/MJ. This range corresponds to approximately 3.5 to 4.1 kg CO_2e per kg of jet fuel. Ref. [66] cites 3.66 kg CO_2 per kg of jet fuel, with 3.16 kg CO_2 from burning the fuel and 0.5 kg CO_2 from production, which is within the range given by Jing et al. Assuming a specific energy of 11.95 kWh/kg for Jet A, this converts to 306.3 gCO_2e/kWh, which is assumed to be the case in this study. As for future projections, Jing et al. [65] suggests that with investment in supply chain decarbonization, the global volume-weighted average carbon intensity of jet fuel could be reduced by 2.1 to 7.1 gCO_2e/MJ under different technology improvement scenarios. However, it is likely that changes in well-to-wake numbers will also depend on other factors, such as the amount of sustainable aviation fuel used instead of jet fuel. Due to the uncertainty surrounding this assumption and for consistency, 306.3 gCO_2e/kWh jet fuel is assumed as a baseline when comparing future technologies.

VI. Results

A. Advanced Conventional Aircraft

In this study, two conventional baseline aircraft models are used for comparison: a "notional" model and an "advanced" model. The notional model represents a notional ATR42-600, with inputs shown in Table 4. This model is validated against literature values, as detailed in Table 5. The advanced model represents a 2030s-era conventional aircraft, incorporating a linear progression of technology. Cai et al. [58] outlines technologies appropriate for such a regional aircraft entering service in 2030. To isolate the propulsion system benefits between conventional and electric systems, only the technological advancements related to propulsion outlined by Cai et al. [58] are incorporated into the "advanced" model. This results in a 14.6% reduction in fuel burn (and therefore energy expenditure and fuel cost) and a 4.2% reduction in MTOW compared to the notional baseline. Table 9 below shows the notional and advanced baselines for the trade studies.

Table 9 Baseline Notional and Advanced Aircraft Parameters.

Parameter	Units	Notional Model	Advanced Model
MTOW	kg	18,758	17,970
Energy	MWh	31.21	26.65
Well-to-Wake CO_2 Emissions	kg	9,519	8,130
Block Fuel Cost	USD (2024)	2,081	1,777

B. Battery Electric Aircraft Trade Study

In the following trade studies, battery electric aircraft results are compared against the notional and advanced aircraft summarized in Table 9. As discussed in Sec. II.A, such aircraft can present substantially different power-to-weight ratio (or power loading) values, compared to conventional aircraft. Therefore, the power loading of the electric aircraft was computed based on the three constraints discussed in Sec. III.A.4. For this analysis, a mission range of 703 nmi applies for the conventional turboprop aircraft based on Ref. [58], and a reserve range of 150 nmi. The cruise lift-to-drag ratio is 12, equal to that of the conventional baseline. Figures 6 to 9 compare the top-level performance metrics of the aircraft to a conventional turboprop counterpart, for different values of powertrain efficiency and battery specific energy. Note that in these figures, powertrain efficiency includes the propeller efficiency, i.e. it refers to the tank-to-wake efficiency of the aircraft.

Figure 6 shows the MTOW and total energy usage of a range of battery electric aircraft relative to the notional turboprop aircraft. As expected, as powertrain efficiency and battery specific energy increase, the MTOW of the electric aircraft approaches that of the notional turboprop. The MTOW contour plot indicates that both powertrain efficiency and battery specific energy have a similar impact on MTOW. The MTOW break-even point, where the electric aircraft MTOW equals that of the notional aircraft, is at the top right corner, requiring a battery specific energy of 4 kWh/kg and 80% powertrain efficiency. However, a battery specific energy of 4 kWh/kg at the pack-level is significantly higher than current standards, approximately 16 times the state-of-the-art specific energy of 0.25 kWh/kg. Despite this, the total energy plot in Fig. 6 shows that a break-even in total energy usage can be reached even for a heavier electric aircraft. This is because the electric propulsion system is more efficient in using the chemical energy stored in the aircraft to generate thrust. Similar to the trends seen for MTOW, total energy usage also decreases with increasing battery specific energy and powertrain efficiency.

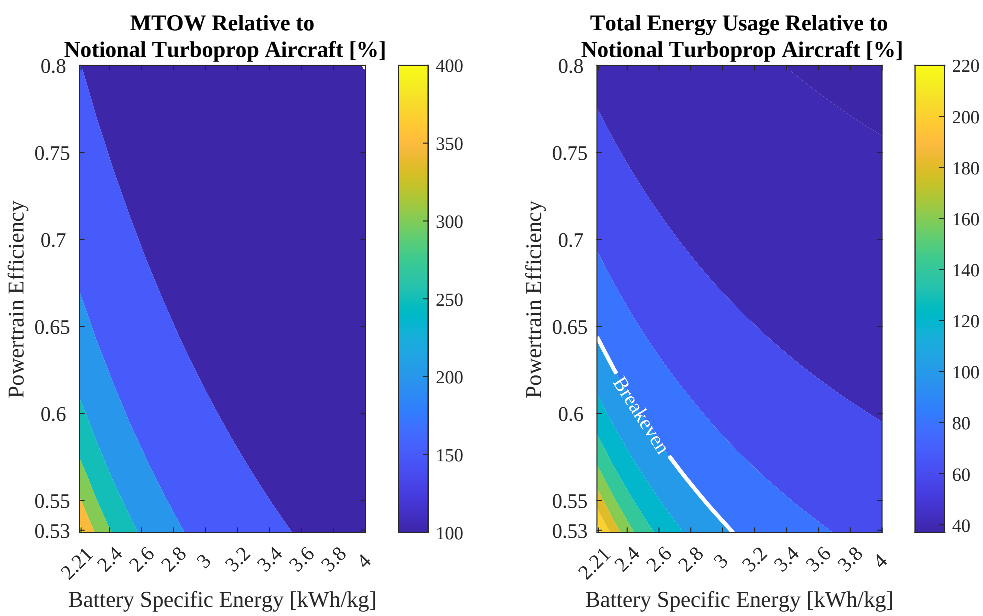


Fig. 6 MTOW (left) and total energy (right) of battery electric aircraft relative to the notional baseline.

Figure 7 shows the comparison of well-to-wake equivalent carbon emissions and cost of energy for a range of battery electric aircraft compared to the notional turboprop aircraft. Because the notional aircraft represents current in-operation technology (i.e., ATR 42-600), the CO_2e and cost figures for electricity correspond to the 2024 values given in Table 8, which are 460 gCO_2e/kWh and 0.122 $/kWh, respectively. For the notional aircraft, 306.3 gCO_2e/kWh and $800 per metric ton of jet fuel (i.e., 0.067 $/kWh) are assumed. Under these conditions, Jet A is more advantageous in terms of carbon emissions and cost of energy. As a result, the break-even curve for carbon emissions requires more aggressive powertrain efficiency and battery specific energy targets than the break-even point for total energy. The target curve for breaking even on the cost of energy is even higher.

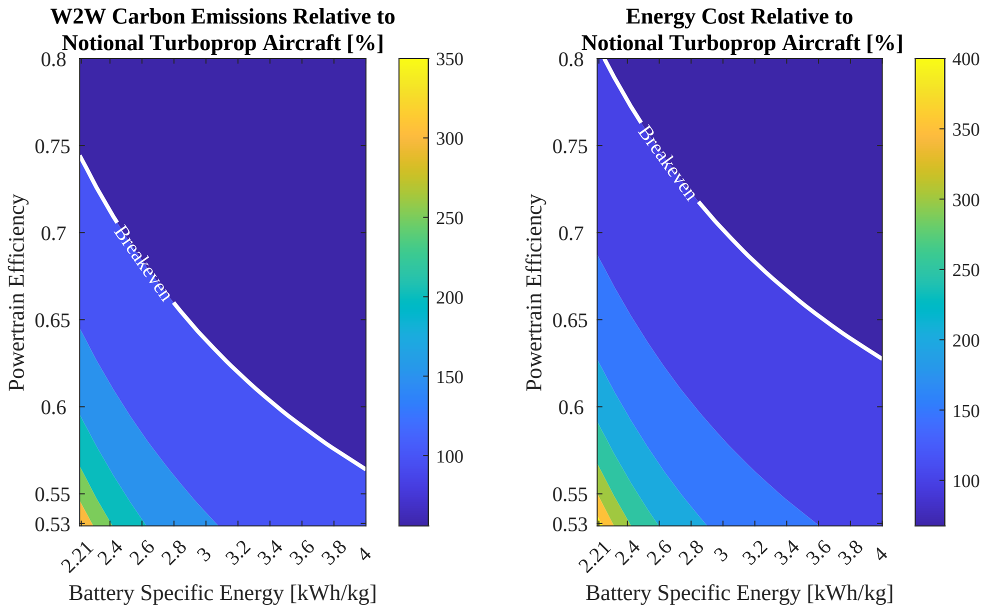


Fig. 7 Well-to-wake (W2W) carbon emissions (left) and energy cost (right) of battery electric aircraft relative to the notional baseline, assuming 2024 values.

However, considering that the time to design, build, and certify a new aircraft generally takes more than a decade, a better comparison would be to look at 2035 and 2050 predictions for the emissions and cost of electricity as given in Table 8, relative to the advanced conventional baseline, which represents a 2030s turboprop aircraft. As such, Fig. 8 compares the MTOW and total energy usage of battery electric aircraft against the advanced turboprop aircraft. The trends are consistent with those observed for the notional turboprop comparison. However, due to the technology improvements infused into the advanced aircraft, it is lighter and consumes less fuel. Thus, the MTOW and energy gaps between electric and advanced aircraft in Fig. 8 are more pronounced than the gaps seen in Fig. 6.

Nevertheless, the situation changes when it comes to comparisons of well-to-wake carbon emissions and cost of energy, as shown in Fig. 9. Even though all the battery electric aircraft shown in Fig. 9 are heavier and require more energy, their well-to-wake emissions are significantly lower than those of advanced conventional aircraft. This is because the average grid composition is assumed to emit 48 gCO_2e/kWh in 2035, which is significantly less than the assumed value of 306.3 gCO_2e/kWh for Jet A. The cost of electricity is assumed to be 0.107 \$/kWh in 2035, requiring a higher technology target for the electric aircraft to break even with the advanced turboprop.

Naturally, if the electric power grid is composed entirely of renewable sources, as predicted for 2050 in Table 8, then a true net-zero could be achieved for the well-to-wake emissions of electric aircraft (excluding the manufacturing and recycling processes). In Table 8, the projected 2050 cost of electricity for electric aircraft is assumed to be between the costs given for 2024 and 2035. Therefore, providing a cost comparison for this price point is deemed redundant. Moreover, not only are prices for such a distant future difficult to predict accurately, but the conventional propulsion system's aircraft technology may also not reflect the improvements assumed in this study.

C. Hydrogen Fuel Cell Electric Aircraft Trade Study

In the following trade studies, hydrogen fuel cell electric aircraft results are compared against the notional and advanced aircraft summarized in Table 9. For these electric aircraft results, the following assumptions have been made: propeller efficiency is assumed to be 0.77, based on the CHEETA model, with an electric machine efficiency of 0.96. Other losses in the powertrain are calculated within the fuel cell model. The calibration factors used are identical to those employed to tune the CHEETA model and are listed in Table 10 along with other FAST inputs for this study.

Similar to the trade studies presented for the battery electric aircraft, the results for hydrogen fuel cell electric aircraft

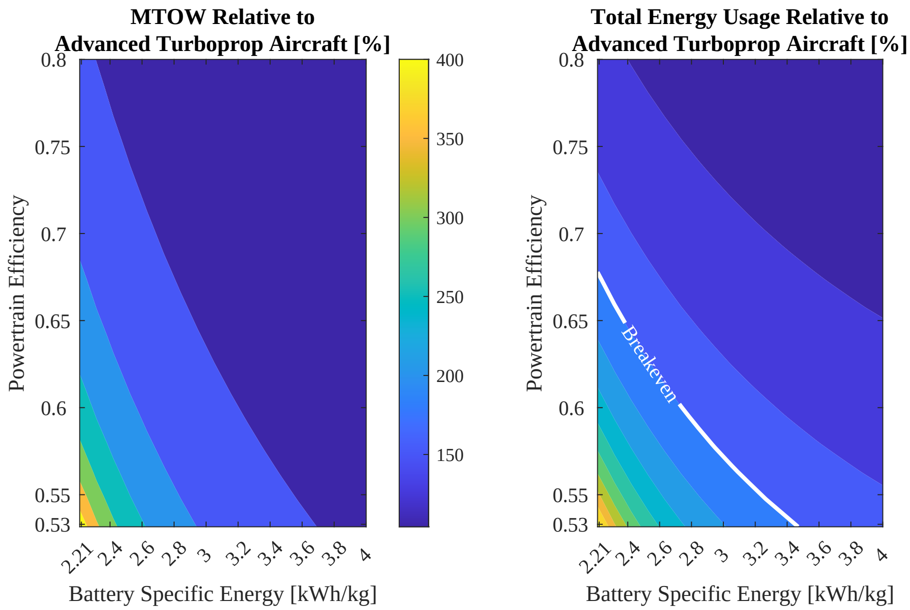


Fig. 8 MTOW (left) and total energy (right) of battery electric aircraft relative to the notional baseline.

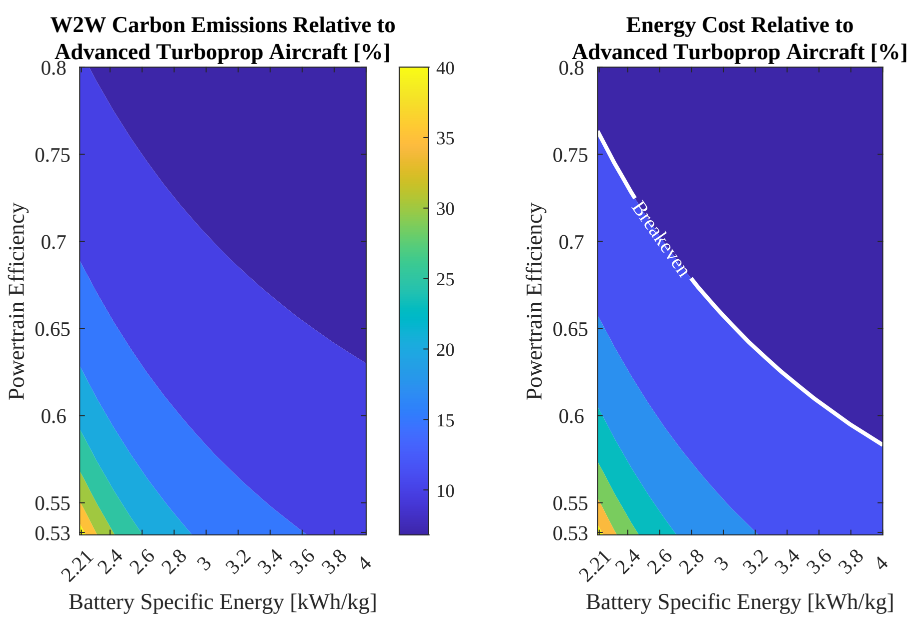


Fig. 9 Well-to-wake (W2W) carbon emissions (left) and energy cost (right) of battery electric aircraft relative to the advanced baseline, assuming 2035 predictions.

were compared in terms of MTOW, total energy usage, well-to-wake emissions, and cost of energy. Figure 10 shows the MTOW and total energy usage of a range of hydrogen fuel cell electric aircraft relative to the notional turboprop aircraft. As expected, as gravimetric fuel tank efficiency (defined as the ratio of fuel weight to fuel weight plus tank weight) and fuel cell power-to-weight (P/W) ratio increase, the MTOW and energy usage of the electric aircraft approach that of the notional turboprop, breaking even at the white curve shown on the contour plots. The contour plot indicates that both MTOW and total energy are more sensitive to changes in fuel cell P/W ratio, especially at low values, than to changes in gravimetric fuel efficiency, which gain more significance at higher fuel cell P/W values. Similar to the results seen in battery electric aircraft trade studies, breaking even in terms of MTOW and energy usage requires quite aggressive technology levels for fuel cells and tank efficiency, which may not be realistic goals in the near or mid-term.

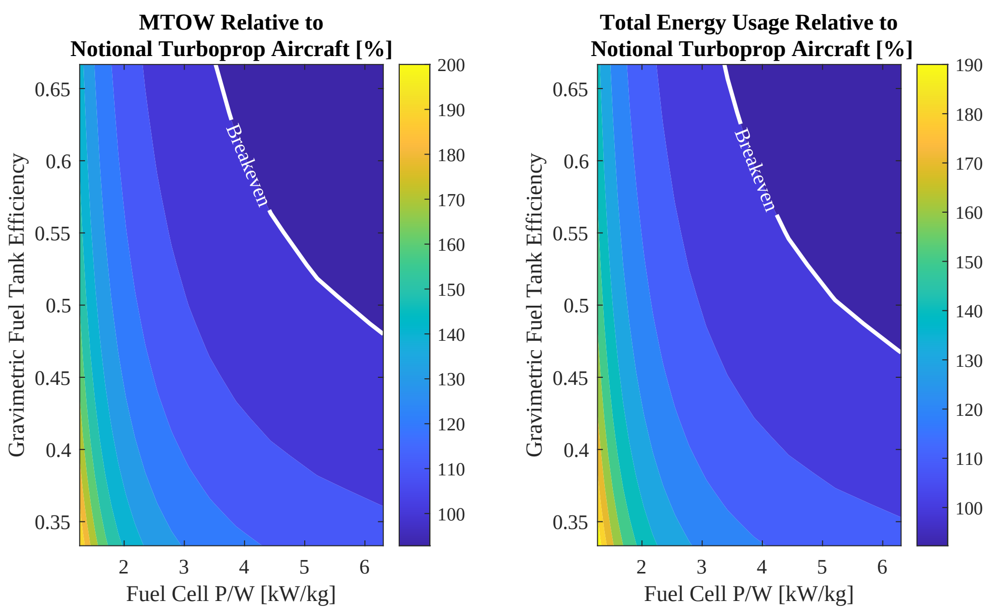


Fig. 10 MTOW (left) and total energy (right) of fuel cell electric aircraft relative to the notional baseline.

Figure 11 shows the comparison of well-to-wake equivalent carbon emissions and cost of energy for a range of hydrogen fuel cell electric aircraft compared to the notional turboprop aircraft. Because the notional aircraft represents current in-operation technology (i.e., ATR 42-600), the CO_2e and cost figures for electricity correspond to the 2024 values given in Table 8, which are 429.8 gCO_2e/kWh and 10 \$/kg, respectively. This corresponds to the gray hydrogen scenario. Thus, Jet A is more advantageous in terms of carbon emissions and cost of energy, with no break-even point achieved under the variable ranges set for this study. The trends show that much higher tank efficiency and fuel cell power-to-weight (P/W) ratios are needed to reach break-even, which might set unrealistic targets. Note that these ranges were selected based on the break-even points achieved for MTOW. Even though hydrogen fuel cells do not emit CO_2 during flight, the means of producing the fuel play a significant role in achieving sustainability targets.

However, it must be assumed that if investments are made to use hydrogen as a fuel for aircraft, then investments and improvements must also be made to reduce carbon emissions during the production of hydrogen. One future scenario is presented in Figures 12 and 13, where blue hydrogen is assumed. Because these results represent future scenarios, the baseline for comparison is the advanced (2030s) turboprop aircraft, which is more weight and energy efficient than the notional ATR42-600 baseline used in the previous comparison. As a result, the MTOW and energy gaps between the hydrogen fuel cell aircraft and the advanced aircraft are more pronounced than the comparisons made against the notional one. This is similar to and expected from the MTOW and energy trends seen for the battery electric aircraft.

Although the blue hydrogen scenario does not break even with jet fuel in terms of costs, even the lowest technology assumptions (in the bottom left corner of Fig. 13) show significantly lower carbon emissions than the advanced conventional aircraft. This indicates that while MTOW and energy requirements for a hydrogen fuel cell aircraft necessitate much more aggressive technology targets to match those of its conventional counterpart, more relaxed (and

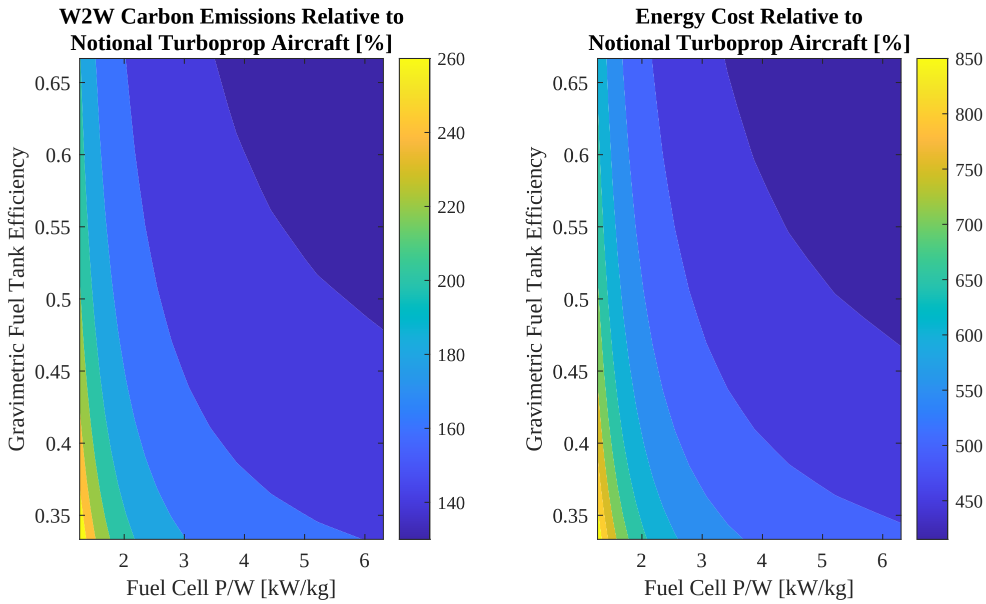


Fig. 11 Well-to-wake (W2W) carbon emissions (left) and energy cost (right) of fuel cell electric aircraft relative to the notional baseline, assuming gray hydrogen.

realistic) targets can still achieve a reduction in well-to-wake carbon emissions, even under the blue hydrogen scenario. However, the feasibility of an aircraft that is double the weight of a conventional one also depends on other constraints, such as wing size and maximum landing weight, which were not considered in this sizing study.

The green hydrogen scenario, summarized in Table 8 for the year 2050, assumes zero CO_2e emissions in the production of hydrogen and a price of \$3/kg for the fuel. The energy cost comparison of this scenario relative to the current jet fuel prices is given in Fig. 14. Because the current price of jet fuel is still much lower than the forecasted value for hydrogen, and no significant energy reduction is achieved under the assumed conditions, no cost benefit from using hydrogen fuel cells is observed over the advanced turboprop aircraft.

D. Assessing Breguet Range Equation in Electric Aircraft Performance Prediction

Finally, the aircraft sizing methods (applied in FAST [45]) discussed in this paper were compared against the modified Breguet Range Equation (BRE) given in Eq. 2. As previously discussed, although the BRE provides useful back-of-the-envelope estimates, it under-predicts the performance of electric aircraft. This is primarily because it does not account for the power requirements from energy sources (which are crucial for batteries) or the additional impact of the thermal management system, which cannot be accurately estimated using the cooling impact models for conventional propulsion systems. Power-off-takes considered in FAST but not represented in BRE also add to the discrepancy.

1. Comparison for Battery Electric Aircraft

The values used in both methods for the battery electric aircraft models are provided in Table 10. The design range was varied, and the resulting battery mass to total aircraft mass ratio was compared in Fig. 15. This comparison shows that, under the same assumptions, the BRE under-predicts the battery-mass-to-aircraft-mass ratio for a given range. Alternatively, this could also be interpreted as the BRE over-predicting the range capability of the battery-powered aircraft for a given battery mass ratio.

As seen from the error graph between FAST and BRE results presented in Fig. 15, the error increases as range decreases. This is expected since the BRE simplifies the mission profile and lumps the total range into a cruise segment, whereas the mission analysis in FAST includes all mission segments (takeoff, climb, cruise, descent, and landing) in a more granular way. Consequently, the peak power requirements are translated into C-rate requirements for the battery

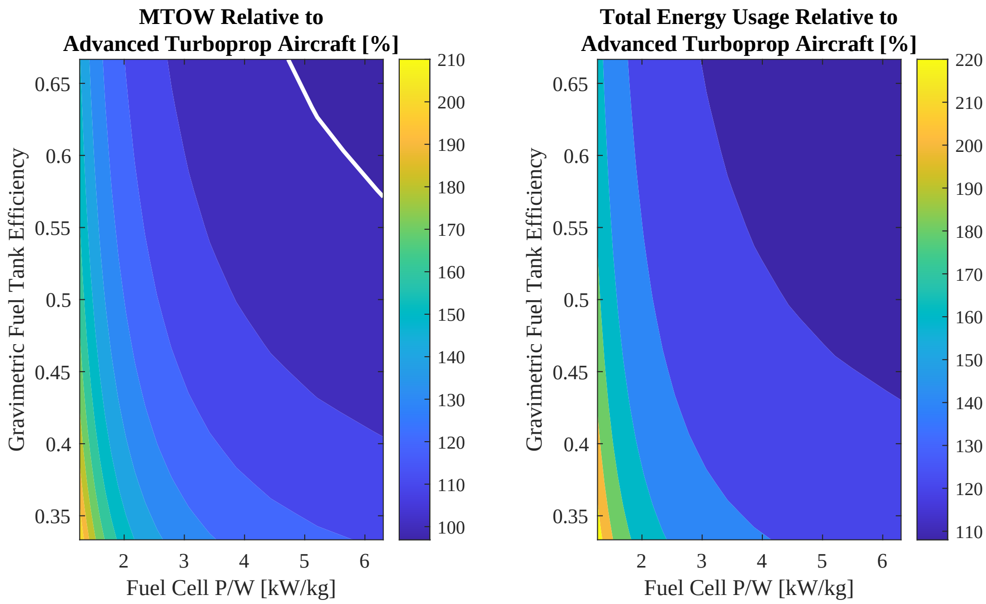


Fig. 12 MTOW (left) and total energy (right) of fuel cell electric aircraft relative to the advanced baseline.

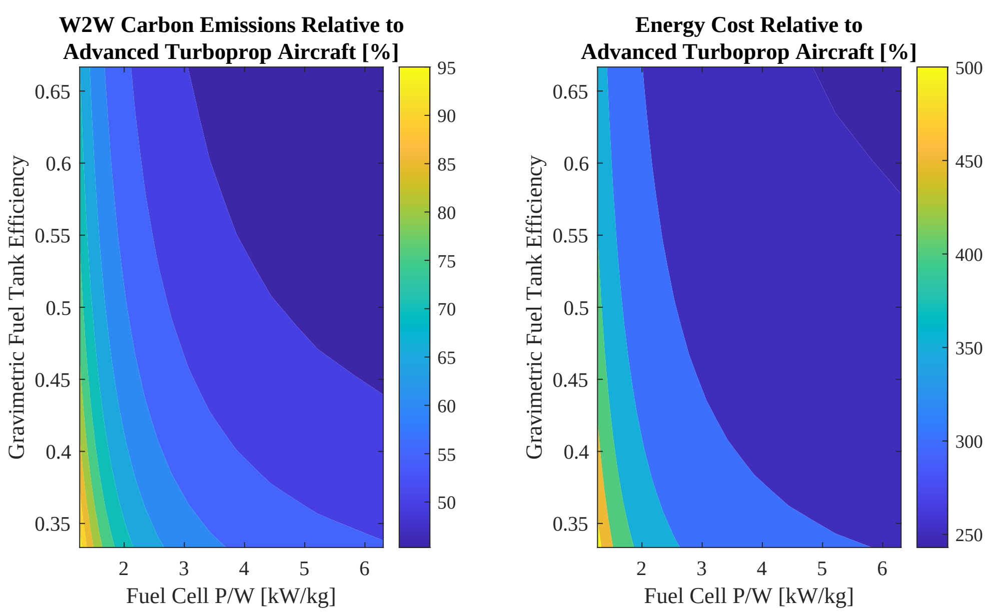


Fig. 13 Well-to-wake (W2W) carbon emissions (left) and energy cost (right) of fuel cell electric aircraft relative to the advanced baseline, assuming blue hydrogen (2035 predictions).

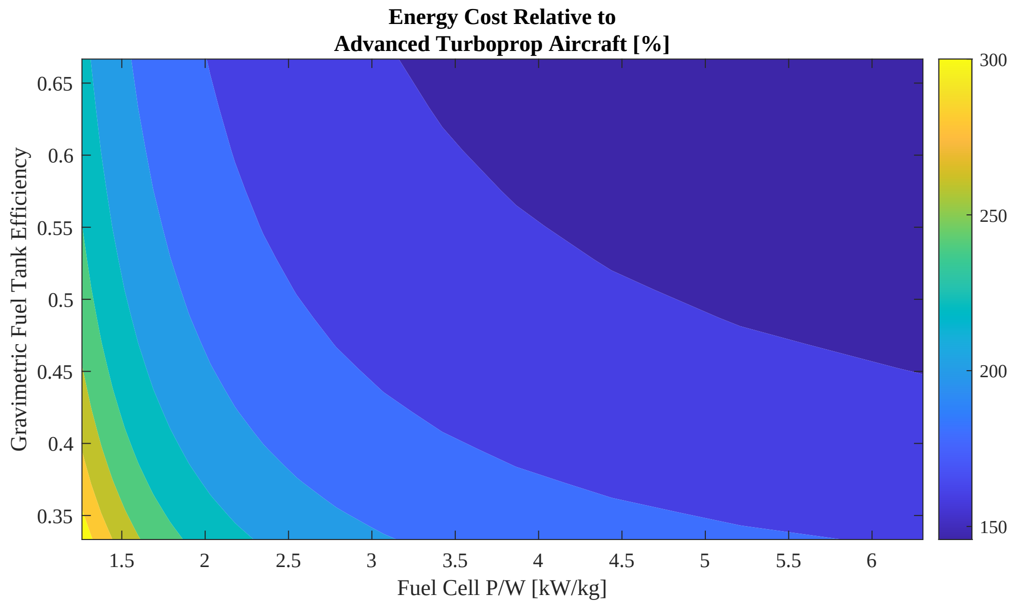


Fig. 14 Cost of fuel cell electric aircraft relative to the advanced baseline, assuming green hydrogen (2050 scenario. Assuming zero carbon emissions.)

Table 10 Inputs for the Battery Electric BRE Study.

Parameter	**Units**	**Values**
Reference Aircraft	–	ATR 42-600
Range	km	variable
Payload	kg	4,560
Maximum Rate of Climb	m/s	7.49
L/D (Climb)	–	10
L/D (Cruise)	–	12
Cruise Speed	Mach	0.4
Cruise Altitude	m	7,620
Wing Loading	kg/m^2	342
Power-to-weight (SLS)	kW/kg	0.2371
Battery Specific Energy	kWh/kg	2.5
Powertrain Efficiency	–	0.6
Battery Voltage	V	204.4
Cells in Series	–	50
Electric Motor Power-to-weight	kW/kg	5.0

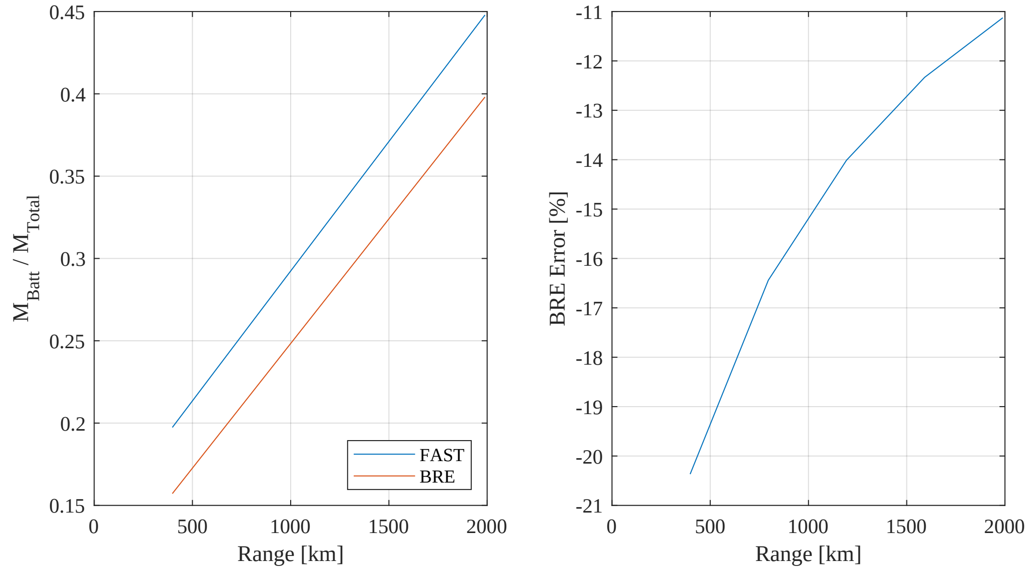


Fig. 15 Comparison of methods for the battery electric aircraft models.

pack, which is one of the sizing conditions for batteries. In longer range missions, as the cruise segment becomes more dominant, energy requirements also become more dominant, and the error in the BRE decreases, reaching a minimum of about 11% under-prediction over a 2000 km range.

2. Comparison for Hydrogen Fuel Cell Electric Aircraft

The values used in both methods for the fuel cell electric aircraft models are provided in Table 11. The same approach was taken for this comparison: design range was varied, and the resulting liquid hydrogen mass to total aircraft mass ratio (M_{LH_2}/M_{Total}) was compared in Fig. 16. This comparison also shows that, the BRE significantly under-predicts the hydrogen-mass-to-aircraft-mass ratio for a given range. Alternatively, this could also be interpreted as the BRE over-predicting the range capability of the fuel cell aircraft for a given hydrogen fuel mass ratio.

VII. Conclusions

This research provides detailed guidelines and a framework for integrating alternative energy systems into conceptual aircraft design, emphasizing battery-electric and hydrogen fuel cell powertrains. Key discussions include:

- **Guidelines for Design**:
  - **Wing and powertrain sizing**: Point performance targets (wing loading and power-to-weight ratio) are adapted to account for distributed propulsion and varying altitude power requirements unique to electric aircraft.
  - **Energy source sizing**: Emphasizes the dual importance of energy and power requirements in battery design, particularly for hybrid missions where power needs can significantly influence battery sizing.
  - **Weight predictions**: Appropriate methods for conceptual design stage are proposed to estimate the weights of new components such as batteries, electric motors, and hydrogen tanks.
  - **Thermal management and electrified subsystems**: New designs for thermal management systems are necessary to handle the distinct heat loads and sinks introduced by alternative energy sources. Additionally, electrified subsystems will contribute to the overall power requirements, which must be accounted for when sizing the power sources. Predicted power needs for such subsystems are provided.
- **Practical Considerations and Regulatory Impacts**: Discusses the impact of regulations on energy pack weight

Table 11 Inputs for the Fuel Cell Electric BRE Study.

Parameter	Units	Values
Reference Aircraft	–	ATR 42-600
Range	km	variable
Payload	kg	4,560
Maximum Rate of Climb	m/s	7.49
L/D (Climb)	–	10
L/D (Cruise)	–	12
Cruise Speed	Mach	0.4
Cruise Altitude	m	7,620
Wing Loading	kg/m^2	342
Power-to-weight (SLS)	kW/kg	0.1731
Propeller Efficiency	–	0.77
Fuel Cell Power-to-weight	kW/kg	1.4286
Fuel Tank Gravimetric Efficiency	–	0.61
Electric Motor Power-to-weight	kW/kg	5.0
Electric Motor Efficiency	–	0.96
Fuel Cell Sizing Calibration Factor	–	0.88
Fuel Burn Calibration Factor	–	1.36
Airframe Weight Calibration Factor	–	1.05

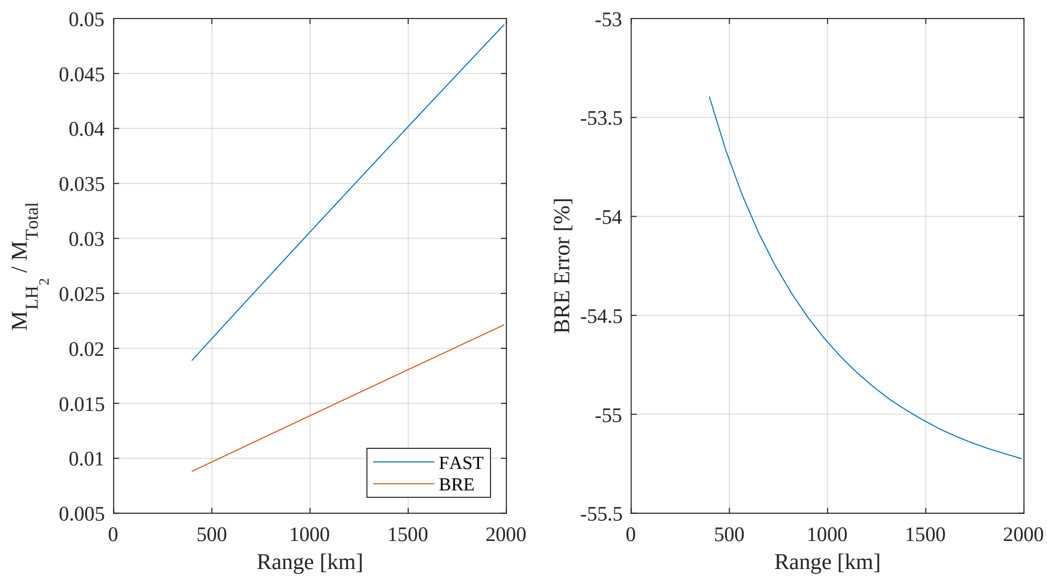


Fig. 16 Comparison of methods for the fuel cell electric aircraft models.

sizing, highlighting the need for compliance with safety standards that traditionally assume jettisonable fuel.

- **Collaborative Framework**: Stresses the importance of a universal communication framework to bridge the gap between system-level aircraft design and component-level technological advancements. This framework is vital for aligning research and development efforts across disciplines to meet the sustainability goals of the aviation industry.

In the battery electric aircraft trade study, results indicate that both powertrain efficiency and battery specific energy significantly impact MTOW and total energy usage. Similarly, the hydrogen fuel cell electric aircraft trade study demonstrates that improvements in gravimetric fuel tank efficiency and fuel cell power-to-weight ratio are crucial for achieving competitive performance. Although the break-even point for MTOW and energy necessitates extremely aggressive technology targets for either propulsion system, the findings reveal that reduced well-to-wake emissions do not require an exact match with the MTOW and energy of the baseline aircraft. Instead, emission reductions compared to 2030s-era turboprop aircraft can be achieved. For economic competitiveness, the total energy required and the cost of electricity or hydrogen must decrease further under the current cost assumptions.

The study also compares the modified Breguet Range Equation (BRE), highlighting its limitations in accurately predicting the performance of electric aircraft. One key finding is that the modified BRE significantly underestimates the battery-mass-to-aircraft-mass ratio required for given ranges. Advanced modeling within the FAST tool reveals the need for incorporating power requirements and thermal management impacts to improve predictions.

The practical results presented here for electric aircraft do not necessarily represent the best solutions or the only options. They are provided to demonstrate a practical application of the proposed guidelines. The results are repeatable using the information listed in this paper and the open-source software, FAST, but the guidelines can (and should) be implemented in any sizing procedure. Different assumptions could lead to more optimized solutions. Additionally, the results show all-electric concepts, indicating that some of the technology targets needed for net-zero benefits might be unrealistically optimistic for the near and mid-term. This was expected from full electrification of an aircraft with the same range and mission profile as its conventional counterpart. For more realistic mid-term solutions, it is recommended to relax these requirements or use hybrid electric configurations.

The study concludes that while alternative energy aircraft hold significant promise for sustainable aviation, achieving practical and competitive designs requires overcoming substantial technological and collaborative challenges. Although the practical results presented in this study are for all-electric aircraft, the guidelines and best practices covered here are applicable to hybrid electric aircraft, which are more realistic intermediate solutions for contributing to the broader goal of net-zero aviation by 2050.

Appendix

CHEETA and AEA-800 Models in FAST

This appendix serves to record the calibration factors that were used to modify the conventional notional turboprop aircraft model. The calibration factors for the battery and fuel cell electric aircraft were set equal to the values that produced minimal errors for the AEA-800 and CHEETA aircraft respectively. The AEA-800 specifications are shown in Table 12, while the CHEETA specifications are shown in Table 13.

Acknowledgments

The authors would like to thank Vivien Lecoustre of Booz, Allen, Hamilton for his thoughtful insights and discussions regarding this research. Additionally, the authors would like to thank the FAST development team at the IDEAS Lab at the University of Michigan, with special thanks to Paul Mokotoff, Yi-Chih “Arenas" Wang, Swapnil Jagtap, and Huseyin Acar for their help and advice in modifying the software for this research.

References

[1] Lee, D. S., Fahey, D. W., Skowron, A., Allen, M. R., Burkhardt, U., Chen, Q., Doherty, S. J., Freeman, S., Forster, P. M., Fuglestvedt, J., Gettelman, A., De León, R. R., Lim, L. L., Lund, M. T., Millar, R. J., Owen, B., Penner, J. E., Pitari, G., Prather, M. J., Sausen, R., and Wilcox, L. J., “The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018,” *Atmos. Environ. (1994)*, Vol. 244, No. 117834, 2021, p. 117834.

Table 12 Inputs for the AEA-800 baseline.

Parameter	Units	Values
Reference Aircraft	–	AEA-800
Range	km	variable
Payload	kg	17,586
Maximum Rate of Climb	m/s	10.16
L/D (Climb)	–	16
L/D (Cruise)	–	18.6
Cruise Speed	Mach	0.4
Cruise Altitude	m	7,620
Wing Loading	kg/m^2	871.8
Thrust-to-weight (SLS)	kW/kg	0.3
Battery Specific Energy	kWh/kg	0.8
Powertrain Efficiency	–	0.661
Battery Voltage	V	204.4
Cells in Series	–	50
Electric Motor Power-to-weight	kW/kg	5.0

Table 13 Inputs for the CHEETA aircraft baseline.

Parameter	Units	Values
Reference Aircraft	–	CHEETA
Range	km	5,436
Payload	kg	15,876
Maximum Rate of Climb	m/s	2.54
L/D (Climb)	–	16
L/D (Cruise)	–	16
Cruise Speed	Mach	0.78
Cruise Altitude	m	11,278
Wing Loading	kg/m^2	505.4
Thrust-to-weight (SLS)	–	0.32
Propeller Efficiency	–	0.77
Fuel Cell Power-to-weight	kW/kg	1.4286
Fuel Tank Gravimetric Efficiency	–	0.61
Electric Motor Power-to-weight	kW/kg	26.0
Electric Motor Efficiency	–	0.96
Fuel Cell Sizing Calibration Factor	–	0.88
Fuel Burn Calibration Factor	–	1.36
Airframe Weight Calibration Factor	–	1.05

[2] Dorbian, C. S., Wolfe, P. J., and Waitz, I. A., "Estimating the climate and air quality benefits of aviation fuel and emissions reductions," *Atmos. Environ. (1994)*, Vol. 45, No. 16, 2011, pp. 2750–2759.

[3] United Nations, "Paris Agreement," , Dec. 2015. UNTC XXVII 7. d.

[4] European Comission, "The European Green Deal," , 2019.

[5] Secretariat of the Council, "Regulation of the European Parliament and of the Council on ensuring a level playing field for sustainable air transport," , Jun. 2022. 2021/0205 (COD).

[6] Federal Aviation Administration, "United States 2021 Climate Action Plan," , 2021.

[7] 117th Congress (2021-2022), "Inflation Reduction Act of 2022," , 2022. URL https://www.congress.gov/bill/117th-congress/house-bill/5376, H.R. 5376, Section 40007.

[8] ICAO Committee on Aviation Environmental Protection, "Report on the Feasibility of a Long-Term Aspirational Goal (LTAG) for International Civil Aviation CO2 Emission Reductions," , 2022.

[9] Hepperle, M., "Electric Flight - Potential and Limitations," 2012.

[10] Jansen, R., Brown, G. V., Felder, J. L., and Duffy, K. P., "Turboelectric aircraft drive key performance parameters and functional requirements," *51st AIAA/SAE/ASEE Joint Propulsion Conference*, American Institute of Aeronautics and Astronautics, Reston, Virginia, 2015.

[11] Duffy, K. P., and Jansen, R., "Turboelectric and Hybrid Electric Aircraft Drive Key Performance Parameters," American Institute of Aeronautics and Astronautics, 2018.

[12] de Vries, R., Hoogreef, M. F. M., and Vos, R., "Range equation for hybrid-electric aircraft with constant power split," *Journal of Aircraft*, Vol. 57, No. 3, 2020, pp. 552–557. https://doi.org/10.2514/1.C035734.

[13] Gnadt, A. R., Speth, R. L., Sabnis, J. S., and Barrett, S. R., "Technical and environmental assessment of all-electric 180-passenger commercial aircraft," *Progress in Aerospace Sciences*, Vol. 105, 2019, p. 1–30. https://doi.org/10.1016/j.paerosci.2018.11.002.

[14] Cinar, G., Cai, Y., Bendarkar, M. V., Burrell, A. I., Denney, R. K., and Mavris, D. N., "System Analysis and Design Space Exploration of Regional Aircraft with Electrified Powertrains," *Journal of Aircraft*, Vol. 60, No. 2, 2023, p. 382–409. https://doi.org/10.2514/1.c036919.

[15] de Bock, H. P., Tew, D. E., Rahman, Z., Lecoustre, V., and Cox-Galhotra, R. A., "Progress Toward Climate-Friendly Aviation in the ARPA-E ASCEND and REEACH Programs," *Volume 1: Aircraft Engine*, American Society of Mechanical Engineers, 2023. https://doi.org/10.1115/gt2023-104109.

[16] Datta, K., and Ansell, P., "Center for High-Efficiency Electrical Technologies for Aircraft (CHEETA)," , 2021. URL https://techport.nasa.gov/view/96122, NASA 20210000093.

[17] Waddington, E., Merret, J. M., and Ansell, P. J., "Impact of Liquid-Hydrogen Fuel-Cell Electric Propulsion on Aircraft Configuration and Integration," *Journal of Aircraft*, Vol. 60, No. 5, 2023, p. 1588–1600. https://doi.org/10.2514/1.c037237.

[18] de Vries, R., Brown, M., and Vos, R., "Preliminary Sizing Method for Hybrid-Electric Distributed-Propulsion Aircraft," *Journal of Aircraft*, Vol. 56, No. 6, 2019, pp. 2172–2188. https://doi.org/10.2514/1.C035388.

[19] Finger, D. F., Bil, C., and Braun, C., "Initial Sizing Methodology for Hybrid-Electric General Aviation Aircraft," *Journal of Aircraft*, Vol. 57, No. 2, 2020. https://doi.org/10.2514/1.C035428.

[20] Cinar, G., Mavris, D. N., Emeneth, M., Schneegans, A., and Fefermann, Y., "Development of parametric power generation and distribution subsystem models at the conceptual aircraft design stage," *55th AIAA Aerospace Sciences Meeting*, 2017, p. 1182.

[21] Deng, Y., Kryuchkov, A., Mokotoff, P., Smith, E., Patel, J., Garcia Lavanchy, S., Li, M. Z., and Cinar, G., "Operational Analysis for Hybrid Electric Aircraft Fleets: A feasibility study for the short- and medium-haul markets," *AIAA AVIATION 2023 Forum*, American Institute of Aeronautics and Astronautics, 2023. https://doi.org/10.2514/6.2023-3868, URL http://dx.doi.org/10.2514/6.2023-3868.

[22] Torenbeek, E., *Synthesis of Subsonic Airplane Design*, Delft University Press, 1982.

[23] Roskam, J., *Airplane Design: Preliminary Sizing of Airplanes*, DAR Corporation, 1985.

[24] Torenbeek, E., *Advanced Aircraft Design*, Wiley & Sons, 2013.

[25] Wolleswinkel, R. E., de Vries, R., Hoogreef, M. F. M., and Vos, R., "A New Perspective on Battery-Electric Aviation, Part I: Reassessment of Achievable Range," AIAA Scitech 2024 Forum, Orlando, FL, USA, January 8-12 2024. https://doi.org/10.2514/6.2024-1489.

[26] de Vries, R., Wolleswinkel, R. E., Hoogreef, M. F. M., and Vos, R., "A New Perspective on Battery-Electric Aviation, Part II: Conceptual Design of a 90-seater," AIAA Scitech 2024 Forum, Orlando, FL, USA, January 8-12 2024. https://doi.org/10.2514/6.2024-1490.

[27] Shi, M., "An Architecting Methodology for Thermal Management Systems of Commercial Aircraft at the Conceptual Design Phase," Ph.D. thesis, Georgia Institute of Technology, 2021.

[28] Clark, R. A., Shi, M., Gladin, J., and Mavris, D., "Design and analysis of an aircraft thermal management system linked to a low bypass ratio turbofan engine," *Journal of Engineering for Gas Turbines and Power*, Vol. 144, No. 1, 2022, p. 011019. https://doi.org/10.1115/1.4052031.

[29] Perullo, C., Shi, M., Cinar, G., Alahmad, A., Sanders, M., Mavris, D. N., and Benzakein, M. J., "An Update on Sizing and Performance Analysis of a Hybrid Turboelectric Regional Jet for the NASA ULI Program," *2020 AIAA/IEEE Electric Aircraft Technologies Symposium (EATS), AIAA 2020-3590*, 2020. https://doi.org/10.2514/6.2020-3590.

[30] Shi, M., Sanders, M., Alahmad, A., Perullo, C., Cina, G., and Mavris, D. N., "Design and Analysis of the Thermal Management System of a Hybrid Turboelectric Regional Jet for the NASA ULI Program," *2020 AIAA/IEEE Electric Aircraft Technologies Symposium (EATS), AIAA 2020-3572*, 2020. https://doi.org/10.2514/6.2020-3572.

[31] Shi, M., Ozcan, M., Cinar, G., Gladin, J., and Mavris, D. N., "Finalized Design and Performance Analysis of a Hybrid Turbo-Electric Regional Jet for the NASA ULI Program," *2022 IEEE Transportation Electrification Conference & Expo (ITEC)*, IEEE, 2022, pp. 444–449. https://doi.org/10.1109/ITEC53557.2022.9814048.

[32] Shi, M., Gladin, J., and Mavris, D. N., "A Systematic Methodology for Populating the Aircraft Thermal Management System Architecture Space," *AIAA Scitech 2021 Forum, (AIAA 2021-1295)*, 2021. https://doi.org/10.2514/6.2021-1295.

[33] Chakraborty, I., and Mavris, D., "Integrated Assessment of Aircraft and Novel Subsystem Architectures in Early Design," *AIAA Journal of Aircraft*, Vol. 54, No. 4, 2017. https://doi.org/10.2514/1.C033976.

[34] Shi, M., Chakraborty, I., Tai, J. C., and Mavris, D. N., "Integrated Gas Turbine and Environmental Control System Pack Sizing and Analysis," *2018 AIAA Aerospace Sciences Meeting, (AIAA 2018-1748)*, 2018. https://doi.org/10.2514/6.2018-1748.

[35] Shi, M., Chakraborty, I., Cai, Y., Tai, J. C., and Mavris, D. N., "Mission-Level Study of Integrated Gas Turbine and Environmental Control System Architectures," *2018 AIAA Aerospace Sciences Meeting, (AIAA 2018-1751)*, 2018. https://doi.org/10.2514/6.2018-1751.

[36] Federal Aviation Administration, "14 CFR Part 25: AIRWORTHINESS STANDARDS: TRANSPORT CATEGORY AIRPLANES," , Latest Amendment: 05/07/2024. URL https://www.ecfr.gov/current/title-14/part-25.

[37] SAE International Information Report, "Architecture Examples for Electrified Propulsion Aircraft, SAE Standard AIR8678," , Aug. 2022. https://doi.org/10.4271/air8678.

[38] Muralidharan, N., Self, E. C., Nanda, J., and Belharouak, I., "Next-generation cobalt-free cathodes–a prospective solution to the battery industry's cobalt problem," *Transition Metal Oxides for Electrochemical Energy Storage*, 2022, pp. 33–53.

[39] Bindra, H., and Revankar, S., *Storage and Hybridization of Nuclear Energy: Techno-Economic Integration of Renewable and Nuclear Energy*, Academic Press, 2018.

[40] EnerSys, "Hawker Aviation Batteries," , 2024. URL https://www.enersys.com/en/products/batteries/hawker/hawker-aviation/, accessed: 2024-06-30.

[41] Boeing, "Batteries and Advanced Airplanes - Boeing 787 Updates," , 2024. URL http://787updates.newairplane.com/787-Electrical-Systems/Batteries-and-Advanced-Airplanes, accessed: 2024-06-01.

[42] Hepperle, M., "Electric flight-potential and limitations," 2012.

[43] ARPA-E, "PROPEL-1K: Pioneering Railroad, Oceanic and Plane ELectrification with 1K energy storage systems," , 2024. URL https://arpa-e.energy.gov/technologies/programs/propel-1k, accessed: 2024-06-30.

[44] Co-Operative Industries for Aerospace and Defense, "Wired for Safety," , 2015. URL https://coopind.com/2015/03/wired-for-safety/.

[45] IDEAS Laboratory, "Future Aircraft Sizing Tool (FAST)," , May 2024. URL https://github.com/ideas-um/FAST.

[46] Cinar, G., "A methodology for dynamic sizing of electric power generation and distribution architectures," 2018.

[47] Cinar, G., Garcia, E., and Mavris, D. N., "A framework for Electrified Propulsion Architecture and Operation Analysis," *Aircraft Engineering and Aerospace Technology*, Vol. 92, No. 5, 2020, pp. 675–684. https://doi.org/10.1108/AEAT-06-2019-0118.

[48] Tremblay, O., and Dessaint, L.-A., "Experimental Validation of a Battery Dynamic Model for EV Applications," *World Electric Vehicle Journal*, Vol. 3, No. 2, 2009, pp. 289–298. https://doi.org/10.3390/wevj3020289, URL https://www.mdpi.com/2032-6653/3/2/289.

[49] White, A. S., Waddington, E., Merret, J. M., Greitzer, E. M., Ansell, P. J., and Hall, D. K., "System-level Utilization of Low-grade, MW-scale Thermal Loads for Electric Aircraft," *AIAA AVIATION 2022 Forum*, American Institute of Aeronautics and Astronautics, Chicago, IL & Virtual, 2022. https://doi.org/10.2514/6.2022-3291, URL https://arc.aiaa.org/doi/10.2514/6.2022-3291.

[50] Elias Waddington, "CHEETA aircraft sizing, performance, and sensitivity," Master's thesis, University of Illinois, Urbana, Illinois, Dec. 2022.

[51] Cai, Y., "Multi-mission sizing and analysis framework for aircraft and subsystem architectures with electrified propulsion systems," Doctoral dissertation, Georgia Institute of Technology, May 2023. URL https://hdl.handle.net/1853/72049, publisher: Georgia Institute of Technology.

[52] Barzkar, A., and Ghassemi, M., "Electric Power Systems in More and All Electric Aircraft: A Review," *IEEE Access*, Vol. 8, 2020, pp. 169314–169332. https://doi.org/10.1109/ACCESS.2020.3024168, URL https://ieeexplore.ieee.org/document/9197600/.

[53] Moir, I., Seabridge, A., and Jukes, M., *Civil avionics systems*, John Wiley & Sons, 2013. URL https://books.google.com/books?hl=en&lr=&id=6bM2AAAAQBAJ&oi=fnd&pg=PR19&dq=%5BI.+Moir,+A.+Seabridge,+and+M.+Jukes%5D&ots=eYGqaAHwxz&sig=CkymDfoYzrNOK6WoiOJdATVyUK4.

[54] Madonna, V., Giangrande, P., and Galea, M., "Electrical Power Generation in Aircraft: Review, Challenges, and Opportunities," *IEEE Transactions on Transportation Electrification*, Vol. 4, No. 3, 2018, pp. 646–659. https://doi.org/10.1109/TTE.2018.2834142, URL https://ieeexplore.ieee.org/document/8355775/.

[55] SAS, A., "A350-900 Flight Deck and Systems Briefing for Pilots," , Sep. 2011. URL https://www.smartcockpit.com/docs/a350-900-flight-deck-and-systems-briefing-for-pilots.pdf.

[56] Chakraborty, I., "Subsystem architecture sizing and analysis for aircraft conceptual design," Doctoral dissertation, Georgia Institute of Technology, Nov. 2015. URL http://hdl.handle.net/1853/54427, publisher: Georgia Institute of Technology.

[57] Raymer, D., *Aircraft Design: A Conceptual Approach, Sixth Edition*, American Institute of Aeronautics and Astronautics, Inc., 2018. https://doi.org/10.2514/4.104909, URL http://dx.doi.org/10.2514/4.104909.

[58] Cai, Y., Xie, J., Cinar, G., and Mavris, D. N., "Advanced 2030 Turboprop Aircraft Modeling for the Electrified Powertrain Flight Demonstration Program," *2022 IEEE Transportation Electrification Conference amp; Expo (ITEC)*, IEEE, 2022. https://doi.org/10.1109/itec53557.2022.9813858.

[59] ATR, "ATR42-600, The Ideal Local Commuter," , 2024. URL https://www.atr-aircraft.com/aircraft-services/aircraft-family/atr-42-600/, [Online], Accessed June 2024.

[60] IEA, "World Energy Outlook 2022," 2022. URL https://www.iea.org/reports/world-energy-outlook-2022.

[61] Administration, U. E. I., "Annual Energy Outlook," , 2023. Data retrieved from EIA, https://www.eia.gov/analysis/projection-data.php.

[62] Wang, M., Elgowainy, A., Lu, Z., Baek, K. H., Bafana, A., Benavides, P. T., Burnham, A., Cai, H., Cappello, V., Chen, P., Gan, Y., Gracida-Alvarez, U. R., Hawkins, T. R., Iyer, R. K., Kelly, J. C., Kim, T., Kumar, S., Kwon, H., Lee, K., Lee, U., Liu, X., Masum, F., Ng, C., Ou, L., Reddi, K., Siddique, N., Sun, P., Vyawahare, P., Xu, H., and Zaimes, G., "Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model ® (2022 .Net)," [Computer Software] https://doi.org/10.11578/GREET-Net-2022/dc.20220908.2, oct 2022. https://doi.org/10.11578/GREET-Net-2022/dc.20220908.2, URL https://doi.org/10.11578/GREET-Net-2022/dc.20220908.2.

[63] Council, H., "Path to hydrogen competitiveness: A cost perspective," , 2020. URL https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf.

[64] International Air Transport Association, "Fuel Price Monitor," , 2024. URL https://www.iata.org/en/publications/economics/fuel-monitor/, accessed: 2024-06-29.

[65] Jing, L., El-Houjeiri, H. M., Monfort, J.-C., and et al., "Understanding variability in petroleum jet fuel life cycle greenhouse gas emissions to inform aviation decarbonization," *Nature Communications*, Vol. 13, 2022, p. 7853. https://doi.org/10.1038/s41467-022-35392-1, URL https://doi.org/10.1038/s41467-022-35392-1.

[66] Carbon Offset Guide, "Climate Impacts from Aviation," , 2024. URL https://www.offsetguide.org/understanding-carbon-offsets/air-travel-climate/climate-impacts-from-aviation/co2-emissions/, accessed: 2024-06-29.