8 (3): 377-384 (2024)

Journal of Aviation

https://dergipark.org.tr/en/pub/jav

e-ISSN 2587-1676

Assessing the Impact of Hybrid Propulsion Systems on the Range and Efficiency of Aircraft

Alihuseyn Maharramov[1], Elif Koruyucu[2*]

[1]Eskisehir Technical University, Airframe and Powerplant Maintenance, Eskisehir, Türkiye. (alihuseyn.meherremov@gmail.com)
[2*]Eskisehir Technical University, Porsuk Vocation School, Eskisehir, Türkiye. (elifkoruyucu@eskisehir.edu.tr)

Article Info

Received: 30 August 2024
Revised: 01 October 2024
Accepted: 06 October 2024
Published Online: 18 October 2024

Keywords:
Aviation
Hybrid propulsion systems
Optimum range
Battery
Hybridization

Corresponding Author: *Elif Koruyucu*

REVIEW ARTICLE

https://doi.org/10.30518/jav.1540893

Abstract

The demand for aviation continues to grow, posing issues in terms of fuel consumption, environmental effect, and operational efficiency. In addition, the COVID-19 pandemic has also highlighted the need for sustainable solutions in the aviation sector. To address these issues, hybrid electric propulsion systems have emerged as a potential option. Hybrid electric propulsion systems have the potential to improve airplane performance while reducing environmental impact. This article looks into the effects of hybrid electric propulsion technologies on optimal aircraft range. The study looks at aviation's environmental impact, several hybrid aircraft prototypes, and battery capacity and density challenges. Fuel usage increases in proportion to the weight of the aircraft. As a result, the range is shorter. In modern technology, along with to the added weight of batteries used as energy storage in hybrid propulsion systems, there are low battery densities and capacities. When the researches were reviewed, it was discovered that overcoming these limitations was easier for small aircraft and more difficult for large aircraft. As a consequence of the studies and research conducted, the development of light and reliable batteries with high energy density and capacity would expand the range of hybrid aircraft and allow them to be used more efficiently over long distances.

1. Introduction

Due to the increasing consumption of fossil fuels, their high cost and their negative effects on the environment, the search for new energy sources continues. In order to use fuel more efficiently in the aviation field, studies are being carried out such as improvements in existing engines and lighter aircraft materials. Recently, studies have mainly focused on hybrid propulsion systems in aircraft to reduce fossil fuel use.

The adoption of hybrid electric propulsion systems in the aerospace industry represents a paradigm shift towards more sustainable and environmentally friendly aviation. The aviation industry faces challenges such as carbon emissions, fuel consumption, and the search for efficient propulsion technologies. In response to these challenges, hybrid electric propulsion systems offer a significant benefit by reducing environmental impact through decreased fossil fuel consumption and harmful emissions.

By combining the power of conventional fuel-powered engines with the efficiency and versatility of electric motors, hybrid electric propulsion systems not only reduce fuel consumption but also diminish the environmental carbon footprint of the aviation industry. Hybrid electric propulsion is seen as a testament to the commitment to a greener future for air travel.

The advantages of hybrid electric drive are not limited to reducing environmental impact; they also have the potential to reduce noise pollution and advance aircraft performance with features such as improved power distribution, high reliability, and operational flexibility. These systems can enhance the capability of aircraft and optimize their range by utilizing both conventional and electric propulsion.

One of the most important performance indicators for aircraft is range. The range of an aircraft directly affects the accessibility and versatility of air travel. This study evaluated the effects of hybrid electric propulsion on aircraft range.

2. Literature Review

Hybrid electric propulsion systems offer advantages over conventional propulsion systems, such as reduced emissions and noise, increased global aircraft efficiency, increased aircraft power distribution/quality and flight range, and the capacity to expand the market to smaller airports (Sliwinski et al. 2017).

The development of hybrid-electric propulsion systems for aircraft has been a subject of interest in recent years due to its potential to reduce fuel consumption and emissions. In the following studies found in the open literature, it has been observed that the effects of these systems on optimum aircraft range have been investigated.

High-weight batteries have a significant influence on designs, as the study by Voskuijl et al. emphasizes when measuring the design space depending on hybridization level and duty range. It also highlights how important it is to take into account other system elements during the design phase, like cabling and battery cooling. By using a parallel hybrid electric propulsion system architecture, making assumptions about future developments in battery technology, and comparing the results with traditional turboprop aircraft, the study shows that hybrid electric propulsion produces significant emissions savings. According to the study, a design that needs 34% electric shaft power, for example, reduces mission fuel consumption by 28%. This, in turn, lowers local emissions and noise levels during takeoff and landing (Voskuijl et al., 2018).

Vries et al. conducted a dimensioning study a passenger aircraft with on-wing distributed hybrid electric drive and evaluated the impact of this configuration on energy efficiency. The comparative analysis revealed that the hybrid electric aircraft is 2.5% heavier and consumes 2.5% more energy compared to the reference aircraft (Vries et al., 2019).

The study by He and his team evaluated the performance of a hybrid passenger aircraft using turbofans and electric fans at different degrees of hybridization, examined the effects of hybridization on the main performance characteristics, and developed an optimization method that allows hybrid electric propulsion systems to quickly enhance the design requirements for series hybrid electric systems. (He et al., 2020).

The research conducted by Xie et al. underscores that although hybrid electric systems exhibit a balance of emission reduction, fuel savings, and performance for small-scale aircraft, the adaptation of these systems to larger aircraft is a subject of skepticism among some researchers. Progress in this field depends on advancements in electric storage technologies (Xie et al., 2021).

The research by Bravo et al. compares all-electric and hybrid propulsion systems in the context of efforts to reduce emissions in the aviation industry. They found that all-electric propulsion tends to have more battery weight, while piston engines are both more efficient and cost-effective. Another study by the same team looks at the aerodynamic efficiency of a distributed hybrid propulsion system. It mentions that although drag is reduced, there's also a decrease in lift, emphasizing the need for thoughtful design (Bravo et al., 2021).

Palaia and Abu Salem investigated hybrid-electric regional aircraft mission systems, assessing their operational performance across diverse conditions through simulation software. They emphasized the distinct operational methods of hybrid electric aircraft compared to traditional fuel-driven ones, particularly regarding load-range diagrams and optimizing power supply techniques for enhanced fuel efficiency and extended flight range (Palaia and Abu Salem, 2023).

Zaghari et al. conducted a study on the aerodynamic and acoustic performance of electric motor and propeller designs. They concluded that aerodynamics significantly influences energy consumption reduction and noise mitigation during flight. Wide engine views were found to enhance both acoustic and aerodynamic performance. This research underscores the importance of noise reduction and increased aerodynamic efficiency in developing sustainable hybrid electric aircraft technology (Zaghari et al., 2023).

3. Changes in Air Transportation and the Impact of Covid-19

Increasing demand for products supplied from different parts of the world necessitates rapid transportation. For example, the global e-commerce industry relies heavily on cargo transportation by air to provide fast deliveries to consumers. Pharmaceutical and perishable goods industries have also become dependent on air-transportation for timely transportation of their sensitive products. As a result, air transport is becoming an integral part of the global trade network and contributes significantly to economic development and prosperity.

The number of airline passengers has been increasing steadily over the last few decades. According to the International Air Transport Association, the global airline industry carries a steadily increasing number of passengers each year, carrying approximately 4.5 billion passengers in 2019 (hhtp-2). Airlines around the world are expanding their fleets to meet increasing demand. Data from Boeing and Airbus, two of the world's largest aircraft manufacturers, show that the global commercial aircraft fleet is expected to double over the next two decades. Airlines ordered thousands of new aircraft in 2019 to meet this increasing demand (http-1; http-2).

Nevertheless, the aviation industry has been hit hard by the COVID-19 pandemic, experiencing an unprecedented decline. The pandemic caused a dramatic decrease in air travel, leading to significant financial losses for airlines. Travel restrictions, lockdowns, and quarantine measures imposed by countries to curb the virus spread resulted in a sharp drop in passenger numbers. Both international and domestic travel almost came to a standstill, leaving airports deserted. In 2020, global passenger demand plummeted by around 65.9% compared to the previous year, as reported by the International Air Transport Association (IATA, 2020).

Thanks to widespread vaccination campaigns, people are feeling more confident about flying again. Many countries have rolled out vaccination programs, and airlines and airports have stepped up their health and safety measures. These include requirements for masks, stricter cleaning routines, and better ventilation systems. These efforts have helped reassure travelers that flying is safe.

As the pandemic situation improved and precautions were put in place, many countries started easing travel restrictions and border closures. This has allowed international travel to slowly resume, which is crucial for the industry's recovery. Bilateral agreements and agreed-upon health protocols have made cross-border movement easier.

The demand for air transportation is increasing steadily under the influence of several key factors. One of the main catalysts is the expansion of the global middle class. As more people reach higher income levels and better standards of living, the desire and capacity for air travel is increasing significantly. The International Air Transport Association estimates that the number of passengers traveling by air will double to 8.2 billion by 2037 (http-3).

Air transportation has a larger share than the land and sea transportation market. Aircraft are becoming the preferred method of long-distance travel, often replacing slower alternatives such as trains or buses. In some regions, such as North America and Europe, air travel holds a significant share of the market, with more than half of all travel being made by air (Caputo et al., 2023).

4. Environmental Impacts of Aviation

The rising demand for air travel presents challenges in terms of environmental impact and sustainability. The aviation industry is actively striving to develop technologies that are more fuel-efficient and eco-friendlier to reduce its environmental footprint. It aims to balance the benefits of air travel with its environmental responsibilities, driving ongoing research and improvement efforts.

To tackle environmental issues in aviation, significant investments are being made in alternative fuel sources like biofuels and renewable energy to minimize greenhouse gas emissions.

In 2022, the aviation sector accounted for 2% of global CO_2 emissions, driven largely by energy use, surpassing emissions from road and sea transportation due to recent growth. With international travel demand rebounding post-COVID-19, emissions in 2022 nearly reached 800 million metric tons of CO_2, about 80% of pre-pandemic levels. Various technical measures, including low-emission fuels and advancements in engine design, are being employed to curb emission growth and work towards reducing emissions to net zero by 2050 (http-4).

5. Methodology

Hybrid propulsion systems ingeniously combine conventional fuel-powered engines with electric motors, significantly reducing focus impact while simply maximizing efficiency and creating an energy-efficient synergy. Such advances are promising efforts towards creating a greener future for air travel through profound technological advances and cutting-edge research in detail technology. In the field of aviation, efforts have intensified to use hybrid drive systems during the transition phase to the use of fully electric propulsion systems.

5.1. Series hybrid propulsion systems

In aircraft, one popular hybrid electric propulsion setup is the series hybrid configuration (Figure 1). Here, the propeller isn't directly linked to the gas turbine; instead, it's solely powered by an electric motor (Rendón et al., 2021). This setup resembles the turboelectric architecture but adds a battery for energy storage and propulsion assistance. In this setup, a generator converts the gas turbine's mechanical energy into electrical power. This electricity can directly run electric motors or be stored in a battery. Since the gas turbine's main job is generating electricity, this setup works well for planes with distributed propulsion (Gogolák et al., 2019).

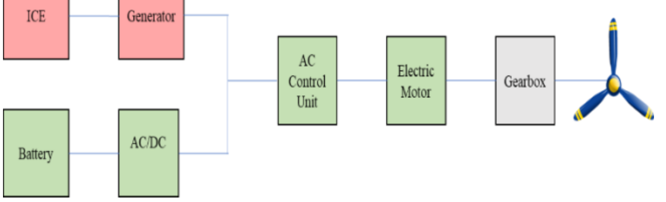

Figure 1. Series Hybrid Propulsion Configuration

In the series hybrid propulsion system, the propeller isn't directly linked to the gas turbine, allowing the turbine to operate optimally throughout the flight, cutting fuel use significantly compared to other setups (Capata and Coccia, 2010). While offering simplicity and flexibility in engine placement, this setup adds weight due to the generator and battery, and it's less efficient due to power losses in conversion (Economou et al., 2019). Moreover, it lacks redundancy in case of engine failure.

In 2011, Siemens, Diamond Aircraft, Austro Engine, and Airbus showcased the first manned serial hybrid electric aircraft at the Paris Air Show. This DA36 E-Star aircraft achieved a 25% decrease in emissions and fuel consumption using a Siemens electric motor and an Austro Engine (http-5; Alvarez et al., 2022). Manufacturers suggest the aircraft's scalability for 100 passengers, but no technical evidence supports this claim.

5.2. Parallel hybrid propulsion systems

Another hybrid electric aircraft setup is the parallel hybrid architecture, showcased in Boeing's SUGAR Volt and SUGAR Freeze concepts (NASA, December 12, 2023). This design utilizes both internal combustion and electric motors to propel the aircraft. The internal combustion engine and electric motor are linked to a gearbox that moves the propeller in parallel. Unlike the series hybrid, this setup offers greater reliability and redundancy by allowing independent operation of both systems (Capata and Corcia, 2010). Additionally, it enables the use of smaller engines to achieve similar power levels as larger ones, thus cutting fuel use and emissions.

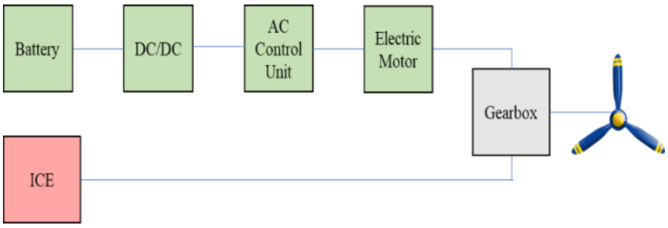

Figure 2. Parallel Hybrid Propulsion Configuration.

In the parallel hybrid architecture, depicted in Figure 6.2, two parallel drive shafts are mechanically connected. One shaft is powered by combustion, while the other by electricity (Rendon et al., 2021). Both electric motor and internal combustion engine shafts are connected to a common shaft driving a fan or propeller, allowing either or both to contribute to propulsion. Moreover, batteries can recharge as the internal combustion engine drives the propeller and the electric motor acts as a generator. Unlike other architectures, there's no electrical generator attached to the internal combustion engine's shaft, reducing component size and weight.

However, this configuration has drawbacks. The mechanical connection between drive shafts adds extra mass (Gogolak et al., 2019), requiring a more sophisticated control system. Additionally, the internal combustion engine's optimal operation may be compromised at different flight phases compared to the series setup, as it contributes to thrust generation (Barelli et al., 2018).

5.3. Series-Parallel Hybrid Propulsion Systems

Another hybrid electric aircraft configuration is the series-parallel hybrid propulsion system, as illustrated in Figure 3, combining elements of both series and parallel setups. This hybrid design incorporates two power sources: an internal combustion engine paired with an electric generator, along with a battery-powered electric motor. These components are connected in series, delivering thrust power to the aircraft (Xie et al., 2021). The series-parallel hybrid system offers benefits from both configurations, allowing flexibility in power source selection for various flight phases and enabling energy recovery through regenerative braking (Jain and Kumar, 2018). While the series part ensures efficient low-speed operations, the parallel section is advantageous for high-power demands like takeoff and climb. However, this system requires an advanced control setup to optimize performance and is more intricate compared to parallel or series architectures (Hong et al., 2018).

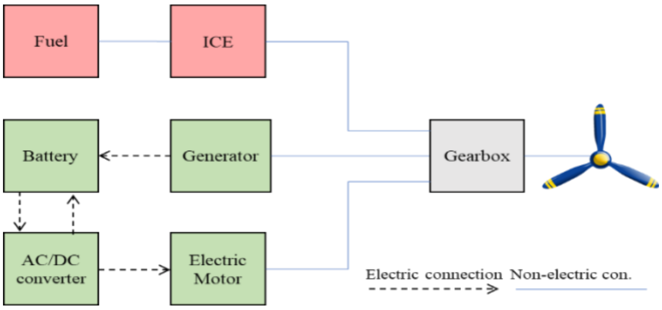

Figure 3. Series-Parallel Hybrid Propulsion Configuration.

5.4. Degree of hybridization

Parallel and combined hybrid vehicles can be classified based on their level of hybridization, determined by the balance of power from the internal combustion (IC) engine and electric motor. In some cases, the IC engine is primary, with the electric motor activating only for extra power. In others, both the IC engine and electric motor share the workload equally. Some vehicles can operate solely on the electric motor system. The degree of hybridization is measured by the ratio of power generated by the electric motor to the total power used by the vehicle. Three main types of hybridization are mild, full and plug-in hybridization.

In a mild hybrid system, the electric motor offers partial assistance to the internal combustion engine. It helps during acceleration or high-power needs but can't propel the vehicle independently. The internal combustion engine remains the main power source, while the electric motor acts as a power booster or energy recovery system. Mild hybrid systems have a low degree of hybridization, with the electric motor contributing only a fraction of the total drive power (Cardoso et al., 2020).

In a full hybrid system, the internal combustion engine and electric motor share power more evenly (Boschert, 2006). Both can propel the vehicle alone or together. This setup utilizes regenerative braking and battery-stored energy to supply electricity during low-speed operations or to assist the internal combustion engine during high-demand situations. Full hybrid systems have a moderate degree of hybridization, with both power sources playing a significant role in propulsion.

A plug-in hybrid system achieves the highest level of hybridization (Maddumage et al., 2021). It features a larger battery that can be charged from an external power source, usually the mains. The electric motor is crucial for vehicle propulsion, with the internal combustion engine serving as a backup or for extended range. Plug-in hybrids can run solely on electricity for short distances, relying on the electric motor (Boschert, 2006). The internal combustion engine is used mainly for longer trips or when the battery charge is low. Plug-in hybrids have the highest degree of hybridization, with the electric motor providing a significant portion of the power.

The degree of hybridization directly impacts overall efficiency, fuel economy, and environmental impact. Higher degrees, like those in full or plug-in hybrid systems, offer better opportunities for energy recovery, regenerative braking, and lower emissions compared to mild hybrids. However, increased hybridization usually means higher complexity, cost, and weight. The choice of hybridization level depends on specific needs, performance requirements, and the desired balance between fuel efficiency and system complexity.

5.5. Energy Management

The aim of energy management in hybrid electric aircraft is to enhance efficiency and performance while reducing environmental impact (He et al., 2020). One of the main hurdles in hybrid electric aircraft is effectively managing energy flow between different power sources. This involves smartly distributing power between the gas turbine engine and electric motor based on flight phase, altitude, speed, and mission needs.

During takeoff and climb, when higher power is needed, the gas turbine engine provides primary thrust. As the aircraft reaches cruise altitude, it shifts to a more electrically-intensive mode where the electric motor takes over, allowing the gas turbine to operate at its most efficient power range. Regenerative braking is another vital aspect of energy management, where the electric motor acts as a generator during descent, converting kinetic energy into electrical energy for storage or powering auxiliary systems (Morishita et al., 2023).

To ensure seamless switching between power sources and optimize energy efficiency, advanced power distribution and management systems are essential in hybrid electric aircraft (He et al., 2020). These systems rely on sophisticated control algorithms and flight management systems to monitor flight parameters and adjust power settings autonomously for efficient operation and enhanced safety.

In the realm of hybrid electric vehicles, power sharing is a crucial aspect of energy management. It involves distributing power between the electric motor and internal combustion engine within the vehicle's powertrain. The power sharing ratio, denoted as S, indicates the proportion of shaft power provided by the electric motor (P_{el}) to the total shaft power (P_{total}) from the internal combustion engine and electric motor. This $S= P_{el}/P_{total}$ ratio helps determine the optimal allocation of power resources for different flight conditions (Voskuijl et al., 2018).

5.6. Analysis of Current Hybrid Electrical Aircraft Prototypes

Investigation of hybrid electrical aircraft, engaged with current research, and examination of multitude of characteristics gave us valuable insights. Each of the researched hybrid aircraft exhibits different capabilities and innovations. Hypstair stands out with its six-fold increase in power/weight ratio and operating range of up to 1000 km, underlining its efficiency and environmental friendliness. In contrast, the E-Genius is impressive with its focus on sustainability, 400 km range and ability to operate at altitudes of up to 6,000 m. Although Zunum Aero promises efficient regional air travel, its current status remains uncertain due to financial difficulties. Combining efficiency and practicality, the Diamond DA36 E-Star has a range of 1,094 km and a significant reduction in fuel consumption and emissions. Meanwhile, the N3-X aims to revolutionize long-haul air travel with the ambitious goal of reducing fuel consumption by 70%. Airlander 10 and Airlander 50 offer solutions for both cargo and passenger transportation with their durability, load carrying capacity and environmental friendliness. The Panthera Hybrid and Ampaire Electric EEL demonstrate the potential of hybrid-electric propulsion in a variety of flight regimes. Finally, the ENFICA-FC Project exemplifies the use of fuel cell-based power systems for light aircraft, emphasizing both environmental friendliness and operational robustness. Collectively, these hybrid aircraft represent the industry's quest for greener and more efficient aviation solutions (Correa et al., 2015), (Ratner, 2018) (Bradley and Droney, 2015), (Doll et al., 2022), (Arabul et al., 2021).

5.7. Range

An aircraft's range, which determines how far it can travel without refueling, is a crucial performance metric. Calculating range involves considering factors like fuel efficiency, weight, aerodynamics, and operating conditions.

The Breguet equation, named after French engineer Louis Charles Breguet, is a fundamental formula used to estimate aircraft range. It relates range to fuel efficiency and other pertinent parameters. The equation computes range by accounting for the change in aircraft weight from start to finish, along with the fuel consumed during this interval. Various flight parameters are also included in the formula to refine the calculation (http-6).

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

The general range formula is shown in equation (1). Here it can be observed that range equals flight time multiplied by the velocity of the aircraft. Additionally, $\frac{L}{D}$ the aerodynamic design, I_{sp} the propulsion system and $\ln\left(\frac{W_i}{W_f}\right)$ weight ratio are interconnected.

The range formula is also written as shown in equation (2).

$$R = \frac{V}{g}\frac{1}{SFC}\frac{L}{D}\ln\left(\frac{W_i}{W_f}\right) \quad (2)$$

Here:
R= aircraft range, km
V=flight speed, km/h
g= acceleration of gravity
L/D=lift to drag ratio
SFC=specific fuel consumption
W_i=initial weight, kg
W_f=final weight, kg

5.8. Optimum Range

The word optimum is defined as "The most suitable, most convenient, suitable value" (http-7). The term optimum flight range in aviation refers to the planned distance that an aircraft must travel. This distance may vary depending on factors such as the aircraft's engine efficiency, aerodynamic properties and fuel consumption. Pilots and flight engineers use performance graphs, flight tables and calculations to determine the flight range of a particular aircraft. This value is determined to obtain the least fuel consumption and the most favorable range. The optimum flight range may vary for different aircraft types, and this value is important for flight planning and fuel or energy economy.

Optimum flight range is also considered an important performance criterion for hybrid aircraft. Because these aircraft use electric propulsion systems in addition to conventional fuel engines, they can be optimized to provide the most efficient energy use at certain speeds and altitudes. This optimization plays an important role in achieving optimum flight range. In addition, energy management, that is, the energy source and engine type to be used at certain speeds and altitudes, is also taken into account.

5.9. Factors Affecting Range

The main factors affecting the range of conventionally fueled aircraft and hybrid electric aircraft are shown in Table 1.

Table 1. Factors Affecting Range

Traditional ICE Aircraft	Hybrid Electrical Aircraft
Internal combustion engine efficiency	Internal combustion engine efficiency
Fuel capacity	Fuel capacity
Fuel efficiency	Fuel efficiency
Aircraft weight	Aircraft weight
Freight and passenger load	Freight and passenger load
Weather conditions	Weather conditions
Altitude and flight profile	Altitude and flight profile
Air traffic and flight operations	Air traffic and flight operations
Technology and engine efficiency	Technology and engine efficiency
Aircraft type and mission profile	Aircraft type and mission profile
	Battery capacity
	Electric motor efficiency
	Energy management
	Regenerative energy

Aircraft weight, which is directly linked to fuel consumption and range, plays an important role in aviation. Aircraft weight is divided into different categories:

- Maximum Takeoff Weight (MTOW) is a very important parameter determined by the aircraft manufacturer and represents the maximum weight that an aircraft is allowed to take off.
- Complementing the MTOW, Zero Fuel Weight (ZFW) covers the total weight of the aircraft without usable fuel, including all items other than fuel.
- Maximum Landing Weight (MLW) refers to the maximum weight allowed for a safe landing; This value is usually determined by aircraft manufacturers or regulatory authorities.
- Empty operating weight (OEW) includes the weight of the aircraft including the crew and all operationally necessary fluids such as engine oil (excluding fuel used and cargo).
- Payload, a critical measurement, describes the maximum weight available for passengers, cargo or freight, expressing the difference between MTOW and OEW.
- Maximum Taxi Weight (MTW) or Maximum Ramp Weight (MRW) means the maximum weight allowed for ground maneuvers, including taxiing onto the runway.

5.10. Range Formula for Hybrid Propulsion Aircraft

In an analysis article by Mark Voskuijl et al., the range equation of an aircraft powered by a parallel hybrid electric propulsion system is defined as shown below (See (3)) (Voskuijl et al., 2018).

$$R_{\text{hybr}=}\frac{\eta_{\text{prop}}}{g\left(c_{\text{P}}\frac{H_{\text{fuel}}}{g}(1-S)+\frac{S}{\eta_{\text{elec}}}\right)}\frac{C_{\text{L}}}{C_{\text{D}}}\frac{H_{\text{bat}}H_{\text{fuel}}}{(\psi H_{\text{fuel}}+(1-\psi)H_{\text{bat}})}$$
$$\ln\left(\frac{\frac{(\psi H_{\text{fuel}}+(1-\psi)H_{\text{bat}})}{H_{\text{bat}}H_{\text{fuel}}}gE_{\text{start}}+W_{\text{empty}}+W_{\text{payload}}}{W_{\text{empty}}+W_{\text{payload}}}\right) \quad (3)$$

The range equation for series propulsion system aircraft is given below (See (4)).

$$R_{series}=\eta_{gt}\eta_{eg}\eta_{em}\eta_{gb}\eta_{p}\frac{c_L}{c_D}\left(1+\frac{\varphi}{1-\varphi}\right)\left(\frac{e_f}{g}\right)$$
$$\ln\left(\frac{W_{OE}+W_{PL}+\left(\frac{E_{o,tot}g}{e_{bat}}\right)\left(\varphi+\frac{e_{bat}(1-\varphi)}{e_f\eta_{gt}\eta_{eg}}\right)}{W_{OE}+W_{PL}+\frac{g\varphi E_{o,tot}}{e_{bat}}}\right) \quad (4)$$

Each parameter in the formulas plays a very important role in affecting the overall range performance of the aircraft. Gas turbine efficiency (η_{gt}), gearbox efficiency (η_{gb}), and propeller efficiency (η_p) collectively represent the efficiency of the propulsion system. The lift-to-drag ratio $\left(\frac{c_L}{c_D}\right)$ reflects aerodynamic efficiency by emphasizing the balance between lift and drag forces during flight. The hybridization factor (φ) determines the power allocation between electric and gas turbine components, affecting the overall system efficiency. Fuel energy density (e_f) highlights its role in taking into account the energy contribution from the fuel. Additionally, empty operating weight (W_{OE}), payload weight (W_{PL}), and total stored energy are important factors that directly affect the weight of the aircraft and the energy available for propulsion. Essentially, the formula provides a comprehensive perspective on how each parameter affects the range of an aircraft using a parallel hybrid electric propulsion system, providing valuable information for optimizing and understanding the performance of such advanced propulsion technologies.

5.11. Effect of Battery Capacity and Energy Density on Range

The integration of batteries in hybrid aircraft significantly influences their performance. Factors such as weight, energy density, capacity, and other battery characteristics are crucial for determining the optimal range and overall performance of the aircraft.

When considering how batteries impact hybrid electric aircraft and their optimal range, it's important to look at the current battery technology, capacity, energy density, and how these factors affect the aircraft's total weight.

Battery capacity for electric aircraft is typically measured in kilowatt hours (kWh). Recent advancements in battery capacity technology, particularly with high energy density lithium-ion batteries, have been notable. Currently, lithium-ion batteries used in aviation have capacities ranging between 200-260 Wh/kg (http-8).

Understanding the energy density of batteries is crucial, especially for large commercial aircraft aiming to maximize their range. Battery energy density refers to the amount of energy stored in a given volume or mass of the battery. Higher energy density means more energy can be stored in a smaller, lighter package, enabling the aircraft to fly longer distances. While battery chemistry and materials advancements are improving energy density, current battery technology falls short of meeting the requirements for widespread commercial hybrid electric aircraft operations. Lithium sulfur and solid-state batteries show promise for higher energy density compared to traditional lithium-ion batteries (Pomerantseva et al., 2019).

As battery capacity and energy density increase, battery weight decreases for the same amount of stored energy. Lighter batteries contribute to reducing the overall weight of the aircraft, which is crucial for extending the range of hybrid electric aircraft (Huang, 2023).

A reduction in the overall aircraft weight positively impacts its range. Lighter batteries mean more payload capacity or longer range for the aircraft, which influences the practicality and feasibility of using hybrid electric propulsion systems (Ward, 2023).

However, it's essential to note the current limitations regarding battery density and weight. Due to technology constraints, as battery capacity increases, so does the total weight of batteries. This increase in battery weight affects the weight of the hybrid electric aircraft, impacting its range negatively. Despite progress in increasing battery capacity, the trade-off is often increased battery weight. This additional weight demands more energy consumption for propulsion, hindering the range of the hybrid electric aircraft. Therefore, developing lithium-ion batteries with higher energy density and lower weight is critical for the advancement and viability of hybrid electric aircraft (Rendon et al., 2021).

6. Result and Discussion

This study examines the potential of hybrid propulsion systems in aviation and their impact on optimal range. It's clear that air travel demand is rising, but like other sectors, aviation has environmental drawbacks. As long as current technologies are used, environmental impacts will worsen with increased demand. Thus, there's a push for new aviation technologies, with hybrid propulsion systems emerging as a key for a more sustainable future.

Hybrid propulsion systems, which are a combination of conventional engines and electric motors, are promising in improving performance, especially in short-range flights. However, they come with drawbacks like added weight, cost, and complexity. Also, the limited capacity and energy density of current lithium-ion batteries constrain the optimal range of hybrid aircraft, especially for long-distance travel. Today, battery technology limitations hinder hybrid aircraft from efficiently reaching optimal range on long-haul flights.

Developing lightweight, reliable batteries with high energy density enhance the efficiency of hybrid aircraft for long-range travel. Innovations like nanotechnology and solid-state batteries hold promise for advancing battery technologies. Hybrid propulsion systems significantly contribute to achieving environmental sustainability in aviation. However, overcoming battery technology limitations is essential to unleash their full potential. Technological advancements in battery design, such as the development of solid-state batteries and the application of nanotechnology, are essential to overcoming these limitations. Lighter, more energy-dense batteries will be key to unlocking the full range capabilities of hybrid aircraft, making them viable for long-haul flights.

Moving forward, focused research and development in battery technology will be critical in extending the operational range of hybrid aircraft, enabling them to play a significant role in making aviation more sustainable.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

References

Arabul, A. Y., Kurt, E., Keskin Arabul, F., Senol, İ., Schrötter, M., Bréda, R., & Megyesi, D. (2021). Perspectives and Development of Electrical Systems in More Electric Aircraft. International Journal of Aerospace Engineering, 2021, 1-14.

Alvarez, P., Satrustegui, M., Elosegui, I., & Martinez-Iturralde, M. (2022). Review of High Power and High Voltage Electric Motors for Single-Aisle Regional Aircraft. IEEE Access, 10, 112989-113004.

Barelli, L., Bidini, G., Gallorini, F., Iantorno, F., Pane, N., Ottaviano, P., & Trombetti, L. (2018). Dynamic Modeling of a Hybrid Propulsion System for Tourist Boat. Energies, 11(10), 2592. Surname, N.N. (Year). The full title of the article. Journal Name, volume and issue 5(3), first and last page 123-185.

Bradley, M., & Droney, C. (2015). Subsonic Ultra Green Aircraft Research: Phase II – Volume II Hybrid Electric Design Exploration (Contract Report NASA/CR–2015-218704/Volume II). Boeing Research and Technology.

Boschert, S. (2006). Plug-in hybrids: the cars that will recharge America. New Society Publishers Surname, N.N.,

Bravo, G. M., Praliyev, N., & Veress, Á. (2021). Performance analysis of hybrid electric and distributed propulsion system applied on a light aircraft. Energy, 214, 118823.

Capata, R., & Coccia, A. (2010). Procedure for the Design of a Hybrid-Series Vehicle and the Hybridization Degree Choice. Energies, 3(3), 450-461.

Caputo, P., Soderberg, M., Crowley, E., & Daher, M. (2023, Nisan 10). Navigating toward a new normal: 2023 Deloitte corporate travel study.

Cardoso, D. S., Fael, P. O., & Espírito-Santo, A. (2020). A review of micro and mild hybrid systems. Energy Reports, 6, 385-390.

Correa, G., Santarelli, M., Borello, F., Cestino, E., & Romeo, G. (2015). Flight test validation of the dynamic model of a fuel cell system for ultra-light aircraft. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, 229(5), 917-932.

De Vries, R., Hoogreef, M., & Vos, R. (2019, Ocak 7). Preliminary Sizing of a Hybrid-Electric Passenger Aircraft Featuring Over-the-Wing Distributed-Propulsion. AIAA Scitech 2019 Forum. AIAA Scitech 2019 Forum, San Diego, California.

Doll, U., Migliorini, M., Baikie, J., Zachos, P. K., Röhle, I., Melnikov, S., Steinbock, J., Dues, M., Kapulla, R., MacManus, D. G., & Lawson, N. J. (2022). Non-intrusive flow diagnostics for unsteady inlet flow distortion measurements in novel aircraft architectures. Progress in Aerospace Sciences, 130, 100810.

Economou, J. T., Tsourdos, A., & Wang, S. (2019, Ağustos 19). Design of a Distributed Hybrid Electric Propulsion System for a Light Aircraft based on genetic algorithm. AIAA Propulsion and Energy 2019 Forum, Indianapolis, IN.

Gogolák, L., Csikós, S., Molnár, T., Szuchy, P., Bíró, I., & Sárosi, J. (2019). Possibilities of optimizing fuel consumption in hybrid and electronic airplanes. Analecta Technica Szegedinensia, 13(2), 65-76.

He, C., Jia, Y., & Ma, D. (2020). Optimization and Analysis of Hybrid Electric System for Distributed Propulsion Tilt-Wing UAV. IEEE Access, 8, 224654-224667.

Hong, J., Zhao, L., Lei, Y., & Gao, B. (2018). Architecture Optimization of Hybrid Electric Vehicles with Future High-Efficiency Engine. Energies, 11(5), 1148.

Huang, Z. (2023). Electric and hybrid-electric aircraft propulsion systems: development, difficulties and opportunities. Theoretical and Natural Science, 5(1), 28-34.

http-1; Retrieved from https://airlines.iata.org/2018/11/26/passenger-numbers-hit-82bn-2037-iata-report, on 15.12.2023

http-2; Retrieved from https://www.icao.int/annual-report-2019/Pages/the-world-of-air-transport-in-2019.aspx, on 18.12.2023

http-3; Retrieved from https://www.boeing.com/commercial/market/commercial-market-outlook/index.page, on 18.12.2023

http-4; Retrieved from https://www.iea.org/reports/net-zero-by-2050, on 15.12.2023

http-5; Retrieved from https://www.airbus.com/en/productsservices/commercial-aircraft/market/global-market-forecast, on 18.12.2023

http-6 Retrieved from https://atag.org/industry-topics/supporting-economic-social-development, on 15.12.2023

http-7; Retrieved from https://www.iata.org/en/pressroom/pressroom-archive /2021-releases/2021-08-03-01/, on 18.12.2023

http-8; Retrieved from https://wwwnc.cdc.gov/travel/page/masks#, on 15.12.2023

IATA, (December 2020). Air Passenger Market Analysis, IATA Report.

Jain, S., & Kumar, L. (2018). Fundamentals of Power Electronics Controlled Electric Propulsion. Içinde Power Electronics Handbook (ss. 1023-1065). Elsevier.

Maddumage, W., Perera, M., Attalage, R., & Kelly, P. (2021). Power Management Strategy of a Parallel Hybrid Three-Wheeler for Fuel and Emission Reduction.

Morishita, N., Funaki, M., Kikuchi, Y., Wakiwaka, H., Sonehara, M., & Sato, T. (2023). A basic study on braking and regenerative braking torques for an axial gap type eddy current brake. International Journal of Applied Electromagnetics and Mechanics, 71, S383-S392.

Palaia, G., & Abu Salem, K. (2023). Mission Performance Analysis of Hybrid-Electric Regional Aircraft. Aerospace, 10(3), 246.

Pomerantseva, E., Bonaccorso, F., Feng, X., Cui, Y., & Gogotsi, Y. (2019). Energy storage: The future enabled by nanomaterials. Science, 366(6468), eaan8285.

Ratner, S. V. (2018). Innovation in the aircraft industry: An analysis of results of research programs for developing alternative types of aviation fuel. National Interests: Priorities and Security. V.A. Trapeznikov Institute of

Control Sciences of Russian Academy of Sciences, 14(3), 492-506.
Rendón, M. A., Sánchez R., C. D., Gallo M., J., & Anzai, A. H. (2021). Aircraft Hybrid-Electric Propulsion: Development Trends, Challenges and Opportunities. Journal of Control, Automation and Electrical Systems, 32(5), 1244-1268.
Sliwinski, J., Gardi, A., Marino, M., & Sabatini, R. (2017). Hybridelectric propulsion integration in unmanned aircraft, Energy, 140, 1407–1416.
Voskuijl, M., van Bogaert, J., & Rao, A. G. (2018). Analysis and design of hybrid electric regional turboprop aircraft. CEAS Aeronautical Journal, 9(1), 15-25.
Ward, C. (2023). Electric Planes: Are They Really The Future Of Flight? Retrieved from https://www.slashgear.com/1391420/electric-planes-future-of-flight/, on 18.12.2023
Xie, Y., Savvarisal, A., Tsourdos, A., Zhang, D., & Gu, J. (2021). Review of hybrid electric powered aircraft, its conceptual design and energy management methodologies. Chinese Journal of Aeronautics, 34(4), 432-450.
Zaghari, B., Kiran, A., Sinnige, T., Pontika, E., Enalou, H. B., Kipouros, T., & Laskaridis, P. (2023, Ocak 23). The Impact of Electric Machine and Propeller Coupling Design on Electrified Aircraft Noise and Performance. AIAA SCITECH 2023 Forum. AIAA SCITECH 2023 Forum, National Harbor, MD & Online.

Cite this article: Maharramov, A., Koruyucu, E. (2024) Assessing the Impact of Hybrid Propulsion Systems on the Range and Efficiency of Aircraft. Journal of Aviation, 8(3), 377-384.