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RESEARCH

Electric Energy Carriers in More Electric Aircraft: Suitability Assessment, Potential Use Case Definition, System Sizing and Fuel Penalty Estimation

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Abstract
The transition toward electrified aviation is driven by the need to reduce the environmental impact of air transport. This study evaluates the suitability of electrical energy storage systems (EESSs), including batteries, flywheels, and supercapacitors, for powering aircraft subsystems in more electric aircraft (MEA). A multi-criteria assessment considering performance, integration, safety, and sustainability identifies supercapacitors as the most suitable option for short-duration applications, batteries for long-duration applications, and both technologies as similarly suitable for medium-duration operations. Flywheels are found to have limited applicability due to safety concerns and integration challenges. A system sizing for representative use cases indicates that fuel-saving potential is highly dependent on the specific energy of the EESS. For a 1500 km mission, a battery system with a specific energy of 0.5 kWh/kg could reduce subsystem fuel consumption by approximately 30% relative to conventional operation, with the reduction increasing to around 70% at 1.0 kWh/kg. Overall, the findings highlight the significant potential of EESSs for next-generation aircraft, provided that continued advancements in energy density and system integration can be achieved.

Keywords More electric aircraft · Electrical energy storage systems · Aircraft subsystems · Suitability analysis · Fuel saving potential · Sustainable aviation

Abbreviations

AEA	All electric aircraft
AES	Aircraft electrical subsystem
BS	Battery system
ECS	Environmental control system
EESS	Electrical energy storage system
FCS	Flight control system
FS	Flywheel system
HEA	Hybrid electric aircraft
IPS	Ice protection system
LIB	Lithium-ion battery
MEA	More electric aircraft
MTOW	Maximum take-off weight
SE	Specific energy
SP	Specific power
ROC	Rate of climb
ROD	Rate of descent
SCS	Supercapacitor system
TRAS	Thrust reverser actuation system
TEA	Turbo electric aircraft
WIPS	Wing ice protection system

Symbols

E	Energy, kWh
EG	Specific energy, kWh/kg
F	Penalty factor
l	Numerical measure
m	Mass, kg
P	Power, kW
p	Points of criterion
PG	Specific power, kW/kg
r	Relative rating
S	Fuel saving potential, %
T	Total criteria points
t	Time, min

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w Relative weighting

Subscripts

AES Subsystem
av Available
d Time domain
E Energy
$EESS$ Electrical energy storage system
f Fuel
fs Fuel saving
i Criterion
j Energy carrier
max Maximum
op Operating
P Power
pen Penalty
req Required
sys System

1 Introduction

Over the past decades, global warming has emerged as a major challenge. The aviation industry is responsible for approximately 2.5% of total CO_2 emissions, with projections indicating a future increase in this number [1, 2]. Therefore, novel aircraft propulsion concepts have been introduced, including the all-electric (AEA), hybrid-electric, turbo-electric, and more-electric aircraft (MEA). In the AEA scenario, the entire energy required for thrust and the aircraft electrical subsystems (AESs) is provided by electrical energy storage systems (EESSs) [3], which can be battery- (BSs), flywheel- (FSs), or supercapacitor-systems (SCSs).

An exploration of future aircraft concepts reveals that, battery systems are most commonly considered for implementation, in advanced electrified aircraft [4–9]. They typically outperform other EESSs with respect to their energy-to-weight ratio (specific energy, SE). Their comparatively lower power to weight ratio (specific power, SP) is offset by the total capacity of the installed BSs. However, the current state of the art (SoA) EESSs still require further advancements in terms of SE to fully cover the energy demands of even short-range civil aircraft [10, 11]. Furthermore, these novel aircraft types are not expected to enter service within the next 15 years [5].

A near term approach to reduce emissions is to replace conventional subsystems with electrical ones, which increases efficiency and reduces weight, resulting in a MEA [12]. Approximately 5% of an aircraft's total power is required to operate its secondary power consumers or subsystems [13]. The AESs in MEA are conventionally powered by generators [14]. Replacing them with EESSs could provide an additional opportunity for fuel savings. This would enable a variety of novel promising use cases across different sections of the aircraft. Especially, the high SP of supercapacitors or flywheel-based systems may be beneficial for power-intense but short-duration applications such as actuation operations. Several studies have already investigated the feasibility of implementing EESSs in aircraft to support propulsion or provide energy to AESs [15–17]. However, a number of constraints must be considered with regards to the performance properties of the various EESSs, including safety, energy density and power density. Moreover, adding mass to the aircraft by implementing energy carriers will result in increased fuel consumption [18]. Therefore, the trade-off between the additional fuel burn, i.e. fuel penalty caused by the mass increase, and the fuel savings due to electrification must be estimated in order to analyze the effective benefit of implementing an EESS. Prior research has also compared the characteristics of various EESS technologies, examining their suitability and performance in aviation applications [17, 19–21]. However, the existing literature still lacks an assessment and comparison of the performance parameters of the proposed energy carriers specifically in the context of powering aircraft electrical subsystems. Furthermore, there is limited discussion on the associated fuel penalty estimations resulting from the additional mass of the EESS within aircraft operations.

Consequently, this study assesses, rates and sizes the aforementioned EESSs, analyzing the suitability of implementing them in MEA. In the following, at first the SoA of the EESSs is presented. Their corresponding properties are outlined and the aircraft's AESs are discussed. Subsequently, the EESSs are rated according to their suitability for powering these AESs. Therefore, relevant aircraft design criteria are derived. Their relative importance is determined using pairwise comparison. Finally, use cases connecting AESs and EESSs are established, a system sizing is performed, and the corresponding fuel penalty is outlined. Finally, the next steps regarding the suitability analysis and potential EESS integration are discussed, along with the associated limitations.

2 State of the Art

2.1 Energy Storage Systems

Replacing conventional subsystems with electrical ones increases an aircraft's total electrical load. The proposed EESSs could cover this increased demand. The different systems rely on distinct energy storage principles and are outlined in Fig. 1. Each system exhibits its own set of

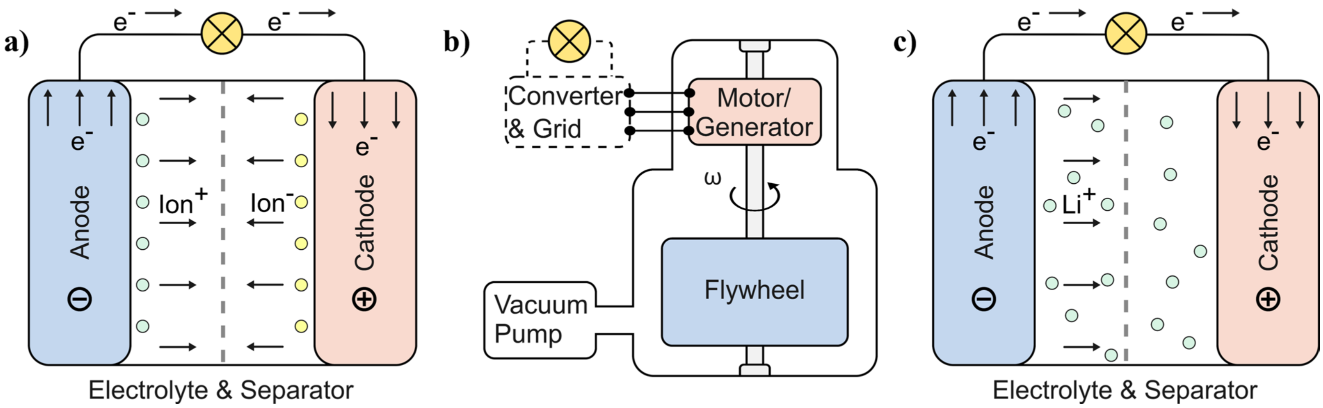

Fig. 1 Schematic depiction of the function principle of three different energy carriers relevant for their implementation in aircraft during discharge a) lithium-ion battery b) flywheel c) supercapacitor

Table 1 State of the art properties of batteries, flywheels and supercapacitors

Property	Unit	Battery cells		Flywheels		Supercapacitor cells	
Specific energy (SE)	Wh/kg	250 − 400	[21]	20 − 80	[26]	1 − 10	[27]
Specific power (SP)	kW/kg	0.3 − 0.5	[21]	1 − 2	[26]	10	[27]
Cycle life	–	103	[28]	$> 10^6$	[28]	$\sim 10^6$	[28]
Self-discharge	%/day	< 0.1	[29]	10 − 100	[22]	0.4 − 5	[30]
Cycle efficiency	%	∼95	[29]	85 − 95	[31]	95 − 98	[32]
Estimated mass overhead	%	25	[11]	50*	[/]	25**	[/]
Response time	s	< 1	[29]	∼0.01	[29]	< 0.01	[29]
Temperature range	°C	- 20 to 65	[22]	- 40 to 40	[22]	- 45 to 85	[27]
Energy cost	$/kWh	100 – 150	[30]	1500 – 6000	[31]	3000	[32]
Maintenance cost	$/kW-year	6	[33]	5	[31]	6	[34]
Recyclability	-	low	[21]	high	[28]	high	[33]
Scalability	-	high	[34]	low***	[/]	high	[33]

*assumption accounts for the requirement to counteract momentum effects using a gyroscope

**assumed to be similar to the overhead of battery systems

***flywheel scalability is considered good for ground applications [35] but system scaling for aircraft appears limited

advantages and disadvantages in terms of their performance parameters, while the most significant are the SP and SE.

The following sections discuss the EESSs, while Table 1 outlines their corresponding properties. It presents the SE and SP of the energy carriers, alongside an overview of their cycle life, daily self-discharge rate, cycle efficiency, cost indicators, response time and operating temperature. In addition, the scalability and recyclability of the systems are outlined. These parameters are later used for assessing the suitability of the energy carriers for aircraft applications. For the discussed EESSs an integration overhead due to additional safety systems is required as also stated in the table. Comparing these parameters aid in determining the suitability of implementing each EESS into MEA. Since both qualitative and quantitative parameters are provided, the overall assessment is performed in a qualitative manner.

2.1.1 Batteries

Rechargeable batteries have become a popular energy storage technology for many of current applications [30, 38]. They are grouped within the electrochemical energy storage systems, and are composed of an anode, a cathode, current collectors and a separator. Furthermore, the elements are typically soaked in an electrolyte. The most common packaging variants are cylindrical, prismatic, and pouch cell housings. Up to the present day, lithium-ion batteries (LIBs) are most commonly used, since they offer the best energy storage capability on the market [21, 22]. Future BSs comprising solid state electrolyte and lithium-sulfur or lithium-air electrode materials are expected to further accelerate the electrification by providing high SE and cycle life [9, 39–41].

The basic operating principle during discharge of a LIB is an oxidation process occurring at the anode side of the cell as displayed in Fig. 1 a). When the reaction process starts, lithium-ions and electrons are released from the anode material's structure. The electrolyte is designed to electrically insulate while offering high conductivity for ion transport [42]. As a result, free electrons are forced to pass through an external circuit, while the ions traverse through the electrolyte and the porous separator. The latter prevents the electrodes from coming into contact with each other, thus avoiding a short circuit. Finally, a redox reaction occurs at the cathode side of the battery, where the free ions and electrons typically form a metal oxide with the LIB cathode material.

Due to their electrochemical nature, LIBs are able to store much higher amounts of energy than compared to other EESSs [21]. However, the relatively long electron transport paths result in only moderate SP for most LIBs. The high SE of BSs makes them especially interesting for electric vehicles, where achieving a minimum battery pack weight at maximum available energy is essential to extend range. The modularity of battery packs benefit their scalability, thereby enabling dynamic adaptation to alternating system requirements [36]. They can store energy for a long time period with low self-discharge, vast availability and relatively low cost [21, 26, 43].

On the contrary, BSs encompass a number of drawbacks which are partially triggered by the chemical process during charge and discharge resulting in cell aging. The aging mechanisms such as lithium plating, corrosion, or electrode cracking can result in reduced capacity, or, in the worst case, cell combustion i.e. thermal runaway [44, 45]. The degradation of the cells is reflected in a relatively low cycle life [46]. Furthermore, they are sensitive to surrounding conditions such as alternating temperatures, which may even accelerate cell aging or trigger thermal runaway. The integration of a thermal management system and battery management system is therefore mandatory to ensure constant temperature conditions, prevent malfunction, and ensure the longevity of the system. Addressing thermal runaway is essential when designing BSs but would exceed the scope of this paper.

2.1.2 Flywheels

Flywheels are mechanical energy storage systems based on the principle of applying momentum to a rotor [26], which is located within an enclosure as shown in Fig. 1 b). Energy is supplied to the rotor by means of a motor or a mechanical shaft. When extracting energy, the motor is switched to generator mode to transform the rotational kinetic energy to electrical energy. The rotation of the flywheel, and therefore its stored energy, is highly susceptible to friction. A vacuum pump and magnetic bearing are therefore used to reduce friction, with the aim of minimizing self-discharge and enhancing efficiency [23, 28].

The primary benefits of FSs are their ability to absorb and release substantial amounts of power instantaneously, while exhibiting a relatively high cycle efficiency [21]. At the same time, the system has a high response time, which enables flexible and fast storage [26]. Novel rotor materials enable FSs with SE in the range between the ones of SCSs and BSs. They also exhibit a very high cycle and calendar life, while showing a low environmental impact when compared to other EESSs [47]. Moreover, maintenance costs are minimized by the modular architecture of the system, which allows individual components to be replaced independently [48]. Lastly, the lower temperature limit at which the FSs can operate appears to be an advantage over BSs [21].

FSs are also associated with a number of weaknesses. In contrast to their high SP, they are limited in terms of their SE especially in terms of their scalability once the system is manufactured. The high speed of the rotor exhibits the risk of material failure, increasing the demand in safety measures, particularly in aviation applications [47]. Additionally, the complex structure of the system leads to high investment cost [31]. The rotating system suffers from self-discharge due to friction, as discussed above. In addition, the negative effect of rotor moment on the aircraft trajectory needs to be addressed in detail [49]. In the context of FSs, Dever et al. [50] predict a surge in the utilization of flywheels, attributable to the advent of innovative materials that yield a high SE. This development suggests that FSs may eventually exceed the performance of BSs. However, due to material scaling limitations this development appears to be of theoretical nature for now.

2.1.3 Supercapacitors

Supercapacitor energy storage systems are classified as electrostatic energy storage systems, despite potentially benefiting from electrochemical processes at the interface between electrode and electrolyte. They primarily store energy through electrostatic charge separation between electrode and the electrolyte, building an electric double layer at each electrode [26]. However, they may also involve fast, surface-confined electrochemical reactions, especially in pseudocapacitive or hybrid designs [51]. The electrodes may be composed of porous carbon electrodes, while those of pseudocapacitors are usually composed of metal oxides or conductive polymers [52]. SCSs are based on the principle of a classical capacitor, while also making use of free-moving ions within an electrolyte. The devices generally comprise two electrodes and an electrolyte, which are separated by a membrane, as illustrated in Fig. 1 c). Applying a voltage across the two electrodes of a supercapacitor results in electrons migrating towards the electrode connected to the negative terminal. Simultaneously, the opposite electrode becomes positively charged due to a deficit of electrons. Negatively charged ions in the electrolyte then accumulate at the positive electrode, while positively charged ions accumulate at the negative electrode [53]. The most commonly utilized electrolyte is of aqueous type which solves ionic salts, consisting of cations and anions, in water. Advanced electrolyte types such as organic, ionic liquid and others are used each enhancing different properties of the SCS, including safety, SE or temperature sensitivity [54]. After disconnection of the power source and connection of a consumer load, electrons traverse the load, thereby transferring their stored energy. The ions, on the other hand, are released back into the electrolyte.

The large surface area of the electrode material enables extensive ion accumulation. This allows SCSs to achieve a higher SE than regular capacitors while maintaining a high SP [55, 56]. As commonly no active storage of ions within the electrode material happens, these SCSs show a much higher cycle life than BSs as no degradation process is initiated [24]. Additionally, SCSs are able to operate within a comparatively wide temperature range, while exhibiting a very fast response time [57]. Similar to BSs, they can be incorporated into modules and packs, making them ideal for scaling up to high-power applications, while also being vastly available [24, 35]. Furthermore, supercapacitors are typically not composed of hazardous materials, and their components can be recycled [35, 58].

Conversely, as the charge in electric double layer SCSs is not chemically bound its SE is rather low [57]. However, pseudo-, hybrid-, and asymmetric capacitors aim to achieve specific energy values in the double-digit Wh/kg range while retaining high specific power, although their performance is inherently governed by the trade-off between specific energy and specific power [51]. Moreover, exceeding the operational temperature limits results in rapid self-discharge, while overcharging can lead to irreversible degradation or destruction of the SCS [24, 27]. In addition, high-capacity SCSs may also pose a fire hazard. Therefore, cell balancing and power management is required to maintain a stable operation. Apart from the temperature, additional discharge-mechanisms discussed by Jagadale et al. [29] may negatively affect the energy storage capability of a supercapacitor.

2.2 Aircraft Subsystems

In the context of aircraft electrification, the focus lies on the replacement of primary and secondary aircraft systems with electrical ones. This enhances efficiency on the one hand and can reduce system weight on the other [59–61]. In order to facilitate the near-term emission mitigation of conventional aircraft, it can be reasonable to replace conventional subsystems with electrical ones and supply energy demands using EESSs, as explained in Sect. 1.

The AESs are integrated into the aircraft's electrical architecture, which includes all the necessary elements to operate them. However, the overall dimensions of the architecture depend mainly on the power consumers, i.e. the required electrical power and time of operation of the AESs, as outlined by Chakraborty [62]. Therefore, a thorough understanding of these parameters is required to design the overall system architecture.

Based on their operating time, AESs can be categorized into three groups: short-duration for systems operating for a few seconds up to one minute, medium-duration for systems operating for several minutes up to 15 min, and long-duration for systems operating for durations beyond that. The energy requirements for the respective AESs can then be determined by the system's corresponding operating time and power demand. An overview of representative AESs is outlined in Fig. 2.

The thrust reverse actuation, landing gear actuation, door actuation, and brake actuation system, along with the engine starter are relevant systems for short-duration operations. With the goal of enhancing efficiency and safety, hydraulic actuation system are replaced with electromechanical ones, with the first commercial implementations already in use [60, 64]. With respect to the engine starter, an electric

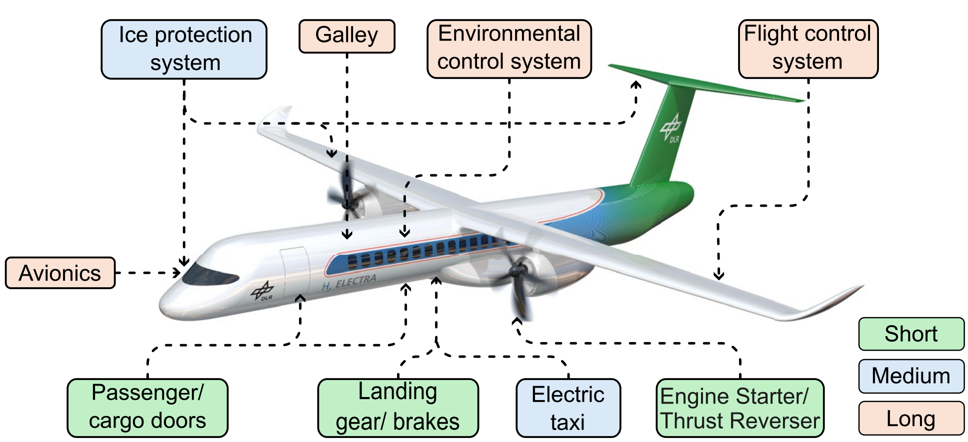

Fig. 2 Position of the various aircraft subsystems within the aircraft; Color coding defines operating time domain: green = short-duration (t ≤ 1 min), blue = medium-duration (1 min < t ≤ 15 min), red = long-duration (15 min < t); Aircraft rendering adopted from [63]

motor is utilized instead of using pressurized air [64]. When considering medium-duration operations, the aircraft's ice protection system (IPS) and electric taxiing system can be regarded as relevant electrical loads. The former may be realized with different methods, however, the implementation of electrothermal mats within the surfaces prone to icing is considered to be the most energy efficient solution [64, 65]. The affected zones are heated depending on weather conditions and within the defined icing envelope, which extends from sea level up to an altitude of approximately 7 km [66]. The conventional method of aircraft taxiing relies on the use of idle thrust from the aircraft's turbines, a practice widely regarded as inefficient and resulting in comparatively high fuel consumption [15, 67, 68]. Consequently, the implementation of electric taxiing for aircraft was proposed [69]. Various studies were already conducted to investigate the feasibility of utilizing EESSs for the execution of the taxiing operation [16, 67–69]. Finally, the long-duration domain encompasses the environmental control system (ECS), the avionics, the flight control system (FCS), as well as miscellaneous systems such as the galley and aircraft lighting [70].

As a result of the aircraft electrification, it is essential to estimate the electrical energy requirements at an early stage of the design process. Consequently, it is necessary to have a reasonable knowledge of electrical energy required for each system of the aircraft. Several studies addressed this topic with Murray et al. presenting an early report estimating power requirements and potential weight savings for a long range aircraft [71]. Chakraborty et al. presented a study on power estimations, in which they proposed a physics-based approach to determine the power requirements of aircraft subsystems [64]. Lampl et al. provided a parametrized sample mission profile for a single-aisle commercial aircraft [70]. Voth et al. approximated power requirements for various phases of a flight for several subsystems and aircraft types. Their analysis outlined data on the power demand of key subsystems, including the ECS, FCS, and IPS [72]. Finally, Johnson outlined the general progression of the power curve during the operation of a thrust reverser actuation system [60].

3 Methodology

The primary objective in system design is to identify the optimal solution to the problem at hand. Given the existence of multiple possible solutions, a methodical approach is required to support the solution-finding process and to enhance the objectivity of decision-making. Various methodologies, based on different underlying principles, have been developed to achieve the defined objectives [73–75]. Due to the early stage with respect to the design process of this study an evaluation approach allowing a preliminary suitability estimation is required [73]. A general evaluation process is shown in Fig. 3. One approach to address this issue is to establish evaluation criteria against which the energy carriers are benchmarked [76]. The criteria must align with the overall aircraft design requirements, as their fulfillment is a prerequisite for ensuring the airworthiness of the system. After the criteria have been obtained, their relative importance with respect to the operating time domains is determined by means of pairwise comparison. Each EESSs is then rated with respect to each criterion and time domain, resulting in an overall suitability rating for the energy carrier.

3.1 Aircraft Design Criteria

The design requirements of any product reflect the demands of the respective stakeholders. When it comes to aircraft, high performance, stringent safety standards, straightforward integration and low costs are essential. Furthermore, the environmental impact of any system should play a considerable role in the design process. As a result, the following criteria are established, which follow the general guideline, of deriving aircraft respective criteria outlined by Sadraey and previous studies from Franke et al. and Kazula et al. [76, 78, 79].

1. *Short Term Performance (ST):* This criterion includes the system's power handling ability. Absorbing and releasing large portions of electrical power is a key aspect here. This goes along with a short discharge time and low energy loss during a cycle. An excellent dynamic

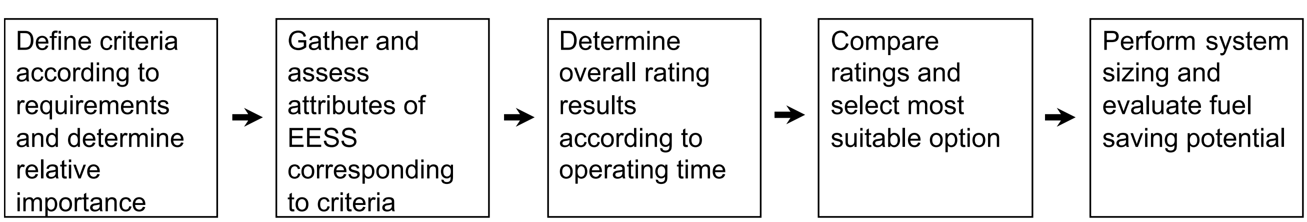

Fig. 3 Evaluation process for rating the suitability of implementing different energy carriers as for supplying energy to subsystems, adopted from Kazula [77]

adaption to system fluctuations, including a quick buffer functionality increases this rating.

2. *Long Term Performance (LT):* The main focus of this criterion is the time independent provision of large quantities of energy to the power consumer. This includes the ability of storing energy over a long time period without substantial losses.
3. *Ease of Integration (I):* The implementation of EESSs in aircrafts is important for a seamless aircraft operation. Therefore, the installation space, the effort of installation and the possible interaction with other parts of the aircraft are covered by this criterion and a low weight. An easy and flexible mounting, with low infrastructure requirements will have a positive effect on this rating.
4. *Safety (S):* One of the most important aspects in aviation is the safe and reliable operation of an aircraft. This criterion considers the liability of the system against failure and the corresponding probability and severity. Also, the system's vulnerability to external influences is implied here.
5. *Cost (C):* The cost criterion consists of the development, production and the maintenance costs. The rating is affected by the maturity of the technology and the estimated development costs. A low manufacturing and operational costs, a good maintainability, robustness, long term stability, durability and low corrosion will increase the rating. Likewise, the degradation, shelf life, and cycling behavior are considered here.
6. *Sustainability (U):* The main objective of implementing EESSs in aircrafts is to reduce greenhouse gas emissions, with the goal to reduce the aircraft's environmental impact. Consequently, the potential impact of the EESS on the environment in terms of lifetime, materials used, and recyclability are included here.

3.1.1 Criteria Weighting

The relative importance of each criterion is determined by means of pairwise comparison [80]. The importance of each criterion in a given row is compared sequentially with the criteria in each column. The relative importance is defined as *0* for *less important*, *1* for *equally important*, and *2* for *more important*. A finer resolution of these values can be introduced in later stages of the development process, once the system's boundary conditions are characterized [73]. Subsequently, the total number of points $p_{i,d}$ for each criterion is computed and divided by total amount of possible points T resulting in the relative weighting $w_{i,d}$ of the corresponding criterion as shown in Eq. 1. The subscript i corresponds to the criterion while d is associated to the time domain.

$$w_{i,d} = \frac{\sum p_{i,d}}{T} \tag{1}$$

Table 2 presents the results of the relative criteria rating. They were obtained through the individual weighting of the criteria by several engineers familiar with the field. The color coding serves to emphasize the relative importance assigned to each criterion with respect to the various time domains. Green denotes the weighting for short-duration operations, blue for medium-duration operations, and red for long-duration operations. Based on the weight analysis, short- and long-term performance emerged to be the most influential criteria, depending on the operating time. At the same time, it revealed that system safety is a dominating factor in the overall assessment as well.

3.1.2 Relative Rating

In order to quantify the overall fulfilment of the EESS's properties corresponding to the evaluation criteria, a numerical measure $l_{i,j}$ is introduced. While j corresponds to the rated EESS, the subscript i again corresponds to the criterion. This measure ranges from *very bad* (*0*) to *very good* (*4*) and describes how well the properties of an individual EESS fulfils each criterion. As a preliminary suitability estimation is performed in this study, this rating scale is defined in a relatively coarse manner [80]. To enhance the comprehensibility of the evaluation process, symbols are employed to

Table 2 Relative criteria importance weighting according to the defined time domains using pairwise comparison

Criteria	Shor Term Performance (ST)			Long Term Performance (LT)			Ease of Integration (I)			Safety (S)			Cost (C)			Sustainability (U)			Rel. weighting $w_{i,d}$		
ST	-	-	-	2	1	0	2	2	0	1	1	0	2	2	0	2	2	1	0.30	0.27	0.03
LT	0	1	2	-	-	-	0	2	2	0	1	1	0	2	2	1	2	2	0.03	0.27	0.30
I	0	0	2	2	0	0		-			0			1			2		0.17	0,10	0.17
S	1	1	2	2	1	1		2			-			2			2		0.30	0.27	0.30
C	0	0	2	2	0	0		1			0			-			1		0.13	0.06	0.13
U	0	0	1	1	0	0		0			0			1			-		0.07	0.03	0.07

Color coding: green = short-duration (t ≤ 1 min); blue = medium-duration (1 min < t ≤ 15 min); red = long-duration (15 min < t) Values: row criterion is more important than column criterion = 2, equally important = 1, less important = 0

Table 3 Numerical and symbolic measures representing the fulfilment of a criterion

Fulfilment	Value ($l_{i,j}$)	Symbol
very good	4	+ +
good	3	+
average	2	o
bad	1	–
very bad	0	– –

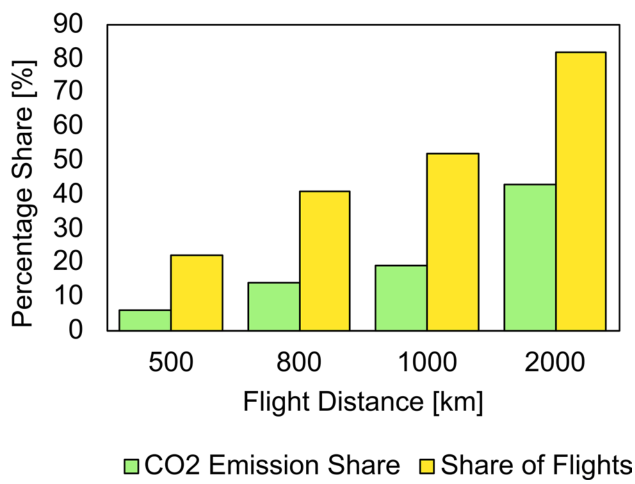

Fig. 4 Share of aviation related emissions and share of flights with respect to flight distance in 2019 [2]

represent the numerical measures. The two different variants are outlined in Table 3.

After assessing the fulfilment of the EESS's attributes with respect to each criterion, the overall suitability rating is performed by means of Eq. 2. Therefore, the numerical measure $l_{i,j}$ is multiplied by the relative weighting $w_{i,d}$ and scaled to a range of 0 to 1 by dividing it by l_{max}, the maximum possible fulfilment (=4). The relative rating $r_{j,d}$ for each EESS and time domain is then determined by computing the sum of all relative criterion ratings for each energy carrier for the given time domains [80].

$$r_{j,d} = \sum_{i=1}^{k} w_{i,d} \cdot \frac{l_{i,j}}{l_{max}} \tag{2}$$

4 Reference Data

The share of flights according to flight distance is presented in Fig. 4, alongside the corresponding share of emissions. It indicates that the majority of flights worldwide are regional or short-haul, including distanced of up to 2000 km, and accounting for around 43% of the industries CO_2 emissions. Consequently, it seems particularly promising to address this segment of the industry for energy storage applications.

Table 4 Assumed flight data for a short-range narrow body aircraft with cruise altitude of 10 km; approximation based on [64, 82, 83]

Flight Phase	ROC/ROD [m/s]	Velocity [m/s]	Distance [km]	Time [min]
Climb	10	150	150	17
Cruise	–	224	1100	82
Descent	6	150	250	28

ROC = rate of climb, *ROD* = rate of descent

Hence, the Airbus A320 is used as reference aircraft as it is utilized for the corresponding mission distances similar to those in the graph [81].

Table 3 Numerical and symbolic measures representing the fulfilment of a criterion.

In order to obtain the energy consumed by an AES, its operating time has to be estimated. With regard to short-duration applications, the operating time does not depend on the flight length, but is determined by the time required for operation e.g. actuation. The landing gear for example is retracted/ extracted within a few seconds during takeoff and landing [64]. Energy requirements for medium- and long-duration operations, with the exception of electric taxiing, are typically determined with respect to the aircraft's mission profile. Consequently, a simplified and approximated sample mission profile for a range of 1500 km is provided to aid in estimating energy requirements. For simplicity, it is assumed that the rate of climb (ROC), rate of descent (ROD) and aircraft velocity are constant during each flight phase. The data has been approximated based on the mission profile provided by Karadotcheva et al. [82]. Table 4 illustrates these assumptions along with the resulting operating times and flight distances for each flight segment. The results are of a similar magnitude to those assumed by Chakraborty et al. [64].

The fuel penalty associated with carrying additional mass, such as that of an EESS, is derived from data provided in the Airbus Operating Manual [84]. This manual specifies the fuel penalty that applies when the maximum takeoff weight (MTOW) is exceeded. In the described scenario, the MTOW (around 77 t in case of the Airbus A320 aircraft) was exceeded by 1%. According to this data, the aircraft consumes approximately 82 kg of additional fuel per 1 ton of extra weight over a distance of 1000 nm. Thus, for the defined mission range of 1500 km (≈ 810 nm), the corresponding fuel penalty factor is $F_{pen} = 0.06642$ kilogram extra fuel per kilogram of additional weight carried by the aircraft. In the following, it is assumed that the fuel penalty relationship is linear up to a MTOW exceedance of 2%. Since the fuel penalty parameter is provided by the aircraft manufacturer without an explicit upper bound, the assumption should be validated in future studies using a more refined aircraft model. While exceeding MTOW is typically not permitted without certification changes, future aircraft designs may incorporate EESSs as part of the baseline mass budget. In such cases, the system's weight would be accounted for during the design phase, potentially enabling a net fuel saving without violating operational limits. The results of this work provide a first benchmark to quantify the potential benefits of integrating EESS into MEA.

The system mass of the EESS under investigation is determined by means of Eqs. (3–6). First, the required energy E_{req} is calculated as the product of the required subsystem power P_{AES} and its operating time t_{op} (Eq. 3). Two constraints must be evaluated in order to ensure that the system can supply both sufficient energy and sufficient power. Firstly, the power-dependent mass m_P is obtained by dividing the required power P_{AES} by the specific power of the energy carrier PG_{EESS} (Eq. 4). Secondly, the energy dependent mass m_E is computed by dividing the required energy E_{req} by the specific energy EG_{EESS} (Eq. 5). The overall system mass m_{sys} is then defined as the greater of the two values, ensuring that both requirements are met (Eq. 6).

To assess the additional fuel consumption caused by carrying the EESS's mass, Eqs. (7–10) are applied. The saved fuel mass m_f, which represents the amount of jet fuel that would otherwise be required to supply E_{req}, is calculated by dividing E_{req} by the specific energy of jet fuel EG_f (Eq. 7). The available SE of jet fuel can be approximated as 5.7 kWh/kg, assuming 50% combustion efficiency and 95% generator efficiency [4, 61, 85]. The fuel penalty due to additional weight is then obtained by multiplying the difference of the system mass and fuel mass $(m_{sys} - m_f)$ with the fuel penalty factor F_{pen} (Eq. 8). The saved fuel mass m_{fs} is determined as the difference between the fuel mass and the fuel penalty mass. The net fuel effect is classified as a fuel saving if $m_{fs} > 0$, and a fuel penalty if $m_{fs} < 0$ (Eq. 9.1 and 9.2). The fuel saving potential S can be estimated by determining the percentage ratio of fuel saving m_{fs} and fuel mass m_f (Eq. 10).

$$E_{req} = P_{AES} \cdot t_{op} \tag{3}$$

$$m_P = \frac{P_{AES}}{PG_{EESS}} \tag{4}$$

$$m_E = \frac{E_{req}}{EG_{EESS}} \tag{5}$$

$$m_{sys} = \max\left(m_E, m_P\right) \tag{6}$$

$$m_f = \frac{E_{req}}{EG_f} \tag{7}$$

$$m_{pen} = \left(m_{sys} - m_f\right) \cdot F_{pen} \tag{8}$$

$$m_{fs} = m_f - m_{pen} \tag{9.1}$$

$$f\left(m_{fs}\right) = \begin{cases} saving, m_{fs} > 0 \\ penalty, m_{fs} < 0 \end{cases} \tag{9.2}$$

$$S = \frac{m_{fs}}{m_f} \cdot 100\% \tag{10}$$

It is important to note that this analysis of fuel penalties is based on theoretical assumptions and a simplified mission profile. To validate the results and enhance the accuracy of the data, a comprehensive mission profile must be developed. This profile should include detailed flight phases, such as taxiing, take-off and climbing, as well as evaluations of altitude, speed and weight, and environmental conditions. At a later stage, this data can be benchmarked against the results of experimental tests on a demonstrator.

Furthermore, the fuel savings quantified in this study represent only the direct reduction in fuel consumption over the specified mission range. A comprehensive assessment of the environmental benefits associated with EESS implementation requires consideration of the entire lifecycle of the energy carriers involved. This includes comparing the emissions generated during the production of batteries and jet fuel, as well as evaluating the carbon intensity of the electricity used to charge the EESS. Consequently, a lifecycle assessment is necessary to determine the overall environmental impact and potential emissions reduction of the proposed electrification concept.

5 Results and Discussion

5.1 Suitability Assessment

The properties of the EESSs discussed in Sect. 2.1 of this study are now used to assess their overall suitably in terms of their implementation in MEA. Table 5 summarizes the results of the relative EESSs rating with respect to the defined time domains. To derive the numeric grading the fulfilment for each energy carrier with respect to each criterion is evaluated. Therefore, the properties that define the EESSs with respect to each criterion are listed in tabular form. Finally, the relative rating is obtained using Eq. 2, while again color coding represents the time domains.

The results of the numeric grading are visualized in Fig. 5 by means of radar charts. This provides a first impression of the EESS's associated suitability performance. A comparison of the charts reveals the respective strengths and weaknesses of the energy carriers. While batteries and flywheels exhibit several limitations, supercapacitors perform better with respect to most criteria. However, BSs

Table 5 Relative Rating of the energy carriers according to the aircraft design criteria with respect to the time domains

Criteria	Battery (BS)	Flywheel (FS)	Supercapacitor (SCS)
Short Term Performance $w_{1,d}(0.30, 0.27, 0.03)$	moderate SP, moderate reaction time o	high SP, fast rection time +	very high SP, very fast reaction time + +
Long Term Performance $w_{2,d}(0.03, 0.27, 0.30)$	high SE, excellent long-term storage, low self-discharge + +	moderate SE, high self-discharge –	very low SE, self-discharge –
Ease of Integration $w_{3,d}(0.17, 0.10, 0.17)$	modular configuration, thermal and energy management required o	compensation of rotor inertia required, bulky design, safety and control equipment required –	modular configuration, implementation of energy management required o
Safety $w_{4,d}(0.30, 0.27, 0.30)$	risk of fire due to thermal runaway, sensitive to external influences, emergency energy storage o	severe safety hazard due to material rupture, high resilience against external influences, fast response power supply o	no risk of thermal runaway, fast response power supply +
Cost $w_{5,d}(0.13, 0.06, 0.13)$	available, high TRL, mass production, exchange every few months, exchange of whole module possible +	high manufacturing cost, low maintenance cost, easy part exchange, rare system replacement +	vastly available, high TRL, mass production, exchange after years, exchange of whole module possible +
Sustainability $w_{6,d}(0.07, 0.03, 0.07)$	relatively short lifetime, resource extraction harmful, recycling difficult –	almost infinite lifetime with maintenance, no hazardous materials, good recyclability +	long lifetime, almost no hazardous materials +
Relative rating $r_{j,d}$	0.53 / 0.65 / 0.67	0.58 / 0.51 / 0.44	0.77 / 0.67 / 0.57

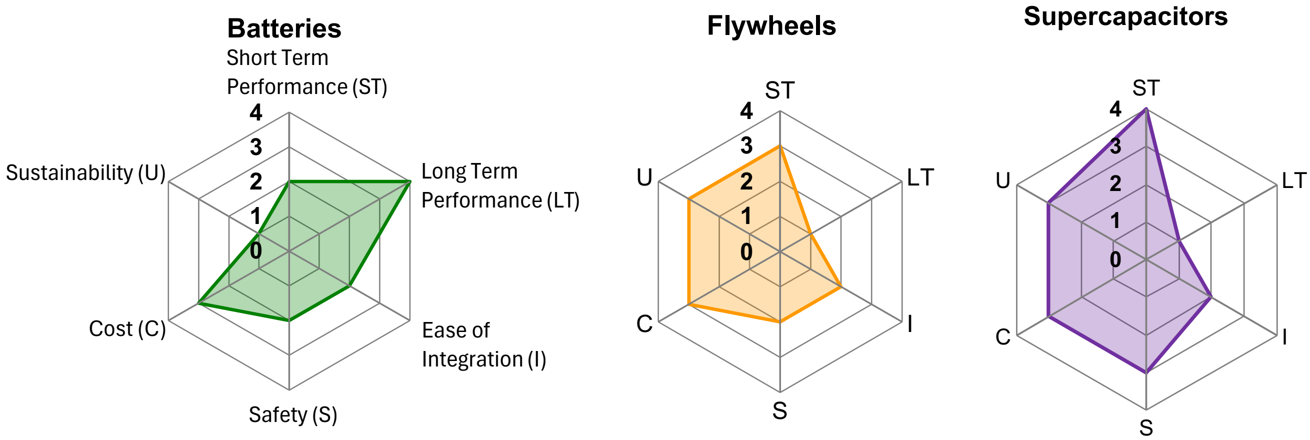

Fig. 5 Radar chart visualizing the resulting numerical measure for each energy storage system with respect to the different criteria, to highlight strengths and weaknesses

excel significantly at storing energy. Conversely, SCSs outperform all other systems at delivering power.

For further assessing the performance of the EESSs, utility charts are utilized, where each EESS is represented by a bar chart as depicted in Fig. 6. The height of the bars represents the numerical measure $l_{i,j}$ and indicates how well the EESS's properties fulfil the respective criteria. The relative importance (weighting) $w_{i,d}$ assigned to the criterion depending on the time domain determines the bar width. The covered area of each plot reflects the percentage by which the energy carrier meets all criteria, which is equal to their relative rating $r_{j,d}$. According to the results, batteries outperform all other systems in terms of long-duration operations, while the same holds true for supercapacitors in the realm of short-duration applications. In the medium-duration domain, both SCSs and BSs perform similarly well.

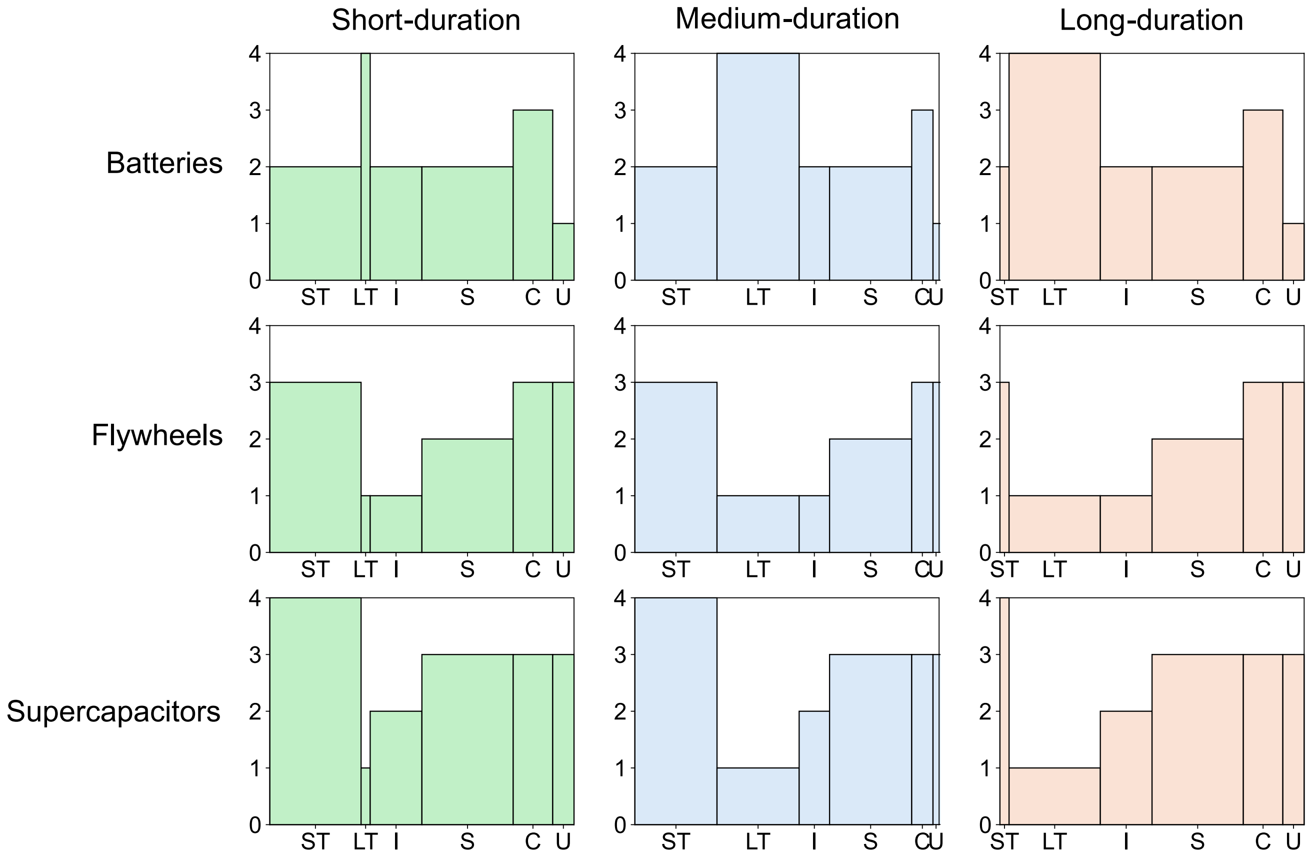

Fig. 6 Utility plots illustrating the results of the relative weighting of the three EESSs by considering the relative importance according to the different time domains

Flywheels on the other hand show limited performance and lag behind the other systems. Thus, in the following system sizing FSs are omitted from consideration.

5.2 System Sizing

In the following, the feasibility of implementing BSs and SCSs for operating AESs in MEA is determined by computing the fuel penalty. If the fuel penalty is greater than the amount of fuel saved by the energy carrier, the integration is considered to be unreasonable. Therefore, three representative use cases are established, one for each time domain. The data corresponding to the use cases is derived from the literature. The cases are selected based either on data availability or on the consistency of the results reported across multiple references. Another reason for selecting these cases is that all of them operate during flight phases when the aircraft's electric generator is running at or near its maximum capacity, i.e. during take-off and landing. Thus, the thrust reverse actuation system (TRAS) based on the data from Johnson [60] is selected for short-duration operations. For medium-duration applications, the IPS with focus on the aircraft wings (WIPS) is selected based on data from Voth et al. [72]. Lastly, the ECS is chosen for sizing the energy carrier for long-duration operating systems also by data from Voth et al. [72]. For simplicity reasons, the power demand associated to the selected AESs is assumed to be constant over the operating time.

Table 6 Assumed data for energy carriers, fuel, fuel penalty and time in icing envelope

Parameter	Battery	Supercapacitor	Jet fuel	Units / notes
Specific energy	0.4	0.01	5.7	kWh/kg
Specific power	0.5	10	–	kW/kg
Penalty factor	–	–	–	0.06642 kg fuel/kg extra weight*
Time icing period	–	–	–	12 min**

*fuel penalty factor for 1500 km mission range based on [84]

**icing envelope defined by EASA CS-25 [60] and time computed for climb using ROC from Table 4

The fuel saving potential is determined based on Eqs. (3) to (10), in the following. The required data for computation is given in Table 6. For both the BSs and SCSs the upper limit in terms of their specific energy and specific power is taken from Table 1. It should be noted that SE and SP are assumed at the pack level, while cycle efficiency losses are neglected. Consequently, the considered values represent optimistic assumptions for future pack-level performance and are primarily guided by current cell-level characteristics. Achieving such performance at the pack level would require significant technological advancements, including higher cell-level energy densities, highly efficient and lightweight thermal management systems, and advanced containment solutions for the EESS.

The results of the system sizing for the defined mission range of 1500 km are summarized in Table 7. When the EESS is sized based on peak power demand, the resulting energy capacity exceeds the subsystem's nominal energy requirement. The fuel savings reported in such cases assume that this surplus electrical energy is effectively utilized by other aircraft electrical loads. This implies a holistic energy management strategy consistent with the vision of a more electric aircraft. As the ratings in the medium-duration time domain are comparable for both BSs and SCSs, sizing was performed for both system types. For high-power TRAS operation, only the SCS is considered, whereas for high-energy ECS operation, only a BS is sized. For each of the presented cases, the available energy E_{av} and available power P_{av} are derived from the resulting system mass.

For the TRAS case, the mass of the SCS is determined by the specific power. Consequently, the available power matches the required power, while the available energy exceeds the demand. A comparison of the fuel penalty with the saved fuel mass shows that the former is greater than the latter. Thus, the additional fuel burned due to the increased system mass outweighs the fuel savings enabled by the EESS. Sizing an SCS in the WIPS case, the system mass is governed by the specific energy. However, the resulting fuel penalty still exceeds the saving by far. In the case of sizing the BS for the WIPS, the energy carrier mass is determined by the SP. This configuration performs much better than the SCS and the associated saving exceeds the penalty, resulting in a net fuel saving. Finally, in the case of a BS sizing for the ECS, the EESS mass is governed by the SE. In this scenario, the resulting the achievable saving is larger than fuel penalty as well. In this scenario, the resulting EESS mass is approximately 1.3% of the MTOW of the considered aircraft. This suggests that the EESS mass could be increased to support operation of the environmental control system for a 2000 km mission while remaining within the 2% mass margin.

The results reveal that the fuel penalty is primarily governed by the system's energy density, whereas dimensioning based solely on power density is of limited relevance. Although the required power must still be met, the overall fuel reduction ultimately depends on the energy density of the EESS. In the cases where the system is sized based on power demand, surplus energy capacity can always be used to power additional AESs. Consequently, the energy carrier must exhibit a sufficiently high SE to ensure that the additional fuel consumed due to its mass remains lower than the fuel savings it enables.

The fuel-saving potential, which indicates the potential fuel reduction for operating an AES with EESSs, as a function of the energy carriers' SE is illustrated in Fig. 7 for various mission profiles ranging from 500 to 2000 km. The trend follows Eq. 10. For the additional mission profiles considered, the cruise segment of the 1500 km reference profile was adjusted accordingly. Negative values of the ratio indicate that more fuel is burned than saved, whereas positive values denote a net fuel-saving potential. The horizontal line at zero on the y-axis represents the transition from a net fuel penalty to a potential net fuel saving.

An examination of the trends reveals that a pack level SE of approximately 0.13 kWh/kg is required to reach the break-even point for a 500 km mission profile. For a 2000 km scenario, however, a significantly higher pack level SE of approximately 0.47 kWh/kg is necessary. In

Table 7 Energy storage system sizing for thrust reverse actuation (short-duration), wing ice protection (medium-duration) and environmental control system (long-duration); power requirement and operating time based on data from [60, 72] or was derived from the mission profile in Table 4

Parameter	Symbol	Unit	Thrust Reverser Actuation (Supercap.)	Wing Ice Protection (Supercap.)	Wing Ice Protection (Battery)	Environmental Control (Battery)
Operation time	t_{op}	min	0.05	11.7	11.7	126.3
Operating power	P_{AES}	kW	27	25	25	200
Req. energy	E_{req}	kWh	0.02	4.86	4.86	421
Mass (power)	m_P	kg	2.7	2.5	50	400
Mass (energy)	$_E$	kg	2.3	486.1	12.2	1052.4
System mass	m_{sys}	kg	2.7	486.1	50	1052.4
Av. Energy*	E_{av}	kWh	0.03	4.86	20	421
Av. Power*	P_{av}	kW	27	4861.11	25	526.21
Fuel mass	m_f	kg	0.005	0.85	3.51	73.85
Fuel penalty	m_{pen}	kg	0.18	32.23	3.09	64.99
Add. fuel burn	m_{fs}	kg	-0.17	-31.38	0.42	8.86

*The available power and energy are determined depending on whether the mass was power- or energy-depending (see Eq. (6))

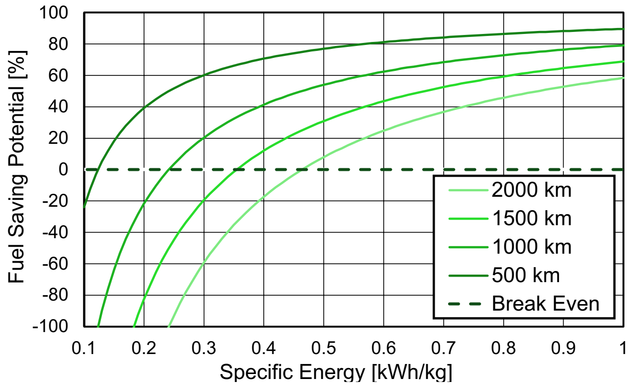

Fig. 7 Fuel saving potential as a function of the specific energy for several mission profiles

case of the 1500 km mission profile, assuming an SE of 0.5 kWh/kg for an EESS results in an estimated fuel saving, for operating an AES compared to a conventional scenario, of approximately 30% due to the integration of the EESS. Furthermore, if an SE of around 1.0 kWh/kg can be achieved, an AES fuel-saving potential of up to approximately 70% becomes feasible for this mission range. Gravimetric energy densities of around 400 Wh/kg are expected for 2030, which is in line with the maximum assumptions made in this study [86]. Nevertheless, recent research has demonstrated a higher specific energy of up to 500 Wh/kg for a lithium iron phosphate cell, although this performance is currently limited by a low cycle life [87]. For the more distant future, Tiede et al. project cell level energy densities of approximately 650 Wh/kg for post-lithium-ion batteries by 2040, increasing to around 750 Wh/kg by 2050 [88]. The increasing demand for energy storage systems due to various applications, such as grid stabilization, electric vehicles, consumer electronics, and electrified aviation, has led to the development of novel technologies with a major focus on enhancing cell energy density and novel cell chemistries. Consequently, constantly increasing energy densities have been recorded in recent years and decades [86, 89–91].

5.3 Discussion of the Results

The results suggest that BSs are better suited to MEA architectures then other EESSs. This is due to the anticipated improvements in their SE. In contrast, SCSs are significantly limited by this parameter and are not expected to achieve such high SE levels. Consequently, further technological advancements are required before the large-scale integration of BSs becomes viable. When BSs are deployed in high-power, high-energy applications such as the ECS, only a marginal increase in system mass is required to enable additional functionalities, such as short-duration actuation or the operation of the WIPS. Accordingly, the integration of BSs emerges as the most viable option for aircraft applications. Nevertheless, the fast response time and high-power capability of SCSs may still be advantageous when integrated into a hybrid system, particularly for covering transient power peaks and mitigating BS degradation under high electrical loads.

For comparison, Lukic et al. [16] investigated the combined use of BSs and SCSs to meet aircraft taxiing energy demands. Their study highlighted the promising potential of this hybrid configuration, which seems particularly well suited for medium-duration operations. Similar advantages were reported by Gladin et al. [17]. Dever et al. [50] predicted that future materials will increase the specific energy of FSs, eventually exceeding that of BSs. However, such improvements currently remain theoretical nature due to rotor material scaling limitations. Consequently, the most practical approach at present appears to be focusing on BSs for aircraft applications, potentially supported by SCSs.

Nonetheless, mass overhead must be carefully considered during the design process. The stated SE and SP values for batteries and supercapacitors refer to cell level. When designing EESSs, an additional mass overhead of at least 25% must be accounted for [11, 88]. Moreover, as discussed above, further technological advancements are required for batteries to achieve the targeted pack-level SE to benefit the discussed 1500 km mission range flight scenario.

The achievable aircraft mission range is simultaneously constrained by the previously defined mission profile associated with the fuel penalty. However, improvements in engine performance and the introduction of novel AES technology could increase efficiency and reduce weight, thereby reducing the fuel penalty. At a more advanced stage of development, EESSs may also be considered for supplying propulsion energy, thereby increasing system flexibility and adaptability to future technological progression.

This study quantifies the fuel penalty associated with carrying mass in excess of the MTOW. Nevertheless, reductions in overall aircraft mass resulting from the integration of modern electric subsystems may partially offset this effect. It should also be noted that exceeding the MTOW is usually not acceptable and might be only feasible only within a narrowly constrained margin. Beyond this threshold, structural modifications are required to maintain compliance with safety and airworthiness requirements and to ensure reliable aircraft operation. If the mass of the EESS is instead included within the MTOW, the payload capability is reduced. The resulting economic implications would therefore need to be evaluated separately.

6 Conclusion and Outlook

This study aims to evaluate the suitability of electric energy storage systems (EESSs), including battery (BSs), flywheel (FSs) and supercapacitor systems (SCSs), for supplying energy to aircraft electrical subsystems (AESs) in more electric aircraft (MEA). First, the state of the art (SoA) properties of the EESSs is presented. This is followed by a description of the AESs and their corresponding requirements. To enable comparability, the AESs are categorized according to their operating time. Subsequently, a set of criteria is derived corresponding to aircraft design requirements. The relative importance of each criterion is determined using pairwise comparison. The suitability of the EESS for supplying energy to the various subsystems is then assessed by benchmarking its properties against aircraft design criteria. It is assumed that the mass of the energy carrier is added to the maximum take-off weight (MTOW), resulting in a fuel penalty. To explore the fuel penalty, a simplified mission profile is established, and the associated SoA data for the energy carriers, as well as the corresponding power and operating time requirements for the AESs are derived from literature to compute the EESSs mass.

The results suggest that supercapacitors are best suited to short-duration operations and batteries to long-duration applications. Both exhibit similar ratings for medium-duration operations. Despite being recognized for their balance of specific energy (SE) and specific power, FSs are subject to several limitations, including safety concerns and constraints related to scaling and installation. Hence, they are excluded from further consideration in this study.

Finally, the fuel penalty is assessed, by performing a system sizing according to the performance parameters of BSs and SCSs. Evaluating the results underscores the dominating role of the SE during the design process. Plotting the net fuel penalty as a function of the SE corresponding to the energy carrier reveals that a minimum of around 0.13 kWh/kg pack-level energy density is required for a 500 km mission range to reach break-even and thus fuel saving. For an aircraft covering a mission range of 2000 km, this value increases to approximately 0.47 kWh/kg. For a mission range of 1500 km, the implementation of an EESS with a system-level specific energy of 0.5 kWh/kg yields a potential fuel saving of approximately 30% relative to conventional fossil-fuel-based operation of the aircraft subsystem. When the system-level specific energy is increased to 1.0 kWh/kg, the potential AES related fuel saving rises to approximately 70%. As BSs are expected to experience significant advancements in terms of their SE, implementing SCSs for reducing fuel burn appears limited. However, a hybrid system implementing both batteries and supercapacitors may be reasonable for mitigating battery cell aging and covering peak power demands. Nevertheless, as stated earlier, the results are of preliminary nature and are partly based on a qualitative evaluation of the EESSs properties. The fuel saving estimations pointed out that BSs are the most probable system to achieve the required pack level SE. To conclusively answer the question of suitability, case studies and experiments must be executed to validate the before made assumptions.

The main limitations with regard to the widespread implementation of the discussed EESS in electrified aircraft are the prerequisite advancements in terms of their available specific energy and the associated mass overhead arising from safety systems such as the thermal management. The proposed mission ranges would also limit the flexibility of the aircraft. However, advancements in aircraft subsystems and propulsion systems may further reduce the fuel penalty.

As the fuel saving is highly sensitive to the weight of the EESS, the mass overhead must be addressed in detail in future studies. Therefore, the battery management system, the thermal management system and safety features such as module packaging or venting path architectures must be thoroughly assessed to ensure compliance with airworthiness requirements while at the same time maintaining high system performance. In addition, this study solely considered the mass saved due to substituting jet fuel with EESSs. Therefore, the weight reduction associated to replacing conventional systems with AESs may be determined and taken into account when computing the fuel penalty. Assessing the economic impact of including the energy carrier mass in the MTOW and thereby reducing the payload fraction will also provide insight into the feasibility of integrating the EESS in an aircraft. Furthermore, an identification of aircraft topology requirements such as voltage and current levels as well as the required power electronics to handle the energy provided by the EESSs must be determined.

The reported fuel savings are based on the assumption that the EESS mass is added beyond MTOW, which is not operationally viable. In practice, the mass would reduce payload or require a larger airframe, affecting economics. The results indicate strong potential, but real-world implementation will depend on balancing this trade-off. In addition, a lifecycle assessment is required to quantify the carbon intensity of the EESS and to further strengthen the findings of this suitability study. Nevertheless, the results of this study highlight the promising potential of EESS in reducing the emissions of future more electric aircraft by replacing the energy currently provided by fossil fuels.

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and Stefan Kazula. Reviewing—Florian Franke and Stefan Kazula.

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Data Availability Data will be made available upon request.

Declarations

Conflict of interest The authors declare no competing interests.

References

1. International Air Transport Association. Aircraft Technology Net Zero Roadmap. IATA (2022)
2. Lee, H. et al.: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland (2023)
3. Brelje, B.J., Martins, J.R.: Electric, hybrid, and turboelectric fixed-wing aircraft: a review of concepts, models, and design approaches. Prog. Aerosp. Sci. (2019). https://doi.org/10.1016/j.paerosci.2018.06.004
4. Thalin, P.: Fundamentals of Electrical Aircraft. SAE International, Warrendale, PA (2018). https://doi.org/10.4271/r-462
5. National Academies of Sciences, Engineering, and Medicine: Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions. The National Academies Press, Washington, D.C. (2016). https://doi.org/10.17226/23490
6. Bradley, M. K., Droney, C. K.: Subsonic Ultra Green Aircraft Research: Phase II - Volume II - Hybrid Electric Design Exploration. NASA CR-218704: 378 (2015)
7. R. H. Jansen, C. C. Kiris, T. Chau, L. Machado, and T. P. Dever: Update on subsonic single aft engine (SUSAN) electrofan trade space exploration. In: 33rd Congress of the International Council of the Aeronautical Sciences (2022)
8. Schefer, H., Fauth, L., Kopp, T.H., Mallwitz, R., Friebe, J., Kurrat, M.: Discussion on electric power supply systems for all electric aircraft. IEEE Access (2020). https://doi.org/10.1109/ACCESS.2020.2991804
9. Voskuijl, M., van Bogaert, J., Rao, A.G.: Analysis and design of hybrid electric regional turboprop aircraft. CEAS Aeronaut. J. (2018). https://doi.org/10.1007/s13272-017-0272-1
10. Tom, L., Khowja, M., Vakil, G., Gerada, C.: Commercial aircraft electrification—current state and future scope. Energies (2021). https://doi.org/10.3390/en14248381
11. Viswanathan, V., et al.: The challenges and opportunities of battery-powered flight. Nature (2022). https://doi.org/10.1038/s41586-021-04139-1
12. Wheeler, P., Bozhko, S.: The more electric aircraft: technology and challenges. IEEE Electrif. Mag. (2014). https://doi.org/10.1109/MELE.2014.2360720
13. Buticchi, G., Wheeler, P., Boroyevich, D.: The more-electric aircraft and beyond. Proc. IEEE (2023). https://doi.org/10.1109/JPROC.2022.3152995
14. Barzkar, A., Ghassemi, M.: Electric power systems in more and all electric aircraft: a review. IEEE Access (2020). https://doi.org/10.1109/ACCESS.2020.3024168
15. Frederick, Z.J., Hallock T. J., Ozoroski T. A., Chapman J. W., Kuhnle C. A., Frederic, P. C.:Design Exploration of a mild hybrid electrified aircraft propulsion concept. AIAA AVIATION 2023 Forum (2023), https://doi.org/10.2514/6.2023-4226.
16. Lukic, M., Giangrande, P., Klumpner C., Galea M. Analysis of energy storage system requirements for aircraft electric taxiing operations. IECON 2019–45th Annual Conference of the IEEE Industrial Electronics Society. (2019).https://doi.org/10.1109/IECON.2019.8926797.
17. Gladin, J. C., *et al*: A Comparison of Hybrid Electric Propulsion Architectures for Civil Aircraft," AIAA AVIATION 2023 Forum. (2023). https://doi.org/10.2514/6.2023-4502.
18. Kühnelt, H.,et al.: Structural batteries for aeronautic applications: the promise of zero weight penalty energy storage.Transport Research Arena Conference.2025.https://doi.org/10.1007/978-3-031-89444-2_36.
19. Rheaume, J. M., Lents, C. Energy Storage for Commercial Hybrid Electric Aircraft. In: SAE Technical Paper Series, 2016, https://doi.org/10.4271/2016-01-2014.
20. Buvarp, D., Leijon, J.: Electric aircraft: a review of challenges and emerging technologies. Discov. Appl. Sci. (2026). https://doi.org/10.1007/s42452-026-08550-z
21. Farhadi, M., Mohammed, O.: Energy storage technologies for high-power applications. IEEE Trans. Ind. Appl. (2016). https://doi.org/10.1109/TIA.2015.2511096
22. Armand, M., et al.: Lithium-ion batteries - current state of the art and anticipated developments. J. Power. Sources (2020). https://doi.org/10.1016/j.jpowsour.2020.228708
23. Aghmadi, A., Mohammed, O.A.: Energy storage systems: technologies and high-power applications. Batteries (2024). https://doi.org/10.3390/batteries10040141
24. Dissanayake, K., Kularatna-Abeywardana, D.: A review of supercapacitors: materials, technology, challenges, and renewable energy applications. J. Energy Storage (2024). https://doi.org/10.1016/j.est.2024.112563
25. Hedlund, M., Lundin, J., de Santiago, J., Abrahamsson, J., Bernhoff, H.: Flywheel energy storage for automotive applications. Energies (2015). https://doi.org/10.3390/en81010636
26. Kurzweil, P., Dietlmeier, O.K.: Elektrochemische Speicher. Springer Fachmedien Wiesbaden, Wiesbaden (2018). https://doi.org/10.1007/978-3-658-21829-4
27. Liu, K., et al.: Recent research advances of self-discharge in supercapacitors: mechanisms and suppressing strategies. J. Energy Chem. (2021). https://doi.org/10.1016/j.jechem.2020.09.041
28. Xu, K., Guo, Y., Lei, G., Zhu, J.: A review of flywheel energy storage system technologies. Energies (2023). https://doi.org/10.3390/en16186462
29. Jagadale, A.D., Rohit, R.C., Shinde, S.K., Kim, D.-Y.: Review—mitigating supercapacitor self-discharge through strategic materials modification. J. Electrochem. Soc. (2021). https://doi.org/10.1149/1945-7111/ac275d
30. Duffner, F., Kronemeyer, N., Tübke, J., Leker, J., Winter, M., Schmuch, R.: Post-lithium-ion battery cell production and its compatibility with lithium-ion cell production infrastructure. Nat. Energy (2021). https://doi.org/10.1038/s41560-020-00748-8

31. Dongxu, H., et al.: A review of flywheel energy storage rotor materials and structures. J. Energy Storage (2023). https://doi.org/10.1016/j.est.2023.109076
32. Sirimanne, D.C.U., Kularatna, N., Arawwawala, N.: Electrical performance of current commercial supercapacitors and their future applications. Electronics (2023). https://doi.org/10.3390/electronics12112465
33. Reedman R.Future energy storage trends. (2015).
34. Hossain, E., Faruque, H., Sunny, M., Mohammad, N., Nawar, N.: A comprehensive review on energy storage systems: types, comparison, current scenario, applications, barriers, and potential solutions, policies, and future prospects. Energies (2020). https://doi.org/10.3390/en13143651
35. Salaheldeen, M., et al.: Empowering the future: cutting-edge developments in supercapacitor technology for enhanced energy storage. Batteries (2025). https://doi.org/10.3390/batteries11060232
36. Elalfy, D.A., Gouda, E., Kotb, M.F., Bureš, V., Sedhom, B.E.: Comprehensive review of energy storage systems technologies, objectives, challenges, and future trends. Energy Strategy Rev. (2024). https://doi.org/10.1016/j.esr.2024.101482
37. Takarli, R., et al.: A comprehensive review on flywheel energy storage systems: survey on electrical machines, power electronics converters, and control systems. IEEE Access (2023). https://doi.org/10.1109/ACCESS.2023.3301148
38. Amici, J., et al.: A roadmap for transforming research to invent the batteries of the future designed within the European large scale research initiative BATTERY 2030+. Adv. Energy Mater. (2022). https://doi.org/10.1002/aenm.202102785
39. Ren, Y., et al.: Oxide-Based Solid-State Batteries: A Perspective on Composite Cathode Architecture,". Adv. Energy Mater. (2023). https://doi.org/10.1002/aenm.202201939
40. Wang, Y., et al.: Stable anode-free all-solid-state lithium battery through tuned metal wetting on the copper current collector. Adv. Mater. (2023). https://doi.org/10.1002/adma.202206762
41. Liang, Z., Wang, W., Lu, Y.-C.: The path toward practical Li-air batteries. Joule (2022). https://doi.org/10.1016/j.joule.2022.10.008
42. Liu, Y.-K., Zhao, C.-Z., Du, J., Zhang, X.-Q., Chen, A.-B., Zhang, Q.: Research Progresses of Liquid Electrolytes in Lithium-Ion Batteries. Small (2023). https://doi.org/10.1002/smll.202205315
43. Mitici, M., Hennink, B., Pavel, M., Dong, J.: Prognostics for Lithium-ion batteries for electric Vertical Take-off and Landing aircraft using data-driven machine learning. Energy and AI (2023). https://doi.org/10.1016/j.egyai.2023.100233
44. Bærheim, T., Lamb, J.J., Nøland, J.K., Burheim, O.S.: Potential and limitations of battery-powered all-electric regional flights—a Norwegian case study. IEEE Trans. Transp. Electrif. (2023). https://doi.org/10.1109/TTE.2022.3200089
45. Qiu, M., Liu, J., Cong, B., Cui, Y.: Research progress in thermal runaway vent gas characteristics of Li-ion battery. Batteries (2023). https://doi.org/10.3390/batteries9080411
46. Asef, P., Milan, M., Lapthorn, A., Padmanaban, S.: Future Trends and Aging Analysis of Battery Energy Storage Systems for Electric Vehicles. Sustainability (2021). https://doi.org/10.3390/su132413779
47. Gkoutzamanis V., 2020 HECARRUS Project Hybrid Electric Small Commuter Aircraft Conceptual Design: State-of-the-art technologies on research and developments underway in the field of alternative propulsion architectures.Aristotle University of Theassaloniki
48. Olabi, A.G., Wilberforce, T., Abdelkareem, M.A., Ramadan, M.: Critical Review of Flywheel Energy Storage System. Energies (2021). https://doi.org/10.3390/en14082159
49. Dagnaes-Hansen, N.A., Santos, I.F.: Magnetically suspended flywheel in gimbal mount - Test bench design and experimental validation. J. Sound Vib. (2019). https://doi.org/10.1016/j.jsv.2019.01.023
50. Dever, T., Duffy, K., Provenza, A., Loyselle, P., 2015 Assessment of Technologies for Noncryogenic Hybrid Electric Propulsion. NASA GRC-E-DAA-TN10454.
51. Mallick, S., Bag, S., Retna Raj, C.: Supercapacitors for energy storage: fundamentals and materials design. J. Chem. Sci. (2025). https://doi.org/10.1007/s12039-025-02394-7
52. Azega, R.K., et al.: Supercapacitors and rechargeable batteries, a tale of two technologies: past, present and beyond. Sustain. Mater. Technol. (2024). https://doi.org/10.1016/j.susmat.2024.e01111
53. Zhai, S., et al.: 2D materials for 1D electrochemical energy storage devices. Energy Storage Mater. (2019). https://doi.org/10.1016/j.ensm.2019.02.020
54. Lu, J., et al.: A review of advanced electrolytes for supercapacitors. J. Energy Storage (2024). https://doi.org/10.1016/j.est.2024.114338
55. Simon, P., Gogotsi, Y.: Materials for electrochemical capacitors. Nat. Mater. (2008). https://doi.org/10.1038/nmat2297
56. An, K.H., et al.: Electrochemical properties of high-power supercapacitors using single-walled carbon nanotube electrodes. Adv. Funct. Mater. **11**(5), 1 (2001)
57. Huang, S., Zhu, X., Sarkar, S., Zhao, Y.: Challenges and opportunities for supercapacitors. APL Mater. (2019). https://doi.org/10.1063/1.5116146
58. Pastra, C.L., Ganzarski, N., Gladin, J.C., Mavris, D.N.: "Projecting Key Performance Parameters for Electric Powertrain Components through 2050 for Aerospace Applications," in *AIAA Aviation Forum*. San Diego (2023). https://doi.org/10.2514/6.2023-4341
59. Rendón, M.A., Sánchez R., C.D., Gallo M., J., Anzai, A.H.: Aircraft hybrid-electric propulsion: development trends, challenges and opportunities. J. Control. Autom. Electr. Syst. (2021). https://doi.org/10.1007/s40313-021-00740-x
60. Johnson, A.T.: Electric Thrust Reverser Actuation Systems. SAE Int (2002). https://doi.org/10.4271/2002-01-2950
61. Haran, K., Madavan, N., O'Connell, T.C. (eds.): Electrified Aircraft Propulsion. Cambridge University Press (2022). https://doi.org/10.1017/9781108297684
62. Chakraborty I 2015 .Subsystem architecture sizing and analysis for aircraft conceptual design.PhD Thesis, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta
63. de Graaf, S., Bahrs, V., Tarbah, N., Kazula, S.: H 2 Electra – a platform for comparative analysis of integration concepts for hydrogen-based electric propulsion in regional aircraft. J. Phys. Conf. Ser. (2024). https://doi.org/10.1088/1742-6596/2716/1/012007
64. Chakraborty, I., Mavris, D.N., Emeneth, M., Schneegans, A.: An integrated approach to vehicle and subsystem sizing and analysis for novel subsystem architectures. Proc. Inst. Mech. Eng. G J. Aerosp. Eng. (2016). https://doi.org/10.1177/0954410015594399
65. Khalid, S.J.: "Mitigating Impact of Bleed and Power Extraction with More Electric Architectures.In SAE Technical Paper Series, Hartford, Connecticut. United States (2016). https://doi.org/10.4271/2016-01-1991
66. EASA, 2023. CS-25 Easy Access Rules for Large Aeroplanes: Amendment 27.European Union Aviation Safety Agency
67. Keçeci, M., Colpan, C.O., Karakoç, T.H.: Reducing the fuel consumption and emissions with the use of an external fuel cell hybrid power unit for electric taxiing at airports. Int. J. Hydrogen Energy (2022). https://doi.org/10.1016/j.ijhydene.2022.04.279
68. Lukic, M., Giangrande, P., Hebala, A., Nuzzo, S., Galea, M.: Review, challenges, and future developments of electric taxiing systems. IEEE Trans. Transp. Electrific. (2019). https://doi.org/10.1109/TTE.2019.2956862

69. Ganev, E., Chiang, C., Fizer, L., Johnson, E.: Electric Drives for Electric Green Taxiing Systems. SAE Int. J. Aerosp. (2016). https://doi.org/10.4271/2016-01-2013
70. Lampl, T., Muschkorgel, S., Hornung, M.: Parameterized Flight Mission for Secondary Power Requirement Estimations of Commercial Transport Aircraft. 17th AIAA Avi Technol Int Oper Con Den Colorado. (2017). https://doi.org/10.2514/6.2017-3066
71. Murray, W. E., Feiner, L. J.,: 1992 Evaluation of all-electric secondary power for transport aircraft. NASA CR-189077
72. Voth, V., Lübbe, S.M., Bertram, O.: Estimating Aircraft Power Requirements: A Study of Electrical Power Demand Across Various Aircraft Models and Flight Phases. Aerospace (2024). https://doi.org/10.3390/aerospace11120958
73. G. Pahl and W. Beitz, "Engineering Design: A Systematic Approach," London, s.l.: Springer London, 2013, https://doi.org/10.1007/978-1-4471-3581-4.
74. Grote, K.-H., Feldhusen, J. (eds.): Dubbel. Springer Berlin Heidelberg, Berlin, Heidelberg (2014). https://doi.org/10.1007/978-3-642-38891-0
75. Bender, B., Göhlich, D., Dubbel, H. (eds.): Dubbel Taschenbuch für den Maschinenbau, 26th ed Springer Vieweg, Berlin, Heidelberg (2020)
76. Sadraey, M.H.: Aircraft Design: A Systems Engineering Approach. Wiley, Chichestet West Sussex (2013). https://doi.org/10.1002/9781118352700
77. Kazula, S.: Variable Pitot-Triebwerkseinlässe Für Kommerzielle Überschallflugzeuge: Konzeptstudie Mittels Eines Entwicklungsansatzes Für Sichere Produkte. Springer Fachmedien Wiesbaden GmbH, Wiesbaden (2022). https://doi.org/10.1007/978-3-658-35456-5
78. Franke, F., Kazula, S., Enghardt, L.: Elaboration and outlook for metal hydride applications in future hydrogen-powered aviation. Aeronaut. J. (2024). https://doi.org/10.1017/aer.2024.53
79. Kazula, S., de Graaf, S., Enghardt, L.: Review of fuel cell technologies and evaluation of their potential and challenges for electrified propulsion systems in commercial aviation. J. Glob. Power Propuls. Soc. (2023). https://doi.org/10.33737/jgpps/158036
80. Feldhusen, J., Schürmann, H., Orloff, M. 2014 Grundlagen technischer Systeme und des methodischen Vorgehens. in *Dubbel*, K.-H. Grote and J. Feldhusen, Eds., Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-38891-0_41.
81. Kenway, G., et al.: "Reducing Aviation's Environmental Impact Through Large Aircraft for Short Ranges," in *48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*, Orlando. Florida (2010). https://doi.org/10.2514/6.2010-1015
82. Karadotcheva, E., Nguyen, S.N., Greenhalgh, E.S., Shaffer, M.S.P., Kucernak, A.R.J., Linde, P.: Structural Power Performance Targets for Future Electric Aircraft. Energies (2021). https://doi.org/10.3390/en14196006
83. Young, T. M., 2017 International Standard Atmosphere (ISA) Table.in Performance of the Jet Transport Airplane: Analysis Methods, Flight Operations and Regulations, T. M. Young, Ed.: Wiley.https://doi.org/10.1002/9781118534786.app1.
84. Airbus SAS. Getting to grips with Fuel Economy.Flight Operations Support & Line Assistance.2004.
85. Venkatesh, G., Chandrakala, K., Poonam, K., Saravanan, S., Balamurugan, S., Ratheesh, P.: Enhanced power density and energy-efficient high-speed permanent magnet starter-generator using multi-physics optimization strategies for future electric aircraft. Results in Engineering (2025). https://doi.org/10.1016/j.rineng.2025.107216
86. Hettesheimer, T., Neef, C., Rosellón Inclán, I., Link, S., Schmaltz, T., Schuckert, F., Stephan, A., Stephan, M., Thielmann, A., Weymann, L. and Wicke, T.2023 Lithium-Ion Battery Roadmap - Industrialization Perspectives Toward 2030.Fraunhofer ISI
87. Sun, Z., Zhang, H., Wang, S., Niu, Y., Zhang, K., Xu, Y.: A Novel Ternary Li-Rich Li4Fe05Mn05V (PO4)3 Cathode for Ultra-High-Capacity Li-Ion Batteries with Potential Far Beyond LFP via Multi-Electron Reaction. Small (2025). https://doi.org/10.1002/smll.202504821
88. Tiede, B., O'Meara, C., Jansen, R.2022 Battery Key Performance Projections based on Historical Trends and Chemistries. in *2022 IEEE Transportation Electrification Conference & Expo (ITEC)*, Anaheim, CA, USA, 2022, https://doi.org/10.1109/ITEC53557.2022.9814008.
89. Link, S., Neef, C., Wicke, T.: Trends in automotive battery cell design: a statistical analysis of empirical data. Batteries (2023). https://doi.org/10.3390/batteries9050261
90. Pattanayak, T., Mavris, D.: Battery technology for sustainable aviation: a review of current trends and future prospects. Appl. Energy (2025). https://doi.org/10.1016/j.apenergy.2025.126356
91. Löbberding H., 2024: Methodik zur Auswahl von Lithium-Ionen-Batteriezellen für Elektrofahrzeuge.PhD Thesis, Fakultät für Maschinenwesen, RWTH Aachen.