1 Benefits of Electrified Propulsion for Large Aircraft

Rodger Dyson, Ralph Jansen, and Nateri Madavan

Introduction

Three main questions are addressed in this book:

(1) What are the benefits of electrified propulsion for large aircraft?
(2) What technology advancements are required to realize these benefits?
(3) How can the aerospace industry transition from today's state of the art to these advanced technologies?

This chapter addresses the first question, making the case for electrified aircraft propulsion (EAP) through numerous trade studies and the analysis of several concept vehicles. This will lay the groundwork for the chapters that follow, which – while remaining focused on question 1 – collectively address questions 2 and 3 in technical detail.

There is substantial interest in the investigation of improvements to aircraft efficiency through the introduction of electrical components into the propulsion system. In the case of turboelectric and hybrid electric aircraft, the electrical systems provide unmatched flexibility in coupling the power generation turbines to the fan propulsors. This flexibility facilitates tight propulsion–airframe integration and can result in reduced noise, emissions, and fuel burn. However, the greatly expanded electrical system incurs substantial weight and efficiency penalties at odds with its benefits. A promising intermediate step between a conventional turbofan aircraft and a fully turboelectric or electric aircraft is an aircraft with a partially turboelectric or hybrid electric propulsion system. Initial studies show that significant aerodynamic benefits can be achieved by sourcing just a small fraction of the propulsive power electrically. However, it is difficult to arrive at authoritative conclusions since the concept aircraft configurations thus far considered and many of the major electrical system components have yet to be built or verified.

In this chapter a breakeven analysis is presented to elucidate the electrical power system performance requirements necessary to achieve electrified aircraft propulsion – specifically fully turboelectric, partially turboelectric, and parallel hybrid electric. This first-order analysis provides a framework for comparing electric drive system performance factors, such as the electrical efficiency, in the context of aircraft propulsion systems. The value of this analysis is both to guide electrical system component research and to provide aircraft configuration researchers with reasonable component expectations.

Similar parametric analyses were presented previously for a fully turboelectric propulsion system [1] and a partially turboelectric system [2]. The study summarized here investigates a broader array of aircraft types, including the fully and partially turboelectric aircraft already addressed, as well as parallel hybrid electric aircraft. In the cases of partially turboelectric and hybrid electric systems, the fraction of thrust power will be varied between the turbofan engines and electric distribution to additional propulsors. A key difference between this study and the prior studies is in the breakeven analysis assumptions. Here the input power and ratio of operating empty weight to aircraft initial weight are held constant among the aircraft types, in addition to equating the range and payload weight. The other studies held either the initial aircraft weight or the fuel weight, as well as the operating empty weight, to be the same.

1.1 Benefits and Costs of Electrified Aircraft Propulsion

1.1.1 Benefits of Electrified Aircraft Propulsion

The turboelectric aircraft propulsion-derived system benefits have been described in previous papers by Jansen et al. [1, 2], and the main points are now summarized. Higher propulsive efficiency due to increased bypass ratio (BPR), higher propulsive efficiency due to boundary layer ingestion (BLI), and lift-to-drag ratio (L/D) improvements are facilitated by EAP.

The introduction of an electric drive system between the turbine and fan enables the decoupling of their speeds and inlet/outlet areas. With this approach, high BPR can be achieved since any number and size of fans can be driven from a single turbine. Increasing BPR results in improved propulsive efficiency. Also, the speed ratio between the turbine and the fan can be arbitrarily set and varied during operation, thereby removing the physical constraint levied by either direct shaft or geared coupling. As a result, the fan pressure ratio and the turbine/compressor ratios can be optimized independently. The propulsive efficiency benefits due to higher BPR could be as high as 4–8 percent [3, 4].

BLI increases propulsive efficiency by ingesting lower velocity flow near the airframe into the propulsors, reenergizing the wake, and thereby reducing drag. BLI can be implemented on both conventional tube-and-wing and hybrid wing body (HWB) aircraft. The propulsor is mounted such that the slow-moving flow near the aircraft is ingested, reenergized, and exhausted where the aircraft wake would have been. The BLI benefits to propulsive efficiency are expected to be 3–8 percent [4, 5]. Combining BPR and BLI propulsive efficiencies listed here yields improvements of 7–17 percent.

Distributed propulsion is expected to improve both lift and L/D ratio through wing flow circulation control. The propulsors can be distributed above or below, or embedded in the traditional tube-and-wing configuration. Likewise, HWB configurations can employ fans distributed across or embedded within the upper surface. Improvements in L/D ratio may result in smaller wing area and reduced drag and weight. The benefits of lift augmentation can be taken in reduced wing area for a given load capacity or shorter takeoff distances. Reduction in wing area lowers wing weight and drag, thereby imparting fuel savings. Alternatively, the improved lift could be focused on increased climb rate and reduced takeoff distance in order to decrease the noise footprint around the airfield. The L/D ratio could be improved by 8 percent [6] to 16 percent [5].

1.1.2 Costs of Electrified Aircraft Propulsion

Introducing an electric drive system, with or without batteries, into the aircraft propulsion system will add weight and reduce efficiency. Here, the electric drive system includes the electric machines, the power management and distribution system, and the thermal system related to heat removal in the two prior systems. Specifically, the electric drive system could include generators, rectifiers, distribution wiring, fault protection, inverters, motors, and the thermal control for those components.

The United States National Aeronautics and Space Administration (NASA) is investigating high-performance motors and batteries that could make electrified aircraft propulsion viable. With regard to the electric drive components, NASA is looking to improve both the efficiency and the specific power of generators, motors, inverters, and rectifiers. A NASA research announcement has a goal of developing technologies and demonstrating an MW-class motor with efficiency greater than 96 percent and power density of greater than 13 kW/kg. This is just one component of the electric drive system. The partially turboelectric STARC-ABL (single-aisle turboelectric aircraft with aft boundary layer propulsor) aircraft concept assumes those values for the motors and generators, as well as rectifiers and inverters with 19 kW/kg and 99 percent efficiency. Stacking up all the components for this aircraft – including cables, circuit protection, and thermal management – yields an electric drive efficiency of 89.1 percent [7].

With regard to batteries, current state-of-the-art lithium-ion batteries have a specific energy on the cell level of up to 200 Wh/kg. Projected values in 15 and 30 years are 650 and 750 Wh/kg, respectively, for lithium–sulfur (LiS), and 950 and 1,400 Wh/kg, respectively, for lithium–air (Li-Air) [8]. These values have to be de-rated based on depth of discharge, battery structure, and battery management. For comparison, the specific energy of aviation fuel is approximately 12,000 Wh/kg.

Clearly, the benefits of improved propulsive efficiency from high BPR and BLI, as well as increased L/D, must be greater than the costs of electrified aircraft propulsion, and the balance of these benefits and constraints are presented here.

1.1.3 Aircraft Concepts with Electrified Propulsion

NASA has been investigating several different EAP systems for aircraft, including fully turboelectric, partially turboelectric, and parallel hybrid electric systems.

The N3-X concept shown in Figure 1.1 is a 300-passenger, HWB aircraft with a fully turboelectric propulsion system and a design range of 7,500 nautical miles (NM).

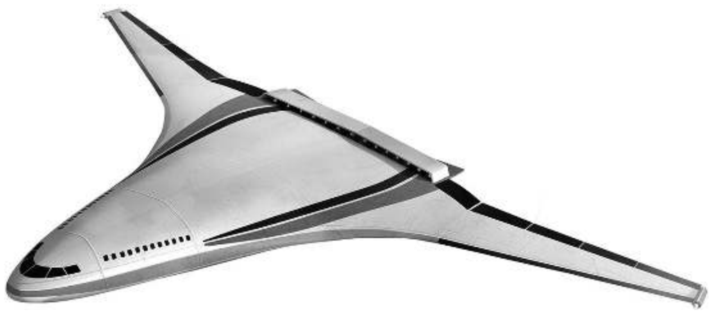

Figure 1.1 N3-X concept vehicle.

Figure 1.2 STARC-ABL concept vehicle.

Turbine engines are located at the wing tips, powering generators. Electric power is then transmitted through cables to a series of motor-driven fans located near the trailing edge of the aircraft. This configuration allows for a higher lift-to-drag ratio due to the hybrid wing body, as well as higher propulsive efficiency due to the increase in fan bypass ratio and boundary layer ingestion. This concept, described by Felder et al. [5], was conceived as a future-generation aircraft to meet NASA's goal of 70 percent fuel burn reduction. Out of the 70 percent overall improvements, 18–20 percent of fuel burn reduction was attributed to the turboelectric propulsion system architecture.

Figure 1.2 shows the partially turboelectric concept STARC-ABL, which is a 154-passenger aircraft with a design range of 3,500 NM. This commercial transport concept was developed for notional entry into service in 2035 and was compared to a conventional configuration using similar technology by Welstead and Felder [9]. The propulsion system consists of two underwing turbofans with generators extracting power from the fan shaft and transmitting it to a rear fuselage, axisymmetric, boundary layer ingesting fan. The power to the tailcone fan is constant and contributes approximately 20 percent of the thrust at takeoff and about 45 percent of the thrust at cruise. Analysis in [9] indicates that the partially turboelectric concept has an economic mission fuel burn reduction of 7 percent, and a design mission fuel burn reduction of 12 percent compared to the conventional configuration. It should be noted that subsequent studies have

Figure 1.3 PEGASUS concept vehicle.

predicted fuel burn reductions that are in the range of 3–4 percent, but they were not available for referencing at the time of this publication.

The Parallel Electric-Gas Architecture with Synergistic Utilization Scheme (PEGASUS) concept is shown in Figure 1.3, which is a 48-passenger parallel hybrid electric aircraft. This concept is described by Antcliff and Capristan [10]. A detailed analysis of an intermediate parallel hybrid electric concept was performed by Antcliff et al. [11], which was based on the ATR-42-500 conventional fuel-based aircraft with a range of 600 NM. The analysis included various levels of battery specific energy, which is a critical parameter as battery weight has been shown to be a significant penalty for these types of aircraft. They found that a specific energy of 750 Wh/kg was required to break even on total energy, even as the aircraft weight increased over the baseline value.

The N3-X, STARC-ABL, and PEGASUS concepts will be used as case studies for the breakeven analysis in this study.

1.2 Breakeven Analysis

1.2.1 Key Performance Parameters and Key Assumptions

In order to conduct the breakeven analysis, we first define the key performance parameters (KPPs), the key assumptions, and the electrical power system boundary. Then we will formulate range equations for each aircraft type. Finally, we find the breakeven relationship by implicitly solving for the electric drive specific power and efficiency while holding constant the ratio of operating empty weight to initial weight, payload weight, input energy (from fuel and/or batteries), and aircraft flight range. The resulting parametric curves can be used as the top-level requirements for the electrical power system and bounding guidelines for further aircraft exploration.

Specifically, the key performance parameters (KPPs) are as follows:

- Electric drive system efficiency η_{elec}, expressed as a percentage.
- Electric drive system specific power Sp_{elec}, in kW/kg.
- Electric propulsion fraction ξ for partially turboelectric and parallel hybrid electric aircraft.

The breakeven assumptions in this analysis used to determine the values of the KPPs include the following:

- The ranges of the conventional and electrified aircraft are equal.
- The input energy (fuel and/or battery energy) of the conventional and electrified aircraft are equal.
- The payload weights of all the aircraft are equal.
- The ratios of operating empty weights (OEW) to initial aircraft weights are equal, where OEW does not include the weights of the electric drive and batteries.

1.2.2 Electrified Aircraft Propulsion System Definitions

Each EAP system will now be described, along with the boundaries of the electric drive system for each case. In Figures 1.4–1.7 are shown simplified diagrams of the conventional (fuel-based) turbofan, fully turboelectric, partially turboelectric, and parallel hybrid electric aircraft propulsion systems, respectively. The conventional turbofan system is considered the baseline aircraft system for comparison. The building blocks of the systems are the energy source (fuel and/or battery), the turbine engine, the propulsor, and the electric drive for the EAP cases. We denote the *conventional turbofan aircraft*, *fully turboelectric*, *partially turboelectric*, and *parallel hybrid electric* parameters with the subscripts *AC*, *TE*, and *PE*, and *HE*, respectively. *Power* is denoted by the letter *P*, *efficiency* by η, *specific energy* by *Se*, and *specific power* by *Sp*.

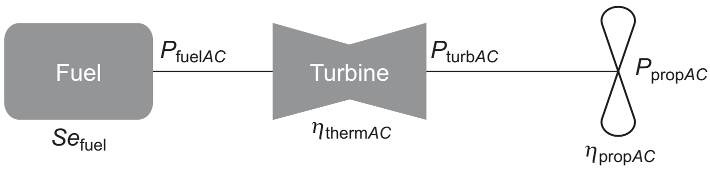

Figure 1.4 Conventional, fuel-based aircraft propulsion system (AC).

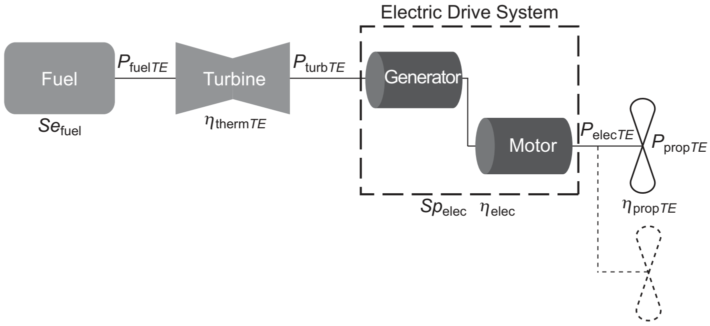

Figure 1.5 Fully turboelectric aircraft propulsion system (TE).

The turbine, propulsor, and electric drive have associated thermal (η_{therm}), propulsive (η_{prop}), and electrical (η_{elec}) efficiencies, expressed throughout this chapter as percentages. The fuel power P_{fuel}, battery power P_{batt}, turbine engine power P_{turb}, electrical power P_{elec}, and propulsive power P_{prop}, all in kW, are defined as output power of the fuel, battery, turbine engine, electric drive, and propulsors, respectively. The variables in Figures 1.4–1.7 illustrate the association between the propulsive subsystems, powers, and efficiencies for each propulsion system. In the partially turboelectric and parallel hybrid electric cases, we must introduce the electrical propulsion fraction ξ, defined as the fraction of total aircraft thrust at cruise produced by electrically driven propulsors. When the electrical propulsion fraction is equal to one, all the thrust during cruise is provided by electrically driven propulsors. The fully turboelectric system is one in which all the thrust throughout the mission, including takeoff and cruise, is provided by electrically driven propulsors. Therefore, the electric drive system will need to be sized accordingly.

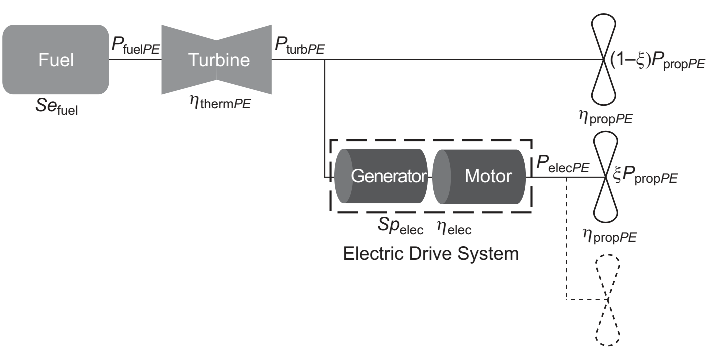

Figure 1.6 Partially turboelectric aircraft propulsion system (PE).

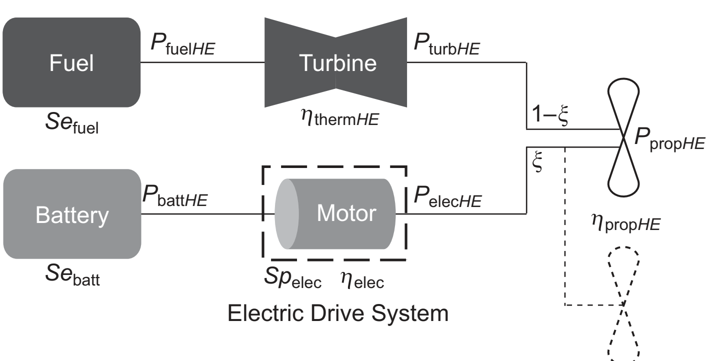

Figure 1.7 Parallel hybrid electric propulsion system (HE).

The electric drive specific power, efficiency, and electrical propulsion fraction are the electrified aircraft electric drive system KPPs. Specific power is the ratio of the rated electric drive output power to its mass. Efficiency is the ratio of the output power to the input power of the electric drive system, multiplied by 100 percent. Electrical propulsion fraction is the fraction of total aircraft thrust at cruise produced by electrically driven propulsors. These three KPPs will be used to describe electrical power system performance and establish necessary levels of performance.

The boundary of the electric drive system is defined to lend meaning to the KPPs. In the analysis presented here, the boundary will include generators, rectifiers, distribution wiring, fault protection, inverters, motors, and the thermal control for those components. The parallel hybrid electric system does not require generators. Some variants of the electrical drive system may use a subset of these components or alternative layouts. The specific power and electrical efficiency analyzed in this study include all of the components inside the boundary. Notably, the turbine engine and the propulsors are outside the electric drive boundary.

A simplified assessment of the relationship of the electric drive system KPPs, aircraft range, and input energy is proposed for top-level aircraft performance comparisons. The range equations are discussed first, followed by the input energy, and, finally, the component weights. The breakeven equations are derived for fully turboelectric, partially turboelectric, and parallel hybrid electric aircraft.

1.2.3 Breakeven on Range

The basis of the analysis is an expansion of the traditional terms in the Breguet range equation for fuel-based aircraft to include the efficiency and weight of the electric drive system. The range equation for battery-powered aircraft from Hepperle [12] is expanded in a similar way. These equations apply to situations where overall aerodynamic efficiency, L/D, and flight velocity are constant over the duration of cruise. Although this is not true for the entire flight envelope, this description is a reasonable approximation for cruise conditions.

We develop range equations of the typical form, representing the conventional and EAP aircraft configurations concurrently for comparison. The range equations for fuel-based and battery-based aircraft are, respectively,

$$R_{\mathrm{fuel}} = \frac{Se_{\mathrm{fuel}}}{g}\frac{L}{D}\eta_{\mathrm{o}} \ln\left(\frac{W_{\mathrm{i}}}{W_{\mathrm{f}}}\right) \tag{1.1}$$

and

$$R_{\mathrm{batt}} = \frac{Se_{\mathrm{batt}}}{g}\frac{L}{D}\eta_{\mathrm{o}} \left(\frac{W_{\mathrm{batt}}}{W_{\mathrm{i}}}\right), \tag{1.2}$$

where R is the range, in m; Se_{fuel} and Se_{batt} are the specific energies of the fuel and battery, respectively, in J/Kg; and η_{o} is the overall efficiency percentage of the propulsion system.

For fuel-based aircraft, the final aircraft weight, W_f, is equal to the initial aircraft weight, W_i, minus the fuel weight, W_{fuel}, where all are expressed in N. Thus, the fuel-based range equation is

$$R_{fuel} = \frac{Se_{fuel}}{g}\frac{L}{D}\eta_o \ln\left(\frac{1}{1 - W_{fuel}/W_i}\right). \tag{1.3}$$

Note that for small values of W_{fuel}/W_i,

$$\ln\left(\frac{1}{1 - W_{fuel}/W_i}\right) \approx \frac{W_{fuel}}{W_i}, \tag{1.4}$$

which shows that Equations (1.1) and (1.2) have a similar form. Thus, the range is approximately proportional to the ratio of the energy source weight to the aircraft initial weight. Since $Se_{batt} \ll Se_{fuel}$, battery weight for the same range will be much larger than fuel weight.

The overall efficiency of each aircraft type is defined in Equations (1.5)–(1.8) in Table 1.1 as functions of propulsive, thermal, and electric drive efficiency. Note that the propulsive efficiency defined here is actually the product of transfer efficiency and propulsive efficiency.

To see how adding the electric drive system affects overall efficiency, the ratio of electrified aircraft to baseline conventional overall efficiency is plotted in Figure 1.8 as a function of electric propulsion fraction. Here it is assumed that the thermal efficiency is 55 percent and the electric drive efficiency is 90 percent. Increasing ξ decreases overall efficiency for the turboelectric cases, since the electric drive system is in series with the turbine engine. Since η_{elec} is larger than η_{therm}, the hybrid electric system has increasing overall efficiency compared to the baseline. However, the battery weight required for hybrid electric will be a significant penalty in the breakeven analysis.

1.2.4 Breakeven on Input Energy

The input energy of fuel is simply the product of the specific energy of the fuel and the fuel mass. Similarly, the input energy of the battery is simply the product

Table 1.1 Overall efficiency equations.

Aircraft type	Overall efficiency	
Conventional aircraft (AC)	$\eta_{oAC} = \eta_{propAC} \times \eta_{thermAC}$	(1.5)
Fully turboelectric aircraft (TE)	$\eta_{oTE} = \eta_{propTE} \times \eta_{thermTE} \times \eta_{elecTE}$	(1.6)
Partially turboelectric aircraft (PE)	$\eta_{oPE} = \dfrac{\eta_{propPE} \times \eta_{thermPE} \times \eta_{elecPE}}{(1-\xi)\eta_{elecPE} + \xi}$	(1.7)
Parallel hybrid electric aircraft (HE)	$\eta_{oHE} = \dfrac{\eta_{propHE} \times \eta_{thermHE} \times \eta_{elecHE}}{(1-\xi)\eta_{elecHE} + \xi\eta_{thermHE}}$	(1.8)

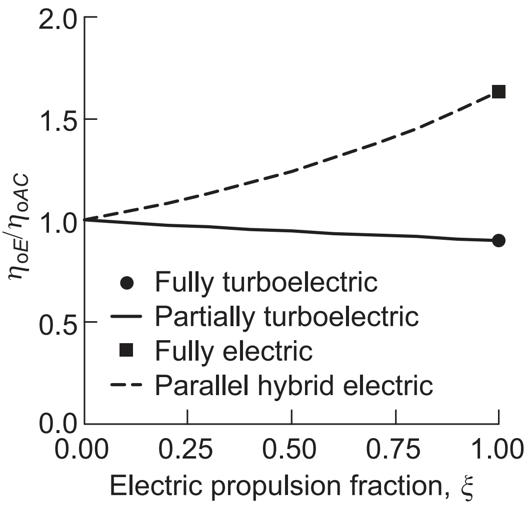

Figure 1.8 Ratio of electrified to conventional aircraft overall efficiency.

of the specific energy of the battery and the battery mass. Thus, the input energy equations are

$$E_{\text{fuel}} = \frac{Se_{\text{fuel}}}{g} W_{\text{fuel}} \tag{1.9}$$

and

$$E_{\text{batt}} = \frac{Se_{\text{batt}}}{g} W_{\text{batt}}. \tag{1.10}$$

1.2.5 Relationship among Aircraft Component Weights

The final part of the breakeven analysis relates the specific power of the EAP system to the other component weights. We know that the initial aircraft weight is defined as the sum of the OEW, payload weight, fuel weight, electric drive system weight (for electrified aircraft), and battery weight (for HE aircraft):

$$W_{\text{i}} = W_{\text{OEW}} + W_{\text{payload}} + W_{\text{fuel}} + W_{\text{elec}} + W_{\text{batt}}. \tag{1.11}$$

From Equation (1.11) we can see that

$$\frac{W_{\text{elec}}}{W_{\text{i}}} = 1 - \frac{W_{\text{OEW}}}{W_{\text{i}}} - \frac{W_{\text{fuel}}}{W_{\text{i}}} - \frac{W_{\text{batt}}}{W_{\text{i}}} - \frac{W_{\text{payload}}}{W_{\text{i}}}, \tag{1.12}$$

noting that the payload weight and the ratio of OEW to initial aircraft weight are constant among the aircraft.

For the TE aircraft, where all the power must pass through the electric drive system, Sp_{elec} will be defined based on takeoff power rather than cruise power.