ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

DESIGN AND FEASIBILITY ANALYSIS OF SMALL AIRCRAFT ELECTRIFICATION WITH BATTERY MODELING

M.Sc. THESIS

Enes ÖZKAR

Department of Electrical Engineering

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

BATARYA MODELLEMESİ İLE KÜÇÜK UÇAK ELEKTRİFİKASYONUNUN TASARIMI VE FİZİBİLİTE ANALİZİ

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MART 2026

Enes ÖZKAR, a M.Sc. student of ITU Graduate School student ID 504221041 successfully defended the thesis entitled "DESIGN AND FEASIBILITY ANALYSIS OF SMALL AIRCRAFT ELECTRIFICATION WITH BATTERY MODELING", which he/she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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Date of Submission : **30 January 2026**
Date of Defense : **9 March 2026**

To my family,

FOREWORD

I would like to express my sincere gratitude to my thesis advisor, Prof. Dr. V. M. İstemihan GENÇ, who guided me through every stage of this process with his deep knowledge, academic guidance, and experience. His insights and support played a crucial role in the successful completion of this thesis.

I would like to extend my thanks to my friend and colleague, İbrahim HAKYEMEZ, who has always been by my side throughout this journey and has made valuable contributions. His ideas and constructive suggestions have added significant value to this work.

Finally, I am deeply grateful to my dear family for their unwavering support and patience. They have always been a source of motivation for me and have stood by my side throughout my life. Their encouragement and dedication formed the strongest foundation of my academic journey.

March 2026

Enes ÖZKAR
(Electrical and Electronics Engineer)

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ABBREVIATIONS

AC	: Alternating Current
AEA	: All Electric Aircraft
Al	: Aluminum
APU	: Auxiliary Power Unit
AR-GE	: Araştırma ve Geliştirme
AVGAS	: Aviation Gasoline
BLDC	: Brushless Direct Current
BMS	: Battery Management System
CH_4	: Methane
Co	: Cobalt
CO	: Carbon Monoxide
CO_2	: Carbon Dioxide
CSD	: Constant Speed Drive
Cu	: Copper
dBA	: A-weighted decibel
DC	: Direct Current
DEP	: Distributed Electric Propulsion
DOC	: Direct Operating Cost
DOD	: Depth of Discharge
EASA	: European Aviation Safety Agency
EFACA	: Environmentally Friendly Aviation for All Classes of Aircraft
EMC	: Electromagnetic Compatibility
EMI	: Electromagnetic Interference
EM	: Electric Motor
EPNdB	: Effective Perceived Noise in Decibels
eVTOL	: Electric Vertical Take-Off and Landing
FAA	: Federal Aviation Administration
H_2O	: Water
HC	: Hydrocarbons
HESS	: Hybrid Energy Storage Systems
HVDC	: High Voltage Direct Current
ICAO	: International Civil Aviation Organization
ICE	: Internal Combustion Engine
IDG	: Integrated Driven Generator
IGBT	: Insulated Gate Bipolar Transistor
INSAT	: Initiative for Sustainable Aviation Technology
IOC	: Indirect Operating Costs
Li-Air	: Lithium-Air

Li-Ion : Lithium-Ion
Li-M : Lithium-Metal
Li-S : Lithium-Sulfur
LiPO : Lithium-Polymer
LTBR : Bursa Yenişehir Airport
MEA : More Electric Aircraft
MOSFET : Metal–Oxide–Semiconductor Field-Effect Transistor
MTOW : Maximum Take Off Weight
MVDC : Medium Voltage Direct Current
NASA : National Aeronautics and Space Administration
NCA : Nickel Cobalt Aluminum Oxide
Ni-Cd : Nickel-Cadmium
Ni-MH : Nickel-Metal Hydride
NMC : Nickel Manganese Cobalt Oxide
NO_x : Nitrogen Oxides
N_2O : Nitrous Oxide
OCV : Open Circuit Voltage
PEM : Proton Exchange Membrane
Pb-Acid : Lead-Acid
PMSM : Permanent Magnet Synchronous Motor
PWM : Pulse Width Modulation
R&D : Research and Development
RAT : Ram Air Turbine
RPM : Revolutions Per Minute
SABERS : Solid-state Architecture Batteries for Enhanced Rechargeability and Safety
SAF : Sustainable Aviation Fuel
SAW : Istanbul Sabiha Gökçen International Airport
SC-VTOL : Special Condition for Vertical Take-Off and Landing
SOC : State Of Charge
SO_x : Sulfur Oxides
SOH : State Of Health
SSCB : Solid-State Circuit Breaker
SRM : Switched Reluctance Motor
SSB : Solid-State Battery
TLAR : Top-Level Aircraft Requirements
TRU : Transformer Rectifier Unit
TUBITAK : The Scientific and Technological Research Council of Türkiye
UHC : Unburned Hydrocarbons
UPS : Uninterruptible Power Supply
VFG : Variable Frequency Generator
VTOL : Vertical Take-Off and Landing

SYMBOLS

$\mathbf{SOC(t)}$: State of Charge at time t (%)
$\mathbf{Q_{curr}(t)}$: Current capacity of the battery (Ah)
$\mathbf{Q_{nom}}$: Total capacity of the battery (Ah)
$\mathbf{SOC(t_0)}$: Initial State of Charge at initial time t_0 (%)
$\mathbf{t}$: Current time (s)
$\mathbf{t_0}$: Initial time (s)
$\mathbf{I(t)}$: Battery current as a function of time (A)
$\mathbf{Q_b}$: Nominal battery capacity (Ah)
$\mathbf{C_{energy}}$: Total energy cost (€)
$\mathbf{E_{req}}$: Net energy required from the battery for flight (kWh)
$\eta_{\mathbf{charger}}$: Charger efficiency
$\eta_{\mathbf{grid}}$: Grid efficiency
$\mathbf{P_{elec}}$: Electricity unit price (€/kWh)
$\mathbf{F_{burn}}$: Amount of fuel consumed (kg)
$\mathbf{P_{fuel}}$: Fuel unit price (€/kg)
$\mathbf{C_{batt\_depr}}$: Battery depreciation cost per flight/cycle (€)
$\mathbf{C_{pack}}$: Total acquisition cost of the battery pack (€)
$\mathbf{RV_{batt}}$: Residual value ratio of the battery
$\mathbf{Cycle_{life}}$: Total cycle life of the battery pack (cycles)
$\mathbf{t_p}$: Preventive replacement age (flight hours)
$\mathbf{C_{maint}(t_p)}$: Expected maintenance cost per unit time (€/hr)
$\mathbf{C_p}$: Cost of preventive replacement (€)
$\mathbf{C_f}$: Cost of failure replacement (€)
$\mathbf{R(t_p)}$: Reliability function at time t_p
$\mathbf{1-R(t_p)}$: Cumulative probability of failure by time t_p
$\int_0^{\mathbf{t_p}} \mathbf{R(t)\,dt}$: Expected mean cycle length (hours)
$\mathbf{R_c}$: Total route charge (€)
$\mathbf{t_r}$: Unit rate (€)
$\mathbf{d}$: Distance factor (Great Circle Distance / 100 km)
$\mathbf{MTOW}$: Maximum Take-Off Weight (metric tons)
$\sqrt{\frac{\mathbf{MTOW}}{\mathbf{50}}}$: Weight factor
$\mathbf{C_{crew}}$: Crew cost per block hour (€/h)
$\mathbf{N_{crew}}$: Number of required pilots
$\mathbf{S_{base}}$: Annual base salary per pilot (€)
$\mathbf{K_{burden}}$: Employment burden factor
$\mathbf{C_{HV\_cert}}$: High Voltage certification training cost (€)
$\mathbf{AH_{annual}}$: Annual block hours (h)

$\mathbf{C_{capital}}$: Capital cost per block hour (€/h)
$\mathbf{P_{ac\_no\_batt}}$: Aircraft price excluding battery pack (€)
$\mathbf{P_{ac\_total}}$: Total aircraft price including battery system (€)
$\mathbf{r_{res}}$: Residual value factor
DP : Depreciation period for airframe (years)
$\mathbf{K_{ins}}$: Annual hull insurance rate
$\mathbf{K_{int}}$: Annual interest or finance rate
V : Actual battery voltage (V)
$\mathbf{E_0}$: Open-circuit battery voltage at full capacity (V)
Q : Battery capacity (Ah)
$\mathbf{it} = \int \mathbf{i\,dt}$: Actual battery charge (Ah)
K : Polarization constant (V/Ah) or polarization resistance (Ω)
A : Exponential zone amplitude (V)
B : Inverse exponential zone time constant $(Ah)^{-1}$
R : Internal resistance (Ω)
i : Battery current (A)

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DESIGN AND FEASIBILITY ANALYSIS OF SMALL AIRCRAFT ELECTRIFICATION WITH BATTERY MODELING

SUMMARY

The aviation industry plays a fundamental role in modern society by enabling global transportation, economic development, and social connectivity. However, the sector also faces significant environmental, economic, and technical challenges. These challenges include growing concerns such as increasing dependence on fossil fuels, rising fuel prices, stringent emissions regulations, and noise pollution. This situation has intensified the search for sustainable aviation solutions. Aviation currently accounts for a significant portion of global greenhouse gas emissions. If current operational trends continue, this contribution is expected to increase significantly by 2050. As a result, decarbonizing aviation and developing alternative propulsion technologies have become strategic priorities.

In this context, the All Electric Aircraft concept has emerged as a promising solution to reduce environmental impact and operational costs. Advances in battery technologies, electric propulsion systems, and power electronics have significantly accelerated research and development activities in this field. Several pioneering projects, such as the Pipistrel Velis Electro, Eviation Alice, and NASA's X-57 Maxwell, have demonstrated the technical feasibility of electric flight. In addition, they have provided the industry with valuable experimental data and operational experience. These developments indicate that electric aviation technologies are maturing, especially for short-range and light aircraft applications.

This study presents a comprehensive technical, environmental, and economic feasibility assessment of converting the Tecnam P2008 JC, a small single-engine aircraft, to a fully electric propulsion configuration. The primary objective is to evaluate the applicability of electric propulsion systems while preserving the aircraft's original structural architecture and certification constraints. The conversion process involves replacing the traditional internal combustion engine and fuel system with an electric motor, a lithium-ion battery pack, and appropriate power electronics units. The aircraft's system-level design constraints and maximum take-off weight (MTOW) are carefully evaluated to ensure compliance with flight safety requirements.

A lithium-ion battery pack with a nominal capacity of approximately 45 kWh has been designed and integrated into the aircraft. Battery selection and sizing were based on the energy requirements of the designed flight profile, discharge characteristics, and safety considerations. Current lithium-ion battery technologies have lower specific energy values compared to traditional aviation fuels. This creates significant performance and weight constraints in electric aircraft design. In particular, the design trade-offs between range, payload capacity, and total system weight must be carefully evaluated.

In this context, the relationships between these parameters have been analyzed in detail. The final configuration maintains operational feasibility while limiting payload capacity within acceptable safety limits. Performance and energy consumption analyses are performed through detailed MATLAB/Simulink-based system-level simulations. Battery behavior is modeled using the Shepherd mathematical model. This ensures accurate prediction of voltage, current, and state of charge (SOC) dynamics throughout the flight mission.The selected flight route is between Istanbul Sabiha Gökçen and Bursa Yenisehir airports.

Simulation results show that the converted aircraft can safely complete the mission with sufficient energy reserves. Environmental and economic assessments highlight the significant advantages of electric propulsion. Direct operational carbon dioxide emissions and energy costs per flight have been significantly reduced compared to the traditional configuration. Furthermore, reduced maintenance requirements due to fewer mechanical components further enhance economic feasibility. However, battery investment costs, limited cycle life, and charging infrastructure requirements remain critical challenges. Overall, the results confirm that fully electric propulsion is technically and economically feasible for short-range, small aircraft missions under current technological constraints. Significant limitations remain in terms of energy density and charging time. On the other hand, continuous advancements in battery chemistry, power electronics, and sustainable energy infrastructure are expected to enable the broader adoption of electric aviation in the near future.

BATARYA MODELLEMESİ İLE KÜÇÜK UÇAK ELEKTRİFİKASYONUNUN TASARIMI VE FİZİBİLİTE ANALİZİ

ÖZET

Günümüzde havacılık sektörü, fosil yakıtlara dayalı uçuşlar nedeniyle ciddi çevresel ve ekonomik zorluklarla karşı karşıyadır. Fosil yakıt fiyatlarındaki dalgalanmalar, karbondioksit emisyonlarına yönelik sıkılaşan düzenlemeler ve gürültü kirliliği gibi unsurlar sektörü sürdürülebilir çözümler arayışına itmektedir. Hava taşımacılığının küresel sera gazı emisyonlarındaki payı sürekli artmaktadır. Mevcut gidişatın sürmesi halinde bu oranın 2050 yılına kadar üç katına çıkabileceği öngörülmektedir. Bu durum, havacılıkta karbonsuzlaştırma ve daha sürdürülebilir teknolojilere geçiş ihtiyacını gündeme getirmiştir. Elektrikli havacılık konsepti, emisyonları azaltmak ve işletme maliyetlerini düşürmek açısından gelecek vadeden bir yaklaşım olarak ortaya çıkmaktadır. Son yıllarda tamamen elektrikli uçaklara yönelik ilgi, çeşitli öncü proje ve prototiplerle birlikte hızla artmaktadır. Örneğin, Pipistrel Velis Electro, Avrupa Havacılık Emniyeti Ajansı tarafından sertifikalandırılan ilk elektrikli uçak projesidir. Bu proje, sıfır doğrudan emisyon, düşük işletme maliyeti ve minimum gürültü hedefleriyle dikkat çekmektedir. Benzer şekilde bölgesel yolcu ve kargo taşımacılığı için geliştirilen Eviation Alice uçağı, geleneksel uçaklara kıyasla enerji maliyetlerinde %80'e varan tasarruf ve sıfır karbon emisyonu sağlamayı amaçlayan yenilikçi bir projedir. Ayrıca NASA'nın X-57 Maxwell projesi de elektrikli havacılık konseptinin enerji verimliliğini artırma hedefiyle yürütülen önemli bir çalışma olarak öne çıkmıştır. Bu tür projeler, elektrikli uçakların uygulanabilirliği konusunda değerli deneyimler ve veri birikimi sağlamaktadır. Bu tezde, küçük bir uçağın tamamen elektrikli bir tahrik sistemine dönüştürülmesinin teknik, çevresel ve ekonomik fizibilitesi kapsamlı bir biçimde değerlendirilmektedir. Tezin amacı, elektrikli tahrik sistemlerinin uygulanabilirliğini tartışarak elektrikli havacılığın mevcut durumu ve geleceğine dair kapsamlı bir mühendislik bakış açısı sunmaktır.

Çalışmanın ikinci bölümünde, elektrikli havacılık teknolojisinin altyapısı ve temel bileşenleri ele alınmıştır. Havacılıkta elektrifikasyon mimarileri temel olarak yalnız elektrik enerjisiyle uçan tam elektrikli uçaklar ve elektrik ile fosil yakıtlı motorları bir arada kullanan hibrit elektrikli uçaklar olarak ikiye ayrılmaktadır. Hibrit sistemlerde seri, paralel ve turbo-elektrik gibi farklı mimari alt türleri incelenmiş ve bunların avantaj ve dezavantajları tartışılmıştır. Elektrikli bir uçağın ana unsurları olan elektrik motorları, güç elektroniği birimleri ve enerji depolama sistemleri detaylı olarak değerlendirilmiştir. Ayrıca, yüksek gerilimli elektrik dağıtım ağları, kablolama ve koruma sistemleri gibi alt sistemlerin tasarımında karşılaşılan mühendislik gereksinimlerine değinilmiştir. Elektrik tahrik sistemlerinde batarya paketi ile motor arasında, gerilimi yükseltmek ve motoru uygun akım ve frekansla beslemek amacıyla güç elektroniği dönüştürücüleri kullanılmaktadır. Elektrikli uçaklarda en kritik bileşen enerji depolama sistemidir.

Bu kapsamda tezde çeşitli batarya teknolojileri ve özellikleri ayrıntılı biçimde incelenmiştir. Günümüzde kullanılan lityum-iyon bataryaların özgül enerji kapasiteleri halen sınırlıdır. Tipik olarak yaklaşık 250 Wh/kg mertebesindedir. Bu değer, Jet-A1 gibi konvansiyonel havacılık yakıtlarının yaklaşık 12.000 Wh/kg düzeyindeki enerji yoğunluğunun çok altındadır. Bu temel fark, tamamen elektrikli uçakların menzil ve taşıma kapasitesini ciddi biçimde kısıtlamaktadır. Bununla birlikte, son yıllarda batarya teknolojilerinde önemli ilerlemeler kaydedilmiştir. Ancak lityum-iyon hücrelerin özgül enerji değerinin önümüzdeki birkaç yıl içinde en iyi ihtimalle 300–400 Wh/kg seviyelerine ulaşabileceği öngörülmektedir. Lityum-kükürt ve lityum-hava gibi yüksek teorik enerji yoğunluğuna sahip yeni nesil bataryalar ile katı hâl bataryaları üzerinde yoğun araştırmalar sürmektedir. Eğer bu tür bataryalar güvenli ve pratik bir şekilde 1000 Wh/kg ve üzeri özgül enerji değerlerine ulaşabilirse elektrikli yolcu uçaklarının menzil ve performansında çığır açıcı gelişmeler mümkün olabilecektir. Ancak mevcut durumda batarya kimyalarının enerji yoğunluğu, uzun menzilli uçuşların gereksinimlerini karşılayacak seviyede değildir. Tez kapsamında farklı batarya tiplerinin avantaj ve dezavantajları karşılaştırılmıştır. Özellikle lityum-iyon bataryaların havacılık uygulamalarındaki fırsatları ve sınırlamaları vurgulanmıştır.

Elektrikli uçaklara geçişin çevresel etkileri tezde kapsamlı şekilde değerlendirilmiştir. Tamamen elektrikli bir uçak, uçuş esnasında egzoz gazı salınımı yapmadığından karbon emisyonlarını ve CO_2, NO_x, SO_x, UHC gibi hava kirletici gazları ortadan kaldırmaktadır. Ayrıca elektrik motorlu tahrik, geleneksel türbin motorlara kıyasla çok daha sessiz çalışmakta ve gürültü kirliliğini büyük ölçüde azaltmaktadır. Elektrik motorlarının kullanımı sayesinde hem uçuş boyunca kabin içinde hem de havaalanı çevresinde maruz kalınan ses düzeyleri belirgin biçimde düşmektedir. Bu durum, özellikle havaalanları ve yerleşim bölgeleri civarındaki gürültü kısıtlamalarına uyum sağlanması açısından önemli bir avantajdır. Bu sayede elektrikli uçaklar, operasyon sırasında sera gazı salımlarını sıfıra yakın seviyelere çekebilmektedir. Tez çalışmasında yapılan bir analiz, elektrikli hale getirilmiş küçük bir uçağın örnek bir uçuşunda karbondioksit emisyonlarında %73,13 oranında azalma sağlanabileceğini göstermiştir. Benzer şekilde, elektrikli taksi ve yer operasyonlarının kullanılmasıyla terminal bölgesindeki emisyonların neredeyse tamamen ortadan kalktığı vurgulanmıştır.

Üçüncü bölümde, tüm yaşam döngüsü etkileri ele alınmıştır. Batarya hücrelerinin üretimi ve ham madde tedarik süreçleri, geleneksel uçak imalatına kıyasla daha yüksek enerji tüketimine ve karbon salımına yol açabilmektedir. Çalışma, lityum, kobalt ve nikel gibi kritik metallerin rafinasyonu ve karbon fiber gibi ileri malzemelerin üretimi süreçlerinde kayda değer miktarda CO_2 salındığını ortaya koymaktadır. Ayrıca, elektrikli uçaklarda kullanılan bataryalar için gerekli lityum, kobalt ve nikel gibi kritik hammaddelerin sınırlı oluşu ve tedarik zincirinin önemi de ele alınmıştır. Bu stratejik materyallerin sürdürülebilir ve sorumlu bir şekilde temin edilmesi gerekliliği vurgulanmıştır. Bataryaların kullanım ömrü sonunda geri dönüşümü ve ikinci kullanım potansiyeli de değerlendirilmiştir. Bu bakımdan, etkin geri dönüşüm uygulamalarının geliştirilmesinin elektrikli havacılığın toplam çevresel yükünü azaltmada kilit rol oynayacağı belirtilmiştir. Dolayısıyla, elektrikli havacılığın gerçek çevresel faydasını değerlendirebilmek için kaynaktan pervaneye tüm süreçlerin incelenmesi gerektiği vurgulanmıştır. Bu bağlamda, batarya üretimi ve şarj için gereken elektriğin yenilenebilir kaynaklardan sağlanması, elektrikli havacılığın toplam karbon ayak izini azaltmak adına önemli bir unsur olarak belirtilmiştir.

Tezde, tamamen elektrikli bir uçağın doğrudan işletme maliyetleri geleneksel muadili ile karşılaştırmalı olarak incelenmiştir. Bu kapsamda yakıt/enerji giderleri, bakım-onarım masrafları ve batarya yenileme maliyetleri gibi kalemler detaylı şekilde analiz edilmiştir. Elektrik enerjisi ile çalışan uçakların işletme maliyetlerinin özellikle yakıt giderleri açısından geleneksel uçaklara göre belirgin ölçüde düşük olabileceği hesaplanmıştır. Örneğin, tezde ele alınan senaryolardan birinde tamamen elektrikli hale getirilmiş bir uçağın tek bir uçuş için harcadığı enerji maliyetinin, benzer bir konvansiyonel uçağın harcadığı havacılık yakıtı maliyetine kıyasla %87,66 daha düşük olduğu bulunmuştur. Bu durum, elektrik enerjisinin birim fiyatının havacılık yakıtından çok daha düşük olmasının ve elektrik motorlu tahrik sistemlerinin yüksek enerji verimliliğinin bir sonucudur. Özellikle geleneksel uçaklarda içten yanmalı motorların periyodik bakım, parça değişimi ve onarım giderleri yüksek düzeydeyken, elektrik motorlu uçaklarda daha az hareketli parça bulunması sayesinde bakım masraflarının belirgin ölçüde azalması beklenmektedir. Bununla birlikte, ekonomik değerlendirmede yalnızca enerji maliyetleri değil, bataryaların sınırlı kullanım ömrü ve yenileme maliyetleri de dikkate alınmalıdır. Tezde, batarya paketinin belirli bir çevrim ömrü olduğu ve bu nedenle her uçuş için batarya yıpranma payının hesaplanması gerektiği belirtilmiştir. Günümüz şartlarında, kısa menzilli uçuşlarda elektrikli bir uçağın toplam operasyon maliyetinin rekabetçi olabileceği, ancak batarya yatırım maliyetleri ve şarj altyapısı gereksinimlerinin ekonomik fizibiliteyi sınırlandıran etkenler olduğu ortaya konmuştur. Ayrıca, elektrik enerjisi fiyatlarının fosil yakıt fiyatlarına göre daha istikrarlı olması, uzun vadeli işletme planlamasında öngörülebilirlik sağlamaktadır. Çalışmada ayrıca, çeşitli devlet teşviklerinin ve altyapı yatırımlarının elektrikli havacılığın benimsenmesini hızlandırmadaki rolüne değinilmektedir. Örneğin, şarj istasyonlarının kurulması ve Ar-Ge destekleri gibi adımların uzun vadede elektrikli uçakların ekonomik avantajlarını artırabileceği ifade edilmiştir.

Dördüncü bölümde, seçilen bir küçük uçağın elektrikli tahrik sistemine dönüştürülmesine yönelik detaylı teknik analizler gerçekleştirilmiştir. Referans platform olarak tek motorlu hafif spor sınıfındaki Tecnam P2008 JC modeli tercih edilmiştir. Bu uçağın mevcut içten yanmalı motoru, yakıt deposu ve ilgili donanımları çıkarılarak yerine bir elektrik motoru ile uygun özelliklerde bir batarya paketi entegre edilmiştir. Dönüşüm sürecinde, uçağın özgün yapısal tasarımına sadık kalınmış ve gövde üzerinde büyük çaplı değişiklikler yapılmamıştır. Dolayısıyla sistem tasarımı, mevcut ağırlık ve hacim kısıtları çerçevesinde planlanmıştır. Bu kısıtlarla uyumlu bir çözüm geliştirebilmek adına tasarım parametrelerinde çeşitli optimizasyonlar gerçekleştirilmiştir. İlk olarak, seçilen uçağın performans karakteristikleri, ağırlık dağılımı ve güç ihtiyacı kapsamlı biçimde analiz edilmiştir. Ardından elektrikli sisteme geçiş için ihtiyaç duyulan üst düzey gereksinimler belirlenmiştir. Elektrik motoru, batarya ve güç elektroniği donanımları, literatürdeki teknik veriler temel alınarak değerlendirilmiş ve dönüşüm için uygun adaylar seçilmiştir. Burada özellikle batarya sisteminin planlanan uçuş profilinin enerji ve güç gereksinimlerini eksiksiz karşılayacak şekilde boyutlandırılmasına odaklanılmıştır. Ağırlık etki analizi kapsamında, uçağın azami kalkış ağırlığı gibi kritik kısıtlar göz önünde bulundurularak yeni elektrikli sistemin ağırlık kırılımı oluşturulmuştur. Konvansiyonel sistemlerin çıkartılmasıyla boş ağırlıkta elde edilen kazanım, eklenen elektrik motoru ve batarya paketi ağırlığı ile dengelenmiştir. Bu ödünleşim sonucunda geliştirilen elektrikli tasarımda, uçağın azami kalkış ağırlığı sınırı aşılmamıştır. Ancak bu durum, taşınabilecek faydalı yük miktarının azalmasını gerektirmiştir. Bu kapsamda yeni tasarımda mürettebat toplam ağırlığı 170 kg, bagaj hakkı ise 10 kg olacak şekilde faydalı yük kapasitesi sınırlandırılmıştır. Dönüştürülen uçakta yaklaşık 45 kWh nominal enerji kapasiteli bir lityum-iyon batarya paketi kullanılmıştır.

Beşinci bölümde, elektriklendirilmiş uçak tasarımının performansını değerlendirmek amacıyla sistem düzeyinde simülasyonlar gerçekleştirilmiştir. Simülasyon çalışmaları MATLAB/Simulink ortamında yürütülmüştür. Bu kapsamda uçağın tırmanış, seyir ve alçalış gibi uçuş evrelerindeki dinamik davranışı detaylı olarak analiz edilmiştir. Bu simülasyonlarda batarya performansını gerçekçi şekilde modellemek için Shepherd batarya modeli kullanılmıştır. Shepherd modeli, bir bataryanın terminal gerilimini, iç direnç etkilerini ve doluluk durumu (SOC) gibi karakteristiklerini matematiksel olarak ifade eden ve hem deşarj hem şarj süreçlerini kapsayabilen bir yaklaşımdır. Çalışmada geliştirilen Simulink tabanlı modelde, bu yöntem kullanılarak batarya paketinin gerilim, akım ve SOC dinamikleri yüksek hassasiyetle taklit edilmiştir. Planlanan uçuş profili, İstanbul Sabiha Gökçen Havalimanı'ndan kalkış yaparak Bursa Yenişehir Havalimanı'na ulaşan ve yaklaşık 45 deniz mili mesafeyi kapsayan bir rotadır ve uçuşun yaklaşık 72 dakika sürdüğü öngörülmüştür. Simülasyon sonuçlarına göre, tamamen elektrikli hale getirilmiş uçak bu rotayı emniyetli bir şekilde tamamlayabilmektedir. Tüm uçuş boyunca bataryadan çekilen toplam enerji yaklaşık 24,12 kWh olarak hesaplanmıştır. Entegre batarya paketi bu enerji ihtiyacını karşılarken, güvenlik amacıyla toplam kapasitenin belirli bir oranı kullanılmadan yedek bırakılmıştır. Simülasyonda batarya kapasitesinin kritik alt sınır olarak belirlenen 20 Ah değerinin altına inilmemiş; uçuş sonunda bataryanın yaklaşık %20 dolu kaldığı gözlemlenmiştir. Shepherd modeli sayesinde bataryanın gerilim, akım ve doluluk seviyesi zamana bağlı olarak izlenmiştir. Böylece elektrikli tahrik sisteminin uçuş süresince davranışı ayrıntılı biçimde değerlendirilebilmiştir. Elde edilen veriler, tasarlanan elektrikli güç sisteminin anlık yüksek güç taleplerine yanıt verebildiğini ve ilgili uçuş profilini başarıyla karşılayabildiğini göstermektedir.

Yapılan analizler neticesinde, küçük ölçekli bir uçağın elektrifikasyonunun teknik açıdan belirli koşullarda mümkün olduğu sonucuna varılmıştır. Özellikle kısa menzilli ve hafif yük taşımalı uçuş görevlerinde, tamamen elektrikli bir uçak konseptinin günümüz teknolojisiyle uygulanabilir olduğu gösterilmiştir. Bununla birlikte, mevcut lityum-iyon batarya teknolojisinin özgül enerji sınırlamaları nedeniyle menzil ve taşıma kapasitesi açısından ciddi kısıtlar bulunduğu tespit edilmiştir. Analiz sonuçlarına göre, günümüz bataryalarıyla yaklaşık 70–80 deniz mili mesafelere kadar operasyonlar gerçekleştirilebilir. Daha uzun menziller için batarya ağırlığı ve kapasite gereksinimi uçağın tasarım sınırlarını hızla zorlamaktadır. Bu durum, elektrikli uçakları orta ve uzun menzilli uygulamalar için henüz elverişsiz kılmaktadır. Teknik açıdan bir diğer önemli zorluk bataryaların şarj süreleridir. Elektrikli uçakların etkin şekilde kullanılabilmesi için yerde şarj için harcanan sürenin mümkün olduğunca kısaltılması gerekmektedir. Bu amaçla yüksek şarj hızlarına imkan tanıyan batarya teknolojilerine ihtiyaç duyulmaktadır. Tezde bu konunun sektör için kritik bir Ar-Ge alanı olduğu belirtilmiştir. Batarya güvenliği ve sertifikasyon gereklilikleri de elektrifikasyonun bir başka önemli boyutudur. Çalışma kapsamında, EASA ve FAA gibi havacılık otoritelerinin elektrikli ve hibrit hava araçlarına yönelik yeni düzenlemeler getirdiğine değinilmiştir. Lityum-iyon bataryalar için hücre seviyesinde zorunlu güvenlik testleri, ek koruma devreleri ve benzeri kriterlerin tanımlanmaya başlandığı belirtilmiştir. Bu durum, elektrikli uçak tasarımlarının sertifikasyon sürecinin karmaşıklığını artıran bir unsur olarak ortaya konmuştur.

Ekonomik açıdan bakıldığında ise elektrikli uçaklar için halen bazı sınırlayıcı unsurlar söz konusudur. Her ne kadar enerji maliyetleri önemli ölçüde düşük olsa da, batarya sistemlerinin yüksek ilk yatırım giderleri ve sınırlı ömürleri elektrikli uçakların yaygın ticari kullanımı önündeki temel engellerdendir. Bataryaların belirli sayıda uçuş döngüsü sonunda yenilenme ihtiyacının olması, uzun vadeli işletme maliyetlerine ilave yük getirmektedir. Ayrıca, elektrikli havacılık için gereken şarj altyapısının kurulması da başlangıçta kayda değer yatırımlar gerektirebilir. Dolayısıyla, günümüz şartlarında elektrikli küçük uçaklar kısa mesafeli eğitim ve özel uçuşlar gibi belirli niş uygulamalar için teknik ve ekonomik olarak makul görünmektedir. Ancak geniş ölçekli ticari uygulamalar için batarya teknolojilerinde ciddi iyileşmelere ihtiyaç duyulmaktadır. Sonuç olarak, bu tez kapsamında gerçekleştirilen fizibilite değerlendirmesi, elektrikli havacılığın mevcut avantajlarını ve kısıtlarını somut verilerle ortaya koymuştur. Elektriklendirilmiş küçük uçak konseptinin kısa mesafeli uçuşlarda karbon emisyonlarını ve yakıt maliyetlerini büyük ölçüde azaltabildiği gösterilmiştir. Ancak menzil ve yük kapasitesi bakımından güncel teknolojinin getirdiği sınırlamalar net bir şekilde ifade edilmiştir. Uzun vadede, enerji depolama teknolojilerindeki ilerlemeler ve destekleyici altyapı yatırımları sayesinde bu sınırlamaların aşılmasıyla elektrikli havacılığın daha yaygın ve verimli hale gelebileceği öngörülmektedir.

1. INTRODUCTION

[1]

The aviation industry has become an indispensable global building block in the modern world with its significant contributions to humanity. It plays a vital role in many areas, from transportation to trade and from tourism to military activities. While the sector is increasing its impact daily, it also poses several global challenges that cannot be ignored and need to be addressed. Presently, the widespread use of conventional aircraft systems leads to the consumption of fossil fuels and, thus, to the production of greenhouse gases and environmental pollution. According to the International Civil Aviation Organization, the aviation industry accounted for approximately 2.5% of global anthropogenic CO_2 emissions in 2019 and is projected to triple by 2050 if these trends continue [1]. Aviation emissions are increasing due to structural problems such as the limited share of electric aircraft in the sector and the lack of sustainable fuel production. In addition, the increase in the intensity of demand for the sector increases emissions in absolute terms, while the decline in emissions due to developments in other sectors makes this increase more visible in relative terms.

Despite such potential risks, the sector's search for solutions and research has accelerated. In line with regulatory frameworks such as the International Aviation Carbon Offsetting and Reduction Program, the development and widespread use of all-electric aircraft utilizing battery-based propulsion systems that eliminate direct emissions and significantly reduce operating costs are important solution alternatives [2]. The use of this concept will contribute to a significant reduction of CO_2 emissions from the aviation sector, as electrically powered propulsion systems do not require the use of fossil fuels. Additionally, electricity offers a more stable pricing compared to jet fuel while also helping to lower direct operating costs and reduce noise pollution [3].

[1]This chapter is based on the following published article: E. Ozkar and I. Genc, 'Electrification of a Small Aircraft: Technical Feasibility, Cost Analysis, and Environmental Impact," *International Journal of Aviation Science and Technology*, vol. vm07, pp. 35-47, 2025

As the potential and future of the AEA concept has attracted attention, many important studies and projects have been launched. In that context, there is a growing interest in this concept around the world. The Pipistrel Velis Electro is an important project as the world's first EASA-certified electric-powered aircraft. The project aims for zero direct CO_2 emissions, low operating costs, and minimized noise levels [4]. Another important and exemplary project, Eviation's Alice, is an aircraft within the scope of the AEA concept and has similar objectives. Designed for regional passenger and cargo transportation, this project aims to achieve zero carbon emissions as well as a reduction in energy costs by up to 80% compared to conventional aircraft [5]. NASA's X-57 Maxwell project, another noteworthy study, has taken its place in the sector as an exemplary study with the aim of increasing energy efficiency in terms of the development of the AEA concept and aviation electrification [6]. Figure 1.1 shows a demonstration of NASA's Maxwell X-57 aircraft.

Figure 1.1: Conceptual flight depiction of the X-57 Maxwell aircraft [7].

On the other hand, the project was canceled due to financial and safety considerations. The technical reports, knowledge transfer, and design of electric aircraft technologies that emerged in this project have been a great contribution to the industry. It will also be a guide for future aviation standards [8].

The transformation of the aviation industry with the introduction of electric aircraft requires significant updates in standards and regulations. Unlike conventional fuel-based aircraft, electric aircraft need to be examined more comprehensively in terms of battery and electrical system safety. In addition, the lack of comprehensive historical data in the field of electric aviation, rapid developments in battery chemistry and energy systems, and differences in regional requirements are the main challenges in this process. One important step in this direction is the publication of the SC-VTOL standards by EASA for the certification of eVTOL aircraft [9].

A historical review of electric propulsion in aviation shows that the first use of electric motors was by Tissandier in 1883 to power an airship [10]. However, other different historical studies on the concept are known to date back to the mid-20th century [11]. Especially with the impact of the energy crisis in early 1970, interest in renewable energy sources and electrical systems increased. However, as a result of the energy density of batteries and the weight of electric motors, they were not sufficient for commercial aviation [12]. In the 2000s, as the energy densities of batteries and other power electronics developments have accelerated, the work on the AEA concept has also accelerated again. During this time, there have been a number of ongoing or successfully completed projects, including major industry players such as Pipistrel, Eviation Alice, Ampaire, Wright Electric, Boeing, Airbus, Joby Aviation, Archer Aviation, Beta Technologies, EHang, and NASA.

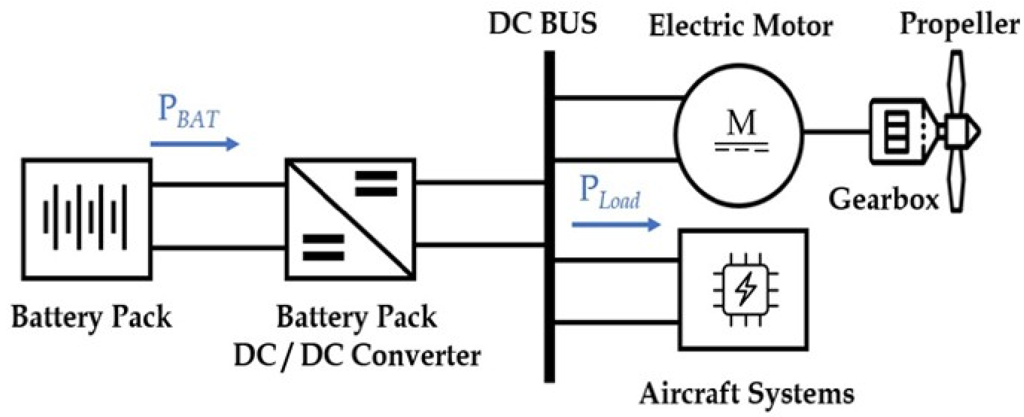


Figure 1.2: All electric aircraft architecture.

In the AEA concept, instead of internal combustion engines, propulsion is provided by electric motors, usually powered by energy storage devices such as batteries or fuel cells [13]. The architecture of this concept is shown in Figure 1.2.

Conventional propulsion systems have negative environmental impacts as they are based on jet engines and consume fossil fuels. In recent years, sustainable aviation and greener impacts have increased as electrification in the aviation sector has expanded, especially in aircraft propulsion systems. For instance, according to one study, a battery-powered aircraft can reduce CO_2 emissions by around 40% and NO_x emissions by more than 60% compared to a new aircraft design with conventional propulsion [14]. Air travel by electric aviation can offer an economical alternative to land transportation by shortening travel times, reducing costs, and being an environmentally friendly option. In addition, problems such as traffic congestion and parking problems caused by land transportation can be minimized [15]. Important parameters such as the energy density, weight, and cost of the batteries used as energy sources are among the factors limiting the development process of electrically powered aircraft. The fact that all energy needs are met by batteries has made it necessary for batteries to have high energy storage capacity. However while current battery technologies are not sufficient to fully meet these demands, significant progress is being made with technological developments [16]. In this case, the energy density of the battery selected as the energy source directly affects the weight of the aircraft and its flight range. Compared to conventional aircraft, the use of batteries in electric propulsion aircraft has a constant weight effect on the aircraft. Since aviation fuel is consumed throughout the flight duration, the weight effect on the aircraft decreases accordingly. In fully electric airplanes, the current weight of the installed battery remains largely unchanged depending on the energy consumption. Therefore, it is very important to include the battery weight in the design by minimizing the weight of the battery when selecting a battery to suit the needs of the flight profile [17].

Lithium-ion batteries are preferred as an energy source in electric and hybrid aircraft due to their higher energy density and voltage values compared to other battery types. As can be seen in Figure 1.3, Li-ion batteries have a higher energy density than other battery types. During the flight profile, Li-ion batteries are an ideal choice for high energy requirements such as take-off and propulsion. Companies such as NASA, Airbus, and Boeing, which has conducted important studies in the sector and in the electric aircraft concept, has also adopted the use of Li-ion batteries in its designs [18].

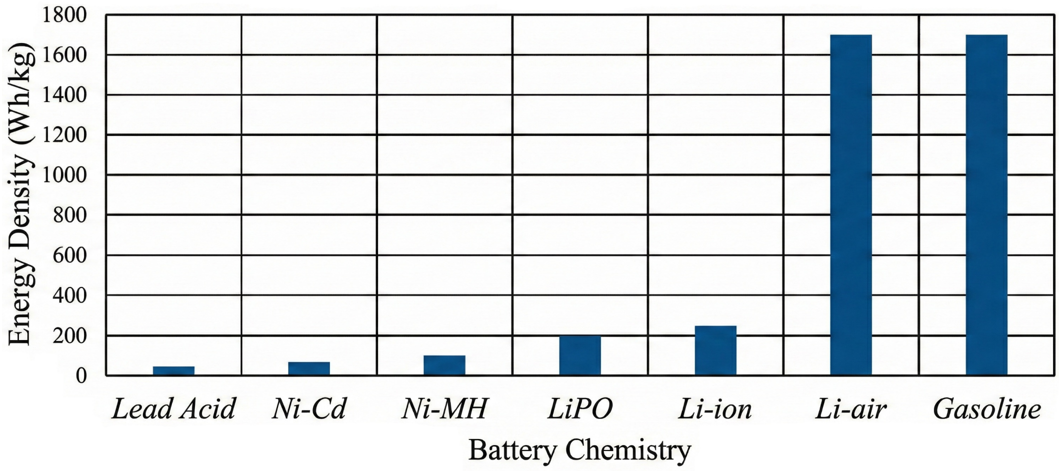


Figure 1.3: Comparison of various battery chemistries with gasoline [19].

Li-Air batteries are also a promising technology for energy storage. However, ensuring the need for fresh air during the reaction is a challenge to be overcome in order for the batteries to work efficiently. It needs technological developments to become a commercial and practical solution [20].

In summary, all-electric aircraft contribute to reducing the negative factors, such as carbon emissions and environmental and noise pollution caused by the aviation industry. It minimizes the high maintenance costs caused by mechanical and moving parts in conventional aircraft. Ongoing developments in battery technologies, along with the current situation, will significantly benefit the development of the concept with higher power density and lighter batteries. As the aviation industry moves towards the goal of net-zero carbon emissions, it will be possible to see all-electric aircraft projects with longer ranges and higher payload capacity. Additionally, it should be noted that in real-world applications, battery energy densities tend to be lower than their theoretical values.

1.1 Purpose of Thesis

The main purpose of this study is to examine the conversion of the Tecnam P2008 JC aircraft to an electric propulsion system from a technical perspective. The analysis process was conducted while adhering to the aircraft's existing structural architecture and certification constraints. The study investigated the feasibility of a fully electric design based on lithium-ion batteries. In this context, the system's operational performance, energy consumption characteristics, and economic impacts were addressed using a holistic engineering approach. The design process began with power and energy analyses tailored to the mission profile of the reference aircraft. Based on these data, the most suitable battery pack and electric propulsion architecture were determined. The Shepherd mathematical model was used to model the battery pack. This model, created in the Simulink environment, accurately represents terminal voltage, current, and state of charge dynamics. Through simulations, the behavior of the electric propulsion system during different flight phases has been examined in detail.

The study includes a comparative analysis between the designed electric configuration and the traditional internal combustion engine version. This analysis will be based on energy consumption, operating costs, and carbon emissions. It concretizes the potential gains of electric aviation. These analyses are also linked to the 2050 carbon-neutral targets set by the International Civil Aviation Organization. Thus, the role and limitations of current battery technologies in aviation applications have been clearly evaluated.

The aim is to demonstrate, with the findings obtained, that a fully electric propulsion architecture is feasible for short-range and light-class aircraft. Conversely, the technological limitations encountered in long-range and high-payload missions will be systematically analyzed. Ultimately, this thesis aims to provide a comprehensive technical perspective on the current state and future development directions of electric aviation.

1.2 Literature Review

The aviation industry is undergoing a fundamental transformation in line with environmental concerns and carbon emission reduction targets. This transformation includes efforts to move away from traditional fossil fuel-based systems. The transition to More Electric Aircraft the ultimate goal of All Electric Aircraft concepts is rapidly continuing. Studies in the literature address this transition process in detail. The process presents critical challenges in terms of both architectural design and energy storage technologies. At the same time, these challenges also bring significant advantages.

The fundamental challenge of electrification in aviation is meeting the increased power demand. The design of efficient power systems to manage this demand is crucial. In this context, electrical power systems for MEA and AEA concepts are being investigated. It is emphasized that Medium Voltage Direct Current (MVDC) systems are inevitable in future aircraft projects. The studies focus particularly on concepts such as NASA N3-X. The situation where hydraulic and pneumatic systems are completely replaced by electrical systems is being analyzed. The load that this change will bring is being calculated [21].

In addition, technological limitations are being identified. Current power electronics and protection equipment are not yet at the desired level. Large passenger aircraft require power levels of 25–30 MW during take-off. Current technology is insufficient to meet this need. These constraints further increase the importance of hybrid and distributed propulsion architectures. On the other hand, hybrid-electric propulsion trends in aviation are also being investigated [22]. Series and parallel hybrid architectures are noted as the most viable solutions. These architectures are particularly prominent in the short term for regional aviation. In addition, distributed propulsion technology is drawing attention [23]. In this system, propulsion units are distributed throughout the fuselage. Studies show that this technology increases aerodynamic efficiency. It is also emphasized that it reduces noise. These studies prove an important fact. Electric aviation is not just a motor replacement. This process represents a comprehensive architectural transformation.

The most critical component of electric propulsion systems is energy storage units. The studies examine the historical development of aircraft batteries [24]. Lithium-Ion technology is stated to be the most suitable candidate for aviation. In this context, older technologies such as Lead-Acid and Nickel-Cadmium are used for comparison. Li-Ion batteries offer significant advantages over these. They particularly provide high specific energy and energy density. This is demonstrated by technical data. These findings explain the rationale behind current designs. Li-Ion cells are predominantly preferred in current electric aircraft designs.

Accurate modeling is crucial for the design of battery management systems. It is also necessary for predicting flight performance. The study classifies battery modeling techniques [25]. These are divided into electrochemical, mathematical, and circuit-based models. The study particularly highlights mathematical approaches such as the Shepherd model. These models are effective in establishing the relationship between voltage and state of charge. They also provide efficiency in terms of computational load.

Similarly, different battery models are analyzed comparatively. The studies demonstrate the advantages of the Shepherd model [26]. The parameters of this model can be derived solely from manufacturer data sheets. It also represents discharge characteristics with high accuracy. This eliminates the need for complex experimental processes. Reliable simulations can be easily performed.

The literature compares modeling methods using NASA's X-57 Maxwell electric aircraft. The simplicity of the model is crucial during the conceptual design phase. At the same time, its accuracy directly affects the results of the task analysis. The studies emphasize this balance. The importance of Shepherd and similar models is demonstrated. These models are accepted as the industry standard in the initial design phases of complex systems [27].

The success of theoretical models is also supported by practical applications. One study examines the Cessna-172S, a popular training aircraft. It addresses the conversion of the aircraft to a hydrogen fuel cell and battery hybrid system. This work is performed in the MATLAB/Simulink environment. The role of the battery in damping sudden power changes is detailed. The energy management of the hybrid structure is also examined [13].

On the other hand, studies are also being conducted for similar applications such as port energy storage [28]. MATLAB generic battery modeling and Shepherd equations are used. Ultimately, successful data is obtained. These examples validate the selected modeling approach. Simulation tools provide reliable results in energy systems of different scales.

In conclusion, the literature supports the dominant role of Li-Ion batteries. Furthermore, the balance provided by the Shepherd model in modeling these batteries stands out. Current studies generally focus on architectural design and component analysis. However, the dynamic behavior of specific battery cells remains a research topic. Detailed modeling studies, especially in aviation mission profiles, remain relevant.

1.3 Hypothesis

The fundamental hypothesis of this study concerns the electrification conversion process of the Tecnam P2008 JC, a conventional single-engine aircraft. This process can be integrated into an electric propulsion system without requiring structural modifications. With this integration, it is anticipated that operational costs and carbon emissions will be significantly reduced without compromising flight safety.

Simulations using the Shepherd model show that battery dynamics match theoretical calculations. This validation proves that the designed system can safely meet the power requirements for short-range mission profiles. The results support the electric architecture as a commercially and technically viable alternative for short-range flights.

However, the energy density constraints of current battery chemistries are another focus of the study. Another hypothesis of the thesis is that these weight constraints limit the feasibility of long-range flights. The modeling quantitatively verifies the physical limits of current battery technology and their operational implications.

2. FUNDAMENTALS OF ELECTRIC AIRCRAFT PROPULSION

The electrification of aircraft propulsion systems encompasses various architectures in which propulsion power is partially or entirely derived from electrical energy. These architectures are classified as all-electric, hybrid-electric (combining fuel and electricity), and turbo-electric (generating electricity via a fuel-powered turbine for propulsion).

Today, aviation electrification continues to evolve as these architectures are implemented and widely adopted in various projects. Figure 2.1 shows architectures.

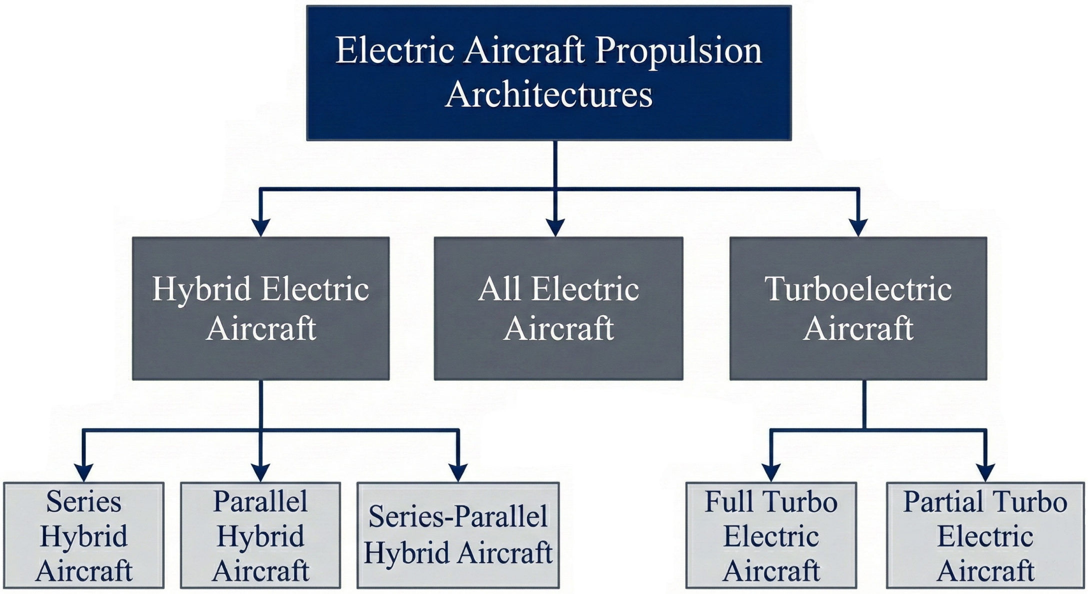


Figure 2.1: Schematic overview of the electric aircraft propulsion architectures.

In a conventional aircraft, fossil fuels provide all propulsion power, and direct electrification plays no role in the propulsion system. In a fully electric aircraft, all propulsion power is provided by batteries or similar electrical energy storage technologies. Fossil fuels are not used. In hybrid electric aircraft, both fuel and electrical energy are utilized simultaneously. In this architecture, part of the propulsion power comes from internal combustion engines and part from electric motors. Therefore, fossil fuels and battery systems coexist in the same architecture. In turbo-electric architecture, fuel is used as the energy source, but the turbine engine does not directly provide propulsion. Instead, electricity is generated via a generator, and power is supplied to electric motors that turn the propellers/fans. The common feature in all these architectures is that, unlike conventional aircraft, aircraft electrification plays a specific role in providing propulsion power.

2.1 Architectures of Electrified Propulsion Systems

2.1.1 All electric aircraft

In the all-electric aircraft architecture, all the aircraft's thrust is provided by electrical energy. In other words, only electric motors are used in the aircraft, and there are no fossil fuel engines. Therefore, the aircraft's energy is provided only by electrical energy storage systems, such as rechargeable batteries, fuel cells, or supercapacitors. Among the most significant advantages of the all-electric architecture are environmental contributions such as zero emissions during flight and reduced noise levels. Electric motors operate more quietly than jet turbines. In addition, noise can be significantly reduced by distributing several small electric fans throughout the aircraft [29].

On the other hand, current technology restricts fully electric aircraft to short ranges and limited payloads. This is because the specific energy of today's lithium-ion batteries is only about 2% of that of conventional aircraft fuels. For instance, as of the 2020s, the typical energy density of lithium-ion cells is around 250 Wh/kg [30], whereas Jet-A1 fuel has an energy density of approximately 12,000 Wh/kg [31]. This difference means that battery-powered aircraft can only be used for short-range missions. At the same time, the amount of payload that can be carried is limited. Studies show that all-electric aircraft concepts are suitable for flights under 1000–1500 km [32]. Significant advances in battery technology are needed to exceed this limit. With current technology, long-range flights are not considered feasible.

In an all-electric architecture, all propulsion system subcomponents are electric-based. In this context, electric motors are selected as the motors. Power electronics and energy distribution systems are also designed to be electric-based. In this architecture, batteries serve as the sole energy source within the aircraft. Power requirements vary during the take-off, climb, and cruise phases of flight. This variation is taken into account during the design process. Power demands are managed accordingly. This ensures more efficient use of battery capacity. Therefore, energy management is critical in the architecture of all-electric aircraft. High power is provided by batteries during the take-off and climb phases. During the cruise phase, the power requirement remains lower. Efficient use is targeted at this stage. This is because the cruise phase requires less power than take-off and climb. Increased energy efficiency is among the advantages of the fully electric architecture. The reduction in maintenance requirements is also considered an important benefit. The simpler operational structure is another prominent feature of this architecture. This is because electric motors consist of fewer moving parts. Thus, they do not require lubrication or complex fuel systems. However, with current battery technologies, the operating costs of fully electric aircraft remain high compared to those of conventional aircraft [32]. It is predicted that long-term economic competitiveness can be achieved once the specific energy and cost of batteries reach significantly optimal levels. Figure 2.2 shows a basic all-electric aircraft architecture.

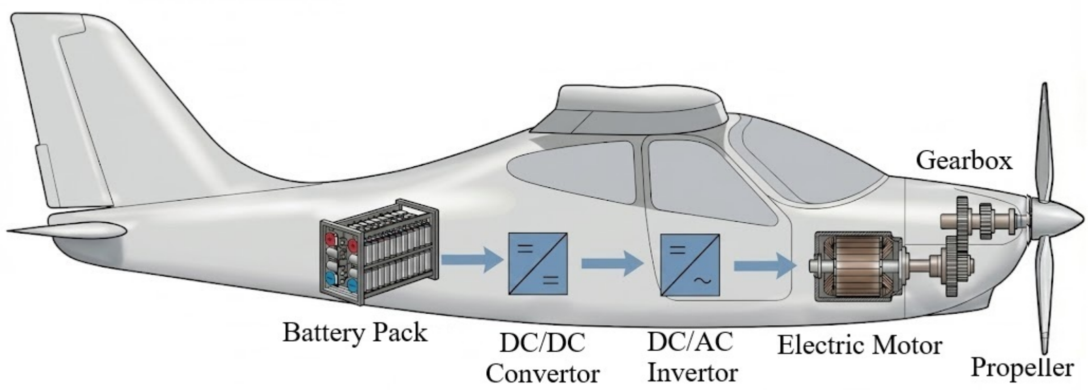


Figure 2.2: Schematic overview of the all-electric aircraft architecture.

The architecture of all-electric aircraft consists of energy storage systems, a power distribution grid, power electronics converters, and electric motors as its most fundamental components. In an aircraft with this architecture, batteries or fuel cells are the sole energy source. There are no fossil fuel-powered engines in this system. The required electrical energy is supplied to the aircraft using appropriate battery packs. Power electronics converters are used to convert this stored electrical energy to the appropriate voltage levels. The electric motor serves as an essential component that provides the aircraft's thrust.

2.1.2 Hybrid electric aircraft

Hybrid electric architectures describe propulsion systems that utilize both fossil fuels and electrical energy. In these architectures, one or more turbine or piston-based conventional engines and one or more electric motors contribute to propulsion in various combinations. Although hybrid systems are similar to the concept of hybrid cars in land transportation, there are some differences specific to aviation. For example, the idea of regenerative braking, known as energy recovery through braking in cars, exists. This is theoretically possible in aircraft during landing, but is inefficient. Therefore, aircraft hybrids benefit less from energy recovery compared to automobile hybrids. Aircraft hybrids are designed more like plug-in hybrid vehicles that can be charged from the grid [31]. When the aircraft is on the ground, the batteries can be charged, or short-range flights can be powered solely by electricity. For long-haul flights, the aircraft's range is increased by using internal combustion engines. Hybrid-electric aircraft architectures are primarily divided into two subgroups: Series Hybrid and Parallel Hybrid. Additionally, series-parallel hybrid structures, which combine these two, are also defined in the literature.

2.1.2.1 Series hybrid electric aircraft

In a series hybrid architecture, the aircraft's propellers or fans, which generate thrust, are driven solely by electric motors. Internal combustion engines are not directly connected to the propellers. In this architecture, one or more internal combustion engines are connected to a generator to produce electricity. The generated electric current passes through power electronic converters and is transmitted to electric motors, which use it to turn the propellers. If necessary, the generated electricity can also be used to charge the batteries. During phases of flight that require less power, such as the cruise phase, the generator can also transfer power to the batteries to recharge them. The fact that the internal combustion engine is not directly linked to propulsion is the main advantage of the series hybrid configuration. This allows the engine to be operated continuously at a constant and optimal power/speed point [22]. For example, the turbine engine can be kept at a constant, most efficient RPM and torque to power the generator. Furthermore, the absence of mechanical transmission components, such as a transmission or axle, simplifies the design and control.

On the other hand, a disadvantage of the series architecture is that the electric motor must provide all the thrust power on its own. To achieve this, the electric motor must be high-powered and therefore heavy. The electric motors that turn the propellers and the power electronics devices that power them are sized to the aircraft's highest take-off power. This results in additional weight and volume costs for the aircraft. Extra weight and volume increase are among the most undesirable aspects of aircraft design. Within this architecture, energy conversions occur sequentially: from fuel to mechanical power, from mechanical power to electrical power, and then back from electrical power to propulsion power. Thus, losses in the energy conversion chain can accumulate and become greater. Therefore, the efficiency achieved in a series hybrid architecture is lower than that of a parallel hybrid architecture.

Figure 2.3 shows a basic series hybrid aircraft architecture.

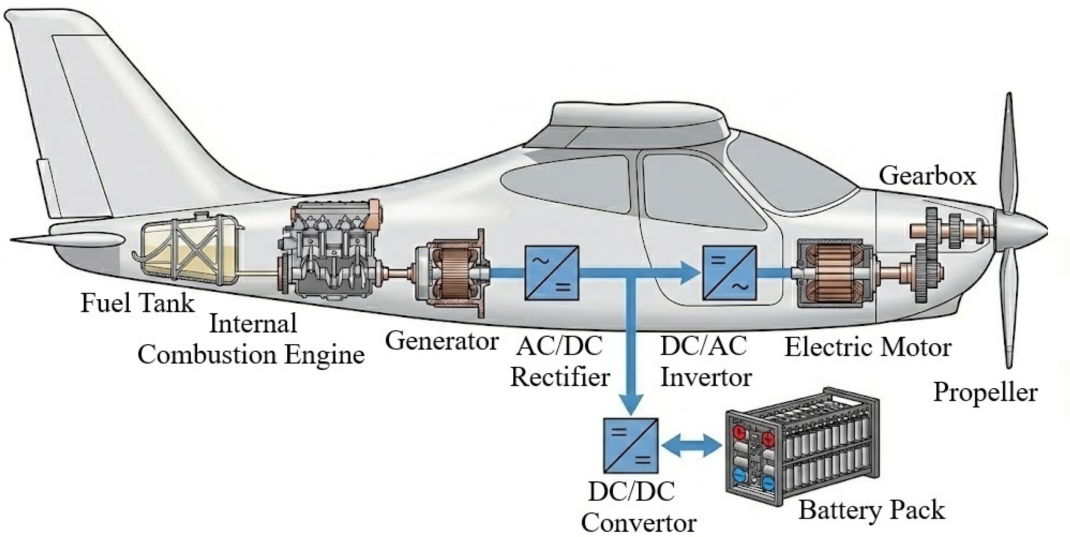


Figure 2.3: Schematic overview of the series hybrid aircraft architecture.

Despite all this, series-hybrid architectures offer a suitable, relatively easy-to-control solution, especially for applications requiring high torque and low speed, such as

VTOL and general aviation aircraft [22]. One of the concrete applications of the series hybrid propulsion architecture in aviation history is the DA36 E-Star platform, jointly developed by Diamond Aircraft, Siemens, and the EADS consortium. This aircraft made its mark in the literature as the world's first series hybrid aircraft demonstration with its flight at the 2011 Paris Airshow [33]. This demonstrated the feasibility of the series-hybrid system through a real project. Additionally, for series-hybrid architectures, designs are being developed in which multiple electric fans are distributed along the wing, and one or more motor-generator units provide the necessary electrical energy.

2.1.2.2 Parallel hybrid electric aircraft

In a parallel hybrid architecture, the propeller or fan, the aircraft's propulsion unit, is driven either jointly or alternately by the internal combustion engine and the electric motor. Within this architecture, there are typically two parallel power lines. One contains the internal combustion engine (ICE), while the other includes the electric motor (EM). These two are connected to the same propeller via a suitable transmission/gear system. Thus, the propeller can be turned by the ICE and EM together or separately. In a parallel hybrid system, a critical capability is that the internal combustion engine can charge the batteries by turning the electric motor into a generator when necessary [22].

For example, during cruise flight, the piston/turbine engine can rotate both the propeller and the connected electric machines, providing energy to the battery. The parallel architecture has some advantages over the series architecture. Since the ICE is directly connected to the propeller, the electrical power required for the same thrust is lower. Thus, the electric motor and power electronics components can be designed to be smaller and lighter [34]. Furthermore, in a parallel configuration, there is no need for a separate generator on the ICE. The internal combustion engine provides thrust through a mechanical connection while also contributing to electrical energy through the same line. This eliminates the need for an additional generator. This results in weight savings within the aircraft.

One disadvantage of the parallel hybrid system is the mechanical connection between the ICE and the EM on the aircraft. This is because an additional clutch/gear mechanism is required to connect these components. These mechanical components also add to the aircraft's weight and complexity. Furthermore, since the ICE is directly integrated in propulsion, it cannot perform at peak efficiency throughout the entire flight due to varying power requirements [22]. The engine cannot be optimized to a fixed point as in a series design due to the varying power distribution and requirements on the aircraft. Controlling parallel hybrid systems also requires a more complex control algorithm than series systems, as it requires coordinating two power sources.

Figure 2.4 shows a basic parallel hybrid aircraft architecture.

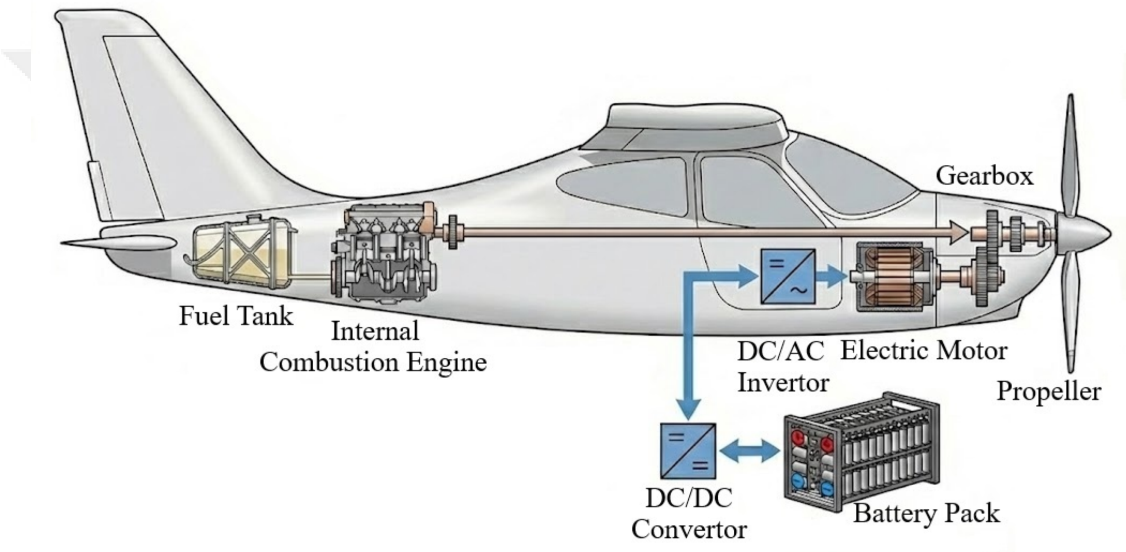


Figure 2.4: Schematic overview of the parallel hybrid aircraft architecure.

2.1.2.3 Series-parallel hybrid electric aircraft

The series-parallel hybrid architecture combines the series and parallel hybrid architectures. This approach offers the opportunity to benefit from the features of both architectures. As in a parallel hybrid architecture, the mechanical power from the aircraft's ICE can be transferred directly to the propeller via a clutch system when needed. Similarly, in the series-hybrid architecture, this power can be converted to electrical power by the generator and used as a source for the batteries. The flexibility of this architecture is used according to the needs of the different phases of flight. During the low-power phases of flight, thrust can only be provided by electric motors. In these phases, the internal combustion engine is only operated for the purpose of generating electrical energy [35]. This situation is considered a noteworthy feature in terms of the redundancy approach that is highly valued in aviation. There is a possibility of failure in the aircraft due to the internal combustion engine or fuel system. In such a case, thrust can be provided by the aircraft's batteries and electric motors. Similarly, an electrical failure related to the batteries or electric motors may occur. In this scenario, thrust power is generated by the internal combustion engines. This reciprocal working structure increases the aircraft's safety level. At the same time, system redundancy is strengthened. During flight phases that require high power, such as take-off, internal combustion engines and electric motors work together. In this phase, the required propulsion power is provided by the joint contribution of both systems.

Figure 2.5 shows a basic series-parallel hybrid aircraft architecture.

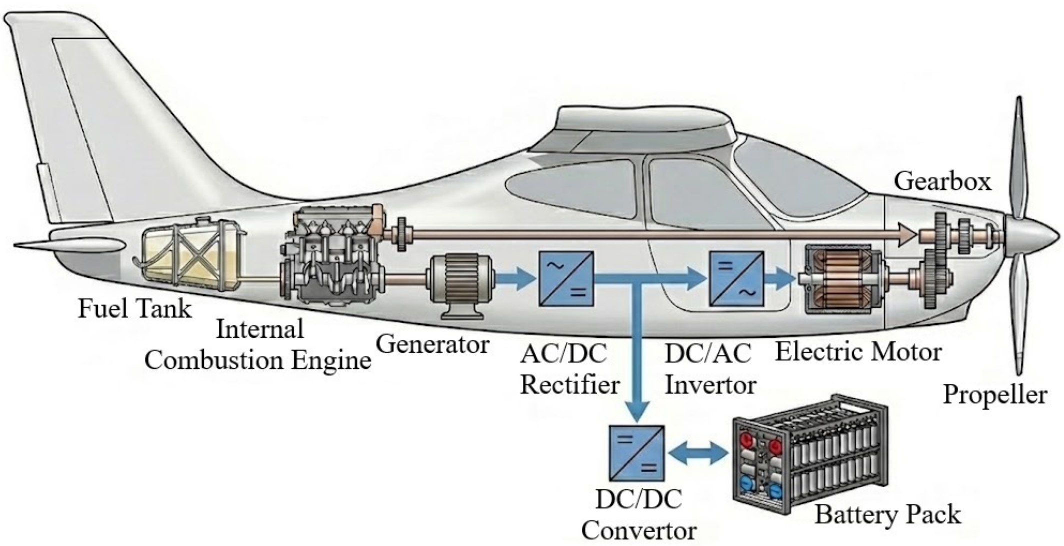


Figure 2.5: Schematic overview of the series-parallel hybrid aircraft architecure.

On the other hand, although the availability of appropriate choices for different flight phases and the compatible operation of various systems appear to be essential features, the series-parallel hybrid architecture is not yet a highly preferred system for aviation applications. This is primarily due to the system's complexity, the inclusion of elements from two different architectures, the greater increase in volume and weight in the aircraft, and the more comprehensive design and certification processes. High parameters such as safety and redundancy do not mean that one architecture can meet all aviation requirements. All components and aspects within the architecture must meet the defined objectives optimally. For this reason, it is currently preferred more for automotive architectures [22], and its development in aviation continues.

2.1.3 Turbo electric aircraft

Turboelectric aircraft feature fuel-powered turbine engines and associated electrical systems. In this architecture, electricity is generated using one or more gas turbines on the aircraft. This powers the aircraft's electric motors and drives the propellers/fans. Therefore, these gas turbines do not directly produce thrust. Furthermore, energy storage systems such as batteries are not used as energy sources. The turbogenerator systems formed by the gas turbine and generator provide electrical energy. Turboelectric aircraft configurations are divided into two architectures: Full Turboelectric Aircraft architecture and Partial Turboelectric Aircraft architecture.

2.1.3.1 Full turbo electric aircraft

In a fully turbo-electric aircraft architecture, the aircraft has one or more gas turbine engines. These engines generate electrical energy within the aircraft via a generator. The electrical energy obtained through these generators is used to turn the propellers/fans of the electric motors. Therefore, gas turbine engines do not directly produce thrust for the aircraft. Thrust is provided by electric motors powered by the electricity produced by gas turbines. In this respect, the architecture resembles that of a series hybrid electric aircraft.

On the other hand, within this architecture, there is no battery or similar energy storage system on the aircraft. All of the aircraft's energy is primarily derived from conventional fuel. Within this architecture, the ICE operates continuously throughout all flight phases and provides electricity generation. Thus, the electric motors provide thrust by turning the propellers. In addition, the mechanical decoupling of the turbine and propellers provides design flexibility and potential efficiency gains for the aircraft [36]. For example, the turbines can be located inside the aircraft fuselage or in any suitable location. The electrical energy they generate can also be transmitted via transmission lines to the fans distributed across the aircraft's wings or tail. NASA's N3-X project is implementing a turbo-electric architecture in a real-world application [37]. The implementation of this architecture does not completely eliminate the use of fossil fuels. Figure 2.6 shows a basic full turbo electric aircraft architecture.

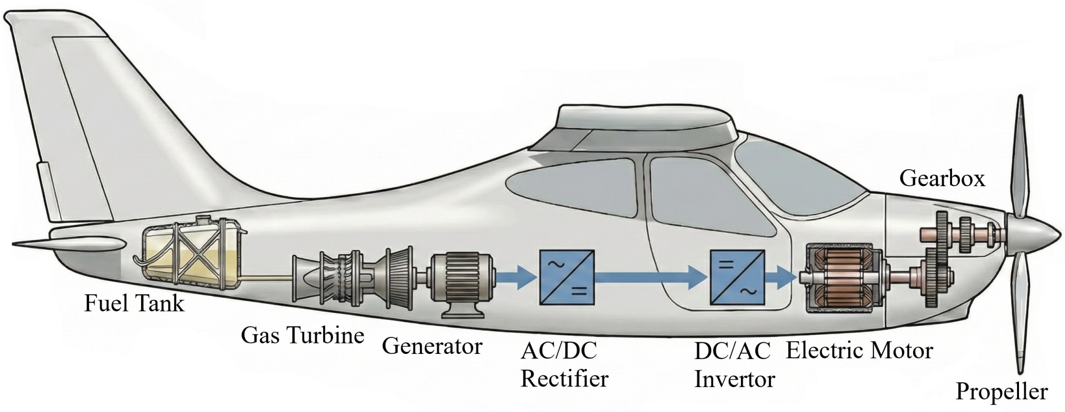


Figure 2.6: Schematic overview of the full turbo electric aircraft architecure.

However, dependence on fossil fuels is significantly reduced. Turbo-electric aircraft systems utilize the high energy density of fuel. At the same time, they benefit from the efficiency advantages offered by electric propulsion. This approach brings together the strengths of both systems within the same architecture. The goal is to improve the overall performance of the aircraft. Also, the aim is to reduce environmental impacts. These goals are among the fundamental issues facing the aviation industry.

2.1.3.2 Partially turbo electric aircraft

In a partial turbo-electric aircraft architecture, thrust power is derived from two different sources. This power is supplied directly from a conventional turbofan engine. At the same time, electricity generated by the turbofan via a generator powers additional electric fans. Unlike turbo-electric architecture, the turbofan engine produces thrust directly. This allows a reduction in the number of electrical system components used in the aircraft. The number of generators can be reduced. Electric motors and cable systems can be used more sparingly. Furthermore, this equipment can be designed in smaller sizes. This reduces weight and volume within the aircraft. When examining sample projects, the STARC-ABL concept developed by NASA stands out. This concept is based on a partial turbo-electric architecture. The work focuses on new aerodynamic solutions and performance improvements. In this NASA concept, an electric fan at the rear of the aircraft's fuselage is powered by electricity supplied by two turbofan engines in the wings. The turbofans both generate thrust and act as generators. Thus, thrust is provided by the electric fan at the rear of the fuselage, increasing overall efficiency. The size of the turbofans is reduced, resulting in fuel savings. According to recent assessments, the STARC-ABL concept promises approximately 9% reduction in cruise fuel consumption compared to a similar conventional aircraft. Partial turbo-electric designs are considered a transitional technology that could be implemented in medium-haul passenger aircraft in the near future [36]. Figure 2.7 shows a basic partial turbo electric aircraft architecture.

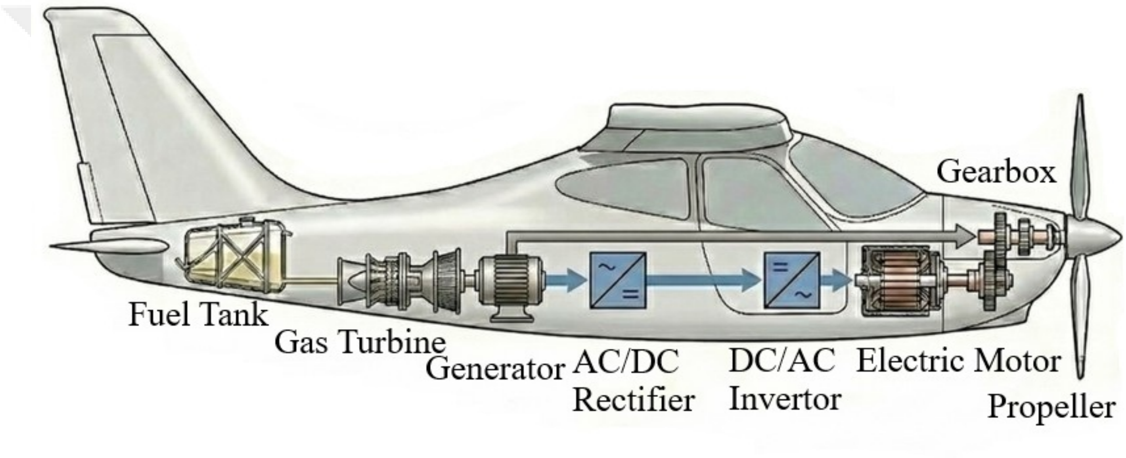


Figure 2.7: Schematic overview of the partial turbo electric aircraft architecure.

Table 2.1: Key highlighted characteristics of electric propulsion architectures.

Architecture	Highlighted Characteristics
All-Electric	• Zero-emission and low-noise operation. • High electrical efficiency. • Limited range due to battery mass and low energy density.
Series Hybrid	• ICE can operate near optimal efficiency. • Flexible electric propulsion control. • Additional mass from generator and storage components.
Parallel Hybrid	• ICE and electric motor jointly support propulsion. • Improved performance during high-thrust phases. • Increased mechanical and control-system complexity.
Series-Parallel Hybrid	• Multi-mode operation enabling adaptive optimization. • High potential for mission-based efficiency gains. • Highest structural and control complexity.
Full Turbo	• High range and high specific power. • Lightweight drivetrain. • High emissions and noise.
Partially-Turbo	• Electric assist enhances peak-power performance. • Moderate hybrid efficiency benefits. • Additional mass from hybrid subsystems.

2.2 Key Electrical Components and Technologies

The future of electric or hybrid aircraft is not only dependent on the propulsion architecture of the aircraft. The efficiency of the process also relies on all components that make up the aircraft's electrical power system and the technological competence of these components. Within the scope of this section, power generation systems, energy storage units, and electric motors, which are critical to the aircraft electrification process, are examined. In addition, power electronics circuit elements, converters, protection systems, and electrical distribution infrastructure, which enable all these components to work in harmony, are also addressed. Each of these critical components has different requirements than those of equivalent systems used in conventional aircraft. At the same time, these components also bring various technical challenges. These elements play a decisive role in the transition process from the MEA concept to the AEA concept. The technological maturity of each piece of equipment directly affects this transition process. The progress of aircraft electrification depends on these developments. In this context, each component is considered a critical building block in the electrification process.

2.2.1 Power generation system

The power required for an aircraft powered by electrical energy can be supplied from various sources. This power is not solely obtained from energy storage systems such as batteries. Electrical energy can also be generated on board the aircraft. This situation is particularly evident in aircraft designs where the entire energy requirement is not met by batteries. In hybrid and turbo-electric aircraft designs, the onboard power generation systems play a critical role. These systems ensure the continuity of the electrical energy required during flight. Integrated-driven generators (IDG) are commonly used in conventional aircraft. These generators operate based on the engine's output shaft. They are designed to rotate at a constant speed. In typical applications, power is generated at 115 VAC. This power is obtained at a constant frequency of 400 Hz.

On the other hand, the speed of an internal combustion engine can vary depending on the energy requirements that change during different flight phases. Consequently, obtaining fixed-frequency power requires complex mechanical systems, such as Constant Speed Drives (CSD), or significant power-electronics conversions. With today's advancing technology, IDG units integrated with CSD are used to maintain the generator at a constant speed even when the engine speed changes. With the introduction of newer, more advanced solutions such as the Variable Frequency Generator (VFG), the generator output can vary within a specific frequency range depending on engine speed. Consequently, aircraft avionics systems are designed to be compatible with and resilient to this variation. This approach contributes to weight reduction by eliminating the need for mechanical equipment, such as CSD [21].

In aircraft with electric propulsion systems, generators integrated into the main engines serve as the primary power source due to high power demands. For instance, high-capacity generators are used on the Boeing 787 platform, which features the MEA concept. These generators power both hybrid and turboelectric motors. They also support the aircraft's electrical components like cabin and avionic systems. In addition to the main engine generators, there are other energy sources, such as auxiliary power units (APUs) and ram air turbines (RATs). The APU is used to provide electricity and pressurized air when the engines are not running, such as on the ground and during pre-take-off [38]. It typically contains a small gas turbine and an integrated generator. In current designs, APUs can also be designed as combinations of batteries and fuel cells. For example, in some concepts, a lithium-ion battery pack and a hydrogen fuel cell are combined in the APU to continuously supply energy to the 270 VDC and 115 VAC buses. On the other hand, the RAT is used as a small wind turbine that activates in emergencies. It automatically activates in the event of a complete failure of the aircraft's electrical systems and generates the electrical energy required by critical systems by rotating with the airflow. For example, the Boeing 787 has one RAT located near each wing and one near the fuselage, and these systems can supply both AC and DC emergency lines [21].

In hybrid-electric aircraft, power generation systems are often designed as specialized units called turbogenerators. A turbogenerator is obtained by integrating a small gas turbine, which rotates at high speed, with a generator. It operates as a power unit focused solely on electricity generation. Particularly in series hybrid configurations, such turbogenerators are used to convert fuel into electrical energy. Additionally, fuel cells can also be integrated into hybrid systems for electricity generation. Hydrogen fuel cells could be seen as an attractive option for long-term emission-free electricity generation, provided that fuel supply and storage issues are resolved. The DLR's HY4 aircraft, which made its first flight in 2016, has a hybrid power system combining a hydrogen fuel cell and a battery [39]. The use of fuel cells in aircraft power systems is still in the experimental stage. Energy provided solely by batteries cannot fully meet the long-range needs of aircraft flights. With the development and use of effective technologies such as fuel cells, the range of hybrid aircraft is also expected to increase significantly.

In summary, different power generation systems are used together in electric and hybrid aircraft. These systems include traditional engine-integrated generators. Auxiliary power units are also considered an important resource. Battery and fuel cell combinations are also used in these architectures. Emergency turbines are utilized when necessary. In aviation, providing reliable and uninterrupted power is a fundamental requirement in terms of design. This approach is maintained across all architectures. Under normal operating conditions, each power source supplies its own loads. In the event of a failure, the electrical network is reconfigured. This process is carried out through circuit breakers. The energy supply to priority systems is thus maintained. Thanks to this flexible structure, modern electrical power systems offer a high level of safety. If one generator fails, other power sources can come online. This ensures flight safety is maintained.

2.2.2 Energy storage system

The storage of electrical energy is considered one of the most critical technological limitations for fully electric and hybrid aircraft. Battery systems are currently used as the primary energy storage solution in electric aircraft concepts under development. Current lithium-ion battery technology struggles to meet the performance requirements of aviation applications. Specific energy and specific power values are particularly limiting in this regard. Current lithium-ion batteries offer approximately 200 Wh/kg of specific energy [30]. This value is quite low compared to the energy density of aircraft fuels. This situation creates a significant disadvantage for batteries in aircraft design. This is because conventional jet fuel is consumed during flight, reducing the aircraft's initial weight, while batteries carry their entire initial weight even at the end of the flight. While these battery characteristics significantly affect the range of electric aircraft, promising developments and studies continue in the sector. For example, the Pipistrel Taurus G4 model is the longest-range fully electric aircraft, with a range of approximately 400 km [40]. The increase in battery-specific energy is of great importance for the development and widespread adoption of aviation electrification. For this reason, academic and industrial research and development activities are primarily focused on developing new-generation battery chemistries. Lithium-ion batteries have been maturing since the 1990s, and despite increasing their specific energy several times over the past 30 years, they are expected to reach only 300–400 Wh/kg in the coming years. In this context, new battery types with a theoretical energy density of 2,000–3,000 Wh/kg are under development. These include different battery types such as lithium-air (Li-Air) and lithium-sulfur (Li-S). If Li-Air and Li-S batteries can operate safely and practically at levels above 1000 Wh/kg, revolutionary developments in the range and carrying capacity of electric passenger aircraft are expected. Experts predict that if such batteries are developed, medium-sized fully electric passenger aircraft could emerge within the next 20–30 years. Given the chemical properties of batteries, developing the most optimal models is crucial to solidifying their place in the industry [21]. In addition to batteries, other electrical energy storage devices, such as supercapacitors and flywheels, are integrated to assist hybrid systems. Supercapacitors support batteries during short-term high-power demands, such as take-off and climb, thanks to their high power density. This extends the life of the batteries. For example, NASA is working on graphene-based ultra-capacitors and aims to use them in aircraft equipped with combined battery and capacitor systems called Hybrid Energy Storage Systems (HESS) to meet sudden power demands. Although supercapacitors are generally insufficient on their own due to their low energy densities, they prove their value as part of a hybrid storage system. Similarly, flywheel systems provide high specific power by storing electrical energy as mechanical kinetic energy. However, they have not yet been adopted in aviation due to safety and weight issues. Another emerging technology for energy storage in electric aircraft is fuel cells. Hydrogen fuel cells, in particular, convert chemical energy directly into electricity. With these characteristics, they are preferred as an alternative to or an additional source to batteries [41]. Fuel cells operate with high efficiency and produce only water vapor as emissions. This makes them advantageous in the aviation field. However, there are some challenges, including the low-temperature and high-volume requirements of liquid hydrogen tanks to be carried on the aircraft, and the fuel cell's low dynamic response speed. For these reasons, fuel cells in aviation are generally used in a hybrid approach, together with batteries. The fuel cell provides the base power and increases total power by kicking in during peak demand, such as during take-off. For example, the DLR HY4 aircraft is an example of this system. During cruise flight, the 30 kW PEM fuel cell provides continuous power. During the take-off phase, lithium-ion batteries generate an additional 45 kW of power. This configuration enables the engine power to reach approximately 80 kW. With this hybrid energy management approach, the HY4 platform can transport four passengers over short distances in an emission-free manner. There are some technical obstacles to the widespread use of fuel cells in aviation. The hydrogen supply infrastructure needs to be developed. It is important that tank systems are designed to be safe and lightweight. Fuel cell life and operational safety are also issues that need to be resolved. Nevertheless, fuel cells offer significant potential in the medium term. They are often considered range-extender systems. They are considered feasible for use in regional aircraft as an efficient power source during the cruise phase [39].

In summary, energy storage systems are recognized as a fundamental component of electric aircraft. They are also one of the areas most in need of technological advancement. Current battery technologies do not enable long-range electric passenger flights. Progress in this area is directly dependent on battery technology. Supercapacitor support and fuel cell integration support this development. Studies show that specific energy value is a critical parameter. Batteries with approximately 800 Wh/kg can achieve ranges of around 1000 km. Reaching an energy density of 1200 Wh/kg could enable ranges exceeding 1500 km. However, achieving these targets is not possible with current technology. These developments depend on advances in materials science. Electrochemistry-based studies play a decisive role in this process [32].

For AEA and MEA concepts, the storage and utilization of electrical energy within the aircraft are critical issues for making these concepts more feasible and advanced. The battery installed in an aircraft directly affects the most fundamental components of aircraft performance, such as range, operational area, and reliability. Additionally, battery packs used as energy sources increase the weight and volume of the aircraft. Today, the proliferation and increased usability of electric aircraft are linked to the limiting parameters of batteries, such as their specific energy and specific power. This is because the battery chemistries currently used in this field do not yet have the energy densities to meet the long-range requirements of conventional aircraft. Despite this, significant advances have been made in battery technology over the past decade. These developments contribute directly to electric aviation research. Current batteries can store more energy. At the same time, they are being developed to have a lower mass. This enables the emergence of electric aircraft with longer ranges and higher performance.

The battery's characteristics directly affect the aircraft's overall performance. Various battery parameters define these characteristics. These parameters are not limited to chemical and electrical properties. Environmental and financial factors are also evaluated in this context. Specific energy is among these parameters. Specific power is an important criterion. Specific capacity and charge capacity are also taken into account. Charge rate, cycle life, and operational temperature range are examined during the design process. Weight, state of charge, and depth of discharge values are also important. Battery cost is also among the fundamental elements that must be evaluated. These parameters play a critical role in electric aircraft design. The intended use guides the design process. The targeted mission profile is decisive in selecting these values. Therefore, battery parameters are among the fundamental technical data that must be examined in electric aircraft design.

Specific Energy [Wh/kg]: Specific Energy is defined as the total energy a battery can store per unit mass or perunit volume. This parameter is of great importance in aviation applications where mass constraints are decisive. The energy density of batteries used in electric aircraft is carefully evaluated during the design process. The specific energy value of a battery cell is not the same as that of the battery pack. Battery packs contain modular structures. There are also inactive components such as wiring and mechanical carriers. These elements increase the total mass. Therefore, the specific energy value obtained at the battery pack level is lower. When designing the battery pack, the weight limitations specified for the aircraft must be considered. These limits directly affect the battery placement and capacity selection. During the design process, the balance between specific energy and total mass is maintained.

Specific Power [W/kg]: Specific Power is the maximum power output a battery can deliver per unit mass. This parameter meets the high current demand required, especially during take-off. High specific power values determine how quickly energy can be discharged. This directly affects the instantaneous performance of engines.

Specific Capacity [Ah/kg]: Specific Capacity defines the total amount of electrical charge stored per unit mass. It is generally analyzed in ampere-hours/kilogram units. The capacity limits offered by battery chemistry are measured based on this value. It is directly related to the cell's physical dimensions and mass.

Charging Capacity and Rate: Charge capacity and speed indicate the battery's performance during charging. The C-rate parameter represents the ratio of the current value to the nominal capacity. High C-rates enable fast charging and discharging. The thermal effects of this process on the cell are carefully monitored during the engineering phase. The 1C value indicates the current that would theoretically allow a battery to be fully charged or fully discharged in 1 hour. For example, for a battery with a capacity of 100 Ah, the 1C charging current is 100 A. It is possible to charge the same battery at 2C. In this case, the current value rises to 200 A. Theoretically, the charging time is reduced to approximately 30 minutes. Charging speed is a critical design parameter in electric aviation applications. The goal is to reduce the ground time between flights. Shortening the turnaround time directly affects operational efficiency. Therefore, batteries with high C-rates are emerging as an important requirement.

In electric aviation applications, batteries with high C-rates are crucial for minimizing turnaround time between flights and enhancing operational efficiency. Therefore, intensive research is being conducted on fast-charging technologies that maximize the C-rate to shorten charging times.

Cycle Life: Cycle life is the number of charge-discharge cycles a battery can complete without experiencing performance loss. This parameter measures the process until a certain capacity threshold is reached. It is important for the battery's operational life. It is used as fundamental data in calculating maintenance costs in aviation. A decrease in the battery's cycle life may occur. This situation is mostly associated with physical and chemical deterioration occurring within the battery's internal structure.

Operating Temperature: The operating temperature is the range of temperatures at which the battery functions efficiently. The stability of the chemical reactions within the cell depends on these temperature limits. Excessive heating or low temperature conditions lead to capacity losses. More importantly, serious safety risks may arise. Thermal runaway is one of the primary risks. Therefore, advanced thermal management systems are required in aircraft designs.

Weight: Weight is the total mass of the battery pack and all its components. The range and carrying capacity of electric aircraft are directly limited by this parameter. In engineering calculations, the total weight of the system is considered a critical input. The overall efficiency of the propulsion system is related to this mass value.

State of Charge (SOC): The charge status indicates the ratio of the remaining energy in the battery to its total capacity. It is monitored in real-time by energy management systems throughout every phase of the flight. Remaining range estimates and power distribution decisions are shaped based on this data. Accurate SOC estimation is considered essential for flight safety. The SOC value cannot be measured directly via a sensor. Instead, indirect estimation methods are used. Current data is evaluated for this purpose. Voltage and temperature measurements are also included in the calculation.

Coulomb counting is one such method. Advanced algorithms such as Kalman filters are also widely used. It is vital to know the SOC accurately for the following reasons:

(i) It is possible to prevent overcharging and over-discharging situations. This ensures operational safety.

(ii) The system's remaining range or current operating time can be accurately calculated. This is critical for mission planning.

(iii) It is possible to avoid stressful charge levels that negatively affect battery life. This approach supports the long-term and safe use of the battery.

$$SOC(t) = \frac{Q_{curr}(t)}{Q_{nom}} \times 100 \tag{2.1}$$

$$SOC(t) = SOC(t_0) - \frac{1}{Q_b} \int_{t_0}^{t} I(t)\,dt \tag{2.2}$$

$SOC(t)$	: State of Charge at time t (%)
$Q_{curr}(t)$	: Current capacity of the battery (Ah)
Q_{nom}	: Total capacity of the battery (Ah)
$SOC(t_0)$	: Initial State of Charge at initial time t_0 (%)
t	: Current time (s)
t_0	: Initial time (s)
$I(t)$	: Battery current as a function of time (A)
Q_b	: Nominal battery capacity (Ah)

Depth of Discharge (DOD): Depth of Discharge (DOD) indicates the percentage of the battery's total capacity that has been used. There is an inverse relationship between this value and State of Charge (SOC). High DOD rates cause the chemical structure within the cell to deteriorate more quickly. This directly shortens the battery's total cycle life. In aviation applications, a specific discharge limit is applied to protect cell health.

$$\text{DOD} = 100\% - \text{SOC} \tag{2.3}$$

Cost [$/Wh]: The cost parameter represents the expenses incurred per unit of energy storage capacity. Certification and safety tests in the aviation sector significantly increase these costs. Not only the initial purchase cost but also the system's total operating cost are taken into account. The battery's cycle life directly affects the cost per unit flight hour. For an economical design, optimization between battery life and performance is required.

The electric aircraft concept cannot be evaluated independently of these battery parameters. Each battery parameter is directly related to the others. This interaction occurs in a chain reaction. As a result, the aircraft's range is determined. The performance level depends on these values. The cost structure is also affected in the same way. Operational processes are shaped according to these parameters. Battery technology plays a key role in the aviation industry's transition to sustainability. In this context, the Environmentally Friendly Aviation for All Classes of Aircraft (EFACA) project stands out. Within the scope of the project, batteries are examined under different categories and Figure 2.8 shows the essential battery performance parameters. Their potential for aviation applications is analyzed. At the same time, technical limitations are also evaluated [42].

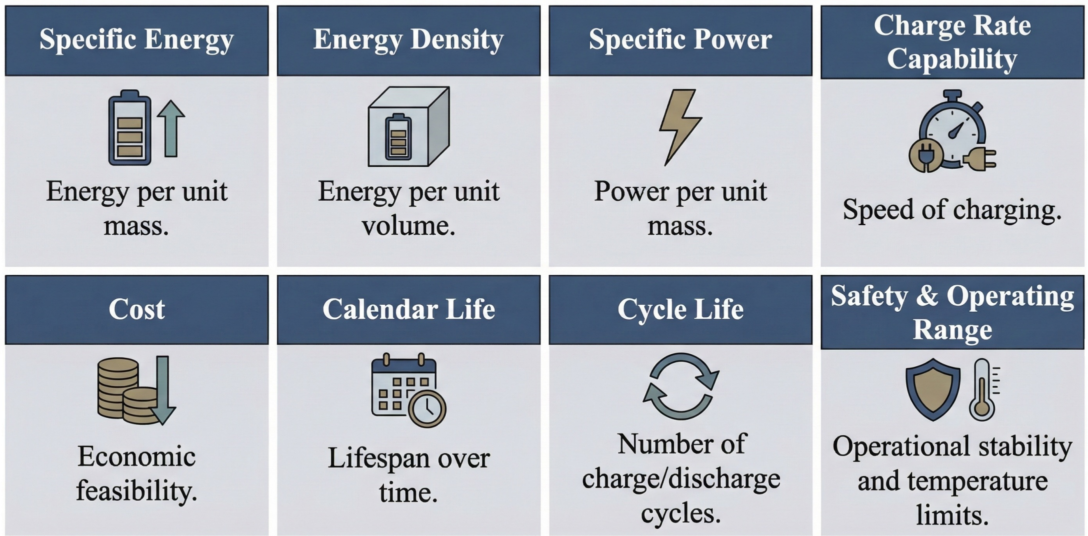


Figure 2.8: Essential battery performance parameters.

2.2.2.1 Lithium-ion batteries

Lithium-ion batteries have been in commercial use since 1991 [43]. Significant developments in battery technology have occurred since then. With these developments, lithium-ion batteries are now widely preferred in energy storage systems. The operating principle of lithium-ion batteries is based on electrochemical principles. Lithium ions move during charging and discharging. These ions are transported in an organic liquid electrolyte. Ion transfer occurs between the cathode and anode structures. This transfer is facilitated by a porous separator. The process is defined by intercalation and deintercalation mechanisms [44]. Lithium-ion batteries are used in many sectors. Electric vehicle applications are at the forefront of these areas. Aviation applications also constitute an important area of use. In addition, they are widely used in various industrial and consumer applications.

Lithium-ion batteries stand out for their high specific energy values. These values range from approximately 118–250 Wh/kg. Their specific power levels are also high. Typically, performance ranges from 200–430 W/kg. The monthly self-discharge rate remains low. This rate is generally below 5%. The cycle life is long. In most applications, it can exceed 2000 cycles. Charging and discharging efficiency is also high [30]. These parameters enable lithium-ion batteries to be used in areas requiring high energy density and reliability, such as electric aircraft. The mass advantage of batteries is an important design criterion. These features offer significant advantages for aviation applications. However, lithium-ion batteries also have some disadvantages. With today’s technology, the energy density of these batteries remains lower than that of fossil fuels. Therefore, fossil fuels still maintain their superior position. Their greater energy density supports this situation. Fossil fuels also come to the fore in terms of reliability. The electrochemical structure of lithium-ion batteries involves certain risks. Volumetric changes can occur in the electrodes during charging and discharging. These changes can increase the risk of internal short circuits. Thermal runaway is also a potential hazard [45]. These risks are unacceptable in areas requiring high safety, such as aviation. Therefore, additional safety measures must be taken. Furthermore, recycling processes are costly. Battery performance may decrease in extremely hot and cold conditions. These situations are considered among the fundamental limitations of lithium-ion batteries. Figure 2.9 shows the performance of different lithium-ion battery chemistries.

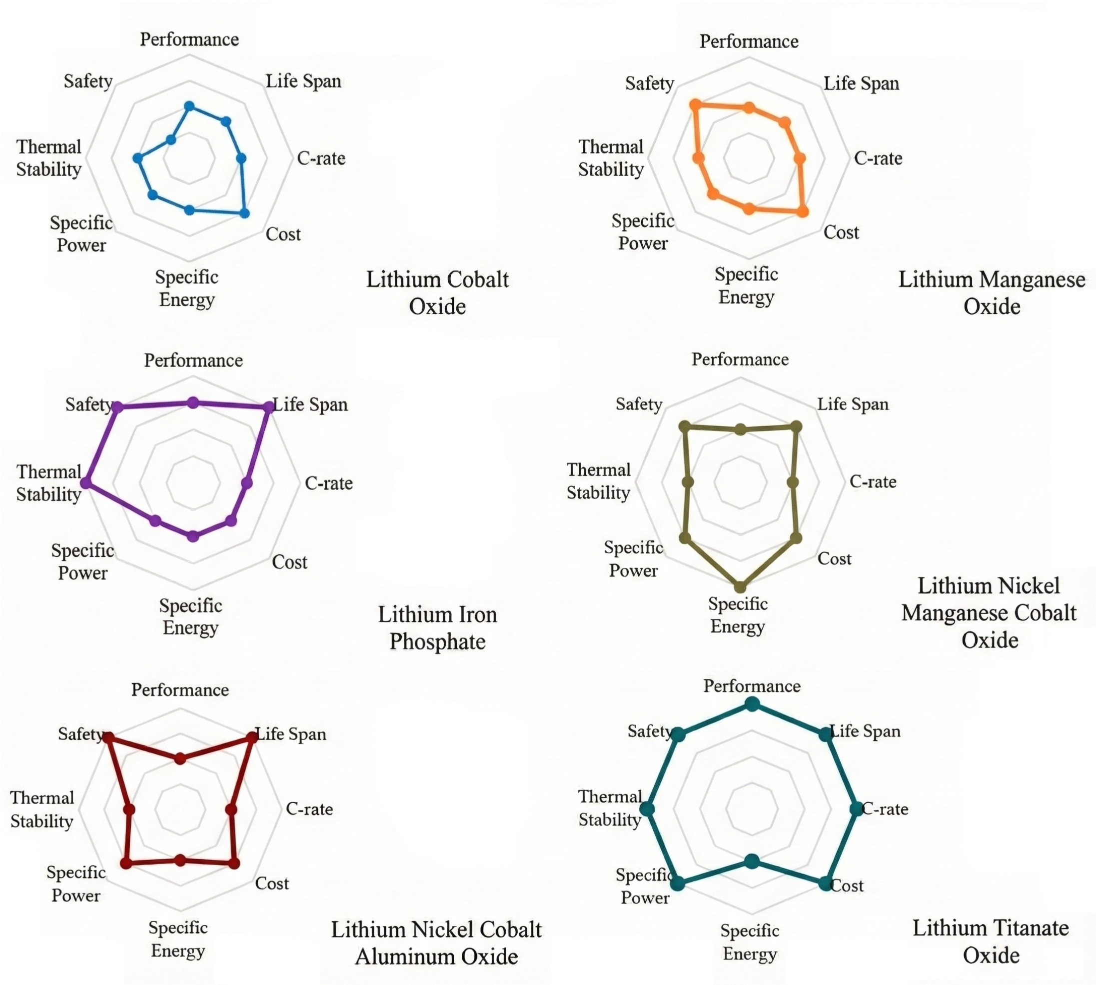


Figure 2.9: Comparative performance of lithium-ion chemistries [46].

Lithium-ion batteries are considered an indispensable component in aviation electrification, given their characteristics. These batteries stand out in the industry due to their current level of technological maturity. They are capable of meeting the fundamental requirements of aviation applications. Different battery technologies are being evaluated for more electric aircraft, all electric aircraft, and eVTOL platforms. As a result of these evaluations, lithium-ion batteries are considered among the most suitable options. Technological maturity is decisive in this choice. Reliability and performance also support this choice. Lithium-ion batteries play an important role in the industry. They are actively used in many critical projects. For example, they are used in auxiliary power systems as part of the More Electric Aircraft concept on the Boeing 787 Dreamliner platform. They are also used in all-electric aircraft projects such as the Airbus E-Fan [47]. Furthermore, they power electric propulsion systems in the X-57 Maxwell research project [48]. These examples demonstrate the practical role of lithium-ion batteries in the aviation industry. These platforms also demonstrate the potential of these batteries to shape the future of air transportation. Advances in battery technology will further enhance this impact. Developments in lithium-ion batteries will continue to make significant contributions to aviation electrification.

2.2.2.2 Lithium-sulfur batteries

Lithium-sulfur batteries theoretically have a specific energy value of approximately 2500 Wh/kg [49]. This feature represents a significant advantage for the development of aviation electrification. Therefore, lithium-sulfur batteries are considered a powerful battery alternative. High specific energy is a critical parameter in this type of battery system. Achieving this parameter enables longer flight ranges. It also contributes to the development of lighter energy storage systems. This directly affects aircraft performance. Going beyond theoretical calculations increases the importance of this technology. The emergence of real applications demonstrates the potential of lithium-sulfur batteries. This is considered a noteworthy development for the aviation industry. In this context, NASA's SABERS Program is an important example [50]. Within the framework of the program, Li-S cells with specific energy values exceeding 500 Wh/kg have been produced. These cells have been used in practical applications. The results obtained demonstrate that lithium-sulfur batteries can also be used in real systems.

Despite the existence of numerous real-world project examples, Li-S batteries are not widely used in aviation electrification. The main reason for this is a limitation arising from the battery chemistry. This field requires high reliability and safety. Current Li-S battery chemistry is insufficient to meet these requirements. At the root of this limitation is a battery mechanism called polysulfide bridging [51]. This mechanism causes a continuous internal leakage within the battery. At the same time, inefficiency arises throughout the system. This situation leads to accelerated capacity loss in each charge and discharge cycle of the battery. In terms of battery parameters, the cycle life is quite short. Charging efficiency also remains low. These results limit the performance of Li-S batteries. In the aviation sector, an aircraft is expected to have thousands of flight hours. At the same time, a large number of battery charge cycles must be completed safely. With today's technology, Li-S batteries cannot meet these requirements in a stable and long-lasting manner. Therefore, they cannot be used as an uninterrupted energy storage system. This situation is not only a technical problem. It also has negative financial consequences. Disadvantages also arise in terms of environmental impacts. For these reasons, the use of Li-S batteries in aviation applications remains limited today. Figure 2.10 shows the Li-S battery structure designed for the SABERS program.

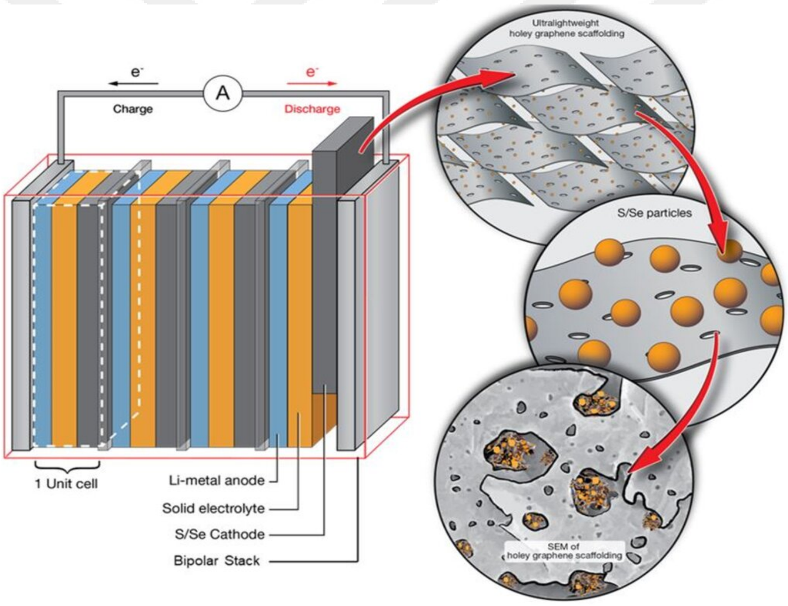


Figure 2.10: Lithium-Sulfur battery design developed for the SABERS program [50].

As a result, Li-S batteries are currently being evaluated primarily through experimental studies in the field of aviation electrification. These batteries are being used in development projects such as SABERS. Test activities are being conducted in a laboratory environment within this scope. Commercial applications remain limited at the current level of technology. The identified technical shortcomings of the battery must be addressed. Progress in these areas is critical. With these developments, Li-S batteries are expected to find greater use in commercial and practical applications.

2.2.2.3 Lead-acid batteries

Pb-Acid batteries are among the first developments in rechargeable battery technology. This type of battery was invented by Gaston Planté in 1859 [52]. Since then, it has been recognized as an important energy storage solution. It continues to be used in various applications today. The basic electrochemical structure of lead-acid batteries relies on specific components. Lead is used as the anode material. The cathode structure consists of lead dioxide. A sulfuric acid-based solution is preferred as the electrolyte. This structure forms the working principle of the battery [53]. Pb-Acid batteries are used in many industries today. UPS systems are one such area. Automotive applications constitute a widespread area of use. They are also preferred in communication systems. There are various reasons for their wide range of applications. These batteries remain low in cost. Their long-term use has proven their reliability. They can also operate over a wide temperature range. These features are decisive in the preference for Pb-Acid batteries.

On the other hand, despite their wide range of applications, Pb-Acid batteries are not preferred in aviation electrification. The main reasons for this are related to battery parameters. In particular, high weight is a significant disadvantage. In addition, energy density remains at low levels. Pb-Acid batteries offer a specific energy of approximately 35 Wh/kg [30]. This value is quite low when compared to other battery technologies preferred today. Therefore, the battery's weight-to-energy ratio is not suitable for aviation applications. In the aviation sector, even the smallest cable weights are calculated. Given this sensitivity, it is unlikely that Pb-Acid batteries will be a priority for aircraft energy storage. In addition to these limitations, there are other disadvantages. The cycle life is generally less than 1000 cycles [30]. Charging times are long. Furthermore, the lead contained in the battery is considered an environmentally hazardous substance. These factors further restrict the use of Pb-Acid batteries in aviation electrification.

As a result, Pb-Acid batteries are not used in aircraft primary propulsion systems. These batteries are preferred in auxiliary power units located in various places. They also perform secondary non-propulsion tasks [47]. In modern aviation applications, battery performance is a priority criterion. Low weight is also considered a fundamental requirement. Therefore, technologies offering higher performance are chosen over Pb-Acid batteries. Battery solutions with a lighter structure are prominent in aviation electrification.

2.2.2.4 Nickel-cadmium batteries

Nickel-cadmium batteries were developed in 1899 by Waldemar Jungner [54]. They have been used as a reliable component in energy storage systems for many years. This type of battery has been preferred in various application areas. The basic electrochemical structure of the battery is based on specific components. Cadmium is used as the anode material. The cathode structure consists of nickel hydroxide. A potassium hydroxide-based solution is preferred as the electrolyte. This structure forms the working principle of the battery [55]. Ni-Cd batteries are characterized by their long cycle life. The cycle life exceeds 2000 cycles in most applications. They can also operate within a wide operational temperature range. They are known to have a mechanically robust structure. These features are compatible with the requirements of the aviation sector. Their ability to operate within a wide temperature spectrum is considered a significant advantage. Their resistance to physical stress supports their preference. Long cycle life is also effective in this choice [30]. Ni-Cd batteries were used especially in periods when lithium-ion batteries were not as widespread as they are today. They have been used in starter systems in large aircraft. They have also been used in helicopter applications. They are used to provide energy in emergency situations [47].

Their areas of application are significantly limited. Environmental and electrochemical disadvantages contribute to this situation. Ni-Cd batteries contain cadmium due to their structure. Cadmium is known to be a highly toxic substance. Therefore, it has serious negative effects on the environment. This situation leads to the battery being considered environmentally disadvantageous. In addition, there is also an operational flaw. If the battery is recharged without being fully discharged, a memory effect occurs. This effect reduces the battery's usable capacity. As a result, battery performance drops significantly [56]. Furthermore, the self-discharge rate is high. This rate is approximately 20% per month. The high cost of cadmium is also considered another negative factor. Furthermore, specific energy values remain low. These values range from approximately 50–80 Wh/kg. When all these factors are considered together, there is a growing trend toward alternative battery technologies over Ni-Cd batteries. This trend is becoming more pronounced today [30].

2.2.2.5 Nickel-metal batteries

Ni-MH batteries stand out for their reliability and cost-effectiveness. These batteries have been commercialized since the 1990s as an alternative to Ni-Cd batteries [55]. Their use has become increasingly widespread during this period. The aim was to reduce the environmental damage caused by cadmium in Ni-Cd batteries. Ni-MH technology was developed for this purpose. At the same time, a more reliable structure has been achieved. A more balanced solution has also been offered in terms of cost. The chemical structure of Ni-MH batteries is different from that of Ni-Cd systems. Metal hydride alloys that can store hydrogen are used on the anode side [57]. This approach eliminates the use of heavy metals such as cadmium and lead. This provides a significant environmental advantage. This structure also supports operational robustness. Ni-MH batteries are known for their long cycle life. They exhibit high tolerance to overcharging and over-discharging conditions. They can provide stable discharge performance at low temperatures. These features increase the reliability of the batteries. Thanks to this reliable structure, Ni-MH batteries are preferred in different sectors. Electric vehicle applications are among these areas. They are also used in critical systems such as medical devices. In this respect, Ni-MH batteries are considered to have an important position among energy storage technologies [55].

On the other hand, the battery has a high self-discharge rate. This situation becomes more pronounced at high temperatures. The monthly self-discharge rate is approximately 20%. This characteristic negatively impacts battery performance. In addition, the specific energy value remains low. This value ranges from approximately 70–95 Wh/kg. These levels fall short of the parameters of lithium-ion batteries commonly used today. Therefore, Ni-MH batteries cannot be considered a competitive option in terms of energy density [30].

As a result, Ni-MH batteries cannot match the performance level of lithium-ion batteries despite their features. However, they are considered an important alternative to Ni-Cd batteries. These batteries offer a more balanced solution in terms of environmental and operational aspects. There are application examples related to this situation. Ni-Cd batteries were used in the modernization processes of military platforms such as the F-16. Today, these batteries are being replaced with Ni-MH batteries. This conversion provides a safer structure. At the same time, environmental impacts are reduced. Therefore, this application is considered a more environmentally friendly solution [24].

2.2.2.6 Zinc-air batteries

The chemical structure of Zinc-Air batteries is based on a specific principle. In this structure, atmospheric oxygen is used as the cathode reactant. This approach is similar to the operating principle of lithium-air batteries. Therefore, the system is defined as an air-breathing structure. Zinc-Air batteries theoretically have a specific energy potential of approximately 1080 Wh/kg. In commercial cells, this value is around 300 Wh/kg. These levels are noteworthy for their energy density. Thanks to these characteristics, Zinc-Air batteries are considered a suitable alternative for systems where weight restrictions are critical, such as aircraft. The balance between energy density and weight provides an advantage in this regard [48]. In addition, zinc, the anode material, is low-cost. Zinc is abundant in nature. This creates a significant financial advantage. These characteristics make Zinc-Air batteries an economically attractive option.

However, the high specific energy values theoretically offered by Zinc-Air batteries do not translate to the same level in practical applications. This advantage remains limited in real systems. In aviation applications, the power requirement during flight is not constant. The instantaneous power demand increases during the take-off and climb phases of the aircraft. High current demand arises during these phases. Zinc-Air batteries cannot meet such instantaneous high current requirements. This situation poses a critical problem for aviation applications. In addition, the power density of these batteries remains low. Their cycle life is also limited. Typically, values in the 200–500 cycle range are obtained. The interaction of the electrolyte with the atmosphere creates operational difficulties. When these limitations are considered together, the widespread use of Zinc-Air batteries in practical applications is not feasible. For these reasons, their potential for preference in aviation electrification remains limited. [58].

As a result, these batteries cannot meet the basic requirements of aviation applications. The reliability level is insufficient. Long-term service life cannot be ensured. High energy density cannot be consistently achieved. The charging performance is also not at the desired level. The inability to provide these parameters together creates a significant limitation. Today's technological capabilities are insufficient to overcome these shortcomings. Therefore, these batteries cannot be considered strong candidates for the aviation sector.

2.2.2.7 Lithium-air batteries

Lithium-air batteries are considered a key component in advancing aviation electrification due to their high specific energy potential. This battery type has a theoretical specific energy potential of approximately 11,500 Wh/kg. For practical applications, values of around 5,200 Wh/kg are expected to be achievable [47]. The basic chemical operating principle of the battery is based on specific components. Metallic lithium is used on the anode side. Atmospheric oxygen acts as the cathode reactant. Thanks to this structure, the battery has an open chemical architecture. The use of atmospheric oxygen on the cathode side is a significant advantage. This approach eliminates the need for the battery to carry its own oxidizer. This significantly reduces the total weight of the battery system. This reduction in weight directly affects the energy density [48]. Thus, the theoretical energy density of Li-Air batteries can reach very high levels. These levels are considered to be competitive with jet fuel.

On the other hand, despite all these positive features, Li-Air batteries have some fundamental limitations. The cycle life of these batteries remains low. Energy efficiency has not reached a sufficient level. Charging and discharging speeds are also insufficient for practical applications. In addition, controlling chemical reactions becomes difficult. Reaction stability cannot be ensured. This negatively impacts battery performance. Consequently, significant shortcomings arise in practical and reliable use. The industry has commercialization goals for the next decade. However, current chemical limitations complicate this process. Design-related obstacles also slow down development. For these reasons, the maturation process of Li-Air batteries is being disrupted [45].

As a result, all positive and negative parameters are evaluated together. Based on this evaluation, Li-Air batteries are considered an important and critical component for aviation electrification. This technology occupies a strategic position. Li-Air batteries are evaluated as a potential candidate for integration into regional aircraft. They are also considered a suitable option for the propulsion systems of narrow-body aircraft. They also have long-term potential for wide-body aircraft [47]. This battery technology has the potential to surpass the performance of li-ion batteries. Theoretical and practical studies support this. It is considered to be a technology that could replace fossil fuels in the long term. Advances in engineering will support this process. Chemical developments will help reduce existing problems. With these improvements, Li-Air batteries are expected to make meaningful contributions to the electrification process.

2.2.2.8 Solid-states batteries

Solid-state batteries (SSBs) are among the key energy storage solutions under evaluation for electric aircraft systems. This type of battery is a strong candidate due to its performance and potential. It provides a structure that can meet the critical requirements for aviation applications. Solid materials are used as ionic conductors in solid-state batteries. This approach is similar to the fundamental electrochemical principles seen in Lithium-Ion batteries [59]. However, the use of liquid electrolytes is eliminated. This eliminates risks associated with flammability and volatility. The risk of thermal runaway is also significantly reduced [24]. In addition, the use of high-capacity anode materials becomes possible. Lithium-metal anodes stand out in this context. The use of these anodes increases the battery's specific energy. Specific energy levels are expected to reach 400–600 Wh/kg. Solid-state batteries also offer long cycle life potential. It is stated that the number of cycles can reach 8000–10000 levels. These features make Solid-state batteries an attractive option for aviation electrification [60].

On the other hand, some fundamental obstacles to the widespread use of Solid-State batteries in real-world applications remain. These limitations are decisive in terms of today's technology. From a chemical perspective, the ionic conductivity of solid electrolytes remains low. These values are insufficient compared to liquid electrolytes. This limits the battery's power and efficiency. In addition, the solid-solid interface between the electrode and the electrolyte poses a significant problem. Ensuring stable and long-term contact in this area is difficult. Interface resistance negatively affects battery performance. Furthermore, production processes are costly. Current production techniques are not considered suitable for mass and economical production. This high cost level limits commercial applications. When all these factors are considered together, it is evident that there are significant obstacles to the widespread use of solid-state batteries in the current perspective. Overcoming these obstacles depends on technological developments.

Despite these obstacles and limitations, solid-state batteries are considered to have significant potential for aviation electrification. This potential is based primarily on the expectation of high energy density. The advantage of long-term use also supports this assessment. The use of solid-state batteries is expected to become widespread in the coming years. Hybrid-electric regional aircraft stand out in this context. They are also seen as a suitable option for fully electric short-range commuter aircraft. It is estimated that the energy density of 400–500 Wh/kg required by these platforms can be met. This makes solid-state batteries a key component of aviation electrification. Applications requiring higher energy density are also being considered. Solid-state batteries are emerging as a strong candidate, particularly for fully electric regional aircraft that require energy densities above 500 Wh/kg. In this context, the strategic importance of solid-state batteries is increasing [61].

2.2.2.9 Structural batteries

Structural batteries are defined as an innovative approach that clearly differs from traditional battery systems. In this approach, the battery is not only considered as a power system component. It is also made into a structural part of the aircraft. With these batteries, the electrochemical energy storage and power supply function is maintained. In addition, they contribute to the formation of the airframe structure. In other words, the battery serves as an energy storage device. At the same time, it also performs a structural load-bearing function. This makes it possible to reduce the mass defined as parasitic weight in aviation. The structural battery approach aims to eliminate this weight. Thus, a more efficient mass distribution is achieved throughout the system. Theoretical studies clearly demonstrate the potential of this technology. It is predicted that the battery mass, which corresponds to approximately 10–40% of the aircraft's take-off weight, can be integrated into the structure. With this integration, the flight range can be increased by 11% to 66%. These results show that structural batteries are an important candidate for aviation applications.

The Ragone diagram in Figure 2.11 compares energy storage technologies technologies at the cell level.

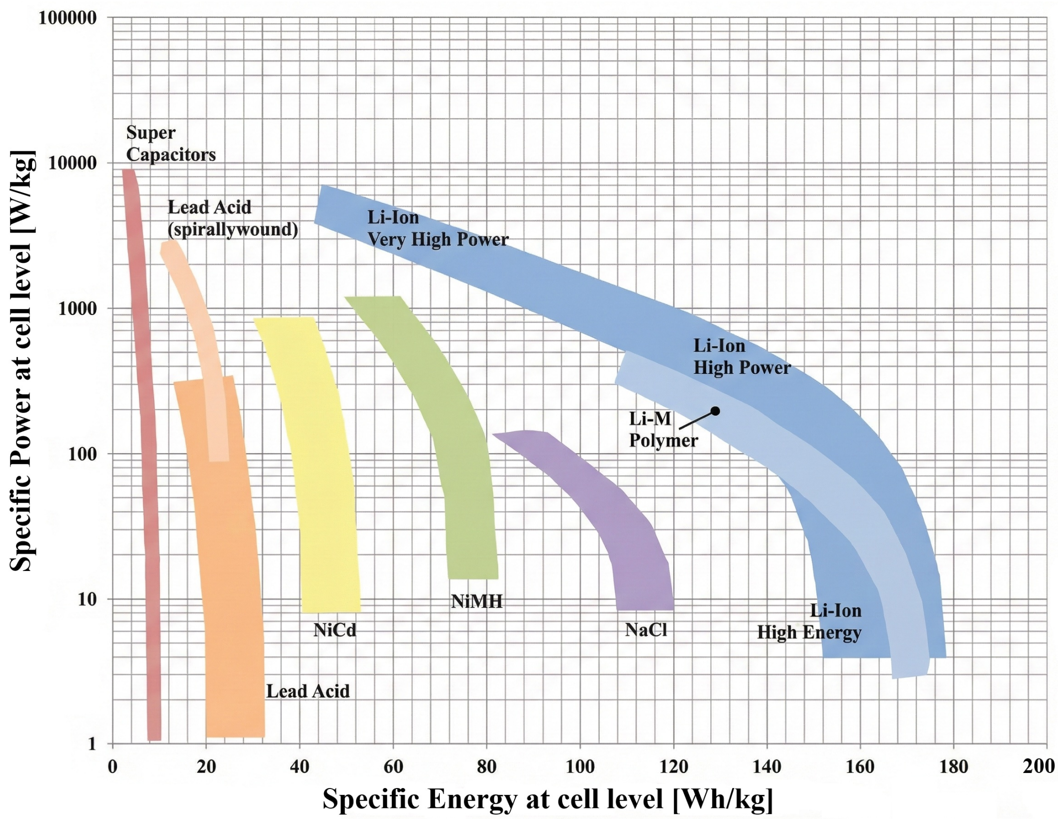


Figure 2.11: Ragone diagram of energy storage systems at the cell level [62].

However, this approach requires striking a balance between the battery's electrochemical and mechanical properties. Electrochemical performance parameters such as energy density and power density are evaluated in this context. At the same time, the mechanical properties of the battery material, such as strength and hardness, are also important. An inevitable trade-off arises between these two groups of properties. Improving one parameter often reduces the performance of another. Therefore, multidisciplinary optimization is required during the design process. Without achieving this balance, structural batteries cannot be used effectively in practical applications.

In light of this information, it is anticipated that structural batteries will mostly be integrated into secondary structural elements in practical applications. This approach is preferred for safety and structural integrity reasons. Fuselage panels are among the suitable areas for this integration. Wing skins are also evaluated in a similar manner. Additionally, cabin floor panels, which have been studied in Airbus A220 aircraft, are cited as examples of such applications. The performance targets set for structural batteries are quite ambitious. A specific energy of approximately 200 Wh/kg is targeted for hybrid-electric aircraft. A specific power value of approximately 120 W/kg is anticipated for these platforms. Higher values are defined for fully electric aircraft. The specific energy target rises to approximately 400 Wh/kg. The specific power requirement is set at 700–800 W/kg. Achieving these targets depends on various conditions. The development of multifunctional materials plays a critical role in this process. Advanced manufacturing techniques must be used. Innovative structural integration methods are also important. The success of research and development efforts in these areas will be decisive [61].

2.2.3 Electric motors

Electric motors are among the main components of electric propulsion systems. They play a critical role in aircraft design, both in terms of propulsion and generator function. The motor power level is decisive. The weight value directly affects the design process. Efficiency shapes flight performance. Reliability is a fundamental requirement for safety. All of these parameters determine the overall performance of electric aircraft. Today, there are prominent types of electric motors in aviation applications. Permanent magnet synchronous motors (PMSM) are included in this group. Brushless DC motors (BLDC) are widely used. Switch-reluctance motors (SRM) are also considered as an alternative option. PMSM and BLDC motors provide high power density. They also offer high efficiency values. For this reason, they are preferred in many prototype aircraft. One notable example in this field is the lightweight BLDC motor developed by Siemens in 2017. This motor has a power output of 260 kW. The motor in question was used in the Extra 330LE aerobatic aircraft. The aircraft flew with a motor weighing approximately 50 kg. This platform reached a speed of 337.5 km/h. This performance was recorded. These results demonstrate the power provided by electric motors per unit mass. Figure 2.12 shows a comparison graph of the efficiency and specific power ratios of different electric motors.

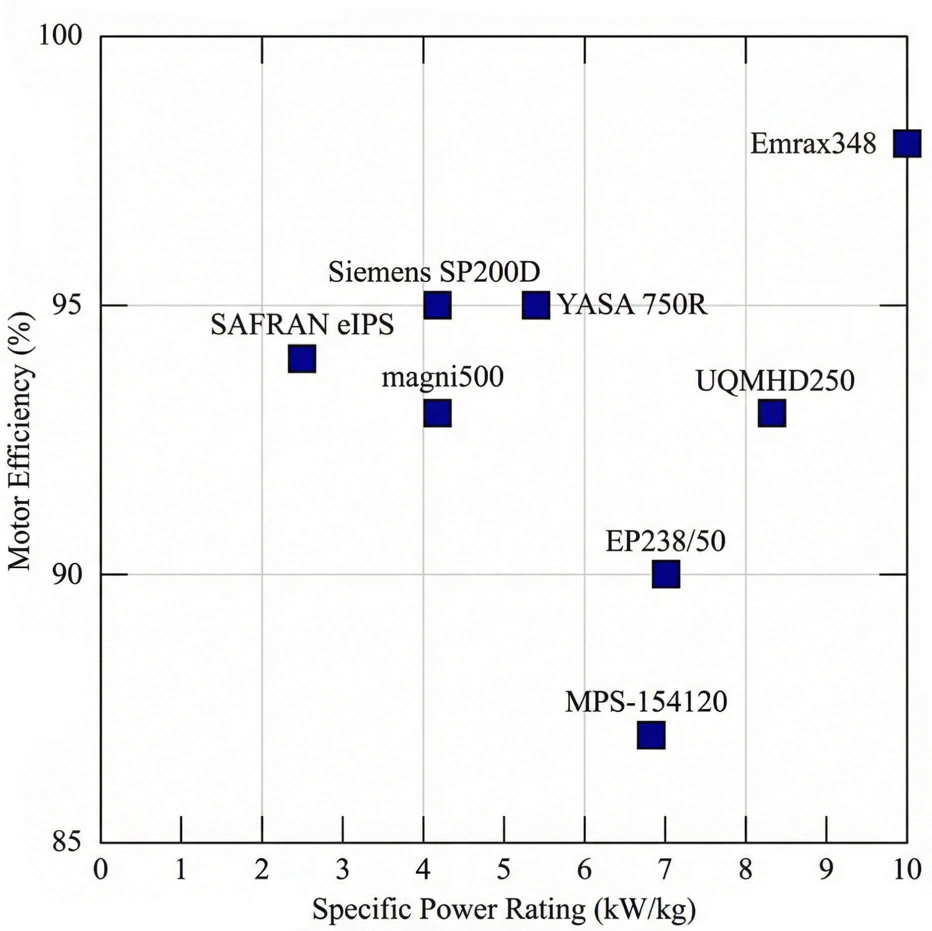


Figure 2.12: Specific power and efficiency comparison of different electric motors [63].

The power density of electric motors can reach levels close to those of internal combustion aircraft engines. The power density of the motor developed by Siemens is stated to be approximately 5.2 kW/kg. This value indicates that it offers performance comparable to that of traditional light aircraft engines. Switched reluctance motors stand out for their unique features. These motors have a simpler structure. They offer high reliability. Their rotors do not contain magnets. This structure enables resistance to high temperatures. Thus, fault tolerance is increased. However, SRM motors have some limitations. Their power density generally remains lower. Their noisy operating characteristic is noteworthy. For these reasons, they are currently preferred more in prototype applications [33].

In the coming period, as other technological developments in the industry advance, the need for megawatt-level electric motors is also expected to increase. Passenger aircraft concepts for the 2030s foresee multiple electric motors, each with a power of 2–3 MW. However, motors of this size are not yet mature in today's technology. The highest motor power currently used in aviation is in the range of several hundred kW. For instance, Magnix's 560 kW motor is undergoing test flights with a Cessna Grand Caravan [63]. To close this technological gap, research is ongoing on high-temperature superconductor motor technology. In superconducting motors, resistance losses are eliminated by using superconducting coils at cryogenic temperatures instead of copper windings. This allows much higher currents to be carried [33].

NASA and various research institutions are developing superconducting motors with approximately 10 MW of power for large passenger aircraft, designed for approximately 2035 and beyond. These motors significantly reduce the weight of standard motors and offer advantages only when evaluated together with the additional weight of cryogenic cooling systems. For instance, NASA's N3-X concept designs 16 superconducting fan motors with a total power of 50 MW. These motors are expected to deliver significant energy efficiency and reduced weight. Electric motors can operate in both directions. An electric motor can switch to generator mode when necessary, converting the mechanical power it receives from the shaft into electricity. This feature is used, particularly in parallel hybrid systems, to recover energy during braking or landing. However, regenerative energy recovery provides limited benefit in aircraft. This is because aircraft typically land in a state of continuous thrust or in a free glide. This feature is evaluated more for testing purposes or in emergency scenarios. Electric motors are also considered an important research topic in terms of flight safety and economics. These two factors are decisive in aviation applications. As a result, electric motor technologies are developing rapidly. This development is progressing in line with the needs of the aviation sector. In the 2010s, power densities of approximately 5 kW/kg were achieved. More ambitious targets are being set for large passenger aircraft. The goal is to increase power density to over 10 kW/kg by 2030. In addition, the aim is to maintain motor efficiency above 99%. New technologies are needed to achieve these goals. The use of superconducting materials is being evaluated in this context. Next-generation semiconductor drivers play an important role. The development of effective cooling methods is also a necessity. The use of electric motors provides significant flexibility in aircraft design. Distributed propulsion systems are noteworthy in this regard. It is possible to use multiple small motors along the wing. This approach offers aerodynamic advantages over traditional single large motor systems. Thrust efficiency is increased through boundary layer interaction. Higher efficiency is achieved thanks to low disk load. Simultaneously, quieter flight conditions are provided. Consequently, advancements in motor technology are not limited to performance improvements alone. These developments are also fundamentally changing aircraft design approaches [37]. Figure 2.13 shows the distributed propulsion architecture of NASA's N3-X aircraft.

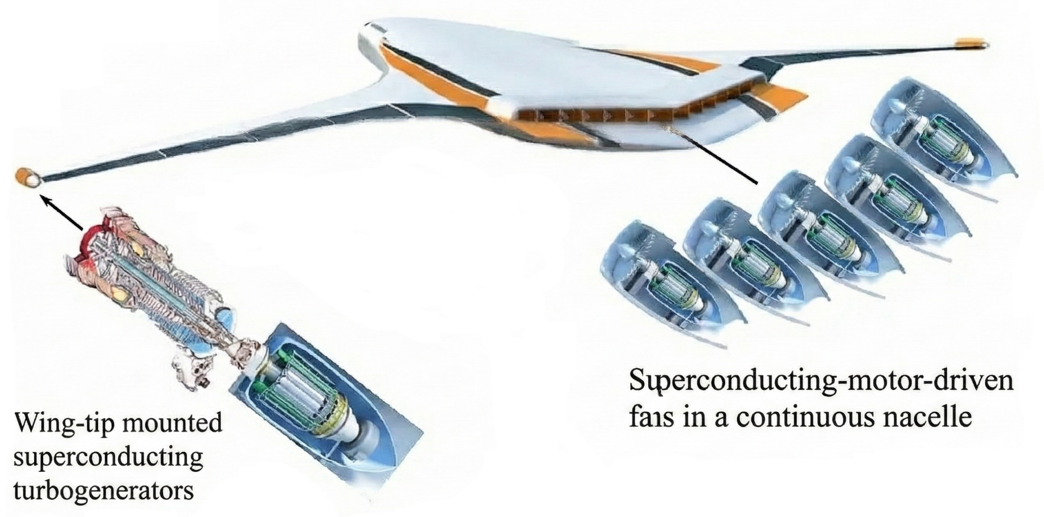


Figure 2.13: NASA N3-X turboelectric distributed propulsion aircraft [64]

2.2.4 Power electronics

Power electronics play a fundamental role in managing energy in electric aircraft. The electrical energy generated or stored in the aircraft is managed through these systems. The energy is converted to the desired voltage and frequency levels. It is transmitted safely to the relevant subsystems. In this process, an uninterrupted and stable energy flow is a critical requirement. Converter circuits, which include inverters and converters, are defined as the main elements of this structure. Semiconductor power switches form the basic building blocks of these circuits. Transistors are included in this group. Diodes and thyristors are also used in these structures. Demanding requirements are defined for power electronics components in aviation applications. These components are expected to operate under high voltage. They must be able to withstand high current levels. At the same time, low weight is an important criterion. High efficiency and reliability are also indispensable requirements in aviation. Traditional silicon-based power switches can be inadequate under these conditions. Performance limitations arise, especially in high-temperature environments. This inadequacy becomes more pronounced in megawatt-level applications. Due to these technical limitations, the use of wide-bandgap semiconductors is becoming widespread. Silicon carbide technologies are included in this group. Gallium nitride-based solutions are also preferred. New-generation transistors can operate stably at high temperatures. Switching losses are reduced in these components. This allows systems to operate at higher frequencies. High switching frequency provides a design advantage. It enables the use of smaller magnetic components. This reduces the physical size of power converters. Total system efficiency is thus increased. Industry roadmaps support this technological direction [65].

One of the most critical power electronics components in electric propulsion systems is defined as motor drive inverters. These inverters are powered by direct current sources such as batteries, fuel cells, or generators. Direct current energy is converted into high-power alternating current waves through these systems. This conversion provides the power supply to electric motors. The output waveform produced by inverters directly affects motor behavior. The control algorithms used are decisive for motor performance.

Therefore, inverter characteristics are of critical importance in aviation applications. Figure 2.14 shows the future prospects for converter equipment.

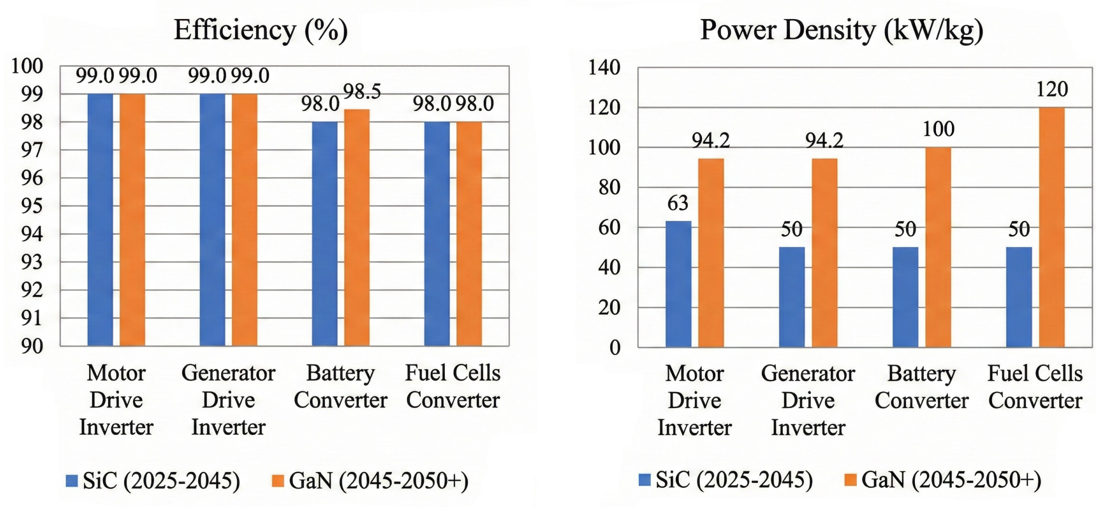


Figure 2.14: Future prospects for converter equipment [66].

Inverters used in aviation are mostly designed in a three-phase full-bridge configuration. Motor torque and speed are adjusted using PWM-based control techniques. Cooling inverters at high power levels is a fundamental requirement. Heat management is critical at this point. Liquid-cooled coolers are preferred for this purpose. Advanced thermal management systems are also integrated into these structures. Among sectoral applications, Boeing's work is noteworthy. Research is being conducted on fully electric regional aircraft concepts. In this context, lightweight inverters are being designed for each motor. These inverters are being developed using silicon carbide-based semiconductors. Calculations show that the total mass of the power electronics in a four-motor system can be kept to a few hundred kilograms. An important limitation emerges when examining the current level of technology. Semiconductor elements capable of continuously switching powers in the order of ten megawatts do not yet exist. This situation is considered one of the fundamental obstacles to scaling up electric aircraft. Efforts are focused on different research areas to overcome these limitations. Series and parallel switch arrays are among these approaches. Superconducting cable and switch concepts are also being explored. Additionally, research continues on advanced thermal materials such as diamond-based substrates. These solutions support the future development of power electronics systems [67].

Power electronics components are not only used in motor drives. These components are found in almost all of the aircraft's electrical subsystems. They have a wide range of applications throughout the system. Rectifiers are used to convert alternating current from generators into direct current. This application is becoming particularly widespread in more electrified aircraft architectures. In this context, Transformer Rectifier Units are preferred in systems. Inverters convert direct current supplied from a battery or fuel cell into alternating current. This energy powers electric motors. Other loads operating on alternating current are also powered through this structure. DC-DC converters ensure voltage level adaptation. The battery output voltage is converted according to system requirements. This conversion allows different voltage buses to be powered. For instance, a 28 VDC avionics bus or a 270 VDC propulsion bus is created in this way. When examining the power systems of electric aircraft, it is observed that the number of converters has increased. This number is higher than that of conventional aircraft. The main reason for this is the placement of a regulation element between each load and the source. This increase directly affects the system architecture. Therefore, the reliability of power electronics components becomes critical. Fault tolerance is one of the fundamental design criteria. System continuity depends on these elements. As a result, developments in power electronics technology play a fundamental role in the implementation of electric aircraft. In particular, the use of wide-band-gap semiconductors has increased since the 2010s. This has increased power density. Significant improvements have been achieved in efficiency values. The technological development process continues today. Solid-state circuit breakers capable of operating at high voltages are being developed. Integrated control systems are being incorporated into this structure. Performance limits are being pushed with high-frequency modulation techniques. Expectations for electric aircraft systems remain high. Motor drivers and other subsystems are evaluated in this context. There is a need for lightweight power electronics components. The development of low-loss and intelligent systems is vital. When evaluating the future vision, a transition to medium-voltage direct current systems is anticipated. Approximately 5 kV is targeted. Academic and industrial studies are shaping up in this direction. Research is ongoing on power transistors capable of operating safely at these voltage levels. Power converter technologies are at the center of this development [21].

2.2.5 Convertors

Electrical converters are functional systems formed by combining the previously mentioned power electronics components. The basic electrical converters used in aircraft include AC/DC rectifiers, DC/AC inverters, and DC/DC converters. AC/DC rectifiers convert alternating current supplied by generators or the ground grid into direct current. This provides the necessary energy flow to charge aircraft batteries or supply DC bus bars. When examining traditional aircraft architectures, it is generally observed that 28 V direct current avionics power is supplied by a 115 V, 400 Hz alternating current system. Transformer Rectifier Units (TRUs) are mostly used for this conversion process. In modern electric aircraft concepts, however, the situation is different. Generator output can be taken directly as direct current or converted to the desired direct current level with high efficiency using semiconductor power converters. DC/DC converters are used to adjust the voltage of direct current sources, such as batteries, to different levels. For example, in a hybrid aircraft system, a 500 V battery pack can be used as a power source. This pack can supply both the 270 V motor bus and the 28 V electronic bus via two-stage DC/DC converters. High-frequency switching techniques are generally used in the design of these converters. Structurally, boost or buck topologies are applied. These circuits, developed for aviation applications, must be highly efficient. Furthermore, the design must demonstrate Electromagnetic Interference (EMI) compatibility. DC/AC inverters convert direct current to alternating current. The converters in electric aircraft architectures are controlled by intelligent power management systems. An intelligent distribution system can change the set points of the converters, taking into account the current flight phase. Furthermore, these systems can supply loads in order of priority or have the ability to instantly reorganize the power transfer path in the event of a fault. As an example of this process, when a fault occurs in the generator, the bidirectional DC/DC converter located between the battery and the generator busbar is activated. This intervention enables the battery to continuously supply critical loads. Effectively managing such situations is crucial. To this end, numerous studies have been conducted in the literature. These studies involve the development of hierarchical control algorithms. At the same time, state monitoring systems are being designed. In addition, the increase in the number of converters in the system brings some technical difficulties. This situation brings the issue of Large Signal Stability to the fore. The stable operation of the aircraft electrical network is critical. Stability must be ensured, especially under non-linear loads. Analysis methods for this issue are found in the literature. Another important consideration for converters is the switching frequency. Waveform optimization is also evaluated in this context. Switching frequencies in the range of several hundred kilohertz enables a reduction in filter size. However, this choice can lead to increased switching losses. Therefore, a more balanced approach is adopted in aviation applications. Frequencies are generally selected within the range of 20 to 50 kHz. This range provides a balance between losses and size. Advanced semiconductor technologies are used to reduce switching losses. Silicon carbide and gallium nitride-based elements are utilized. In summary, converters are considered indispensable components of electric aircraft power systems. The number of these components is greater than in conventional aircraft. Diversity is also increasing similarly. Therefore, the efficiency of each converter is of great importance. The reliability level directly affects the overall system performance [21].

2.2.6 Protection systems and circuit breakers

Electrical protection and safety are critical in aircraft equipped with high-power electrical systems. With the advancement of electrical systems and components, new risk assessments must be conducted. This requirement is becoming even more pronounced for electric aircraft architectures. These risks stem from the nature of high-voltage and high-current levels. Therefore, the safe operation of electrical systems is considered a fundamental design goal. In this context, circuit breakers and protection relays are used as basic protection elements. These components open the circuit in the event of a fault or error. The flow of electricity is thus interrupted. This intervention reduces the risk of fire. The spread of the fault throughout the system is prevented. Equipment damage is avoided. This ensures safe operation in electrical aircraft systems.

Conventional aircraft mostly use mechanical circuit breakers that operate on the thermal-magnetic principle. This design has been considered sufficient for many years. However, the system dynamics of electric aircraft create different requirements. Therefore, existing solutions may be inadequate. Electric aircraft architectures require protection elements that can respond much faster. At the same time, high breaking capacity has become a critical requirement. In this context, solid-state circuit breakers come to the fore. SSCB-based solutions are preferred for electric aircraft systems. Hardware protection alone is not considered sufficient. The integration of software protection systems is also becoming mandatory. This requirement is particularly evident in high-voltage direct current systems. Arc formation in high-voltage DC systems is considered a serious technical problem. This makes it difficult to safely interrupt the current. For example, even in systems at 270 V, a powerful arc can form when the circuit breaker is opened. This arc can quickly transform into a plasma structure with high temperature and pressure. This makes it difficult to extinguish. Fully electric aircraft designs aim for higher efficiency. Higher voltage levels are planned to provide lower current. In this context, the use of systems in the 500-1000 V range is anticipated. Short circuits that can occur at these levels pose serious risks. Arc events become a critical threat to flight safety. Intensive work is underway on high-speed solid-state circuit breakers to reduce these risks. The development of these technologies continues. Solid-state breakers operate on a different principle than classic mechanical breakers. Current control is achieved through semiconductor elements. IGBT and MOSFET-based switches are used in this structure. This allows the circuit-breaking process to be performed in a very short time. The response time can be reduced to less than a millisecond. It is possible to open the circuit before arcing occurs. This feature provides a significant advantage for safe operation in electric aircraft systems [65].

Redundancy and coordination concepts play a fundamental role in the design of protection systems. In the event of a potential aircraft failure, the primary objective is to maintain system integrity. In this context, the failure is prevented from propagating throughout the entire system. In line with this approach, only the faulty section is electrically isolated. The remaining parts of the system continue to operate. To achieve this isolation, protection relays and circuit breakers are arranged in a hierarchical structure. Cascade arrangement is preferred for this purpose. Current and voltage values are continuously monitored throughout the system. This monitoring allows the fault location to be identified. When a problem occurs on the main DC bus, the circuit breakers of the relevant subsystems are opened. This process protects the main line. A similar protection approach is also applied to motor drivers. When a fault occurs in a motor driver, only the power to that line is cut off. The power supply to other motors is not affected by this situation. This structure ensures both flight safety and system continuity [21].

The widespread adoption of power electronics systems has made protection processes more technically complex. To manage this complexity, smart grid protection algorithms are being developed. These algorithms address system behavior in real time. A study in the literature presents a new approach for aircraft electrical grids. The goal is to redirect the power flow in the event of a failure. For this purpose, a finite state machine-based control structure has been designed. With this structure, different operating states of the system have been defined. Analyses have confirmed that critical loads are supplied without interruption. High-power electrical systems also bring new risk factors. Thermal runaway is among these risks. Battery fires also pose a significant safety threat. For this reason, the scope of circuit protection systems is being expanded. Protection is not limited to transmission lines. Battery packs are also included in this protection structure. Lithium-ion batteries are sensitive to certain operating conditions. Overcharging is one such condition. Over-discharging and short-circuiting also pose risks. In such undesirable situations, thermally triggered chain reactions can occur within the cell. This process can result in the battery catching fire. Therefore, the reliability of battery protection systems is critical.

Past events clearly demonstrate the seriousness of these risks. In this context, two separate battery fires that occurred during the entry into service of Boeing 787 aircraft are considered significant examples. These incidents serve as a serious warning regarding flight safety. Following these developments, the Federal Aviation Administration (FAA) temporarily grounded the entire 787 fleet in 2013. This decision highlights the magnitude of the risk. The process that unfolded led to a re-examination of regulations regarding the use of lithium batteries in aviation. In this context, the

FAA published a special certification document coded AC 20-184. This document defines additional requirements for lithium-ion batteries. Under the new regulations, safety testing at the cell level has been made mandatory. These tests ensure a detailed assessment of the battery's behavior. Additional measures regarding the design of battery compartments have also been implemented. The use of fire-resistant insulation has been standardized. The addition of ventilation systems is mandatory. The integration of fire suppression systems is also being evaluated in this context. These requirements must be addressed collectively in electric aircraft designs. The integrated design of battery thermal management and protection systems is mandatory. This approach is considered a fundamental design criterion for ensuring flight safety.

Human safety is considered the primary and fundamental consideration in the design of electrical systems. Safety criteria occupy an extremely critical position in the aviation sector. These criteria must be taken into account at every stage of the design process. High-voltage lines pose a potential risk. This risk applies to both maintenance personnel and passengers. Therefore, it is imperative that high-voltage lines be controlled. To manage these risks, cable routes must be properly insulated. Unauthorized access to high-voltage lines must be prevented. Only authorized personnel are permitted to access these areas. During maintenance activities, the system must be completely de-energized. This procedure is considered a fundamental practice for maintenance safety. The power cut process does not only cover power sources. The controlled discharge of electrical charges stored in capacitors is also included in this process. These measures ensure that maintenance processes are carried out safely. Human safety is preserved as a fundamental design criterion for electrical aircraft systems [31].

In summary, the protection systems used in electric aircraft have a more complex structure than those in conventional aircraft. This complexity stems from the system architecture. Nevertheless, these systems play a vital role in flight safety. Safety requirements in aviation applications are met through these systems. Different protection layers must work together to ensure flight safety. The use of new-generation circuit breakers is becoming mandatory in this context. Intelligent fault detection algorithms must be integrated into the system. Battery safety systems must also work in harmony with these structures. All of these components must be addressed within an integrated protection approach. Current technological developments support this transformation. Prototype solutions have been developed in laboratory environments. Solid-state circuit breakers operating at approximately 1 kVDC are being tested. These breakers have demonstrated a breaking capacity of 1–2 kA [65]. These technologies are expected to mature in the coming years. It is anticipated that the integration process into electric aircraft systems will progress in this direction. Certification authorities are playing an active role in this process. High-voltage test procedures are being developed. Electromagnetic Interference and Electromagnetic Compatibility standards are being updated. New test methods are being defined in this context. Ultimately, the successful implementation of electric aircraft designs depends on an effective protection system. Without reliable and responsive protection structures, the safe operation of these systems is not feasible. Therefore, protection systems are among the fundamental building blocks of electric aviation.

2.2.7 Cabling and distribution network

The generation and storage of electrical energy within an aircraft, as well as its distribution, requires a comprehensive engineering process. The power distribution architecture directly affects aircraft performance. Therefore, distribution systems are considered a critical part of the design. In conventional aircraft, power distribution is typically carried out via 115 VAC and 28 VDC networks. This structure has been used as standard for many years. However, this approach is not sufficient for electric aircraft concepts. Higher voltage levels are preferred. At the same time, more complex distribution architectures are being implemented. The main reason for this trend is the goal of efficiently transmitting high power. When the voltage level is increased, the current value decreases. This reduces the current carried through the conductors. As a result, resistance-related losses are reduced. These losses are expressed as the I^2R term. This approach increases energy efficiency. Cable weights can be reduced. Electric aircraft power distribution systems are being redesigned according to these principles [21].

Among sectoral applications, the Boeing 787 stands out as a notable example. In this aircraft, the main alternating current distribution lines are designed at 230 V. Direct current distribution lines, on the other hand, are implemented at ±270 V. This voltage selection is determined through deliberate optimization. This optimization reduces transmission currents. The reduction in current allows for smaller cable cross-sections. Consequently, weight reduction is achieved across the entire system. In fully electric and large-scale hybrid aircraft concepts, however, different expectations arise. Much higher direct current voltage levels are required for these platforms. Distribution systems reaching 10 kVDC (±5 kVDC) levels are recommended in design studies. Furthermore, NASA studies indicate that voltages in the range of ±4.5 kVDC to 12 kVDC may be necessary. This approach, defined in the literature as Medium Voltage Direct Current, is referred to as the MVDC concept. This architecture offers significant advantages in power distribution systems. It enables the transmission of high power at lower currents. This reduces cable weights and increases system efficiency. For these reasons, MVDC distribution architectures are considered a strategic option in electric aircraft design.

For instance, significant results are being obtained in a study conducted on the STARC-ABL power system at the 2.6 MW level. This study examines the increase in the distribution voltage from 540 V to 4.8 kV. The analyses show that approximately 1.4 tons can be saved in the system's total mass. This result is considered a direct benefit of using high voltage. By opting for high voltage levels, transmission currents are reduced. The reduction in current prevents excessive growth in conductor cross-sections. Consequently, there is no increase in cable weight. This situation clearly demonstrates the advantages of MVDC architectures, particularly for propulsion systems. The weight factor is considered a decisive design criterion in cabling and power-distribution network design. The total length of electrical cables used in an aircraft can reach kilometers. These cables represent a significant load on the total aircraft weight. With the transition to more electric aircraft concepts, a noticeable increase in cable weight has been observed. The Boeing 787 model is a concrete example of this situation. This aircraft uses approximately twice as much electrical cabling as its predecessors. The total cable length reaches approximately 200 km. This value represents a significant additional weight for the system as a whole. With the proliferation of electric propulsion systems, these cable lengths and weights are expected to increase further. Research is being conducted on alternative conductor materials to mitigate this problem. The use of aluminum alloys instead of copper is among these solutions. Carbon nanotube-based conductors are also being investigated. Furthermore, the use of superconducting cable segments in certain applications is under evaluation, and this approach is considered a potential solution [22].

Superconducting cables require cryogenic cooling systems to operate. These cables can carry very high current levels with near-zero electrical resistance. This feature eliminates losses during transmission. Thus, the total weight of the system, consisting of the cable and cooling unit, can be lower than conventional solutions for certain power levels. This approach is being evaluated in advanced concept studies. For example, the NASA N3-X concept plans to implement in-wing power distribution via superconducting cables. This aims to transport high power with low mass. Topology selection is a critical design parameter for the power distribution network. Partitioning strategies also play an important role in this process. Aircraft typically prefer power lines with dual or triple redundancy. This structure increases system reliability. In electric aircraft architectures, power lines carrying energy to different areas can be separated from one another. The power supply for engines located in the nose and tail regions is provided through separate lines within this scope. Furthermore, each power line is designed to be powered by multiple sources. This multi-source and multi-load center structure exhibits a microgrid-like character. Power management systems are at the heart of this structure. The aim is to optimally direct the generated electrical energy to the relevant load areas. Innovative distribution concepts are being developed to achieve this goal. Wavelength-division distribution approaches are among these studies. Direct current buses transferred directly are also being evaluated as an alternative solution.

Cable installations and connection points are subject to strict requirements during the design process. High voltage levels make these requirements even more pronounced. Therefore, cable insulation must be thicker. In some applications, the use of special insulation materials is mandatory. Environmental conditions encountered during flight have a significant impact. Pressure changes affect the cable structure. Wide temperature ranges are decisive for dielectric properties. Vibration loads also directly affect the long-term durability of cables. When these factors are considered together, maintaining insulation performance becomes critical. Rapid switching of high currents can cause electromagnetic interference problems. This poses a risk to the aircraft's sensitive avionics systems. Therefore, ensuring electromagnetic compatibility is considered a fundamental design goal. Shielded structures are preferred in cable routes to manage these risks. Power cables are physically separated from signal lines. This separation reduces electromagnetic interaction. Ferrite core filters are used when necessary. These measures ensure that electromagnetic interference levels are kept under control [31].

Power electronics-induced fast-switching harmonics can cause interference in radio communication and navigation systems. Therefore, specific limit values are defined in the standards applicable to the aviation sector. These limits are applied to ensure electromagnetic compatibility. Safety elements play an important role in the design of electrical distribution networks. Maintenance processes are also considered critical in this context. Carrying high-voltage lines inside the aircraft fuselage requires special precautions. For this purpose, special channels are used for cables. Distance separator structures are also preferred. With these applications, cable bundles are physically isolated. Protecting maintenance personnel from high voltage risks is a fundamental requirement. Various warning systems are defined for this purpose. Safety procedures are standardized. For example, it is verified that energy-storing units are deactivated before maintenance. Batteries and capacitors are included in this scope. Lockout and tagout systems are used for this control. Additional safety steps are implemented before maintenance activities begin and lines are grounded. Accumulated charges in capacitors are discharged in a controlled manner. These procedures are considered mandatory for ensuring maintenance safety. In general, the electrical distribution network and cabling systems are critical components for electric aircraft. The design of these systems is an engineering field that requires careful consideration. An inadequately designed distribution architecture can negate the efficiency gains achieved. At the same time, serious safety risks may also arise. For this reason, current academic and industrial studies focus on specific topics. Optimal selection of distribution voltage is among these topics. Optimization methods aimed at reducing cable weight are being researched. Current limiting systems are also an important topic [21].

3. COMPREHENSIVE ASSESSMENT OF ELECTRIFIED AIRCRAFT

3.1 Enviromental Impact And Life Cycle Assessment

For All Electric and More Electric Aircraft concepts, the storage and utilization of electrical energy within the aircraft are critical issues for making these concepts more feasible and advanced. The battery installed in an aircraft directly affects the most fundamental components of aircraft performance, such as range, operational area, and reliability. Additionally, battery packs used as energy sources increase the weight and volume of the aircraft. Today, the proliferation and increased usability of electric aircraft are linked to the limiting parameters of batteries, such as their specific energy and specific power. This is because the battery chemistries currently used in this field do not yet have the energy densities to meet the long-range requirements of conventional aircraft. Nevertheless, significant advances have been made in battery technology, particularly over the last decade. These developments are making significant contributions to the field of electric aviation. Batteries that are now lighter while storing more energy are also bringing about longer-range and better-performing electric aircraft.

There are battery parameters that determine the battery's characteristics and, therefore, directly affect the aircraft's performance. These parameters encompass chemical and electrical properties, as well as environmental and financial considerations. These are key values that must be taken into account, including specific energy, specific power, specific capacity, charge capacity, speed, cycle life, operating temperature, weight, state of charge, depth of discharge, and cost. In electric aircraft design, the most critical and technical data to be examined in line with the intended use and targeted mission are these battery values.

3.1.1 Gaseous emissions and air quality

All-electric aircraft (AEA) do not produce exhaust-related pollutants during flight. Because they do not use fossil fuels in their propulsion systems. CO_2, NO_x, SO_x, and UHC emitted by conventional turbine engines are not present in electric motor architectures. For example, burning 1 kg of jet fuel results in approximately 3.16 kg of CO_2 emissions. With electric motors, this value is zero. Similarly, electric propulsion systems do not emit NO_x or particulate matter. This eliminates the greenhouse gas effect and the degradation of air quality during flight [68].

Environmental gains are also evident in ground operations. Taxiing and push-back operations performed with conventional engines or diesel vehicles produce significant emissions per passenger. Studies show that taxiing with main engines results in approximately 415 kg of CO_2 emissions. In comparison, when electric taxi systems or electric tow trucks are used, emissions decrease significantly. With these systems, emissions drop to levels of approximately 3.6 kg. The use of electric ground systems reduces emissions in the terminal area to almost zero [69].

However, when assessing the environmental impact of AEA systems, only operational processes are not considered. The source from which energy is produced is also included in the assessment. The method of producing the electricity drawn from the grid to charge the batteries causes indirect emissions. These emissions affect the system's overall environmental impact. Based on current European grid averages, an emission factor of approximately 0.3 $kgCO_2/kWh$ is used. Even under these conditions, AEA systems offer a significant advantage. Despite the carbon load from the grid, a reduction of 50–70% in total emissions can be achieved. This result demonstrates that the AEA concept is an environmentally friendly alternative [68]. Figure 3.1 shows the environmental impacts.

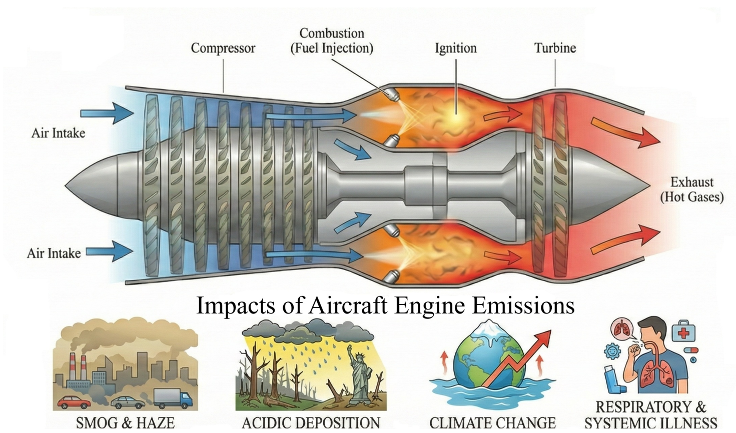


Figure 3.1: Environmental impacts resulting from the use of gas turbines.

3.1.2 Acoustic impact and noise analysis

Electric propulsion systems do not contain the jet exhaust noise or high-speed fan noise components present in conventional gas turbine engines. The electric propulsion architecture has an acoustic profile. The main source of this noise is aerodynamic noise generated by the aircraft's rotor or propeller blades. When comparing a conventional aircraft of equivalent power with a fully electric aircraft in terms of noise, it is seen that the fully electric aircraft has a significantly quieter operation. This is because the mechanical and combustion-related noise found in conventional aircraft is absent in electric aircraft. Simulation and analysis studies conducted by NASA reveal that an electric motor integrated into a Boeing 737-class aircraft reduces noise levels by up to 29 dB compared to traditional turbofan engines. On the design side, Distributed Electric Propulsion (DEP) systems offer advantages. The use of multiple propellers reduces disk loading. Thus, the thrust required by the aircraft is provided at lower rotational speeds. In this case, propeller tip speeds decrease. This allows for the optimization of propeller-wing interactions, improving the noise characteristics [70].

Field tests confirm the theoretical gains. In NASA measurements conducted on the Joby eVTOL platform, the noise level during a cruise flight at an altitude of 500 m was recorded as approximately 45 dBA. This value is almost equivalent to the background noise level in an urban environment. Noise levels measured during take-off and landing phases remain remarkably low [71].

Noise certification in aviation is assessed according to specific international standards. This assessment is carried out in accordance with Annex 16, published by the International Civil Aviation Organization. The Doc 9911 document is also a key reference for this process. Noise performance is expressed in EPNdB using the Effective Perceived Noise metric [72]. At many airports, landing and take-off fees are determined based on these certification results. Aircraft with low noise levels are placed in more advantageous classes. This practice is widely used in airport operations. Fully electric aircraft are rated in the quietest category within these classifications. Their VTOL capabilities and low acoustic emission characteristics support this result. Pilot studies predict a significant decrease in cumulative EPNdB values. This decrease is over 5 dB compared to conventional aircraft. This result demonstrates that electric aircraft offer a significant advantage in terms of noise. This is a critical gain, especially for airports located within cities. Electric aircraft are considered to offer an effective solution for reducing aviation-related environmental noise [70].

3.1.3 Life cycle assessment of systems

Life cycle assessments are considered a fundamental method for evaluating the environmental sustainability of a product or service. This approach ensures that environmental impacts are addressed comprehensively. It is also used to evaluate the environmental performance of fully electric aircraft systems. Fully electric aircraft do not produce direct gas emissions during flight. This feature constitutes a significant environmental advantage. However, it is acknowledged that the environmental impact extends beyond the operational phase. Therefore, all life stages of the system are examined using the Life Cycle Assessment approach. This method analyzes raw material procurement. The production processes of components are evaluated. Logistics and transportation activities are also taken into account. The operational use phase is addressed in detail. The end-of-life phase is also included in the assessment. This scope examines recycling and disposal processes. Thus, the system's total environmental impact is revealed. Comparative analyses are performed based on the results obtained. The environmental impacts of conventional aircraft systems and electrically powered aircraft are evaluated together. These comparisons clearly reveal the environmental advantages and limitations of different propulsion concepts.

3.1.3.1 Raw material supply and production

The production processes for battery cells in electric aircraft have characteristics different from those of conventional aluminum-bodied aircraft. These processes are more complex and involve specialized stages. The refining of critical metals such as lithium, cobalt, and nickel used in battery production is carried out at high temperatures. Special processes are applied during these stages. Chemical processes are also integral to the production chain. Therefore, these production steps exhibit a more energy-intensive structure compared to conventional systems. During these production activities, CO_2-equivalent emissions are released at specific levels. Consequently, the production of battery cells is considered an environmentally burdensome process. A similar situation applies to carbon fiber reinforced polymer structures, which are widely used in aviation. The production of these structures has a high carbon footprint. The literature indicates that this value ranges from 10 to 30 kg CO_2/kg. However, it is possible to supply the electrical energy used in the production processes from renewable sources. This approach allows for a significant reduction in initial emission levels [73].

3.1.3.2 Logistics processes

Supply and logistics stages are critical to ensuring system continuity. These processes must operate seamlessly and without disruption. The stability of the supply chain directly affects system performance. The procurement of necessary raw materials is evaluated within this scope. The procurement of subcomponents is also part of the same chain. These needs are met on a global scale. Transportation activities are carried out by sea. Rail transport is also used in this process. Air transport is preferred for time-critical components. Studies show that this supply chain, when carried out by sea, produces approximately 100 times lower emissions per ton-kilometer compared to air transport. Analyses reveal that air cargo transportation generates approximately 100 times more CO_2 than sea freight transportation. In this regard, optimizing the supply chain in AEA production and opting for sea freight reduces total emissions across the product life cycle [74].

3.1.3.3 Operational use

All-electric aircraft do not produce direct emissions during flight. However, assessing their true environmental impact involves examining and analyzing the entire process. This approach is referred to in the literature as Well-to-Wake. In other words, the analysis includes the whole process from energy generation at the power plant to the moment it powers the aircraft's propeller.

If the electrical energy comes from a system that also uses fossil fuels in its production, such as the European grid, indirect CO_2 emissions continue. This is because carbon emissions actually start at the very beginning of this process. When energy in these production processes is entirely sourced from renewable sources instead of fossil fuels, the carbon footprint is cut in half. All-electric training aircraft, like the Pipistrel Alpha Electro, use approximately 16 kWh per flight. For larger aircraft with more passengers, this can rise to hundreds of kWh. Therefore, as the energy consumption increases, obtaining this energy from clean sources becomes even more essential for reducing emissions [75].

3.1.3.4 End-of-life management, second life and recycling

Electric-powered aircraft consist of numerous battery cells that form battery packs. The life cycle of batteries is not limited to their service life on the aircraft. Aircraft require sudden power demands during certain flight phases, such as take-off. When the capacity of the batteries drops to 80%, they can no longer meet aviation safety standards. However, this does not mean that the battery is completely useless. It can be used in stationary systems such as grid storage or solar power plants. This process is referred to in the literature as Second Life. Evaluating existing batteries delays the need for new production and balances the environmental burden. When the battery or such components reach the end of their useful life, recycling processes come into play. Valuable metals such as Li, Ni, Co, Cu, and Al are separated using thermal processing or chemical separation methods [75]. When these processes are carried out in modern facilities, recovery rates are high. Thanks to the advanced recycling techniques applied, this rate can exceed 90%. The use of recycled raw materials provides significant environmental benefits. This approach reduces the environmental damage caused by mining activities. Pressure on natural resources is also reduced in this way. As a result, the system is evaluated holistically. When the life cycle approach is applied, a clear environmental advantage emerges compared to conventional aircraft. Approximately 50–60% lower CO_2 emissions are projected throughout the total life cycle [76].

3.1.4 Critical raw materials and strategic resources

The life cycle emissions of fully electric aircraft technologies are largely dependent on the critical raw materials used in battery and airframe production. The extraction and processing of these raw materials play a decisive role. These processes directly impact the overall environmental burden. At the same time, the supply chain presents significant environmental and geopolitical challenges. Lithium is a fundamental component of battery chemistry. Together with graphite, it is one of the main elements of the electrochemical structure. Lithium is mostly sourced from saltwater basins in South America. In this context, Chile and Argentina are among the leading supply regions. In addition, hard rock mining is also used in some regions. This method is particularly applied in countries such as Australia. Lithium extraction from saltwater basins is typically performed using the evaporation method. This method causes significant consumption of fresh water in arid regions. This situation disrupts the local water balance and pressure is exerted on ecosystems. Converting lithium into its carbonate or hydroxide form requires additional processing steps. These stages involve chemical processes that require high energy. Performing these processes in fossil fuel-powered facilities increases the carbon footprint. This situation magnifies the environmental impact of battery production.

Cobalt raw material plays an important role in high-energy-density battery chemistries. It is used, in particular, to ensure thermal stability in NMC and NCA chemistries. Cobalt supply is largely sourced from the Democratic Republic of Congo. The limited availability of alternative supply sources creates a negative impact on the supply chain. This concentration increases both environmental and geopolitical risks. Mining activities carried out to extract raw materials have certain environmental impacts. These impacts include serious problems such as acids used during mining mixing with soil and water, and the release of heavy metals. In addition, unregulated mining activities in the region lead to undesirable social and ethical situations. Consequently, all these circumstances are reflected negatively in product life cycle assessments in terms of mineral resource consumption and human toxicity.

Nickel and manganese raw materials are the primary elements that provide capacity in NMC/NCA batteries. Nickel is sourced from Indonesia and the Philippines. Extracting nickel from laterite-type ores involves more complex and energy-intensive hydrometallurgical processes than from sulfide ores. These extraction activities can cause large-scale land use changes, deforestation, and disruption of aquatic ecosystems. Graphite can be obtained through natural mining or synthetic production. China is the main country where natural graphite mining takes place. Synthetic graphite production, on the other hand, requires thermal processing at very high temperatures in an industrial sense. This process requires extremely high energy consumption. Therefore, a significant portion of the total carbon load of graphite is generated at this stage. Energy-intensive production steps significantly increase the environmental impact.

Carbon fiber raw material is used in lightweight composite body structures. This material plays an important role in reducing the structural weight of aircraft. Carbon fiber production stages require very high temperatures. This requirement makes the production process energy-intensive. As a result, the CO_2 equivalent emissions per kilogram of carbon fiber reach tens of kilograms. This production process incurs high environmental costs. However, this cost is offset in the operational phase. Fuel or energy consumption decreases as the aircraft becomes lighter. The energy savings achieved over the operational lifetime amortize this initial burden.

Rare earth elements are among the critical raw materials for motor technologies. Permanent magnets are used in high-efficiency electric motors. These magnets contain elements such as neodymium, praseodymium, dysprosium, and terbium. These elements are decisive in improving motor performance. Processing rare earth elements involves complex procedures. Intensive chemical use is required during the separation and purification stages. These processes lead to the formation of toxic waste. Environmental risks increase during these stages. A large portion of rare earth element resources and processing capacity is located within China. This creates significant dependencies within the global supply chain. The control of strategic raw materials by a single country carries risks. These risks create geopolitical uncertainties for AEA motor manufacturers.

As a result, the supply of raw materials for AEA systems involves multidimensional risks. Water stress is a major problem in lithium basins. There is a risk of ecotoxicity in areas of cobalt and nickel production. In the rare earth elements market, supply monopolies are noteworthy. The high environmental burdens generated during the production of these raw materials should not be overlooked. However, these burdens should not overshadow the zero-emission advantage provided during flight. Therefore, alternative battery chemistries need to be developed. The high-efficiency recovery of critical minerals from end-of-life batteries is crucial for sustainability. At the same time, raw material production and processing facilities must be operated using sustainable energy sources. This approach is decisive in reducing the carbon footprint. This holistic approach strengthens the environmental gains of AEA technologies [77].

3.1.5 Regulations and incentive mechanisms

Various financial policy instruments play a decisive role in the commercialization process of electric aircraft. Carbon pricing mechanisms are among these instruments. Direct R&D grants also constitute an important support element. Investment tax credits help reduce capital costs. These tools support the widespread adoption of aviation electrification. Government incentives play a critical role in the sustainability of carbon reduction targets. For this reason, different incentive models are applied in different geographical regions. These models are shaped according to the industrial capacities of countries. At the same time, climate targets also affect this structure.

The European Union addresses the environmental costs of the aviation sector under the Emissions Trading System. This system directly reflects carbon costs in operations. Free emission allowances provided to airlines during the 2024–2026 period are being gradually reduced. These allowances are expected to be completely eliminated by 2026. This regulation increases the carbon cost per ton for fossil fuel flights. This creates a clear cost advantage for electric flights. The ReFuelEU initiative is being implemented as part of the European Union's Fit-for-55 climate package. This regulation will make the use of sustainable aviation fuel mandatory from 2025 onwards. SAF must be blended into jet fuel at specific ratios. ReFuelEU does not directly target electric propulsion. Nevertheless, it represents a positive step towards reducing carbon emissions. Furthermore, the Emissions Trading System aims to increase SAF production capacity [78].

In the United States, the Inflation Reduction Act of 2022 provides a comprehensive framework for clean energy investments. Under this law, priority in the aviation sector is given to the production of sustainable aviation fuel. Tax credits are provided for SAF production. A direct tax credit for electric-powered aircraft has not yet been defined.

Nevertheless, battery production is supported. Advanced materials technologies are encouraged. Support for charging infrastructure is also provided. These elements create indirect cost advantages for the electric aviation ecosystem.

In Canada, sustainable aviation technologies are supported through direct funding. The INSAT initiative announced in 2023 is an example of this approach. This program aims to develop eVTOL and hydrogen-electric aircraft architectures. To this end, CAD 350 million has been allocated. In addition, the Clean Technology Investment Tax Credit is in effect. This mechanism provides tax credits of up to 30% for clean technology investments. Electric aircraft and battery production facilities are supported under this program [79].

Japan's aviation policies are shaped by its Green Growth Strategy. The country aims to replace 10% of jet fuel with SAF by 2030. Hydrogen and electric-based aircraft projects are encouraged through state-supported R&D grants. There is no specific tax exemption for electric aircraft yet. Nevertheless, the country's general electrification policies create a suitable environment for the development of these technologies [80].

Under Türkiye's current regulatory framework, there are no specific tax breaks for electric aircraft. There is no equivalent in the aviation sector to the incentives provided for electric vehicles in road transport. Fully electric aircraft projects are addressed within the scope of general R&D support. These projects are supported by TUBITAK [81]. The Presidency of Defense Industries also contributes with technology development funds. This support enables the continuation of electric aviation studies.

3.2 Cost Evaluation And Certification Framework

3.2.1 Cost analysis in electric aircraft

Developments in all-electric and hybrid aircraft technologies in the aviation sector bring about many differences and transformations. The global aviation industry must maintain a delicate balance. On one side of this balance are the sector's growth targets. Demand increases are also decisive on this side. On the other side is the 2050 carbon-neutral commitment made as part of the fight against climate change. In this context, the fact that all electric aircraft and hybrid electric aircraft concepts produce zero or near-zero gas emissions during flight provides a significant advantage. However, emission performance is not the only determining factor in this picture. Another fundamental factor that directly affects project sustainability is cost analysis. The production process is being re-evaluated. Operating conditions are being reassessed. The maintenance approach is also changing as part of this transformation. End-of-life recycling processes are similarly being redefined. From an engineering perspective, the benefits provided by a technology alone are not sufficient. The operational conveniences provided are also not the sole determining factor. Financial and economic impacts must be taken into account. This is because these impacts directly shape the project's future. The project's long-term sustainability also depends on these factors.

Therefore, comprehensive cost items are analyzed for all electric aircraft and hybrid aircraft. Production costs are included in this analysis. Ownership and acquisition costs are examined. Operating costs are included in the assessment. Fuel and energy costs constitute a separate heading. Maintenance costs are also addressed at the system level. Infrastructure investments are a critical item in this context. Recycling and scrap costs are also taken into account. These costs need to be analyzed in detail. In addition, dynamic factors affect the cost structure. Technological policy interventions are among these factors. Economies of scale directly change costs. Changes in energy markets are also influential. How these dynamic factors shape the sector's cost structure is a critical issue.

3.2.1.1 Direct operating costs

The economic sustainability of new architectures and concepts developed in the aviation industry is considered a critical issue. This area requires a high degree of precision. Certain fundamental metrics are used to assess an aircraft's economic performance. At the forefront of these metrics are Direct Operating Costs (DOC). DOC is defined as the sum of the direct costs incurred to enable an aircraft to perform its flight operations. This includes fuel or electricity costs. Crew costs are also included in this group. Maintenance and repair activities are evaluated within DOC. Insurance expenses and landing and take-off fees are also included in these cost items. Therefore, mandatory expenses required to keep the aircraft flying are considered within the scope of DOC.

In contrast, Indirect Operating Costs (IOC) cover expenses not directly related to flight activities. Marketing activities are evaluated in this group. The company's management and administrative expenses are also included in IOC. Passenger service costs are included in this category. Airport operating expenses and advertising expenses are also among the indirect costs. Ownership and use of ground service equipment are also among the parameters evaluated under IOC. Figure 3.2 shows the cost structure categories for aviation industry.

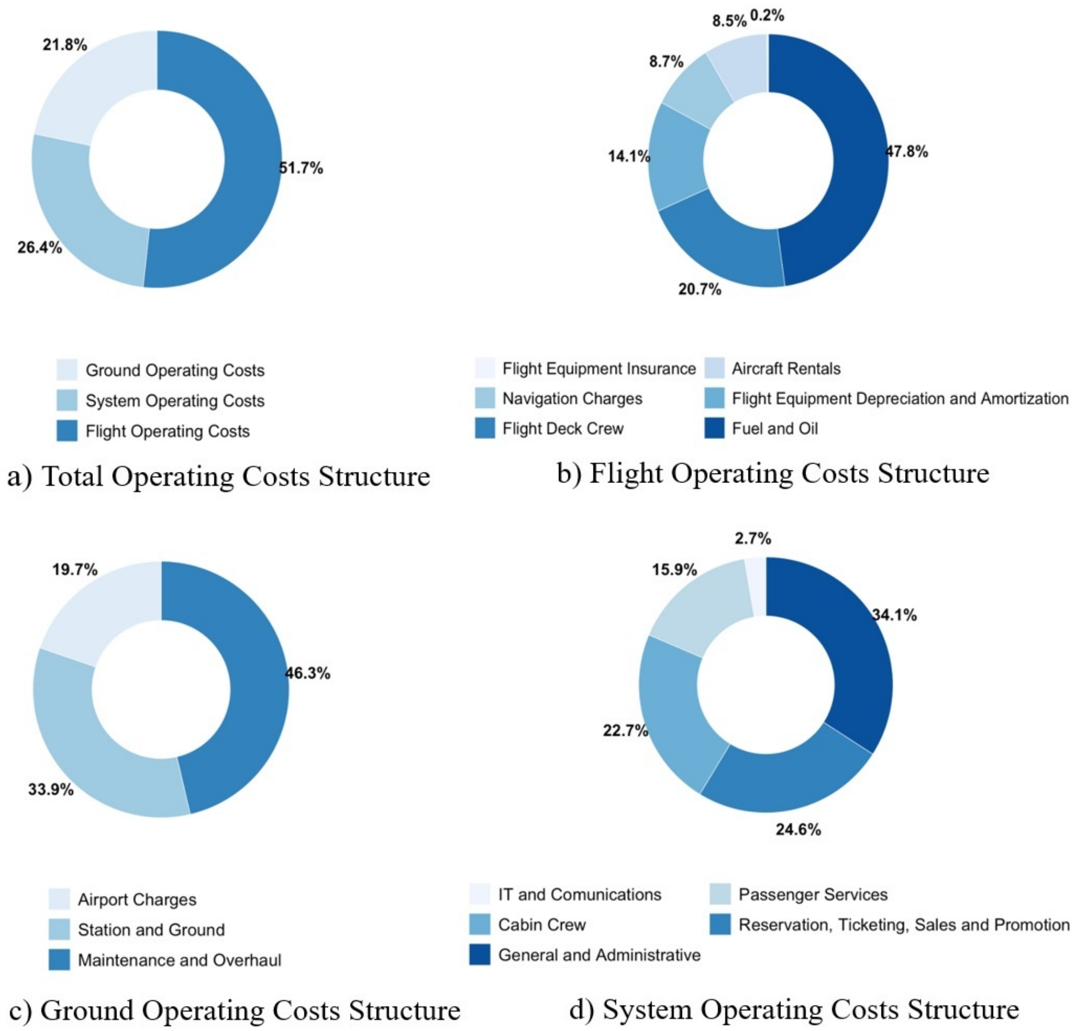


Figure 3.2: Cost structure categories for aviation industry [82].

When considered within the AEA concept, it is evident that changes and innovations are concentrated directly on the aircraft itself and flight operations. Therefore, the most affected cost items arise within the scope of Direct Operating Costs. In line with this approach, DOC components are examined within the framework of the concept. The total weight of the aircraft is a direct determinant of DOC. Aerodynamic efficiency also affects cost analysis in the same way. Fundamental design parameters such as specific fuel or energy consumption play an important role in DOC calculations. These parameters directly shape the aircraft's operational performance. Similarly, electric propulsion systems used in aircraft provide increased efficiency. This creates an advantage in terms of DOC. However, the additional weight of battery systems increases costs. Therefore, in the AEA concept, DOC analysis evaluates both efficiency gains and weight-related disadvantages simultaneously.

DOC analyses are based on conventional aircraft architectures that are widely used in the industry. Evaluations are made based on defined parameters for these aircraft. In this context, the components of fossil-fuel-powered and gas-turbine-based systems are considered from a financial perspective. Fuel consumption, maintenance structure, and engine components form the basis of these analyses. With the introduction of new concepts such as AEA, changes must be made to existing calculation approaches. The addition of new technological components to the system necessitates reorganizing DOC calculations. Therefore, DOC formulations are being revised to accommodate these changes. Electric motors used in AEA systems are considered a critical element. Power electronics components also play an important role in the analyses. The efficiency values of battery technologies are taken into account. Parameters such as battery weight and energy density become decisive for DOC. These components are among the most critical inputs for the analyses. The accuracy of economic analyses depends on certain conditions. Physical flight parameters must be expressed in a manner consistent with financial variables. When this relationship is not established, the reliability of the results decreases. Therefore, it is imperative that the operational dynamics specific to electric aviation are reflected in DOC calculations. From this perspective, cost calculations based on conventional aircraft must be revised to suit the structure of electric aviation [83].

Equation 3.1 shows the equation designed with electric aviation requirements in mind.

$$DOC_{\text{total}} = C_{\text{energy}} + C_{\text{batt\_depr}} + C_{\text{maint}} + C_{\text{nav/landing}} + C_{\text{crew}} + C_{\text{capital}} \tag{3.1}$$

In the fundamental mathematical models in the literature, the US dollar ($) is generally used for cost estimation. In this study, however, the euro (€) is used as the standard currency for all financial parameters. This is because data provided by European authorities, such as Eurocontrol and Eurostat, are used within the scope of the study.

Energy Cost: Energy cost is the economic value corresponding to the total amount of energy expended during an aircraft's flight operations. This cost item is defined as the monetary equivalent of the energy consumed during flight. Unlike the fossil-fuel cost in conventional aircraft, this parameter covers the cost of electrical energy in all-electric and hybrid aircraft. It also includes critical components such as the cost of energy drawn from the grid and electrical efficiency. Energy cost is specified in Equation (3.2).

$$C_{\text{energy}} = \underbrace{\left(\frac{E_{\text{req}}}{\eta_{\text{charger}} \cdot \eta_{\text{grid}}} \times P_{\text{elec}} \right)}_{\text{Electric Costs}} + \underbrace{\left(F_{\text{burn}} \times P_{\text{fuel}} \right)}_{\text{Fuel Cost}} \tag{3.2}$$

C_{energy}	:	Total energy cost (€).
E_{req}	:	Net energy required from the battery for flight (kWh).
η_{charger}	:	Charger efficiency.
η_{grid}	:	Grid efficiency.
P_{elec}	:	Electricity unit price (€/kWh).
F_{burn}	:	Amount of fuel consumed (kg).
P_{fuel}	:	Fuel unit price (€/kg).

When calculating the energy cost of an all-electric aircraft, the product of fuel consumption and the unit fuel price, shown as fuel cost in Equation (3.2), is not included. This is because all-electric aircraft do not consume any fuel other than electrical energy. Grid efficiency is the efficiency coefficient that accounts for losses in transmission lines and transformers during the delivery of electricity from production to the charging station. Similarly, charger efficiency is a coefficient resulting from taking into account the losses incurred in power electronics components when charging the battery with electricity obtained from the grid or a power source. With these parameters included, it is seen that the amount of energy drawn from the grid and stored to charge the battery is a certain amount less than the priced amount of energy. To improve this situation, the efficiencies of the grid and the charger need to be increased.

Battery Depreciation Costs: Unlike conventional aircraft, battery depreciation is a key factor that directly influences operating costs in electric aviation. Battery packs, which are essential components of electric and hybrid aircraft systems, also significantly impact cost analyses. Over time, chemical degradation within the batteries occurs as they are used. Depending on the battery type and its chemical composition, the battery must be replaced after a certain number of charge-discharge cycles. While energy costs in fossil fuel systems are based on the fuel consumed at a specific time, batteries in electric systems have a defined service life.

Therefore, they are reflected in costs as a component that requires periodic replacement. Studies have found that as flight frequency increases, the weight of battery replacement costs in the total DOC increases significantly [84]. Similarly, it is noted that current Li-Ion technologies have a shorter economic life compared to their airframe life [32]. Consequently, it is stated that battery depreciation should be considered a wear-and-tear cost calculated per flight based on the number of cycles and depth of discharge, rather than a fixed expense [85]. Battery depreciation cost is specified in Equation (3.3).

$$C_{\text{batt\_depr}} = \frac{C_{\text{pack}} \times (1 - RV_{\text{batt}})}{Cycle_{\text{life}}} \tag{3.3}$$

$C_{\text{batt\_depr}}$	:	Battery depreciation cost per flight/cycle (€).
C_{pack}	:	Total acquisition cost of the battery pack (€).
RV_{batt}	:	Residual value ratio of the battery.
$Cycle_{\text{life}}$	:	Total cycle life of the battery pack (cycles).

Maintenance Costs: With the transition to fully electric (AEA) and hybrid-electric propulsion systems, aircraft maintenance, repair, and overhaul processes are also changing. Maintenance of conventional aircraft, with their traditional gas turbine engines, is more mechanically focused. In AEA and hybrid platforms, however, the use of high-voltage energy storage systems (ESS), power electronics converters, and electric motors brings with it procedures that are more condition-based. Thus, these maintenance activities focus more on electrical issues, such as monitoring electrochemical aging processes (SOH) in battery cells, thermal fatigue analysis of power switching elements, and maintaining winding insulation integrity. Furthermore, electrically powered aircraft have fewer moving parts than conventional aircraft, which supports this situation. The regular and continuous maintenance of these processes is also critical to the aircraft's airworthiness. To determine the optimal maintenance period, the Renewal Theory has been adopted [86]. In this model, the expected total maintenance cost per unit operating hour is expressed in Equation (3.4).

$$C_{maint}(t_p) = \frac{C_p \cdot R(t_p) + C_f \cdot [1 - R(t_p)]}{\int_0^{t_p} R(t)\, dt} \tag{3.4}$$

t_p	:	Preventive replacement age (flight hours).
$C_{maint}(t_p)$	:	Expected maintenance cost per unit time (€/hr).
C_p	:	Cost of preventive replacement (€).
C_f	:	Cost of failure replacement (€).
$R(t_p)$	:	Reliability function at time t_p.
$1 - R(t_p)$	:	Cumulative probability of failure by time t_p.
$\int_0^{t_p} R(t)\, dt$	:	Expected mean cycle length (hours).

Navigation and Landing Costs: In modeling aircraft operating costs (DOC), one key dynamic variable is task-based cost items, which include navigation (C_{nav}) and landing ($C_{landing}$) fees. In the literature, the C_{nav} parameter is defined as the cost of using ground-based services such as air traffic control (ATC), communications, and meteorology. ICAO standards are used as the basis for calculating this cost [1].

According to the Eurocontrol methodology, which is valid for European airspace and accepted as a reference in academic studies, navigation costs are directly linked to the distance traveled and the aircraft's Maximum Take-off Weight (MTOW) [82].

This relationship is shown in Equation (3.5) below.

$$R_c = t_r \cdot d \cdot \sqrt{\frac{MTOW}{50}} \tag{3.5}$$

R_c	:	Total route charge (€).
t_r	:	Unit rate (€).
d	:	Distance factor (Great Circle Distance / 100 km).
$MTOW$	:	Maximum Take-Off Weight (metric tons).
$\sqrt{\frac{MTOW}{50}}$	:	Weight factor.

The distance factor in the Eurocontrol equation does not reflect the actual distance flown by the aircraft. It is based on the theoretical shortest distance between airports where take-off and landing occur, known as the great circle distance which shown in Figure 3.3. This also represents an advantage for the airline company. This is because fees are charged based on the theoretically shortest distance. The reflection of the weight factor in the cost using the square root shows that the cost increase for heavy-tonnage vehicles continues in a damped, non-linear manner [82].

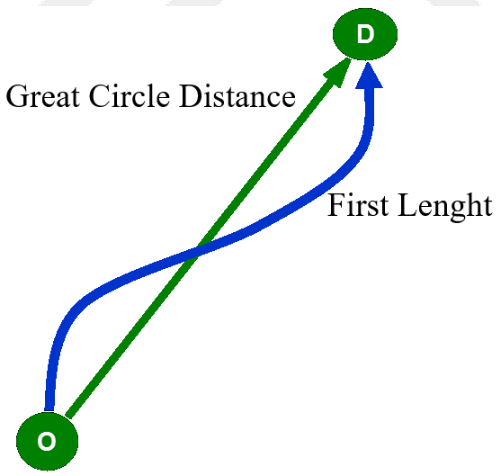


Figure 3.3: Comparison of great circle distance and actual flight path [82].

In this context, the aircraft designed with an electric propulsion system faces the risk of incurring higher operating costs than its conventional competitors due to the additional weight of the battery packs. However, the low noise level and zero-emission profile of electric motors provide significant incentives and discounts for noise-based landing fees ($C_{landing}$) [83]. A current example of this situation is that the Swedish airport authority, Swedavia, is moving towards completely eliminating landing fees for electric aircraft or applying significant MTOW-based exemptions in order to promote fossil-free aviation. Such incentive mechanisms are among the most critical external factors positively changing the operational cost balance of electric aircraft [87].

Crew Costs: With the all-electric aircraft , the complex power management procedures found in conventional aircraft are becoming much simpler. This further eases the complicated, relatively difficult structure that the crew must control. The single-lever power management and high torque sensitivity provided by electric motors are examples of this. The operational workload in the cockpit is reduced compared to that in conventional systems [88]. This technical benefit underpins the concept of Simplified Vehicle Operations (SVO) for the aviation industry. It also makes single-pilot operation certification processes more achievable in the General Aviation and Urban Air Mobility (UAM) sectors. Compared to traditional systems, crew training costs for electric-powered aircraft can be lowered due to this simplicity [83].

Considering all these parameters, only the pilot's salary expenses should not be taken as the basis for crew costs. Components like unique procedures enabled by electric propulsion systems and battery management capabilities are also considered in the cost analysis. Based on this evaluation, the following Equation (3.6) is defined.

$$C_{crew} = \frac{N_{crew} \cdot [S_{base} \cdot (1 + K_{burden}) + C_{HV\_cert}]}{AH_{annual}} \tag{3.6}$$

C_{crew}	:	Crew cost per block hour (€/h).
N_{crew}	:	Number of required pilots.
S_{base}	:	Annual base salary per pilot (€).
K_{burden}	:	Employment burden factor.
C_{HV_cert}	:	High Voltage certification training cost (€).
AH_{annual}	:	Annual block hours (h).

Unlike conventional aircraft, electric-powered aircraft require specific training on high-voltage safety and battery thermal runaway management. Therefore, this is added to the cost analysis. In addition, the low vibration and noise levels in AEA systems minimize pilot fatigue. This allows daily flight hour limits to be used more efficiently [89].

Capital and Ownership Costs: The capital and ownership costs are determined by analyzing the depreciation of the aircraft's purchase price, insurance expenses, and financing interest rates, converted into operational hours. For conventional aircraft, these costs are assessed as a single item, including the fuselage and engines. However, this approach isn't directly applicable to an all-electric aircraft because the economic life of the aircraft's battery systems differs from that of the fuselage. Since battery packs need to be replaced much more frequently than the fuselage, the concept of Battery Excluded Ownership Cost is used [90].

Furthermore, battery depreciation is not included in the capital cost because it is assessed separately. Other key components, such as the aircraft fuselage, electric motor, and avionics systems, are part of this model. Electric motors have fewer parts than traditional gas turbines, which benefits initial production costs. However, adding advanced technological and power-electronics components increases R&D and initial investment expenses [89]. The ownership cost can be calculated using the Equation (3.7) below.

$$C_{capital} = \frac{(1 - r_{res}) \cdot P_{ac\_no\_batt}}{DP \cdot AH_{annual}} + \frac{P_{ac\_total} \cdot (K_{ins} + K_{int})}{AH_{annual}} \tag{3.7}$$

$C_{capital}$	:	Capital cost per block hour (€/h).
$P_{ac\_no\_batt}$	:	Aircraft price excluding battery pack (€).
P_{ac_total}	:	Total aircraft price including battery system (€).
r_{res}	:	Residual value factor.
DP	:	Depreciation period for airframe (years).
K_{ins}	:	Annual hull insurance rate.
K_{int}	:	Annual interest or finance rate.
AH_{annual}	:	Annual block hours (h).

In this analysis, when calculating $C_{capital}$, battery depreciation (C_{batt_depr}) is treated as a separate cost item due to the short cycle life of the battery system. Therefore, the body depreciation calculation is based on the cost excluding the battery ($P_{ac\_no\_batt}$).

However, insurance and financing costs are addressed in accordance with the principle of asset integrity. Therefore, calculations are based on the total aircraft cost (P_{total}) [83].

In the depreciation (DP) calculation, $P_{ac\_no\_batt}$, which is the aircraft price excluding the battery, is used for DP. In contrast, (K_{ins}), the insurance cost, is calculated using the total aircraft price P_{ac_total}. This approach is based on the fact that the battery's depreciation structure is independent of the aircraft. The depreciation cycle for the battery is calculated separately under (C_{batt_depr}). However, in the event of an accident, the insurance coverage extends beyond the airframe. All aircraft components, including the battery, are covered by insurance. Therefore, the total aircraft value is used as the basis for insurance and financing calculations.

3.2.2 Certifications

The aviation industry is undergoing a transformation from fossil fuel-based conventional aircraft systems to electric and hybrid propulsion architectures. This transformation process represents a structural change in the sector. At the same time, it gives rise to new and critical requirements. In this context, it is not sufficient to merely develop the innovative aircraft that are designed and converted. The successful completion of the production processes alone is also not considered sufficient. The aircraft in question must be officially included in flight operations. Completing the certification and operational suitability processes is mandatory. However, social acceptance also stands out as a decisive factor. The reliability and safety of new propulsion architectures must be embraced by the public. Without these elements, the widespread and sustainable implementation of electric and hybrid aircraft concepts is not possible. To ensure this, the aircraft's airworthiness must be certified by independent authorities. In this way, aircraft meet the necessary certification requirements and are recognized by independent authorities.

Traditional certification processes, based on conventional aircraft, cannot fully meet today's technological requirements in some areas. This is because these processes are designed around metal fatigue and piston engine data, as applied to conventional aircraft. With the transformation of aircraft, structural changes are needed to manage new-generation risks such as high-voltage battery packs, distributed electric propulsion systems, and complex autonomous software. In this context, the modern certification process requires mathematical and physical proof that an aircraft can safely terminate its operation without endangering passengers and people on the ground, even in critical scenarios such as engine failure or battery fire. The European Aviation Safety Agency and the Federal Aviation Administration, two of the most important international authorities in this field, require these vehicles to meet a safety standard equivalent to commercial aircraft, with one accident per billion flight hours (10^{-9} risk level) [91,92]. In the future, global harmonization of certification processesis deemed necessary. This harmonization constitutes a critical threshold for the sector's sustainable growth. The establishment of a common framework among regulatory authorities is the target. This situation directly affects product development and market entry processes.

Deficiencies or inadequacies may arise in certification processes. In such cases, risks that could lead to catastrophic consequences in electric aviation may emerge. Managing these risks is imperative. Electric aircraft have a different structure from conventional aircraft. In electric aircraft, the batteries, which are the energy source, and the power transmission components are more closely integrated. This integrated structure can accelerate fault propagation. Therefore, design limits must be clearly defined. A high-voltage architecture that is not designed in accordance with standards poses a critical problem. Pressure drop is possible at high altitudes. With the pressure drop, insulation properties may weaken according to Paschen's Law. This weakening can lead to uncontrolled arcing. Partial discharge events may occur in this context [93]. The occurrence of such an event can have serious consequences for the power system. Complete loss of the power system may occur. A fire risk may also arise at the same time. Therefore, safety margins must be correctly determined in high-voltage design. In addition, power electronics components constitute a different risk area. Electromagnetic interference (EMI) may occur due to switching frequencies. This interference may not be filtered correctly. In such a case, EMI may affect the aircraft's avionics systems. The operation of flight equipment may be disrupted. Situations resulting in the loss of control of critical equipment may arise. In this context, certification is not viewed merely as a bureaucratic approval process. Certification is considered an engineering process that defines the safe limits of the design. The goal is to prevent chain reactions such as thermal runaway. At the same time, the necessary safety infrastructure is being established for the commercialization of the technology. Certain references are used to achieve these safety goals. Basic regulations are referenced in the design, testing, and approval processes for electric and hybrid aircraft.

Technical standards are also taken as a basis in this process. The basic regulations and standards used in this context are listed below.

• **EASA SC-VTOL (Special Condition for VTOL):** It has been determined by EASA, the competent authority in Europe. A specific regulatory framework is being established for vehicles capable of vertical take-off and landing. This framework specifically covers eVTOL aircraft. The aim is to define binding safety criteria for systems to be used in urban air transportation. In this context, a safety level called Category Enhanced is being adopted. This level involves very strict safety targets. One of the most fundamental requirements defined is the fail-safe approach. According to this approach, a single component in the system may fail. In such a case, the aircraft must be able to continue its flight safely. This condition is considered mandatory to ensure an acceptable level of risk in urban air operations [9].

• **FAA 14 CFR Part 21.17(b) (Special Class - Powered Lift):** It has been determined by the US regulatory authority, the FAA. eVTOL aircraft are evaluated under a special class called "Powered-Lift." This classification is based on the assumption that these vehicles have different characteristics from conventional aircraft and helicopter structures. In this context, a separate G-1 Issue Paper is published for each eVTOL model. This document defines the certification requirements. The rules are re-established specifically for the relevant aircraft. This approach provides manufacturers with a degree of flexibility in design and architectural preferences [94].

• **14 CFR Part 23 Amendment 64:** This regulation represents a significant change in small aircraft certification. Certification rules are no longer defined prescriptively. In other words, designers are not directly told which solution to implement. Instead, only the required safety levels are defined. The methods for achieving these safety targets are not specified. The technical approach to be used is left to the manufacturer. This structure introduces a performance-based certification approach. Design flexibility is thus increased. It becomes possible to develop innovative and original aircraft architectures. This facilitates the integration of new technologies into certification processes [95].

• **EASA MOC-3 SC-VTOL (Battery Safety):** This standard is considered one of the most critical regulations for battery safety. It accounts for the possibility of a fire in a high-voltage battery cell. In such a case, the fire must not spread to adjacent cells. This requirement is referred to as non-propagation. In addition, toxic gases that may be produced during battery failure must not enter the cabin. The gases produced must be directed outside the aircraft in a controlled manner. It is not sufficient to define these safety conditions only theoretically. It is mandatory to verify the relevant conditions through physical tests [96].

• **EASA SC E-19 (Electric Propulsion Systems):** Under this standard, electric motors, propellers, and drive units are no longer considered separate components. These subsystems are treated as an integrated motor system. The certification approach is based on this integrated structure. The system's resistance to sudden power changes is examined at the system level. Transient loads and sudden torque changes are evaluated within this framework. Electrical and mechanical interactions are considered together. Heating behavior is tested based on this holistic structure. It is verified that thermal limits are not exceeded. Similarly, vibration tests are also applied to the integrated motor system. These tests prove structural integrity and operational reliability [97].

• **RTCA DO-311A (Rechargeable Lithium Battery Systems):** It is accepted as the basic reference for batteries used in aviation. It includes minimum performance tests, such as shock, vibration, and short-circuit. These tests aim to verify the battery's basic safety level. However, this test set alone is insufficient for electric aircraft applications. The high energy density and system integration of electric propulsion systems create additional risks. Therefore, additional safety requirements must be defined. In this context, special conditions such as MOC-3 are implemented. This approach is considered necessary to ensure adequate battery safety in electric aircraft [98].

• **MIL-STD-704 (Aircraft Electrical Power Characteristics):** This regulation is essentially defined as a military-origin standard. It is widely referenced for power quality assessments in electric aircraft. Voltage limits are clearly defined within the scope of the standard. Sudden voltage changes and transient fluctuations are also addressed within this framework. The acceptable ranges for electrical supply conditions are determined. This approach ensures the safe operation of equipment on the aircraft. The goal is to prevent systems from losing their functionality even in the presence of voltage fluctuations. Thus, power quality and system reliability are ensured together in electric aircraft [99].

• **ASTM F3338 (Electric Motor Design Specification):** This standard has been prepared by the industry for general aviation engines. It is considered an acceptable compliance method by the regulatory authority. It serves as a reference document in certification processes. The standard provides guidance on defining engine performance limits. It explains the principles for determining torque limits. It outlines how engine speed limits should be defined. Methods for determining temperature limits are also included in this scope. This approach clearly defines the safe operating ranges of engines. Performance and endurance requirements are established within a consistent framework. This provides a common technical basis for design and certification processes [100].

• **SAE AS7499 (High Voltage DC Power Quality):** This regulation defines high-voltage direct current (HVDC) networks used in aircraft. It establishes the technical limits for the electrical distribution architecture. High-altitude conditions are specifically taken into account. As altitude increases, air density decreases. This situation increases the risk of arcing. This risk is evaluated within the framework of Paschen's Law. In this context, voltage stability is considered a fundamental requirement. The aim is to control electrical discharges. Design principles for preventing arcing are established. This ensures the safe and stable operation of HVDC networks [101].

• **SAE ARP 60493 (Electromagnetic Compatibility - EMC):** This standard addresses electromagnetic noise emitted by inverters driving electric motors. High-frequency interference may occur during inverter operation. This interference can adversely affect the aircraft's communication and navigation systems. The electromagnetic noise in question can cause distortion in communication signals. This situation is not acceptable from a flight safety perspective. Therefore, the relevant standard aims to control this risk. The standard defines the necessary shielding methods. Protection approaches to be applied at the cable and equipment level are specified. Filtering techniques are also discussed in detail. These measures limit the impact of inverter-generated noise on the systems [102].

4. TECHNICAL FEASIBILITY, COST ANALYSIS, AND ENVIRONMENTAL IMPACT OF SMALL AIRCRAFT ELECTRIFICATION

[1]

This chapter details the transformation of the Tecnam P2008 JC model aircraft into a fully electric aircraft concept. The study's main objective is to integrate an electric motor-driven propulsion system instead of the existing internal combustion engine-based propulsion system of the aircraft using lithium-ion batteries. Although this study focuses on the Tecnam P2008 JC conversion, the systematic methodology developed herein is inherently generalizable, providing a scalable framework applicable to the integration of electric propulsion systems in a wide range of aircraft. Within this framework, the aircraft's electrical system components are designed by considering the energy density, capacity, and performance characteristics of the battery systems. Critical components such as batteries, electric motor, and converters have been analyzed and selected in the conversion process. Depending on the battery parameters, the energy consumption of the aircraft across different operational flight profiles is modeled. Also, within the scope of the range analysis, the energy density, charge-discharge cycles, and weight performance of the batteries were evaluated; in addition, the contribution of post-conversion energy consumption to fuel costs, operational efficiency, and environmental impacts was analyzed. In this study, the dynamic behavior and flight profile-based energy consumption of the electric propulsion system redesigned for Tecnam P2008 JC aircraft are investigated by simulations in the Matlab/Simulink environment. For modeling and simulation studies, the "Electrical Component Analysis for Hybrid and Electric" [103] model prepared by Mathworks was used with necessary revisions.

[1] This chapter is based on the following published article: E. Ozkar and I. Genc, 'Electrification of a Small Aircraft: Technical Feasibility, Cost Analysis, and Environmental Impact," *International Journal of Aviation Science and Technology*, vol. vm07, pp. 35-47, 2025

In parallel, during the conversion process, the existing structural features of the aircraft were kept faithful, and structural modifications were avoided. This necessitated working within certain weight and volume constraints in the system design and required optimizing the design parameters to be compatible with these constraints.

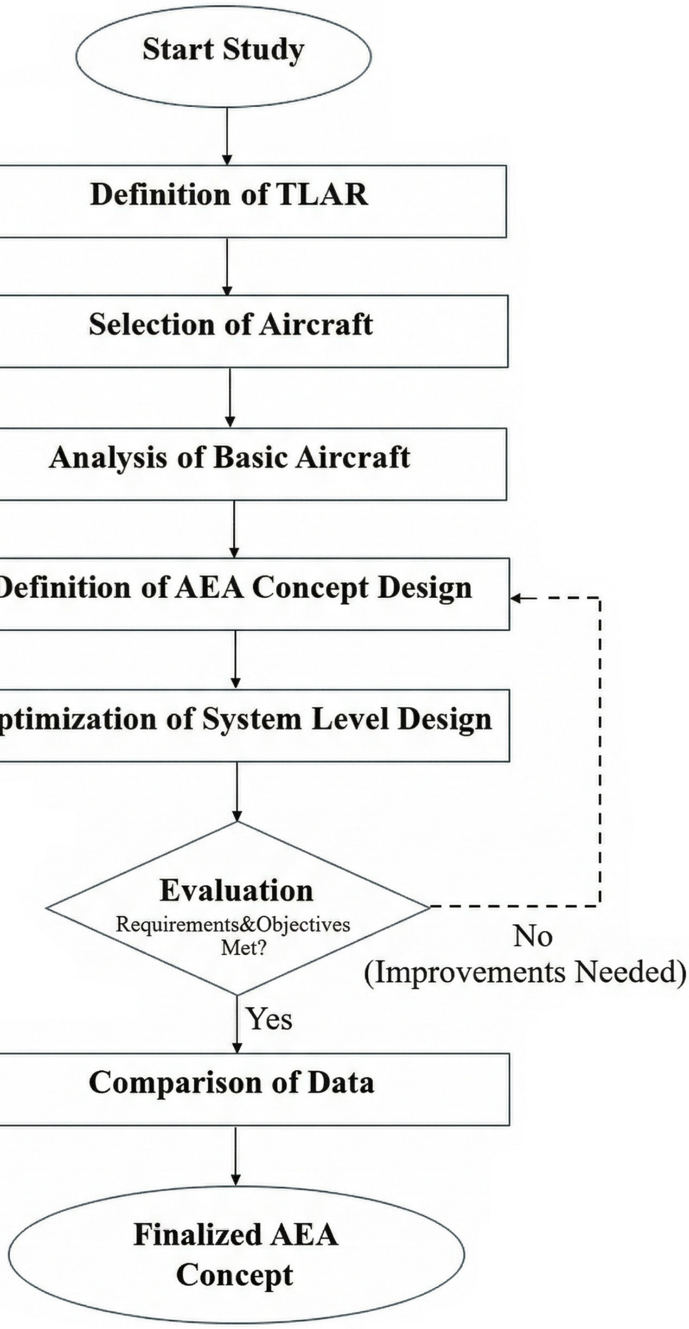


Figure 4.1: Methodological process flowchart of the study.

As a result, the developed methodology represents a systematic framework for in-depth analyses of the engineering and operational performance of electric aircraft and provides baseline data for future electric aviation concepts by assessing the feasibility of lithium-ion battery-based systems. The methodological process of the study is summarized in the flow chart presented in Figure 4.1. Each step indicated in this flow chart has been systematically implemented throughout the study.

Definition of TLAR defines the top-level requirements for which the objectives of the system are defined during the aircraft design process. Top-Level Aircraft Requirements (TLAR) are generally composed of performance requirements, environmental requirements, economic requirements, and regulatory and certification requirements categories. At the end of the study, the requirements are observed by comparing the data of the retrofitted aircraft and the basic aircraft to be analyzed. Selection of Aircraft represents the process of selecting the aircraft that will be analyzed and used as the primary reference in this study. At this stage, special attention must be given to ensuring that the technical documents and aircraft specifications are openly available. To obtain simulation results that are as realistic and accurate as possible for the basic aircraft, reliable and detailed technical data must be utilized. Analysis of Basic Aircraft refers to the examination of key technical characteristics such as the performance, weight-load distribution, and powerplant specifications of the selected basic aircraft. In this context, the basic aircraft's weight breakdown, maximum take-off weight, and other aerodynamic parameters are thoroughly analyzed. The analyses conducted here outline a framework that must be considered in the continuation of the study. Definition of AEA Concept Design defines the transformation of the basic aircraft into an all-electric aircraft concept. The components and systems that will be removed from the conventional aircraft and those that will be integrated to convert it into an all-electric aircraft are identified. The trade-off process is managed. A flight profile is planned based on the redesigned characteristics and parameters of the basic aircraft. Within this flight profile plan, battery and power analyses of the aircraft are conducted, and the suitability of its electrical components is examined. Optimization of System Level Design refers to system-level optimizations performed on the redesigned aircraft to achieve the desired outcomes in line with the targeted objectives. Simulation and analysis results are evaluated according to the defined design requirements. Accordingly, necessary improvements are made to meet operational and performance targets, ensuring the expected outcomes are achieved. Comparison of Data concludes the study by conducting a comparative analysis of the results obtained from the simulations and analyses. At this stage, for both aircraft configurations, the advantages and disadvantages are identified with a particular focus on weight breakdown, greenhouse gas emissions, and energy consumption costs, and their environmental and economic impacts are assessed. Finalized AEA Concept represents completing the AEA concept development process, including the systematic revision of the basic aircraft, simulation and analysis evaluations, optimization and improvement efforts, and the comparative assessment of the obtained data. The final design presents an applicable roadmap for the transition to electric aviation, offering enhanced operational efficiency, energy consumption, and environmental sustainability solutions.

4.1 Aircraft Selection

In the scope of the study, the Tecnam P2008 JC aircraft was selected as the basic aircraft, and its transformation to the AEA concept was examined. The selected aircraft model is single-engine and belongs to the light sport category. Figure 4.2 shows the selected aircraft model. Its maximum take-off weight, structural architecture, and materials make it suitable for electrical conversion and integration. It is widely preferred for training, observation, and personal use. In this way, it allows the testing of different flight profiles and usage scenarios and analysis of flight simulations. After the AEA concept transformation, it provides technical and economic benefits by providing a safe and economical flight with battery integration. In addition, the fact that aircraft parameters, which are important for analysisand simulation studies, are accessible and open source contributes to the future of engineering studies. Using direct and real aircraft parameters allows the analysis results to be evaluated close to reality. While examining the conversion process to the AEA concept, equipment changes and integration were made at the system level.Since the Tecnam P2008 JC is not widely used in academic studies, this study provides a new perspective for analyzing a different aircraft model and the applicability of the AEA concept.

Table 4.1, Table 4.2 and Table 4.3 below provide the actual weight-load, performance, and powerplant specifications of the basic aircraft.

Figure 4.2: Tecnam P2008JC aircraft [104].

Table 4.1: Weight–Loads specifications [104].

Parameter	Value	Unit
Maximum Take-off Weight	650	[kg]
Empty Weight	418	[kg]
Useful Load	232	[kg]
Baggage Allowance	20	[kg]
Fuel Tank Capacity	123	[L]

Table 4.2: Performance specifications [104].

Parameter	Value	Unit
Maximum Cruise Speed	116	[kts]
Rate of Climb	755	[ft/min]
Take-off Run	699	[ft]
Landing Run	568	[ft]
Range	800	[nm]

Table 4.3: Powerplant specifications [104].

Parameter	Value	Unit	Fuel Type
Engine Power	100	[HP]	–
Fuel Consumption	17	[L/h]	Mogas and Avgas

4.2 All Electric Design Modifications

One of the most important parameters to consider when converting an aircraft to all-electric propulsion is the weight constraints. In electric propulsion, battery packs are used as an energy storage system. A DC/DC converter can be integrated into the system to increase the battery packs' DC output voltage and regulate the electric current. The power transmission management is provided by a DC/AC inverter, which controls the magnitude and frequency of the output AC voltage based on the position or speed feedback of the motor. The electric motor drives the propeller by converting the AC electricity received through this inverter into mechanical energy. An intermediate gearbox between the motor and the propeller reduces the high rotational speed of the motor when necessary, increasing the torque transmitted to the propeller and improving the overall efficiency of the system. In Figure 4.3, the modification of the basic aircraft can be seen.

Figure 4.3: Schematic modeling of the Tecnam P2008 JC Aircraft's all-electric propulsion system.

The design requires a comprehensive evaluation of all engineering parameters as well as optimization of key components such as weight and energy storage systems. When evaluated inan interdisciplinary approach, the performance characteristics of electrically powered propulsion systems allow both the elucidation of the origins of current technological challenges and the development of a systematic methodology that can be used in future applications [105].

4.3 Analysis of Retrofitted Aircraft Systems

4.3.1 Battery system sizing

Since the battery system design is the direct energy supply unit in all-electric aircraft, it must be realized ina way that fully meets the energy and power requirements of the aircraft within the planned flight profile. The energy consumption, weight, maximum and continuous power requirements, specific energy capacity (Wh/kg), and specific power capacity (W/kg) ofthe battery are the most basic parameters to be considered in the study for the selection of a suitable battery together with the planning of the intended use and range of the designed aircraft. Figure 4.4 shows a typical flight profile diagram.

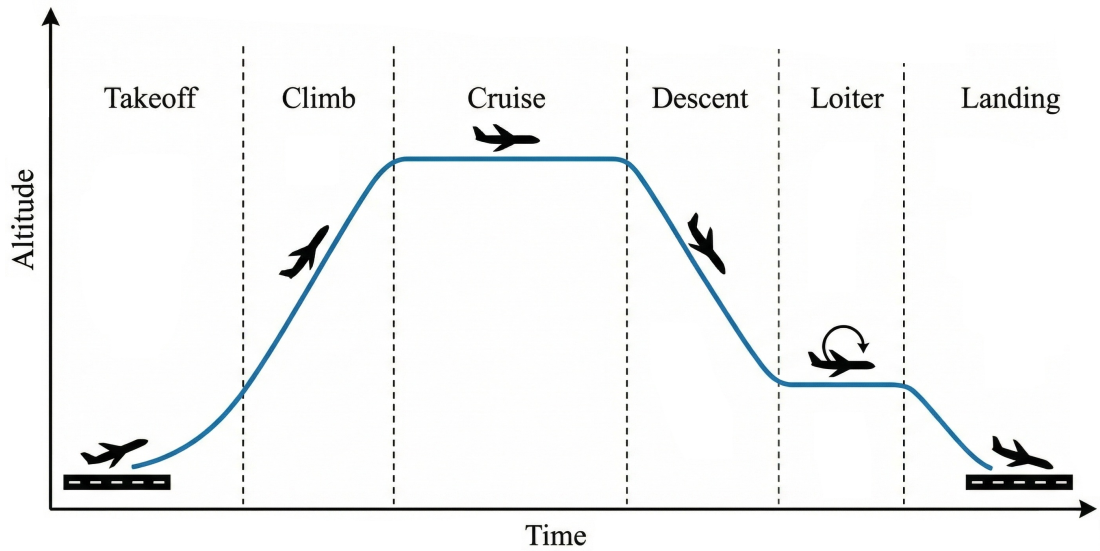


Figure 4.4: Schematic diagram of the standard flight profile.

A standard flight profile consists of take-off, climb, cruise, descent, landing, and reserve phases reserved for contingencies in line with the safety criteria specified in the regulations. The energy consumption can be expressed along the flight profile as shown in Equation (4.1).

$$E_{total} = E_{takeoff} + E_{climb} + E_{cruise} + E_{descent} + E_{loiter} + E_{landing} \tag{4.1}$$

A battery pack has been designed as the energy storage unit for the electric propulsion system. The INR18650–30Q lithium-ion battery model from the Samsung INR series used in similar projects, including NASA's X–57 Maxwell [7] aircraft, was preferred inthis design. The battery pack design is based on the aircraft's energy requirements and flight profiles. In the scope of the design studies for converting the Tecnam P2008 JC aircraft into an all-electric aircraft, the basic specifications of the selected battery are given in Table 4.4.

Table 4.4: Battery cell and pack specifications [106].

	Parameter	Value	Unit
Battery Cell	Type	Lithium–Ion	–
	Nominal capacity	3	[Ah]
	Nominal voltage	3.6	[V]
	Weight	0.048	[kg]
Battery Pack	Number of series cells	120	[pcs]
	Number of parallel cells	35	[pcs]
	Nominal voltage	432	[V]
	Nominal capacity	105	[Ah]
	Energy	45.36	[kWh]
	Weight	201.6	[kg]

The battery pack was prepared with the selected battery model, considering the aircraft's energy requirement and weight limitation. Within the battery pack, battery cells can be connected in series or parallel. The voltage (V) of each battery cell in the battery pack is indicated by V_{cell} and the capacity (Ah) is indicated by Q_{cell}.

The number of series and parallel cells in the battery pack is given as N_{serial} and $N_{parallel}$, respectively, in the Equation (4.2) and Equation (4.3).

$$N_{serial} = \frac{V_{bat}}{V_{cell}} \tag{4.2}$$

$$N_{parallel} = \frac{Q_{bat}}{Q_{cell}} \tag{4.3}$$

As a result, the number of series-connected battery cells in the battery pack was calculated as 120, the number of parallel-connected cells as 35, and the total weight of the batteries as 201.6 kg.

4.3.2 Weight impact analysis

As mentioned earlier in the study, an electric propulsion aircraft will be created by redesigning the equipment without changing the existing structural architecture of the basic aircraft. One of the major problems here is weight constraints. A weight distribution was made by balancing the parameters that directly affect each other, such as maximum take-off weight, empty weight, payload carrying capacity, energy requirement, and flight profile. Within the framework of the all-electric aircraft concept, some equipment specific to conventional aircraft systems, such as internal combustion engine, jet fuel, and fuel tank, are removed, while some equipment, such as electric motor and a designed battery pack, are added for the conversion to the electric propulsion system. As a result of this trade-off, the weight changes on the aircraft are expressed in Figure 4.5. The selected equipment and its efficiency ratios, aerodynamic properties, and weight breakdown can be reconfigured according to specific design requirements. Accordingly, even if the same aircraft is used as a reference, different results can be obtained by changing the parameters of individual components. This allows the overall concept to be analyzed from multiple perspectives.

With the removal of the traditional aircraft's internal combustion engine and fuel system, the weight of these components largely creates space for the integration of the battery pack. In the new design, the useful load capacity has been revised, and the weight of the pilots is expected to be 170 kg, and the baggage capacity is expected to be 10 kg. The

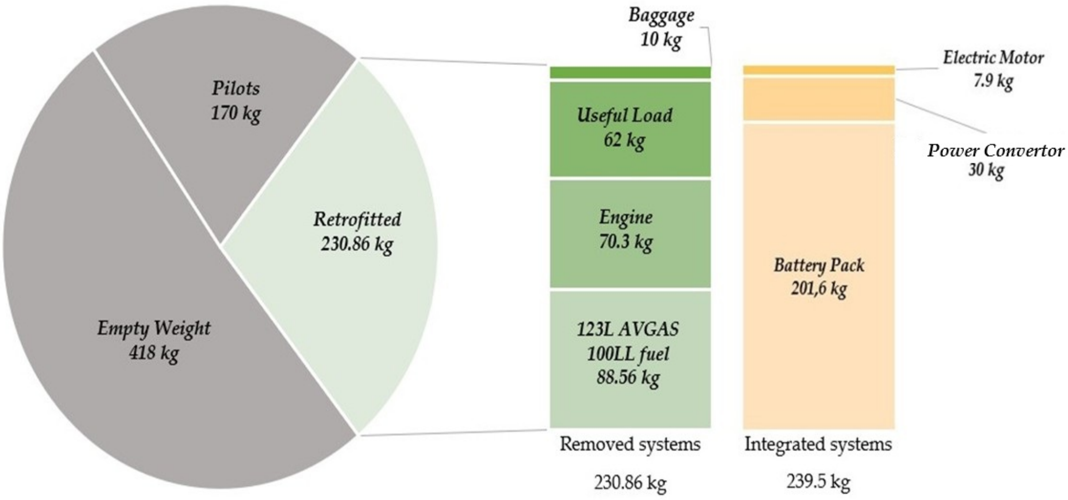


Figure 4.5: Weight breakdown of the retrofitted all-electric Tecnam P2008 JC aircraft.

weight of the main electrical equipment, the electric motor [107] and DC-DC converter, has also been specified. For the DC-DC converter, the weight of other equipment with similar technical characteristics to the equipment planned to be used on the aircraft has been taken into consideration [108]. This method was preferred since the equipment that was to be used directly had to be designed according to the specified requirements. In general, the weight of the integrated system is higher than the weight of the removed system. However,removing mechanical parts from the basic aircraft, such as all the fuel system equipment, will balance this ratio.The maximum take-off weight, one of the aircraft's important structural features, was not exceeded. The aircraft modified with this weight distribution has a battery pack of 45.36 kWh. With the development of battery technologies, battery density is expected to increase, and battery weights are expected to decrease. Thus, higher-capacity batteries will provide great benefits for airplanes in terms of both volume and weight.

4.4 System-Level Simulation Results and Performance Analysis

In the previous sections, the Tecnam P2008 JC aircraft was analyzed to be converted into the AEA concept,considering its specifications and limitations. It was converted to battery-powered within the scope of appropriate equipment selections and weight studies. In this section, a flight profile was created in accordance with the redesigned aircraft. During this flight profile,the behavior and electrical outputs of the aircraft were examined. The basic aircraft is widely used for personal and training purposes. Generally, not very long ranges are preferred. Considering this usage area, a flight route has been planned for the redesigned aircraft. This route is planned to go from Sabiha Gökçen International Airport (SAW) in Istanbul to Bursa Yenisehir Airport (LTBR) in Bursa as shown in Figure 4.6. This range is approximately 45 miles.

Figure 4.6: Flight route (Sabiha Gökçen Airport in Istanbul to Bursa Yenisehir Airport in Bursa).

For safety reasons, a flight is considered completed when the battery capacity reaches the 20 Ah limit before it is completely exhausted. Thus, reserve energy is left for unexpected situations. According to the battery pack specifications specified in Table 4.4, the nominal energy capacity during the flight profile was planned to be 85 Ah instead of 105 Ah. The planned route takes approximately 72 minutes.The flight phases analysed in the simulation are climb, cruise and descent with speeds of 65 knots, 75 knots and 73 knots, respectively.

The flight profile and airspeeds are shown in Figure 4.7.

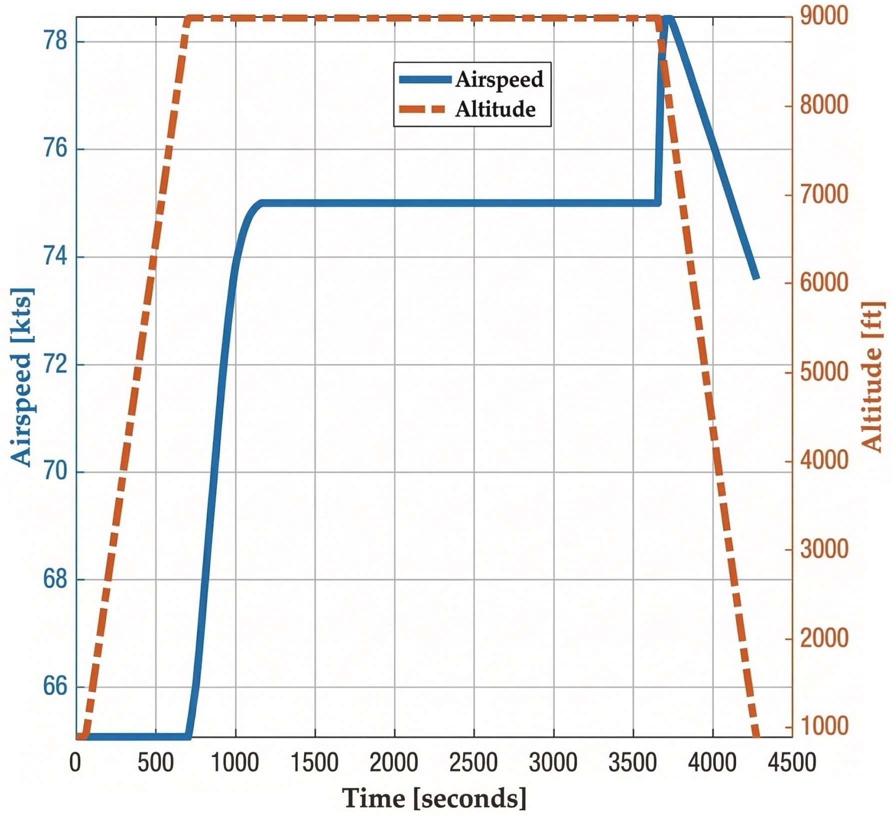


Figure 4.7: Airspeed[kts] and Altitude [ft] simulation results.

According to the flight simulation data shown in Figure 4.8 and Figure 4.9, the maximum power consumption of the engine was 45.5 kW. The maximum power level was reached, especially during the take-off phase and dynamic manoeuvres requiring high performance. This demonstrates the engine's capacity and operational flexibility to respond to transient high-energy demands. In the Cruise phase, a stable value was observed with a power consumption of approximately 20 kW, while in the Descent phase, the power consumption was zero with the engine off. It is seen that the energy used within the scope of this entire flight process is 24.12 kWh. The designed battery pack can meet this energy requirement with a safety margin.

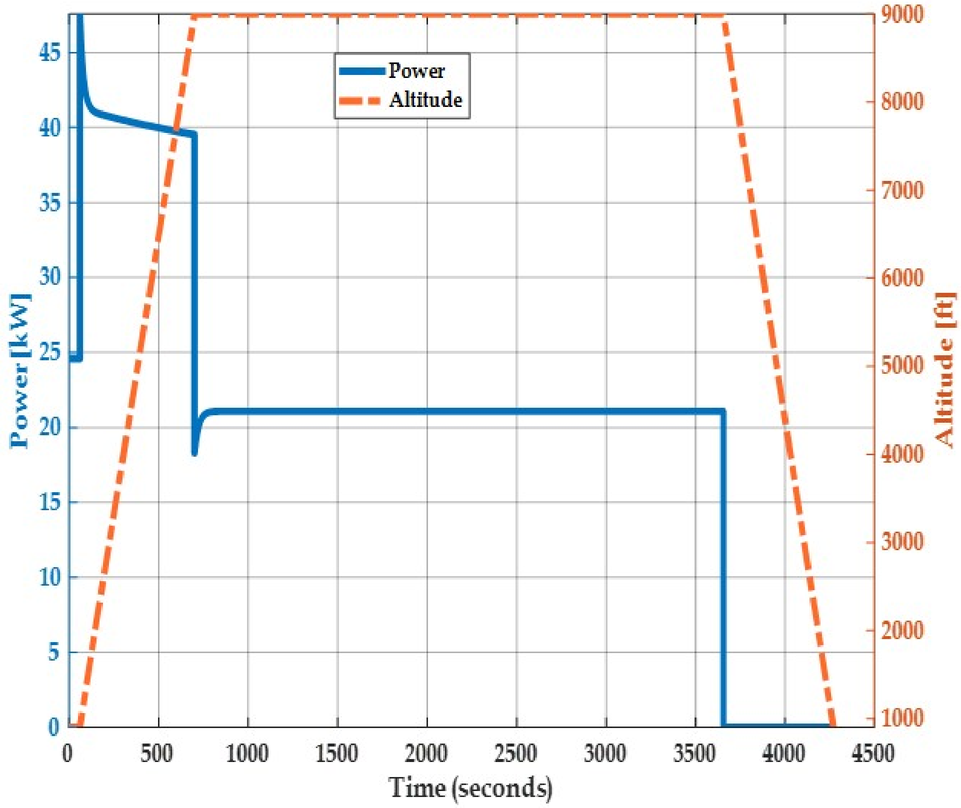


Figure 4.8: Power [kW] and Altitude [ft] simulation results.

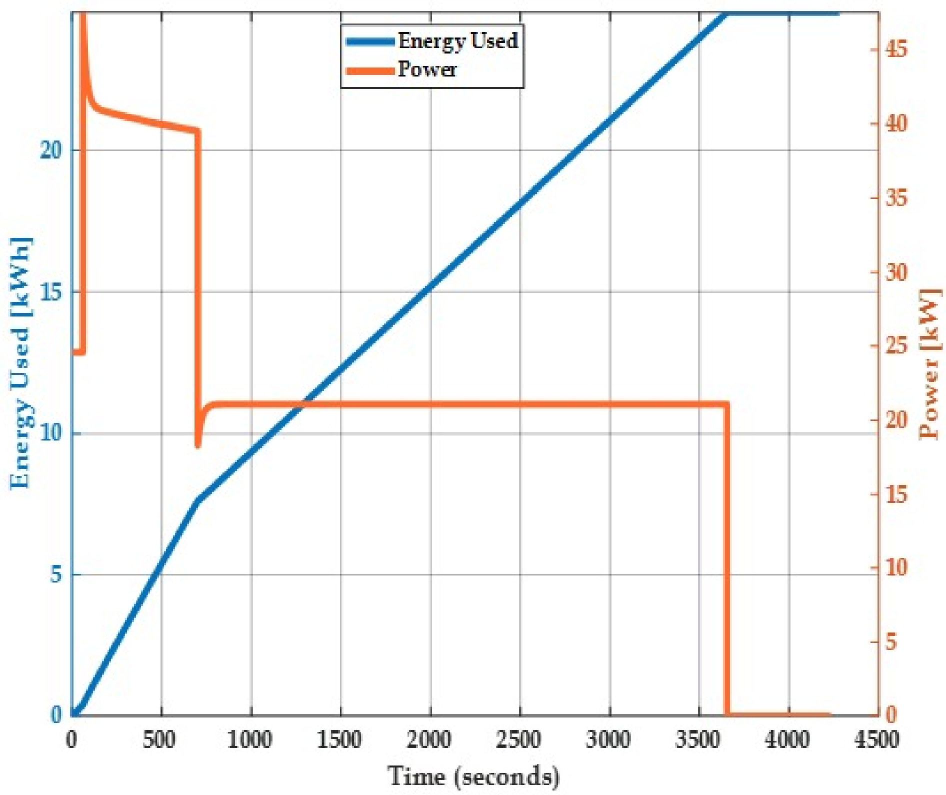


Figure 4.9: Energy Used [kWh] and Power [kW] simulation results.

Battery Charge, Battery Voltage, and Battery Current graphs are shown in Figure 4.10. In accordance with the current capacity and voltage values specified in the Battery Pack design, the energy required throughout the flight profile was met by the battery. For safety reasons,a portion of 20 Ah capacity was reserved for unexpected situations and was not used during the normal flight profile.

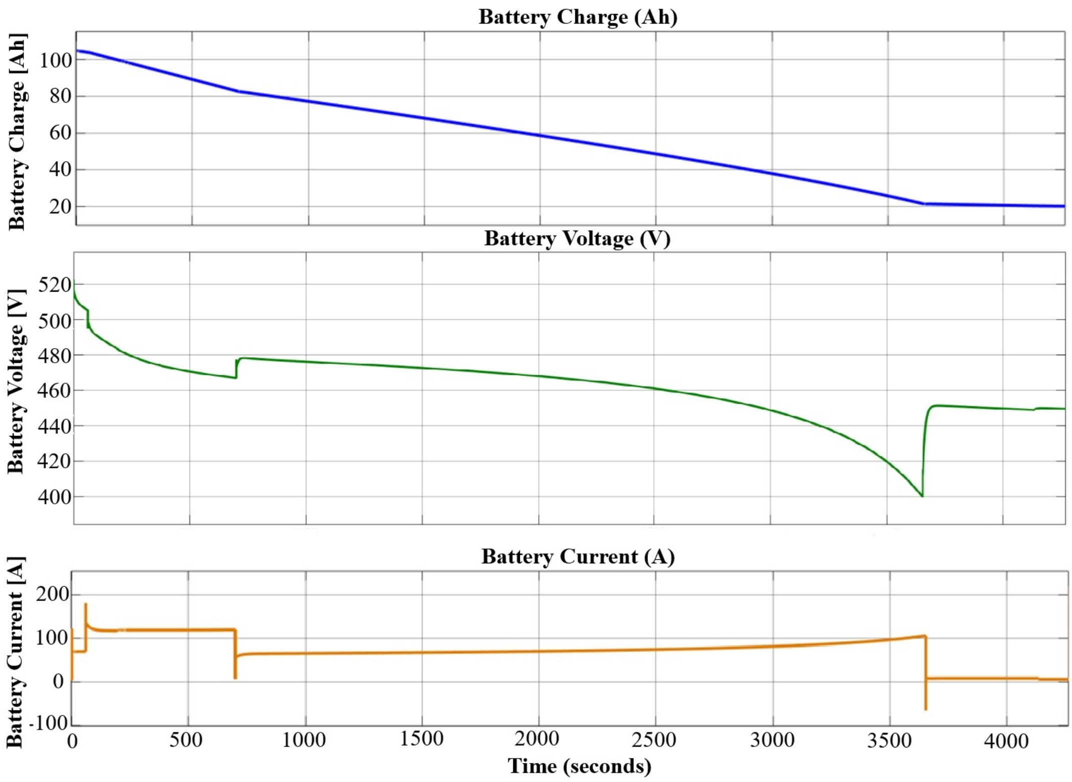


Figure 4.10: Battery charge, battery voltage, and battery current simulation results.

Figure 4.11 shows the direct effect of the interaction between battery capacity and payload mass on the aircraft's flight range. The graph presents the range contours obtained for different battery and payload combinations. The graph also includes a critical boundary line representing the aircraft's total take-off weight limit. The area above this line is defined as the overweight region, where the maximum take-off weight is exceeded. This region represents operationally unacceptable limits.

Upon examining the graph, it is evident that increasing battery capacity provides a significant contribution to flight range. However, this increase comes at the expense of payload capacity. Range performance is naturally limited at low battery capacities. Increasing capacity extends the range. However, the amount of transportable payload decreases due to the increased battery weight. This situation clearly illustrates the energy density–weight–range trade-off encountered in fully electric aircraft designs. To give a numerical example based on contour lines, it can be seen that at approximately 100 Ah battery capacity and a payload range of 100–150 lb, the aircraft can achieve a range of around 70–80 nautical miles. However, if the payload is to be increased, a higher battery capacity is required to maintain the same range. This situation leads to reaching the total weight limit more quickly, thereby narrowing the design space. Consequently, the importance of precise battery sizing tailored to the mission profile in small electric aircraft is once again evident.

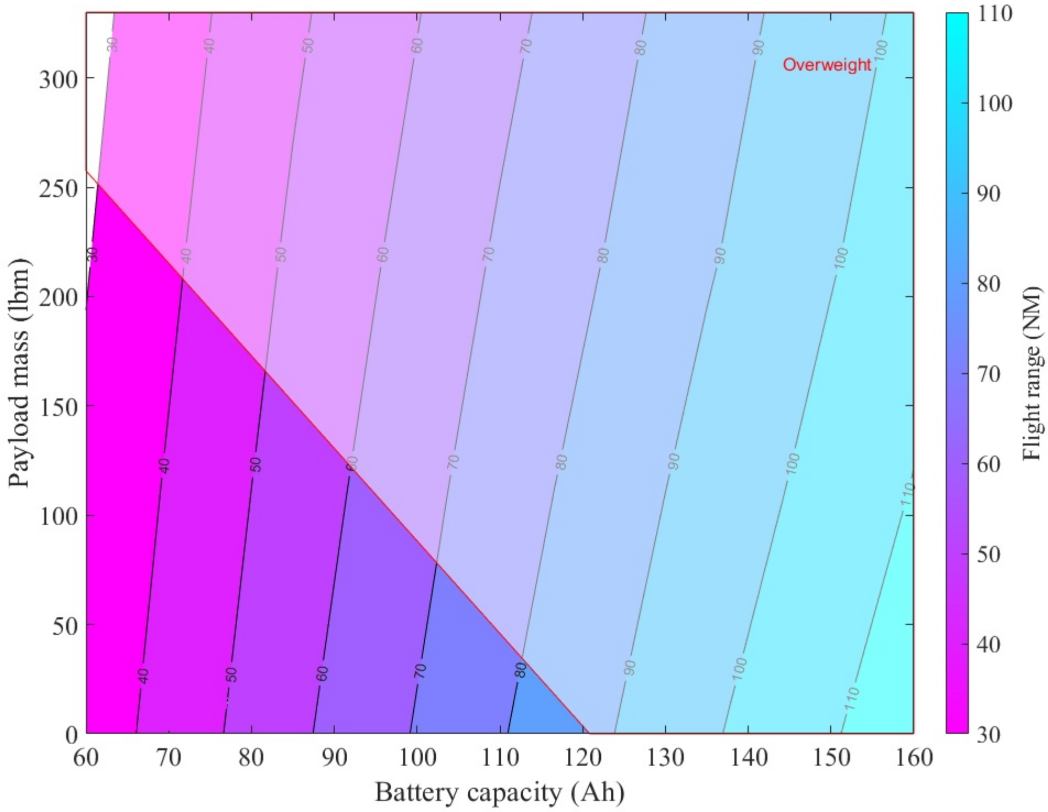


Figure 4.11: Payload–Battery Capacity–Range trade off for the electrified small aircraft.

The excess weight region in the graph indicates combinations that cannot be used due to existing structural and certification limitations. The existence of this large area confirms the limited specific energy density of today's lithium-ion battery technologies. Current technology has not yet reached full maturity for missions requiring long range and high payload. In contrast, the areas defined as the safe operating area in the graph prove that the system is technically feasible for short-range and light load profiles.

Consequently, this graph quantifies the complex relationship between battery capacity, payload, and range. The findings indicate that optimization at the system level is essential. Battery-based electric propulsion systems appear to offer high potential for short-range tasks. However, it is evident that they impose significant design constraints for medium and long-range operations.

For the basic aircraft, the fuel tank capacity and fuel consumption information of the aircraft are given in Table 4.1 and Table 4.2. The hourly fuel consumption of the conventional aircraft has been compared with the hourly cost of electrical energy consumption and carbon emission quantities by redesigning the aircraft as battery-powered. In the current situation in Europe, AVGAS 100LL prices generally range between €2.00 EUR and €2.50 EUR per liter [109]. This study calculates the price of AVGAS 100LL as €2.30 EUR/liter. On the other hand, the average electricity price for non-household consumers in Europe for the first quarter of 2024 is calculated as 0.20 €/kWh [110]. A margin of 20% has been considered for losses that may occur during battery charging and is included in the electricity price. Fuel and energy consumption costs for conventional and battery-powered aircraft configurations are given in Table 4.5.

Table 4.5: AVGAS 100LL fuel and electricity costs.

	Consumption Value (for 72 minutes)	Value Unit	Unit Cost	Total Cost
AVGAS 100LL Fuel	20.4	[lt]	€2.30 EUR	€46.92 EUR
Electricity	24.12	[kWh]	€0.24 EUR	€5.78 EUR

Here, the cost of AVGAS 100LL fuel and electrical energy is calculated, starting from its use in the basic aircraft. The previous costs of AVGAS 100LL fuel and electrical energy from the product life cycle, such as production, transmission, and distribution are not calculated. It is the cost paid by the aircraft as an end user.

The need to use jet fuels together with conventional propulsion systems in the field of aviation also brings carbon emissions. Carbon and harmful gas emissions from the AVGAS 100LL jet fuel used by the aircraft were calculated within the determined cruise plan. The fuel consumption of the aircraft, as previously stated in the specifications, is 17 lt/h. Since the cruise time is 72 minutes within the scope of the flight plan, approximately 20.4 liters of fuel consumption was calculated for the planned flight.

On the other hand, with the redesign of the basic aircraft as battery-powered, carbon and harmful gas emissions were analyzed. Since electric aircraft engines have no fuel consumption, carbon and harmful gas emissions due to electricity generation are considered. During the flight route, 24.12 kWh of energy was consumed. Therefore, the gas emission during the planned flight was calculated as 24.12 kWh of gas emission from electrical energy. In this context, the amount of emissions from AVGAS 100LL fuel used in the conventional aircraft and electrical energy used in the retrofitted aircraft are given in Table 4.6 and Table 4.7.

Table 4.6: Emissions due to AVGAS 100LL fuel consumption [111].

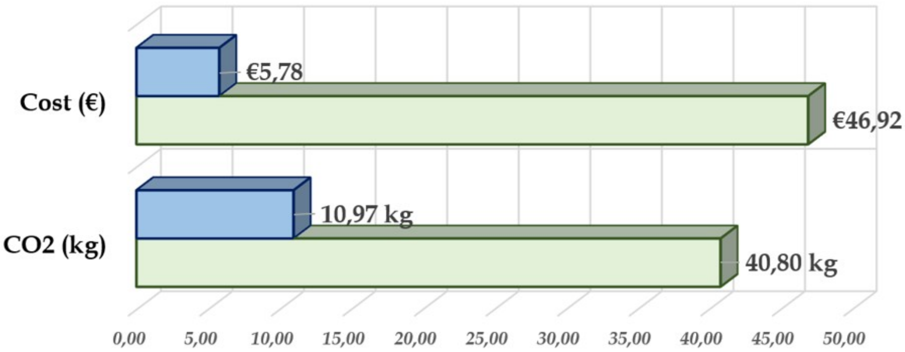
Emission produced	Quantity [kg] (per 1 kg AVGAS 100LL fuel)	Quantity [kg] (for 20.4 lt)
CO_2	2	40.8
H_2O	1.2	24.48
CO	1	20.4
HC	0.015	0.306
NO_x	0.005	0.102
Pb	0.008	0.1632

Table 4.7: Emissions due to electrical energy consumption [112].

Emission produced	Quantity [kg] (per 1 kWh electricity)	Quantity [kg] (for 24.12 kWh)
CO_2	0.455	10.97
CH_4	5.59×10^{-6}	1.34×10^{-4}
N_2O	8.88×10^{-6}	2.14×10^{-4}

Within the scope of conventional aviation, the use of internal combustion engine (ICE) is common, especially in aircraft used for short distances and air transportation. In terms of technology and capabilities, electric propulsion aircraft are preferred for short-haul and air transportation. Therefore, AEA is an alternative not only to jet-powered aircraft in conventional aviation, but also to aircraft using internal combustion engines. Aircraft with the AEA concept do not directly emit CO_2, NO_x, or other pollutants due to their electrical equipment. However, this does not mean that the AEA concept is completely zero-emission. For example, greenhouse gas emissions occur mainly in the manufacturing of battery systems and in the production of the electricity used to charge the batteries.

In this case, there are no direct greenhouse gas emissions, but there are indirect emissions. This is known as the long tailpipe effect and is also discussed in the context of the electric vehicle concept. By extending the life of battery systems and improving recycling processes, the lifetime of batteries can be increased. This will increase the lifetime and reduce emissions per unit aircraft.



	Cost (€)	CO2 (kg)
All-Electric Aircraft	5,78	10,97
Conventional Aircraft	46,92	40,80

Figure 4.12: Comparison of environmental and economic impacts of All-Electric Tecnam P2008 JC Aircraft and Conventional Tecnam P2008 JC Aircraft.

Carbon emissions and energy costs are compared for ajet-fuelled aircraft and an electrically propelled aircraftplanning to navigate the same route, as shown in thegraph in Figure 4.12. The energy cost and CO2 emissions ofthe electric aircraft compared to conventional aircraftare as follows;

- The energy cost has decreased from €46.92 EUR to €5.78 EUR, resulting in an 87.66% reduction.
- CO_2 emissions have decreased from 40.80 kg to 10.97 kg, resulting in a 73.13% reduction.

5. BATTERY MODELING METHODS

Battery systems are critical components in fields such as aviation, electric vehicles, and energy storage systems. Furthermore, their importance is increasing day by day across all these sectors. Along with these developments, academic research is also gaining momentum. The properties of lithium-ion batteries are particularly noteworthy. These batteries have high specific energy density, high specific power, long cycle life, and relatively high efficiency. This allows them to be used in many areas of industry. With this trend toward widespread use, there is a growing need for mathematical and numerical models that can reliably predict the electrical behavior of batteries. Batteries have essential characteristics such as voltage, current, state of charge (SOC), and aging effects. These parameters are selected based on design and requirements. In addition, design components such as system performance and safety are directly affected by these characteristics.

The fundamental purpose of battery modeling is to ensure that a battery's electrical behavior under specific operating conditions is accurately represented. This enables both supporting the system design process and developing battery management algorithms. However, an inevitable trade-off between accuracy and complexity arises during the modeling process. Models offering high accuracy generally have complex mathematical structures and high computational requirements. In contrast, simpler models provide computational speed and ease of application. However, this limits the level of accuracy. Therefore, battery modeling is considered an engineering problem that requires application-specific model selection rather than a one-size-fits-all solution approach. The literature shows that battery modeling approaches are generally grouped under four main categories. These categories are defined as electrochemical models, electrical equivalent circuit models, data-driven models, and mathematical models [25] as can be seen in Figure 5.1.

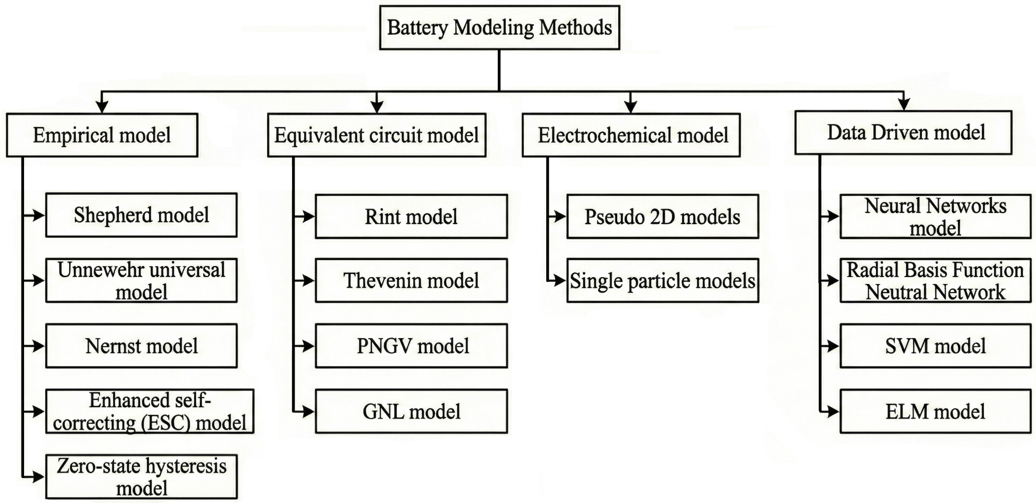


Figure 5.1: Various battery modeling methods [113].

Electrochemical models are based on the physical and chemical processes within the battery. These models take into account lithium diffusion at the electrodes, electrolyte transport, reaction kinetics, and thermodynamic relationships. This approach allows battery behavior to be represented with high accuracy. Electrochemical models are preferred, especially in cell design, material development, and advanced analysis studies. However, partial differential equations are most commonly used to solve these models. This leads to disadvantages such as high computational cost, a complicated parameterization process, and limited suitability for real-time applications. Therefore, the use of electrochemical models is mainly limited to research and cell development studies [114].

Electrical equivalent-circuit models are implemented by representing the battery with circuit elements such as voltage sources, resistors, and capacitors. In these semi-physical models, instantaneous ohmic voltage drops and time-dependent polarization effects in the battery are modeled using circuit theory. Electrochemical models are known to have a relatively low computational cost. These characteristics enable the widespread use of these models in battery management systems for applications such as SOC estimation and terminal voltage prediction. However, accurately determining the parameters of equivalent-circuit models often requires specialized experimental testing. This requirement creates application difficulties, especially in the early design stages [25].

Data-driven models are defined as approaches that aim to learn the electrical and dynamic behavior of batteries directly from experimental measurement data. In this modeling approach, there is no explicit mathematical representation of the battery's internal structure, electrochemical processes, or physical parameters. The modeling process is based entirely on learning the relationship between the measured input and output variables. This relationship is established through statistical learning methods and machine learning-based algorithms. Therefore, these approaches are referred to as black-box modeling in the literature. The black-box concept refers to the inability to interpret the model's internal workings from a physical perspective. The model uses input data such as current, voltage, or temperature to produce a specific output. However, the physical mechanisms that produce this output are not explicitly defined within the model structure. In other words, the model produces results. However, it does not provide direct information about the electrochemical origin of these results. For example, an artificial neural network-based model can estimate the state of charge (SOC) using terminal voltage and current information. However, how this estimate relates to ion diffusion, electrode reaction kinetics, or changes in internal resistance is not explained by the model.

The most crucial advantage of data-based models is their ability to represent nonlinear and complex battery behavior with high accuracy. They deliver successful results, particularly in areas such as SOC estimation, capacity degradation, and aging effects modeling. Thanks to these features, they provide a powerful alternative in situations where classical mathematical or physics-based models fall short. However, the success of these models largely depends on the quality and scope of the training data used. Model performance may decline under operating conditions outside the training data set. This limits the model's generalization ability. Furthermore, the inability of data-driven models to provide physical interpretation hinders a more comprehensive analysis of the system. These models cannot directly identify why battery behavior changes or which physical parameter limits the system. This causes uncertainties in the processes of making design decisions and evaluating system safety. For these reasons, the use of data-based and black-box models alone is insufficient for most applications. In the literature, these models are often used in hybrid structures alongside physics-based or equivalent-circuit models. This hybrid approach provides high accuracy on the one hand. On the other hand, it partially preserves physical interpretability. Thus, a more balanced solution is obtained between accuracy and engineering explainability [113].

Mathematical models express battery behavior through empirical or semi-empirical equations. The primary goal of this approach is to establish the relationship between the battery's terminal voltage and the current drawn. The relationship between the state of charge (SOC) and voltage is also defined within this framework. Simple, functional mathematical functions are preferred for this operation. The models aim to represent the battery's electrical output. Complex physical processes are not solved directly. Instead, relationships derived from measurement data are used.

A large portion of empirical mathematical models is obtained from experimental discharge curves under constant current. In this process, open-circuit voltage and internal resistance effects are included in the calculations. Additionally, polarization behavior is incorporated into the model using parameters calibrated from experimental data. For this reason, these models are typically designed for a specific battery chemistry or cell structure. Parameters are determined based on experimental data. This ensures high accuracy under specific operating conditions.

The most significant advantage of mathematical models is their low computational requirements. This feature offers great convenience for real-time simulations. Embedded battery management systems (BMS) and analyses in the early stages of design benefit from this advantage. Compared to electrochemical models, solution times are significantly shorter. The high numerical stability makes these models preferable.

However, the physical and electrochemical processes within the battery are not directly included in these models. Components such as ion diffusion and electrode reaction kinetics are not explicitly represented. Temperature effects and aging mechanisms are also not directly integrated into the model. The reflections of these processes are only indirectly tracked through model parameters. Temperature fluctuations and high C-rate discharge conditions are factors that limit the accuracy of empirical models. In addition, capacity reduction due to aging also negatively affects model accuracy. In light of all these assessments, computational efficiency comes to the fore in mathematical models. Thanks to its ease of application, it offers a suitable solution for system-level energy analyses and control-focused simulations. Different methods can be developed to increase the accuracy of the analyses. In these cases, mathematical models can be used alongside equivalent-circuit models or data-based approaches. This allows hybrid structures to be created. Different models are shown in Equation (5.1), Equation (5.2) and Equation (5.3).

Shepherd model:

$$y_k = E_0 - R \cdot i_k - \frac{K_1}{x_k} \tag{5.1}$$

Unnewehr universal model:

$$y_k = E_0 - R \cdot i_k - K_2 \cdot x_k \tag{5.2}$$

Nernst model:

$$y_k = E_0 - R \cdot i_k + K_3 \cdot \ln(x_k) + K_4 \cdot \ln(1 - x_k) \tag{5.3}$$

5.1 Shepherd Battery Modeling and Simulation Results

In a study conducted by C.M. Shepherd in 1965, a mathematical approach defining battery cell voltage is presented. In this approach, terminal voltage is expressed in terms of open-circuit voltage (OCV), internal resistance, and current values. A semi-empirical equation structure is developed in this process. This model directly relates the terminal voltage of the battery to the state of charge (SOC) and the discharge current drawn. This makes it possible to mathematically express the changes in voltage as the capacity is depleted. With this modeling, a clear technical analysis of the battery discharge characteristics is performed. The Shepherd equation can be successfully applied to both discharge and charge processes. This structure is commonly referred to in the literature as the Shepherd Model. This model is an early and fundamental approach developed for battery technologies. The model is based on a mathematical formulation. In addition, it has less computational complexity compared to electrochemical approaches. This facilitates the use of the model in real-time applications [115].

The method proposed by Shepherd does not require solving complex electrochemical equations. Instead, it favors a simple and functional formulation that aligns with experimental discharge curves. This aims to enable the rapid and reliable prediction of battery performance. The model also holds historical significance and contributes to the literature. This is because, for the first time, the voltage behavior under load is explained by an equation derived from laboratory data. With this development, battery performance analyses are transformed into a practical engineering tool.

In the following years, various modifications were made to the basic Shepherd model. In particular, by the 2000s, technological needs in the electric vehicle and aviation sectors came to the fore. During this process, the goal is to adapt the basic model to different battery chemistries. Additional parameters and refinement terms are included in the model with the aim of increasing accuracy [116]. For example, polarization effects need to be represented more accurately. To this end, additional voltage drop terms are added to the model. This allows for the correction of some assumptions in the original model.

The simple and understandable structure offered by the Shepherd model attracts attention in academic studies. This structure serves as a fundamental reference point in the development of more complex battery models. In this regard, similar mathematical models such as Unnewehr and Nernst have taken their place in the literature. Today, the original Shepherd model retains its validity and importance. It is particularly used as a quick estimation tool in the early stages of concept design processes. The technical value of the model remains highly significant for modern battery management systems (BMS).

The Shepherd Battery Model is preferred in many different engineering fields such as electric vehicles, renewable energy storage systems, and aircraft. The use of this model is of great importance for the analytical examination of energy storage technologies. In battery management systems (BMS), this model is used for state of charge (SOC) estimation and battery performance predictions. With a proper calibration process, actual battery behavior can be predicted quite quickly. This directly contributes to system optimization and increased efficiency.

In the aviation sector, fully electric and more electric aircraft (eVTOL, MEA/AEA) designs are currently at the forefront. In such advanced platforms, battery performance is a critical parameter in terms of flight safety and operational limits. For this reason, Shepherd-based models are actively included in simulation and modeling processes. In eVTOL concept studies conducted by NASA, this model is used as a reference for estimating battery voltage. In these studies, a curve-fitting approach based on the Shepherd equation structure is adopted [27].

The model is based on discharge curves taken from manufacturer datasheets in relevant engineering applications. In light of this data, the battery output voltage is calculated mathematically. Furthermore, energy consumption forecasts are made according to different flight mission profiles as take-off, cruise, landing. These analyses play a critical role in determining the aircraft's range and power requirements. Accordingly, the aircraft's operational constraints and objectives can be more clearly defined. The Shepherd model generally performs very well under constant or low-variable current conditions. This model is frequently used in the conceptual design phase of battery packs. In addition, this model is used in the comparative evaluation of different battery cells. This allows the compatibility of system components to be quickly checked. In conclusion, the Shepherd model enables the necessary analyses and calculations to be performed during the initial design phases of complex systems [117].

The technical advantages offered by the Shepherd model play a critical role in system design processes. The most fundamental advantage of this model is that it offers easy parameterization. Model parameters are obtained directly from the manufacturer's datasheets. On a typical discharge curve, critical points such as full charge voltage, the end of the exponential region, and the end of the nominal region are determined. Using this data, all model parameters are solved computationally. This process minimizes the need for experimental laboratory testing. This significantly speeds up the process, especially in the early design stages. Another important benefit of the model is its low computational load. The structure in question has a direct equation-based formulation. This keeps the calculation times in the simulation processes quite short. Thanks to this feature, fast and efficient results are obtained in complex optimization studies. Different battery types and pack configurations are practically compared using this model. This saves time and costs for engineering analyses. The Shepherd model is not limited to constant current discharge conditions. Dynamic behaviors can be captured thanks to the filtered current term within the model. This structure allows the battery voltage to be successfully predicted under both static and relatively dynamic operating conditions. This approach falls under the category of mathematical models. Thus, it can represent both the steady-state and transient states of the system [1]. This flexibility ensures that the model is preferred in a wide variety of applications. The model also provides a highly suitable infrastructure for battery management system (BMS) applications. Open-circuit voltage (OCV) predictions based on the state of charge value are performed using this model. This feature of the model provides a significant advantage in processes such as state of charge and state of health estimation. In addition, with precise calibration processes, actual battery performance is predicted with high accuracy. This facilitates the estimation process of critical parameters such as remaining useful life. As a result, the Shepherd model provides a reliable basis for monitoring and managing battery systems [118].

The Shepherd model is based on an empirical approach. Therefore, there are some fundamental limitations in its application. The foremost of these limitations is accuracy constraints. The Shepherd model parameterization process is based entirely on manufacturer datasheets. Therefore, the overall accuracy of the model is directly related to the quality of the data used. Errors in manufacturer curves or complex dynamics in the system limit the model's performance. Thermal effects and aging processes are also outside the model's scope. The Shepherd model does not focus in depth on the chemical and energetic processes within the cell. For this reason, temperature changes and aging effects are not directly considered in the model. In real-world usage scenarios, battery capacity and internal resistance vary with aging. This requires the model to be updated at specific intervals. If heat-induced changes and parameter deviations are not integrated into the model, the margin of error increases over time. Although the model successfully calculates basic electrical outputs, it does not provide data on the microscopic chemical processes within the cell. This situation causes the model to be insufficient in studies where electrochemical analyses are at the forefront.

The Shepherd model strikes a balance between accuracy and computational speed in battery technologies. The goal is to define complex electrochemical processes using simple mathematical expressions. This structure is actively utilized, particularly in eVTOL and electric vehicle designs. The fact that this model is preferred in projects by reputable institutions such as NASA also confirms the technical validity of the method. There are limiting factors such as thermal and aging effects. Nevertheless, the model's fast prediction capacity significantly speeds up the design process. This provides great convenience in the preliminary analysis stages of complex battery packs. In conclusion, the Shepherd model is an important option in the analysis of modern energy storage systems as shown in Table 5.1. This structure is utilized in the development of battery management systems. The analytical framework offered by the model maintains its relevance in electrical engineering literature [26].

Within the scope of this study, the conventional Tecnam P2008 JC aircraft was converted to the All-Electric Aircraft concept. The INR18650-30Q lithium-ion battery cell was selected as the energy storage system. A suitable battery pack was designed based on this cell. The reliability of each component used in aviation projects is of great importance. This reliability is supported by the fact that the components have been used in similar applications before. At the same time, compliance with certification processes is considered a fundamental requirement. In this context, it is significant that the INR18650-30Q cell was preferred in the X-57 Maxwell project conducted by NASA [64]. This indicates that the battery model in question has reached a sufficient level of maturity for aviation applications. Studies in the literature show that the INR18650-30Q cell offers balanced energy efficiency as shown in Figure 5.2.

The cell's power output exhibits a stable structure under different operating conditions. The thermal behavior observed at low temperatures is balanced. This feature provides a significant advantage for safe operation under harsh environmental conditions. It is noteworthy that energy losses remain at a limited level under the same conditions. The continuity of the output power can be maintained. When all these technical evaluations are considered together, the INR18650-30Q battery cell stands out as a suitable solution for electric aircraft systems developed under the AEA concept. This cell meets performance and reliability requirements [119].

Table 5.1: Comparative analysis of battery modeling methods.

Criterion	Shepherd Battery Model	Equivalent Circuit Model	Electrochemical Model	Data-Driven Model
Computational Cost	-Very Low Derived from simple algebraic equations; negligible processing load.	-Low Solves in microseconds; ideal for embedded systems with limited resources.	-Very High Involves solving partial differential equations requiring complex numerical solvers.	-Medium Training is computationally intensive; inference speed depends on hardware acceleration.
Real-Time Suitability	-High Applicable for real-time battery simulation studies and BMS applications.	-High The industry standard for real-time SOC estimation in electrical vehicles BMS applications.	-Low Generally unsuitable for on-board BMS due to high computational complexity.	-Medium Feasible for real-time estimation if optimized, but may face generalization issues.
Ease of Parameter Identification	-High Coefficients are easily derived from manufacturer datasheets or discharge curves.	-Medium Requires laboratory tests such.	-Low Requires detailed electrochemical analysis and determination of numerous physical parameters.	-Low Requires the collection of massive, high-quality, and labeled datasets for training.
Typical Applications	Rapid prototyping and academic baselines.	Electric vehicles, grid storage systems, and BMS design.	Battery design, material development, and generating data.	Remaining Useful Life prediction, fault diagnosis, and offline analysis.

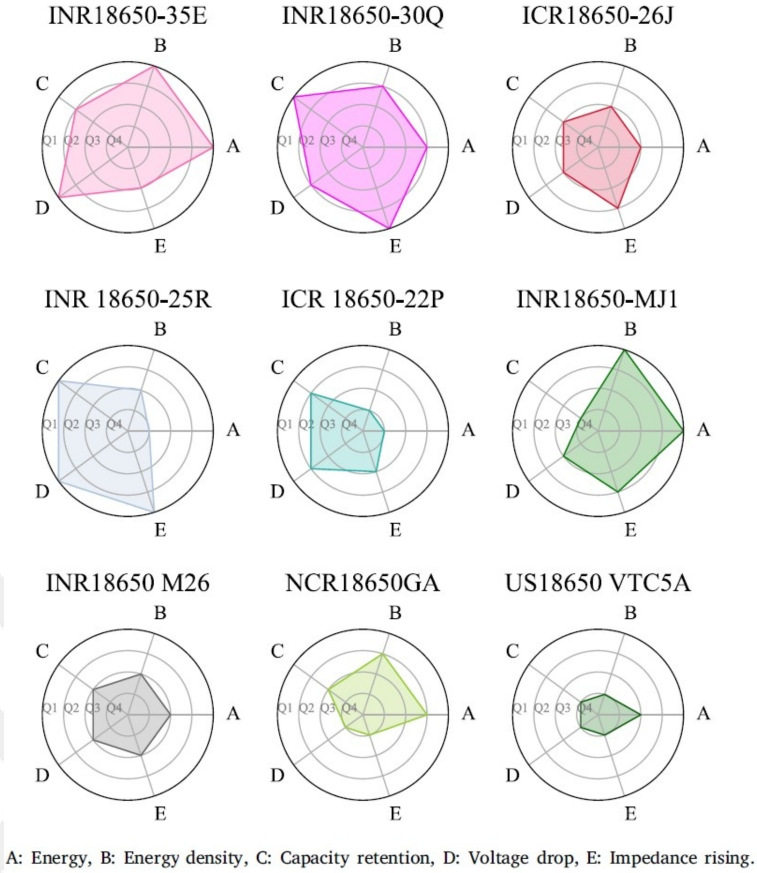


Figure 5.2: Performance comparison charts for different battery cells [119].

The battery pack created within the scope of this study was modeled using the Shepherd battery modeling method. The main equation of the Shepherd model is given in Equation (5.4).

$$V = E_0 - K\left(\frac{Q}{Q-it}\right)i - R_0\, i + A\, e^{-B\, it} \tag{5.4}$$

V	:	Actual battery voltage (V).
E_0	:	Open-circuit battery voltage at full capacity (V).
Q	:	Battery capacity (Ah).
$it = \int i\, dt$	:	Actual battery charge (Ah).
K	:	Polarization constant (V/Ah) or polarization resistance (Ω).
A	:	Exponential zone amplitude (V).
B	:	Inverse exponential zone time constant $(\text{Ah})^{-1}$.
R	:	Internal resistance (Ω).
i	:	Battery current (A).

The battery model expressed by Equation (5.4) is widely used in the literature. This model can represent battery voltage under constant current conditions. However, the model's accuracy decreases in operating conditions where the current changes over time. Voltage dynamics cannot be accurately represented under these conditions. To overcome these limitations, an improved version of the Shepherd battery model is proposed. This approach allows for a more accurate representation of the battery's electrical behavior under real operating conditions. The model's performance in the transient regime is improved. Thus, the accuracy of system simulations performed under variable current conditions is increased [120].

$$V = E_0 - \underbrace{K\left(\frac{Q}{Q-it}\right)i^*}_{\text{Polarization resistance}} - \underbrace{K\left(\frac{Q}{Q-it}\right)it}_{\text{Polarization voltage}} - R_0\, i + A\, e^{-B\, it} \tag{5.5}$$

In this model as shown in Equation (5.5), the current flowing through the polarization resistance is defined as the filtered current i^*. Experimental results show that the battery voltage exhibits a slow dynamic response during sudden changes in current. The use of filtered current enables a more realistic modeling of this transient voltage behavior. This approach eliminates the algebraic loop problem encountered in Simulink-based simulations [116].

Additionally, the charging and discharging equations for the battery are given in Equation (5.6) and Equation (5.7), respectively.

$$V = E_0 - K \cdot \frac{Q}{it + 0.1\,Q} \cdot i^* - K \cdot \frac{Q}{Q-it} \cdot it + A \cdot e^{-B \cdot it} \tag{5.6}$$

$$V = E_0 - K \cdot \frac{Q}{Q-it} \cdot i^* - K \cdot \frac{Q}{Q-it} \cdot it + A \cdot e^{-B \cdot it} \tag{5.7}$$

The Shepherd battery model provides significant convenience for parameter estimation. This method does not require complex experimental testing. Typical discharge curves from the manufacturer's data sheets are used for analysis. A constant current discharge curve is used as the basis for modeling lithium-ion batteries. This curve is divided into three main regions.

Figure 5.3 shows a typical battery discharge curve. Four critical points are defined on the curve to enable mathematical calculation of the model parameters (E_0, K, A, B):

- **Full Charge Voltage (V_{full}):** This is the starting point of the characteristic. It indicates the voltage level when the battery is fully charged. This value corresponds to 100% State of Charge (point 1 in the figure).
- **Exponential Region:** This is the first stage of discharge. The voltage drops rapidly in this region. Then the voltage level stabilizes. This region ends at point (Q_{exp}, V_{exp}). The battery's dynamic response is modeled in this area (between points 1 and 2 in the figure).
- **Nominal Region:** This is the widest part of the discharge curve. In this region, the voltage level tends to remain constant. No significant voltage change is observed. This region ends at point (Q_{nom}, V_{nom}). This is the boundary where the rapid decline begins (between points 2 and 3 in the figure).
- **Maximum Capacity (Q):** After the nominal region, the voltage decreases rapidly. The curve exhibits a non-linear structure here. The final point where the curve ends is the maximum capacity of the battery (after 3 in the figure).

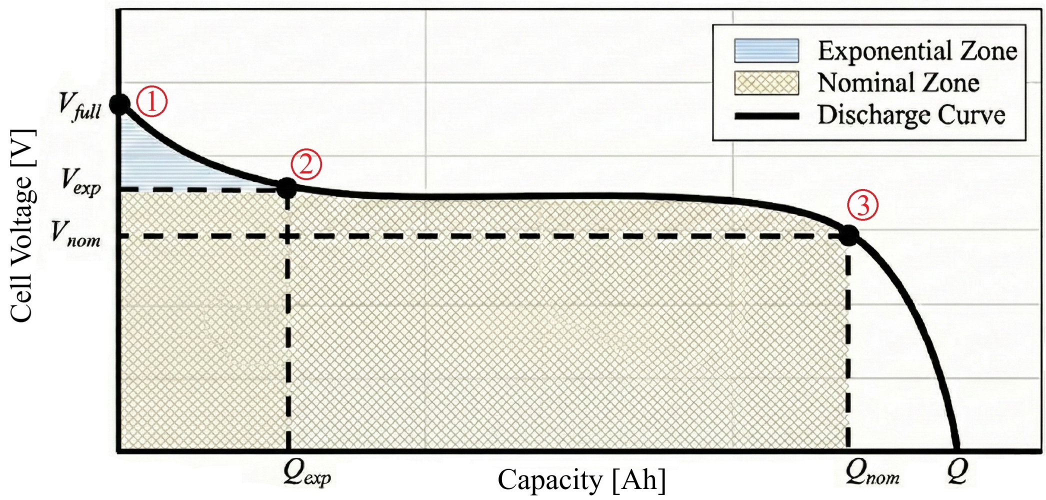


Figure 5.3: Typical battery discharge curve.

The internal resistance (R_0) data is required to complete the model. Additionally, the maximum capacity (Q) value must be known. These two values are usually available in the manufacturer's data sheet. Other data read from the curve ($V_{full}, V_{exp}, Q_{exp}, V_{nom}, Q_{nom}$) are substituted into the equation system. Thus, the unknown model coefficients are mathematically solved.

Here, there are some expressions that are not found in the characteristic curve. These are the parameters E_0, K, A, and B. Known equations are used to derive these parameters.

Considering Equation (5.4), at the beginning of the discharge characteristic, the battery is fully charged. At this point, the terminal voltage corresponds to the full charge voltage. The current drawn from the battery is zero. Therefore, the equation can be explained in Equation (5.8) as follows:

$$V_{\text{full}} = E_0 - R_0 \cdot I + A \tag{5.8}$$

As shown in Figure 5.3, Point 2 represents the end of the exponential region. At this point, the battery voltage is given by Equation (5.9), where the current is set to $i_t = Q_{\text{exp}}$.

$$V_{\text{exp}} = E_0 - K \cdot \frac{Q}{Q - Q_{\text{exp}}} \cdot \left(Q_{\text{exp}} + I\right) - R_0 \cdot I + A \cdot e^{-B \cdot Q_{\text{exp}}} \tag{5.9}$$

As shown in Figure 5.3, Point 3 represents the end of the exponential region. At this point, the battery voltage is given by Equation (5.10), where the current is set to $i_t = Q_{\text{nom}}$.

$$V_{\text{nom}} = E_0 - K \cdot \frac{Q}{Q - Q_{\text{nom}}} \cdot (Q_{\text{nom}} + I) - R_0 \cdot I + A \cdot e^{-B \cdot Q_{\text{nom}}} \tag{5.10}$$

Along with solving the equations obtained here,

$$E_0 = \frac{E_{\text{exp}} C_{\text{nom}} - E_{\text{nom}} C_{\text{exp}}}{\left[(1 - e^{-B C_{\text{nom}}}) C_{\text{exp}} - (1 - e^{-3}) C_{\text{nom}}\right]} \tag{5.11}$$

$$C_{\text{exp}} = \frac{Q}{Q - Q_{\text{exp}}} \left(Q_{\text{exp}} + I\right) \tag{5.12}$$

$$C_{\text{nom}} = \frac{Q}{Q - Q_{\text{nom}}} \left(Q_{\text{nom}} + I \right) \tag{5.13}$$

$$E_{\text{exp}} = -V_{\text{exp}} - R_0 \cdot I + \left(V_{\text{full}} + R_0 \cdot I \right) e^{-B \cdot Q_{\text{exp}}} \tag{5.14}$$

$$E_{\text{nom}} = -V_{\text{nom}} - R_0 \cdot I + \left(V_{\text{full}} + R_0 \cdot I \right) e^{-B \cdot Q_{\text{nom}}} \tag{5.15}$$

$$K = E_0 \left(\frac{1 - e^{-B \cdot Q_{\text{exp}}}}{C_{\text{exp}}} \right) + \frac{E_{\text{exp}}}{C_{\text{exp}}} \tag{5.16}$$

$$A = V_{\text{full}} - E_0 + R \cdot i \tag{5.17}$$

$$B = \frac{n}{Q_{\text{exp}}} \tag{5.18}$$

In Equation (5.20) , the value of n varies depending on the battery type. For lithium iron phosphate (LFP) and nickel manganese cobalt (NMC) batteries, these values are 2 and 4, respectively.

In this study, the characteristic coefficients (A, B, K, E_0) included in the mathematical expression of the Shepherd model cannot be directly obtained from the datasheet provided by the manufacturer. In this context, it is necessary to obtain these parameters accurately and reliably. In this thesis, the semi-empirical "Curve-Fit" approach has been adopted [27]. The main reasons for choosing this article and the proposed set of methods are as follows:

- **Hardware Compatibility and Validation:** The battery cell used for experimental validation of the developed model is identical to the Samsung INR18650-30Q used in this thesis. Unlike other models in the literature, the empirical correction coefficients presented in this study are directly optimized according to the electrochemical characteristics of the INR18650-30Q cell. This significantly increases the similarity of the model's simulation outputs to real battery behavior.

- **Analytical Solution Method:** Unlike traditional trial-and-error methods, this method uses physical points on the discharge curve (V_{exp}, Q_{nom}). This allows the model parameters to be calculated analytically. This approach minimizes uncertainties in the parameter determination process. It ensures the repeatability of the study.

- **Experimental Error Minimization:** These derived equations represent the voltage drops of the battery, particularly in the exponential zone and nominal zone transitions, with minimal error.

As a result, the battery cell used in the thesis is identical to the test sample in the reference article. Furthermore, the method is based on an analytical framework validated by experimental data. Therefore, this approach has been used as a basis for determining the Shepherd model coefficients. In this case, the equations are listed below.

$$A = V_{full} - V_{\text{exp}} \tag{5.19}$$

$$B = \frac{1.4}{Q_{\text{exp}}} \tag{5.20}$$

$$K = 0.185 \left(V_{full} - V_{\text{nom}} + A \left(e^{-B \cdot Q_{\text{nom}}} - 1 \right) \right) \frac{Q_{-} Q_{\text{nom}}}{Q_{\text{nom}}} \tag{5.21}$$

$$E_0 = V_{full} + K + R \cdot I - A \tag{5.22}$$

The modeling of the battery pack designed for the fully electric aircraft was performed in the MATLAB/Simulink environment. The Shepherd mathematical model was used as the basis for the modeling work. A sequential method was used to determine the parameters required for the model's successful operation. In the parameter acquisition process, the basic electrical data was first obtained directly from the manufacturer's datasheet. Dynamic parameters not included in the datasheet were obtained using graphical analysis methods. For this purpose, the battery discharge characteristic curve presented in Figure 5.4 was used. For parameters not found in either source, academic studies in the literature were utilized. These parameters were calculated using experimental formulations.

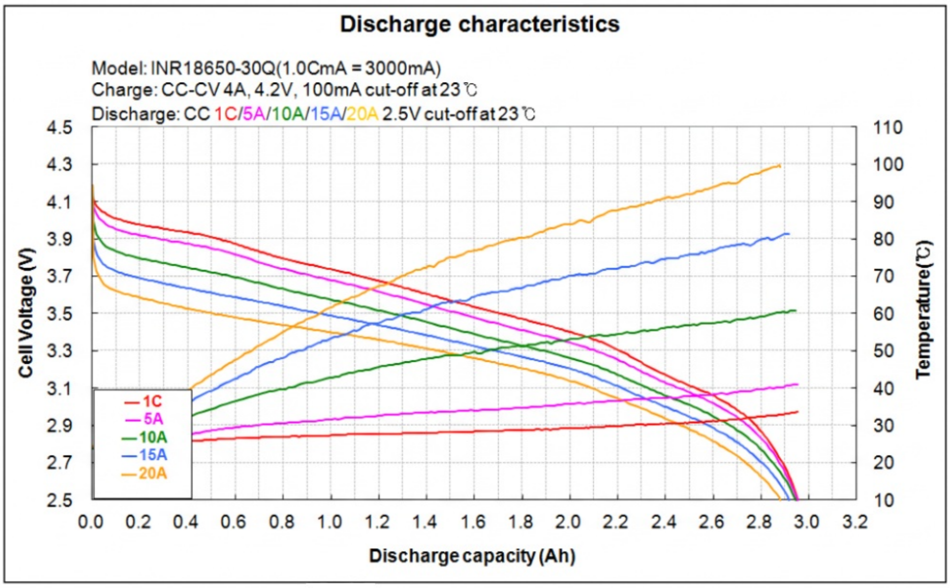


Figure 5.4: INR18650-30Q battery discharge characteristics [121].

The model parameters determined for a single INR18650-30Q cell are listed in Table (5.2). The Shepherd model parameters for the entire battery pack are presented in Table (5.3). This parameter set is based on the battery pack configuration detailed in Section 4. All simulation studies were conducted using parameters validated by this method.

Table 5.2: Battery cell parameters used in the Shepherd model.

INR18650-30Q Battery Cell	Parameter	Value	Unit
From datasheet	V_{full}	4.2	[V]
	Q	3.0	[Ah]
	V_{nom}	3.6	[V]
	R_0	0.026	[Ω]
From datasheet discharge curve	V_{exp}	3.95	[V]
	Q_{exp}	0.25	[Ah]
	Q_{nom}	1.35	[Ah]
From curve fitting	A	0.25	[V]
	B	5.6	[Ah^{-1}]
	K	0.079	[Ω]
	E_0	4.107	[V]

Table 5.3: Pack-level Shepherd model parameters for the INR18650-30Q battery pack ($N_s = 120$, $N_p = 35$).

Parameter	Battery Pack Calculation	Pack Value	Unit
V_{full}	$V_{cell,full} \times N_s$	504	[V]
Q	$Q_{cell} \times N_p$	105	[Ah]
V_{nom}	$V_{cell,nom} \times N_s$	432	[V]
R	$R_{cell} \times \frac{N_s}{N_p}$	0.089	[Ω]
V_{exp}	$V_{cell,exp} \times N_s$	474	[V]
Q_{exp}	$Q_{cell,exp} \times N_p$	8.75	[Ah]
Q_{nom}	$Q_{cell,nom} \times N_p$	47.25	[Ah]
A	Equation (5.19)	30.0	[V]
B	Equation (5.20)	0.16	[Ah^{-1}]
K	Equation (5.21)	0.09	[Ω]
E_0	Equation (5.22)	492.9	[V]

The MATLAB/Simulink implementation of the Shepherd model used in the study has been completed. The block diagram of the created model is shown in Figure 5.5.

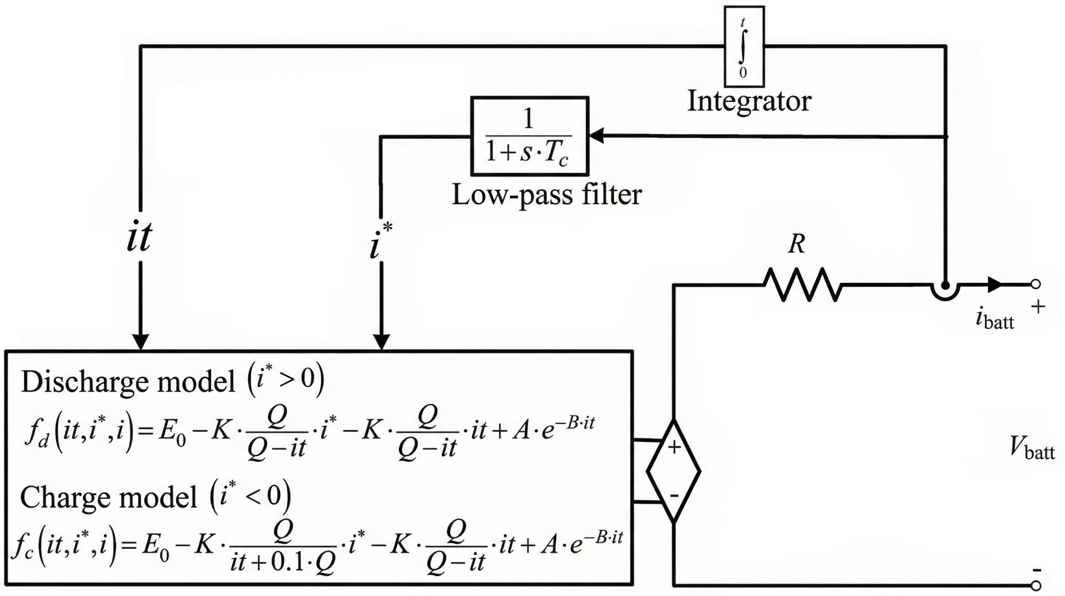


Figure 5.5: Shepherd-based Simulink model schematic of the battery pack.

Figure 5.6 shows the battery pack simulation structure created in the Matlab/Simulink environment based on the Shepherd battery model. This simulation model was created to analyze the battery's terminal voltage, current, and state of charge (SOC) dynamics over time. Within the scope of modeling, the battery pack was examined under variable power demands corresponding to the specified flight mission profile. This allowed the electrical responses of the battery during climb, cruise, and descent phases to be observed separately. Thus, battery behavior was not evaluated only under nominal conditions. Simulation outputs were examined for dynamic conditions close to real flight conditions.

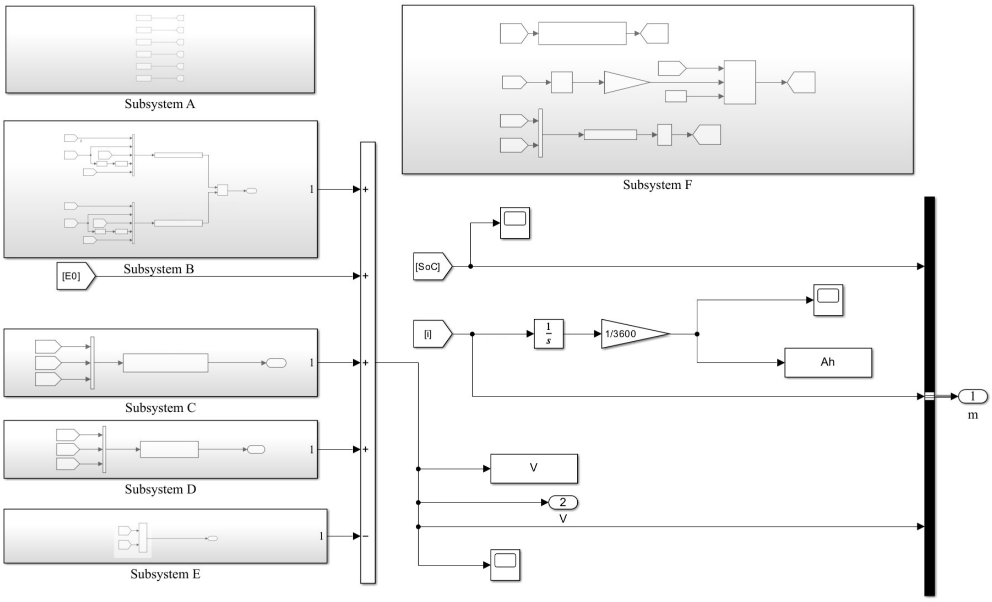


Figure 5.6: Simulink implementation of the Shepherd-based battery pack model.

The results obtained provide the opportunity to analyze the energy management performance of the electric propulsion system at the system level. Figure 5.7 shows the battery pack discharge curve obtained as a result of the simulations performed. This curve reveals the time-dependent change in battery terminal voltage throughout the mission profile.

During take-off and climb phases, a significant drop in terminal voltage occurs due to the aircraft's high power and current requirements. This situation is directly related to the battery's internal resistance and polarization effects. When transitioning to the cruise phase, the voltage change becomes more limited due to the decrease in power demand. At this stage, the voltage profile exhibits a more stable character. The overall shape of the curve obtained demonstrates that the Shepherd mathematical model successfully represents the battery's nonlinear voltage-SOC relationship. Furthermore, the model's dynamic response to sudden load changes has been realistically captured in the simulation environment.

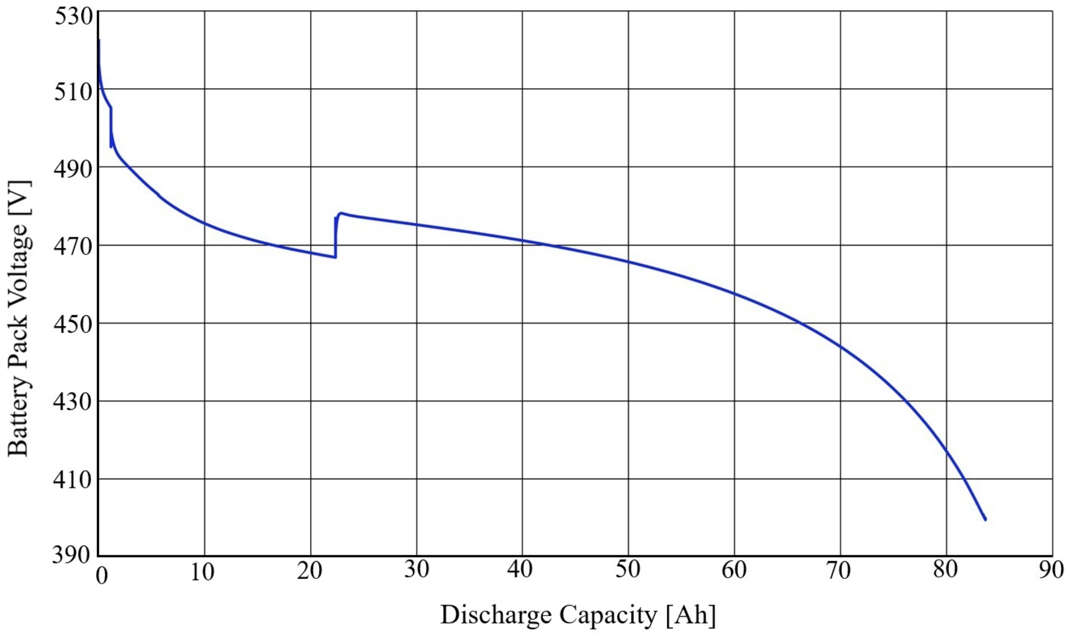


Figure 5.7: Shepherd discharge curve of the battery pack.

Figure 5.8 shows the time-dependent change in the battery pack's state of charge for the same mission profile. The SOC curve numerically represents the amount of energy drawn from the battery during the mission duration. It is observed that the SOC decline rate increases significantly during the take-off and climb phases. The main reason for this is that the motor operates under high power demand during these phases. During the cruise phase, the SOC decline rate decreases to lower levels due to the reduced power requirement. This clearly demonstrates the energy consumption characteristics associated with the mission profile. The SOC level reached at the end of the mission indicates that the selected battery capacity provides sufficient energy reserve for short-range operations. On the other hand, it can be concluded that increasing the battery capacity or hybrid propulsion architectures are necessary for longer-range mission profiles.

In conclusion, the simulation results presented in Figures 5.6, 5.7, and 5.8 demonstrate that the developed Shepherd-based battery model can be successfully integrated into the electric propulsion system. The model accurately represents the time-dependent voltage and SOC behavior of the battery. This provides a reliable analysis infrastructure

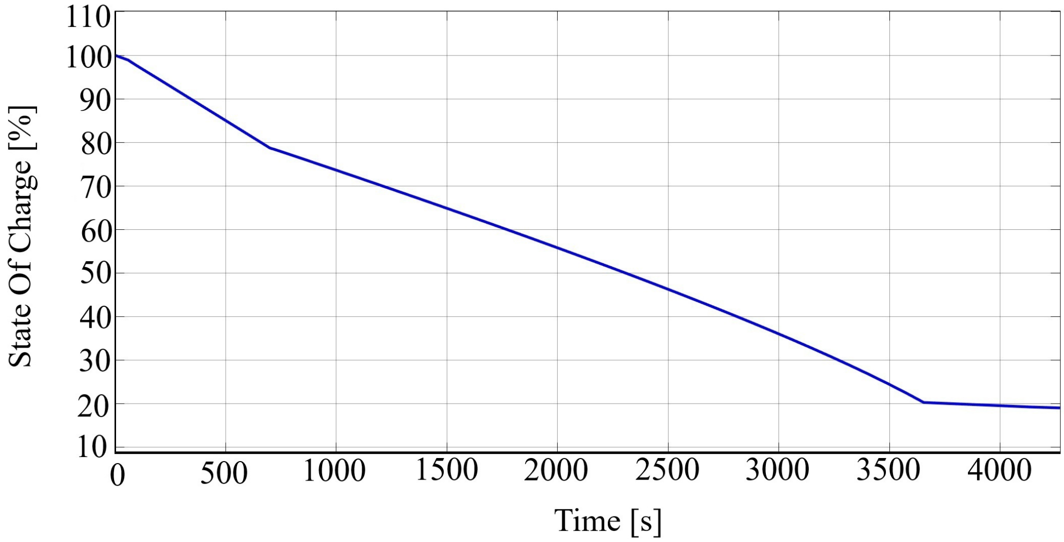


Figure 5.8: State of Charge of the battery pack.

for battery sizing studies. It also makes an important contribution to the evaluation of mission profile-based energy management strategies.

6. CONCLUSIONS

This thesis examines the conversion of a small-class aircraft with a conventional internal combustion engine to a fully electric propulsion system. The conversion process has been comprehensively analyzed in terms of technical, environmental, and economic feasibility. The study is based on the increasing sustainability requirements in the aviation sector. In this regard, the aim was to present a realistic conversion approach using existing technological capabilities. The Tecnam P2008 JC model was selected as the base aircraft. A suitable electric propulsion architecture was designed for this platform, and the battery system was sized. The entire system was modeled using a holistic approach in the MATLAB/Simulink environment. The technical analyses performed have demonstrated the feasibility of the lithium-ion battery-based electric propulsion system. However, this feasibility is particularly valid for short-range and low-passenger-capacity mission profiles. The developed system model was able to meet the power and energy demands required during all phases of flight. It was confirmed that the system parameters remained within safe limits. The battery pack was simulated at the system level using the Shepherd mathematical model. This allowed the terminal voltage, current values, and state of charge (SOC) dynamics to be obtained with high accuracy. This modeling approach enabled reliable performance predictions to be made in the early design phase. Weight analyses revealed the critical impact of the battery system on the total aircraft mass. The specific energy values of current battery technologies are limited. This directly restricts the aircraft's range and payload capacity. Consequently, the applicability of a fully electric configuration for long-range missions remains limited under current conditions. A similar constraint applies to operations requiring high loads. In contrast, electric propulsion systems have been found to offer an effective solution for applications such as short-range regional flights and pilot training.

Environmental impact analyses show that the electric configuration provides significant benefits. Clear advantages have been achieved in terms of carbon emissions and noise levels. The electric flight concept does not produce direct carbon emissions during operation. It also offers much lower noise levels compared to conventional systems. These results are of strategic importance in line with the aviation industry's carbon neutrality goals. However, it should be noted that the overall environmental impact depends on the source of electricity production. An electric aviation ecosystem supported by renewable energy sources will further enhance environmental sustainability.

Economic assessments have proven that electric aircraft provide a significant reduction in direct operating costs. The unit cost of electrical energy is lower than that of aviation fuels. This difference offers significant savings in total energy costs. In addition, electric motors have fewer moving parts than internal combustion engines. This structural simplicity contributes to reduced maintenance and repair costs. However, the initial investment cost of battery systems is high. Furthermore, the limited cycle life of batteries is among the key factors increasing the total cost of ownership. This situation demonstrates that economic feasibility is closely tied to developments in battery technologies.

The Shepherd-based battery modeling used in the thesis has proven to be a suitable approach for system-level simulations. The model has yielded successful results in terms of both computational efficiency and accuracy. Battery behavior has been represented with sufficient precision. Energy consumption and voltage changes associated with the flight profile have been reliably predicted. In this respect, the Shepherd model can be considered an effective engineering tool in the early design stages of electric aircraft projects. The results of the study reveal that current battery technologies are not yet sufficient for the widespread use of the all-electric aircraft concept. Improvements are needed, particularly in specific energy, power density, safety, and cycle life parameters. However, research in battery chemistry and developments in power electronics are progressing rapidly. These advances indicate that current limitations can be significantly reduced in the medium term.

Future studies could explore next-generation battery technologies. The integration of advanced battery chemistries such as lithium-sulfur and lithium-air, which have higher specific energy, into the system should be investigated. The potential effects of these technologies on electric aircraft architectures should be evaluated through comprehensive simulation and experimental studies. Furthermore, the use of hybrid-electric architectures may be preferred to overcome range and payload limitations.

Furthermore, the effects of thermal management systems should be investigated in detail. Battery performance and safety are directly dependent on the management of thermal loads. Managing the heat generated during high-power phases, such as take-off and climb, is critical for system reliability. At the same time, optimization of power electronics, cabling, and energy distribution systems throughout the aircraft is required. These optimization efforts represent an important area of research for future work in terms of reducing total weight and increasing efficiency.

In conclusion, this thesis has demonstrated that the electrification of small aircraft is technically feasible. This conversion has also been shown to be extremely beneficial from an environmental perspective. Due to current technological limitations, the application area is currently limited to short-range missions. However, advances in battery technology and developments in system integration approaches will accelerate the process. The electric aviation concept is expected to reach a wider field of application in the future. In this context, the methods and findings presented are expected to make important contributions to new studies in the field of electric aircraft design.

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