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OVERVIEW OF THE STATE OF THE ART IN BATTERY PACKAGING AND ELABORATION OF A SAFE DESIGN PROCESS FOR BATTERY PACKS IN LARGE ELECTRIC AIRCRAFT

Alperen Oğuzhan Altun*, Florian Franke*, Stefan Kazula*

* German Aerospace Center (DLR) - Institute of Electrified Aero Engines, 03046 Cottbus, Germany

Abstract

A significant part of the aviation industry is currently working on the transition to all-electric aircraft, which use battery systems for power supply, to further reduce emissions. While some manufacturers have already announced appropriate battery solutions, the energy density at battery cell level is only sufficient to power small electric aircraft for short range flights. Thus, there is currently no commercially available large aircraft powered solely by batteries. Moreover, the mass and volume overhead at module and pack level poses a challenge as well.

Hence, the purpose of this paper is to provide an overview of the state of the art in battery pack design in order to derive conclusions for future design concepts and to suggest design combinations for use in large electric aircraft. For that, the different options for the core elements of a module, namely the battery cells, the battery management system (BMS) and the battery thermal management system (BTMS) are compared and evaluated. In accordance with the VDI 2221 guideline, a design process for battery packs is developed. Based on that, the selection process is explained in detail and conducted to elaborate appropriate concepts. The concept evaluation demonstrates which of them are viable and how the individual elements affect each other. Hence, this study contributes to the reduction of the volume and mass overhead of the pack design and will increase the feasibility of battery-powered all-electric aircraft.

Keywords

Battery pack design; Safe design; Energy density; Battery thermal management system

NOMENCLATURE

Abbreviations

BMS	Battery management system
BTMS	Battery thermal management system
CO_2	Carbon dioxide
EASA	European union aviation safety agency
ED	EUROCAE document
EUROCAE	European organization for civil aviation equipment
eVTOL	Electric vertical take-off and landing
LFP	Lithium iron phosphate
Li-metal	Lithium metal
Li-S	Lithium sulphur
NCA	Nickel cobalt aluminium
NMC	Nickel manganese cobalt
NO_x	Nitrogen oxide
P2P	Pump two-phase system
PCM	Phase change material
RTCA	Radio technical commission for aeronautics
SHX	Skin heat exchangers
SOC	State of charge
SOTA	State of the art
TRL	Technology readiness level
TR	Thermal runaway
VTOL	Vertical take-off and landing

1. INTRODUCTION

In the context of the Flightpath 2050, series of targets has been established for the advancement of European aviation across a range of domains, such as safety, infrastructure, competitiveness, climate-neutral mobility and research. With regard to emissions, the objective is to reduce, inter alia, NO_x

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emissions by 90 % and CO_2 emissions by 75 % in comparison to the level recorded in the year 2000 [1]. One of the approaches to achieve these targets is developing battery electric aircraft. These are currently associated with low energy density and safety-related issues [2, 3]. Current more specific solutions are far too conservative to enable battery electric aircraft at regional level, as they entail too heavy and voluminous additional equipment to achieve a sufficient safety level [4–6]. New design concepts are required to increase volumetric and gravimetric energy density while ensuring safety margins. In the following, an overview of the essential configurations and components of a battery module will be provided, with the aim of fostering a qualitative understanding of the relationships between the elements and to be able to assess the future potential.
A number of individual studies have been conducted in the past where the components of a battery module have been comprehensively assessed [7–9] or standards and regulations discussed [10, 11]. However, based on the authors' best knowledge there is a gap in the literature regarding studies that assess the effect of individual component on each other to highlight promising module concepts and to evaluate their specific advantages and disadvantages. The objective of this study is to address that research gap.
All the battery modules of an aircraft stacked together are described here as a battery pack. The design of a battery module comprises cells with mechanical, electrical, thermal, structural and control elements. Thermal elements are essential for the thermal management of the module, while control elements constitute the battery management system (BMS). Both of these elements will be discussed in detail in this paper in section 2. Electrical elements such as bus bars, cables and fuses as well as mechanical/structural elements will be neglected due to their lower impact on the performance and design process [12].
Section 2 also covers an overview of the main standards and a description of thermal runaway. Moreover, the various cell type option, cell chemistries that are suitable for electric aircraft, and the impact of cell size on module design are addressed. In section 3 different product development processes will be compared before adapting it for the exemplary conduction of the battery-specific product development process of this study in section 4.

2. STATE OF THE ART

2.1. Safety requirements of battery modules

2.1.1. Thermal runaway

The hazards and mechanisms of thermal runaway (TR) in lithium-ion batteries are comprehensively discussed in the referenced literature [13–15]. TR poses to be a critical condition for electric propulsion and can be triggered by various abuse conditions including mechanical failure (e.g., collision, crush, penetration), electrochemical failure (e.g., short circuits, over(dis)charging) or thermal failure (e.g., overheating, high ambient temperatures) [11, 16].
Several key characteristics of TR are the rapid temperature increase and the large amounts of gases produced. For current cell chemistries like Nickel manganese cobalt (NMC), Lithium iron phosphate (LFP) and Nickel cobalt aluminium (NCA) the majority of gases (>80 %) emitted during TR are a mixture of H_2, CO_2 and CO. The rapid release of gases during TR can also lead to flame formation and explosion risks [11, 13].
Several key factors can influence the likelihood or severity of TR: A high state of charge (SOC) can lead to earlier melting of the separator and increased heat release. The type of cathode material used in the battery cell can affect its thermal stability, with some materials being more prone to TR than others (e.g. NMC) and cells with higher energy density being less stable [11, 15]. Different test methods can have a significant influence on the results of TR testing, highlighting the need for a standardized testing methodology [16].
To mitigate TR hazards, it is essential to develop a deeper understanding of the causes and mechanisms of TR, improving the thermal stability of battery cells through design modifications or new materials development [15] and implement standardized testing protocols to ensure accurate and reliable results to meet the requirements in the standards that are discussed in the next section [16].

2.1.2. Standards and regulations

In the context of the design process for a battery electric aircraft, it is fundamental to firstly consider the relevant standards. These include the following publications:

- EASA:
  - Second Publication of Means of Compliance with the Special Condition VTOL [17],
  - Third Publication of Means of Compliance with the Special Condition VTOL [18],
- EUROCAE:
  - ED-289 [19],
  - ED-312 [20],
- RTCA:
  - DO-311A [21],
  - DO-160G [22].

These documents are currently employed for the certification of eVTOLs with the prospect of application for large aircraft powered solely by batteries.
The "Second Publication of Means of Compliance with the Special Condition VTOL" especially points out fire protection in three designated fire zones. The first one is the "Explosive Fire Zone", which is a volume that includes the electrical energy storage system and may also include an electrical lift/thrust

unit. The effects of flames, sparks, hot parts ejection and explosives due to accumulated gases are contained in this volume. The second zone is the "Designated Fire Zone", which considers fires fuelled by a high amount of flammable fluids and the last zone is the "Fire withstanding Zone", which represents a volume surrounding electric lift/thrust units and does not contain hazardous quantities of flammable fluids. The last one is capable of withstanding the effects of flames, sparks and the ejection of hot parts.

It is essential to consider the selection of appropriate materials, particularly for the fire withstand wall, which must be flame-resistant, and for the flight controls, lift/thrust unit mounts, and other flight structure components, as well as for electrical lines and fittings near one of the three designated zones. The implementation of an isolation system, such as a fire-resistant wall or explosive firewall, is necessary for the protection of the lift/thrust unit and the electrical energy storage system. Furthermore, the disconnection of these components from the main electrical circuit is crucial to ensure the safety of the surrounding area [17].

The RTCA DO-311A, on the other hand, is not directly mandatory, as the RTCA is not a government regulator. However, the DO-311A is mentioned as a necessary measure for safety tests in the "Third Publication of Means of Compliance with the Special Condition VTOL". The RTCA DO-311A names equipment requirements for which verification via test is required. In order to ensure that these tests are conducted in a satisfactory manner, it is necessary that there are no releases of fragments, escape of flames, emission of gas/smoke/soot/fluid outside of the battery system (depending on the venting category) and no rupture of the battery system. The RTCA DO-311A also explains the test methodology to be followed for single and multiple cell TR containment test initiated through overcharging or overheating. For tests of battery systems conducted according to RTCA DO-311A the environmental conditions of RTCA DO-160 have to be met [21].

In comparison, the "Third Publication of Means of Compliance with the Special Condition VTOL" proposes an alternative test methodology for the assessment of batteries, with the objective of developing innovative solutions for the protection of battery systems. The main reasons for an alternative method to the RTCA DO-311A “Thermal Runaway Containment Test” are, that on the one hand, it solely relies on containment, which can result in a thermal energy requirement for the battery system, caused by the heat release of the cell, that can be far too oversized and would represent an extreme condition that would not occur in service. On the other hand, the system can be undersized for two reasons. Firstly, the variability in cell characteristics of the cells and degradation are not considered. Secondly, the number of cells to meet the test objective is too low.

Therefore, two approaches are presented. The first one is the battery TR containment test which should be done in accordance to the RTCA DO-311A. In addition, it should lead to 20 % of the cells in the system being in TR condition.

The second approach, which could be used as an alternative to the first one, refers to Continued Safe Flight and Landing. As more than one cell can enter a TR event due to an unforeseen failure mode, it has to be proven that the situation can be managed at propulsion battery system level and installation level (Battery Explosive Fire Zone) ensuring continued safe flight and landing in accordance with the designated fire zones explained above.

However, for both approaches, a test guideline to prevent propagation from a single cell to another one in case of TR must be followed [18].

Furthermore, the objective of the ED-289 is to facilitate the determination of the maximum permissible error in the prediction of the worst case flight scenario for the energy storage system based on load profile, ageing profile, state of function indicators e.g. SOC, temperature, current (...), and safety margins [19].

Finally, the ED-312 describes failure modes of lithium ion cells, failure causes which initiate these modes and the failure effects as a final consequence. The affected cell component is also named. The failure mode analysis is divided into the following categories: operational considerations (high/low temperature, over(dis)charge, high current, SOC swing), storage considerations (low/high SOC storage and low/high temperature storage), and manufacturing considerations. Each failure cause can result in different failure modes leading to one of the failure effects listed in the FIG. 1 based on [20]. In the worst case, this can result either in TR or loss of available power and/or energy, highlighting the two most important failure results for the design process.

The hazardous condition in the event of TR, in conjunction with the stringent limitations imposed by the standards, underlines the critical importance of the safety aspect of the battery pack design.

2.2. Battery cells

2.2.1. Cell type

Battery cells are available in three distinct shapes: cylindrical, prismatic and pouch. A simplified sketch of a stack of cylindrical, pouch and prismatic cells is illustrated in FIG. 2, without considering any other elements contained in a module. Special attention should be given to the stack of cylindrical cells, as the sketch demonstrates the most optimal arrangement in terms of volume utilisation.

Pouch cells exhibit the highest gravimetric and volumetric energy density [24, 25] at both cell and module level, which can be attributed to the high packing density [26] and the low weight of the cell housing, considering that pouch cells are soft-packaged [9]. Nevertheless, retaining plates will be necessary to counteract the expansion of cells at elevated SOCs. The soft casing also results in a lack of resilience to high internal pressure [8]. It is crucial to ensure the safety

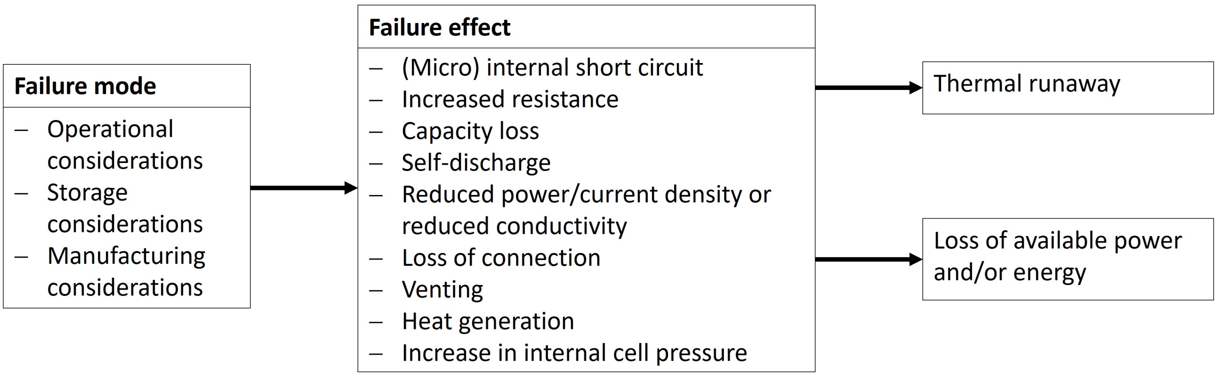

FIG 1. Failure progression according to ED-312 [20]

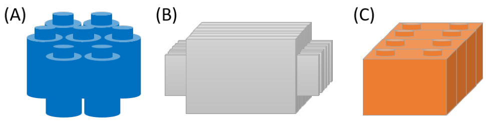

FIG 2. Simplified stacking of different cell types (A) cylindrical, (B) pouch and (C) prismatic according to [23]

at module level, as the necessary safety features of cylindrical and prismatic cells described below are not present at cell level for pouch cells [9,25]. They can be easily stacked adjacent to each other with cooling layers between them with the greater surface area per unit volume enabling an easier heat transfer [27]. It is important to consider the lower durability and mechanical stability, poor compressive force holding as well as local stresses [26].

Cylindrical cells also exhibit a high gravimetric and volumetric energy density at cell level [24,25], but the inability to stack them as densely as the other cell types results in a lower volumetric energy density at module level [28]. Safety features are already available at cell level, including positive temperature coefficient, current interruption device , solid structure and rupture devices [9]. However, cylindrical cells tend to be smaller, necessitating a high number of cells in a module to achieve the same total energy at module level as other cell types [8]. In such instances cell failure of each cell becomes a bigger challenge to detect [9]. These cells have a longer cycle life [27], high cell robustness and high mechanical stability [8, 26]. They demonstrate excellent compressive force holding and are highly resilient to high internal pressure, a quality that is attributed to their hard case [9,25]. However, an increase in complexity of the thermal management is evident in scenarios involving a high number of cylindrical cells, necessitating a more complex monitoring process and increasing the likelihood of thermal ageing deviation [9].

Prismatic cells achieve the lowest gravimetric and volumetric energy density [24, 25], despite slightly superior packing density in comparison to pouch cells [8]. They possess the same safety features as those described for cylindrical cells and are also hard-packaged, which increases the mass but also leads to enhanced cell robustness, mechanical stability and resilience to high internal pressure [25]. Like pouch cells, they have a greater surface area per unit volume and cell expansion is possible [26]. Even though durability might be high, they are prone to poor compressive force holding and the manufacturing process is costly, as often more complex production processes and materials are required [9].

2.2.2. Cell chemistry

After assessing the cell types, the cell chemistry needs to be discussed. Firstly, reference is made to Bills et al. who performed Monte Carlo simulations for three classes of aircraft, regional, narrow-body, and wide-body, to estimate the pack specific energy requirement. The ranges used were roughly 650, 900 and 1900 km. The number of passengers was assumed to be 30, 150 and 300 and the mass to be 50, 100 and 250 t. The result was that even regional class aircraft will require a gravimetric energy density of 500-700 Wh/kg, while wide body aircraft would even require a gravimetric energy density of 1100 to 1500 Wh/kg [2]. According to a forecast by the Fraunhofer Institute for Systems and Innovation Research, up to 1000 Wh/L and 400 Wh/kg at cell level might be achievable by 2030 with current cell chemistries like NMC or NCA. [25]. Both results are shown in FIG. 3.

In order to achieve the aforementioned values and fulfill the specified requirements at pack level in future applications, the introduction of new cell chemistries is of critical importance. These include Lithium sulphur (Li-S) or solid-state electrolyte with a Lithium metal (Li-metal) anode [29, 30]. The replacement of the graphite-dominated anode with a silicon-dominated anode also represents a promising solution, one that has already been adopted by companies such as Lilium [31] and cell manufacturer Amprius [32].

The theoretical capacity of silicon is approximately ten times that of graphite, due to the fact that a silicon atom can hold four lithium atoms, whereas six carbon atoms are required to hold one lithium atom. The major challenge associated with silicon anodes is the significant volume expansion that occurs during the charge/discharge cycles. This expansion can result

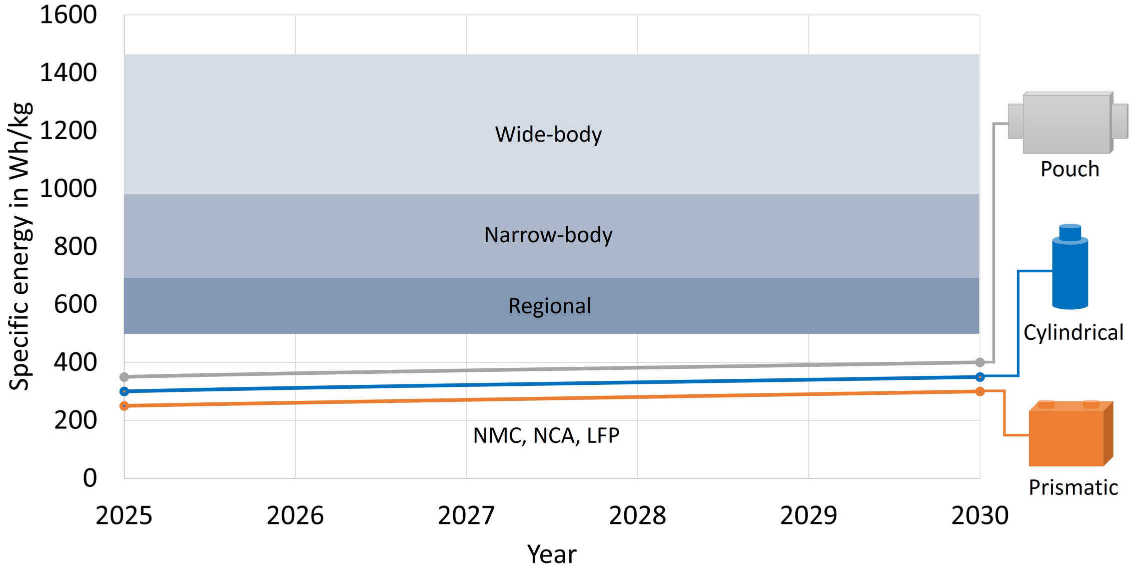

FIG 3. Specific energy forecast at cell level for different cell types considering current cell chemistries (NMC, NCA, LFP) and specific energy requirement at pack level for different classes of aircraft based on [2, 25]

in mechanical degradation which in turn leads to a reduction in the cycle life of the anode [29, 33, 34].
Li-metal has also the potential to be a highly promising material, offering a high theoretical capacity. However, it also poses certain challenges, including the risk of dendrite growth during charging which can cause internal short circuits. Additionally, its rechargeability is limited, and it is susceptible to volume changes [33, 35, 36]. Nevertheless, dendrite growth can be circumvented through the utilisation of lithium metal anodes with solid-state electrolytes, given that the thermal stability of solid electrolytes is superior to that of liquid electrolytes [35,36]. However, the high performance of Li-metal in combination with the high safety of solid-state electrolytes must be demonstrated [36, 37]. The advantages of solid-state electrolytes include a long cycle life, as side reactions do not occur in solid electrolytes. As the amount of combustible electrolyte increases with an increasing battery size, solid-state is an appropriate alternative to overcome this challenge [38]. Despite this, the low power density and volume changes remain significant issues with solid-state electrolytes [38, 39].
Finally, the advantages of a sulphur cathode with a lithium anode include the low cost and natural abundance of sulphur [33], the potential of a long cycle life [40], and the wide temperature operation range. The theoretical gravimetric energy density is approximately seven times higher than that of Li-Ion, while the theoretical volumetric energy density is two times higher. Despite that, the practical energy density is currently only 200-300 Wh/kg with 600 Wh/kg expected in the near future [40, 41]. Additionally, the high self-discharge rate of 8-15 % per month and the capacity decrease during cycling (up to 0.4 % per cycle) poses a challenge for the operation [41].

2.2.3. Cell size

Battery cells are available in a variety of sizes. The choice between a small number of large cells or a large number of small cells must be made in advance, taking into account the specific characteristics of the intended application.
The operation of smaller cells is safer due to the lower amount of heat dissipation. The tendency towards thermal ageing is reduced and the utilisation of available space within a module is more flexible by the smaller dimensions of the cells [26]. However, a larger number of interconnections results in increased wiring complexity, a higher probability of interconnection failure [26] and a more complex monitoring process for the cells. Furthermore, the energy loss experienced when overcoming the external contact resistance reduces the total energy output of the module. The high effort for maintenance, the complexity of the control system and the large quantity of cell protection circuits are some other disadvantages of modules comprising a high number of small cells [9].
In contrast, larger cells offer a higher energy density and greater reliability. While the assembly costs are reduced, the production costs of the cells are higher [26]. Furthermore, the capacity fading rate is higher for larger cells [9].

2.2.4. Parallel-series configuration

In order to achieve the desired voltage, cells are connected in series and in order to increase the capacity of the battery module, cells are connected in parallel [42]. Lithium-based cells can deliver more than 3 V, depending on the potential difference between the negative and positive electrode [43]. In a series configuration the power of the battery module will be limited by the performance of the weakest cell. Therefore, if more cells are connected in parallel, the reliability of the battery module will increase, minimising the impact of low quality cells. Nevertheless, a thick connector will be necessary to transfer high current flow [9, 44]. It is therefore recommended to employ a balanced configuration of series and parallel connections, with a maximum voltage of 50 V. This is in accordance with the National Code of USA, which considers voltages in excess of this value to be hazardous, potentially resulting in arcing [3, 28]. Consequently, smaller modules are easier to be managed. A parallel-first configuration, where cells are first connected in parallel and afterwards in series is recommended. This approach results in a reduced number of tap points for the BMS [44]. A design according to these requirements would lead to a maximum number of 12 to 16 cells stacked in series in a module.

2.3. Battery management system

The BMS has to monitor the battery pack to

- prevent the operation outside the safe operating range to avoid over(dis)charge, overcurrent and short circuiting,
- balance or redistribute the energy within the pack,
- control the battery temperature range,
- collect and communicate data, and
- perform a state estimation including the state of charge, the state of health and the state of power [45].

As previously outlined in the failure modes of the ED-312, disregarding the operational limits can lead to TR or a loss of available power/energy.

2.3.1. Topology

Battery management systems can be classified into four topologies, which are centralized, modular, master-slave and distributed systems. TAB. 1 provides an overview of the properties, while a schematic illustration of all topologies is shown in FIG. 4.
In a centralized system, a single controller is connected to all battery cells [46]. The reduced number of components results in a more compact design and a lower cost. The components are easy to replace and the direct access to the cells allows for precise control [44]. However, in a larger system, the central control unit is overwhelmed with wires as a result of its total dependence on the system [46].
In a modular topology, the BMS is divided into multiple identical independent modules, with one of them designated as the master module, responsible for managing the pack. In such a configuration, it is easier to manage the wiring of the cells, even in case of an expansion to larger packs. However, it is essential to consider the coordination between the modules to ensure optimal control and balancing of the cells [44].
The master-slave option may also be regarded as the centralized option with slaves. While the master module is responsible for the computation and communication, the slaves are employed for the measurement of voltages. The advantages and disadvantages are similar to the modular topology, with the exception that the cost of each slave is less, as it is optimized to only measure cell voltages [44].
Lastly, in the distributed topology, a BMS board is installed at each cell, with a single communication cable between the battery and the controller [46]. The boards have to communicate with each other to coordinate their actions. The wiring is more straightforward and the system is highly redundant, in that the failure of one board does not affect the operation of the entire system. Nevertheless, the coordination and communication between boards introduces an increased complexity and potential for failure [44].
The centralized and distributed configurations can be neglected as independent operation is not possible, complexity is high and reliability is low [46]. The master-slave and modular configurations share a number of similar characteristics. However, the cooling ability of the master-slave option is predicted to be more favourable according to Saw et al. [9]. Finally, the weight and volume of the BMS can be neglected, as it is insignificant compared to the total battery system values [47].

2.3.2. Balancing strategy

While protectors are sufficient for small packs, larger packs require balancing as the switch of a protector cannot handle high-power loads [44].
Balancing is the process of keeping the cells at the same SOC [46]. The balancing strategy, which is is the major determining factor in the cost of the BMS, is divided into active and passive strategies [44].
Passive balancing represents a cost-effective option, whereby excess energy of the cells with the highest SOC is dissipated as heat energy until all cells are at the same SOC. In a system where energy levels are of critical importance, passive balancing may not be the optimal solution. Furthermore, the heat generated during this process poses a challenge for the battery thermal management system (BTMS) [46]. In an active balancing process, energy is transferred from cells with a higher SOC to the cells with a lower SOC until all cells are at the same SOC. The components required for active balancing are larger, heavier [46], and up to ten times more expensive than those required for passive balancing [44].
Nevertheless, for large systems, the total cost saved through an active balancing strategy can be higher, due to lower operational costs, despite the higher initial setup costs [44].

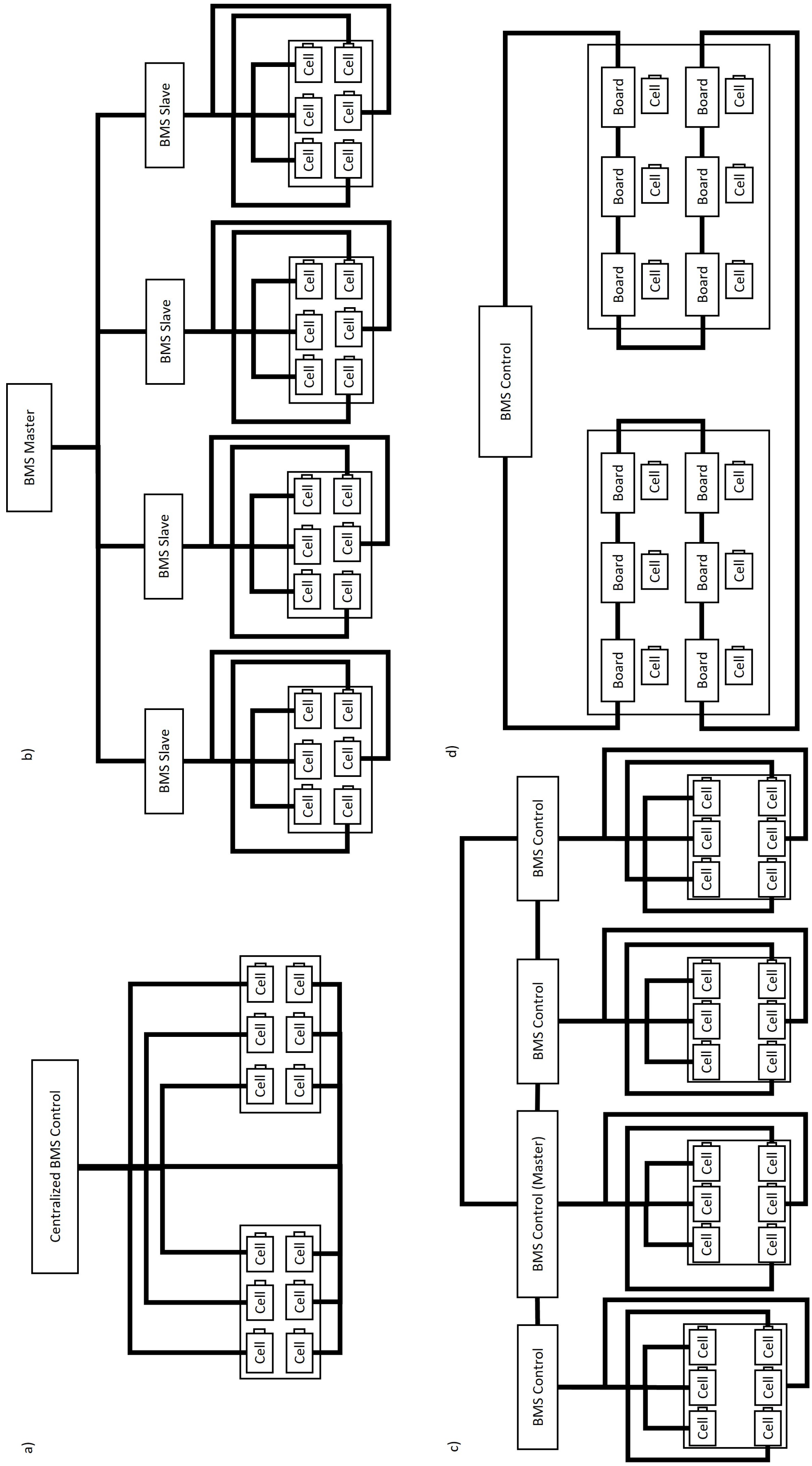

FIG 4. BMS topologies: a) Centralized, b) Master-slave, c) Modular, d) Distributed derived from [44]

TAB 1. Comparison of different topologies for the BMS [9, 44, 46]

	Centralized	Master-slave	Modular	Distributed
Complexity	High (for large systems)	Medium	Medium	High (Coordination between boards increases complexity)
Cooling	Easy	Medium	Difficult	Difficult
Independent operation	No (depends on central unit)	Yes	Yes	No (Depends on coordination between boards)
Reliability	Low	High	High	Low
Installation and maintenance	Difficult (Easy replacement and compact but overwhelmed with wires)	Medium	Easy (Flexible design possible)	Easy (Easier wiring possible)
Cost	Least expensive	Lower than modular topology	Lower than distributed topology	High

2.4. Battery thermal management system

In consideration of the focus of this paper on state of the art (SOTA) battery packaging technologies, only heat transfer technologies are discussed with a technology readiness level (TRL) higher than seven. These comprise liquid cooling systems, direct air cooling systems, skin heat exchangers (SHX), pump two-phase systems (P2P) and although the TRL is still slightly lower, phase-change materials (PCM) are also considered [48]. A TRL of seven indicates that a prototype has been tested in the relevant environment, thereby providing a level of confidence in the development process [49]. The different options are compared in TAB. 2.

The design of the BTMS is highly dependent on the duty cycle of the operation, the region in which it is to be located and the behavior of the cell. Clearly, the BTMS should avoid operation of the cells outside the temperature limits and should also keep the difference between the cells to less than 6-8 °C in order to have an uniform temperature distribution in the module [46]. Other requirements are high efficiency, low mass, and easy maintainability, which can be simplified by the use of fewer components [50].

There are several challenges associated with the design of the BTMS. In the improper case, the BTMS decreases the performance of the battery pack. Even a temperature difference of 5 °C can lead to a 10 % degradation in performance, a 25 % increase in thermal ageing kinetics and a 1.5-2 % of capacity loss as shown by Feng et al. and Kuper et al. [51, 52]. Therefore, the battery system should neither be operated at high temperatures nor at low temperatures. The design of the BTMS can be highly complex, which would prolong the development process and increase costs. In particular, low TRL solutions, may encounter challenges in obtaining certification. Charging the battery at high charging rates and low temperature can cause lithium plating, an ageing mechanism of lithium-ion batteries. Furthermore, the charge acceptance, energy and power capacity will decrease [53]. High temperatures can cause self-discharge, capacity and power fade resulting in a loss of energy. In a worst case scenario, TR may occur, for which propagation has to be prevented by all means [54]. Besides from the upper and lower temperature limit, temperature gradients should also be avoided, as this can lead to hotspots within the module also resulting in TR [55]. For an in-depth analysis of temperature-related issues in batteries, the work of Abada et al. [56] is a valuable reference point, providing a comprehensive overview on this subject.

BTMS can be classified as direct or indirect cooling, depending on whether the coolant is in direct contact with the area requiring cooling and active or passive systems. In an active system, forced convection is used, whereas for passive systems, natural convection is applied. In the case of active systems, additional hardware, such as fans, ducts and heat transfer plates, is required. However, these systems are relatively effective at responding to fast changing temperatures. In contrast, passive systems operate in a different manner. The utilisation of less components reduces the cost and weight and simplifies installation and maintenance of the system. Furthermore, the potential for leakage is also reduced. They can use cabin air, which is available in the aircraft, reducing operation costs. Heat pipes are one example of passive systems. They are compact, light and highly efficient, but have not yet been able to prove the performance necessary for large systems [46]. In direct systems, there is a high degree of compactness and the cooling rates are higher than for indirect systems. In order to guarantee fire protection, the addition of flame-retardant additives will be necessary, given that the coolant is in direct contact [25].

2.4.1. Direct air cooling

The structure of direct air cooling systems, which can be active or passive, is relatively simple, comprising fewer components than other systems. This results in a number of advantages, including a reduction in mass, cost, and maintenance requirements, as well as an increase in ease of installation. Leakage is not a challenge [62–64].
However, the cells at the beginning of the duct are typically at a lower temperature than the cells at the end of the duct, as the air temperature increases while passing through each cell, resulting in a temperature gradient. This poses a bigger challenge with increasing module size at high-power condition [46].

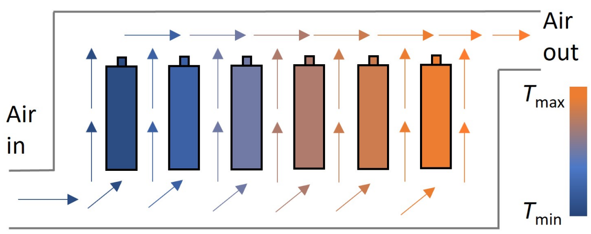

FIG 5. Direct air cooling design [64, 65]

2.4.2. Indirect air cooling with skin heat exchangers (SHX)

In contrast to the ingestion of air, which causes performance loss due to momentum loss of the air, a skin heat exchanger (SHX) rejects the waste heat through exposed areas of the aircraft to the ambient air. The hot fluid is in contact with the exposed area, which is in contact with the ambient air, thus facilitating indirect air cooling. This method is optimal at high altitudes, where the temperature of the air is low [66]. In a study conducted by Kellerman et al. [67], it was demonstrated that a SHX could be employed for a range of aircraft sizes, with the capability to handle the associated heat dissipation. The drawback of this system is that ambient air is not sufficiently cool to be used at low altitudes, where it is most critical during take-off .
One significant challenge in the design of a SHX is that as the surface is heated, the boundary layer is also heated up leading to a higher probability of disturbances in the flow. Subsequently, an earlier transition and separation can occur, resulting in an increase in drag [68]. However, Kallath et al. [69] identified an optimal combination of the Reynolds number, angle of attack, heat exchanger location and magnitude of heat flux, which resulted in a decrease in the drag coefficient and an increase in the lift coefficient.

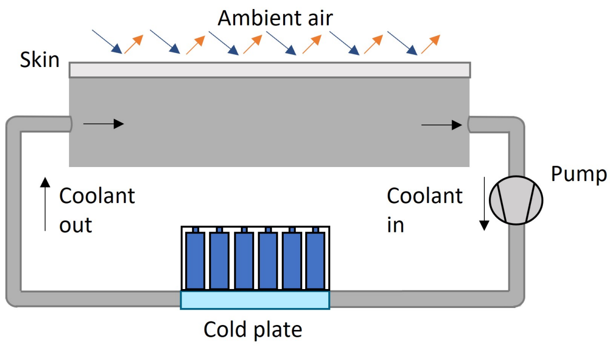

FIG 6. Skin heat exchanger as heat sink [70]

2.4.3. Liquid cooling

Liquid cooling systems are more efficient than air cooling systems, consuming less power and exhibiting significantly enhanced cooling capabilities, due to higher specific heat and thermal conductivity, resulting in higher heat transfer coefficients. However, even if the maximum temperature can be effectively reduced, temperature gradients may still present an issue. The variation of the temperature, which poses a challenge in single-phase systems, can be reduced by increasing the fluid flow rate. Conversely, this approach increases the weight and size of a single-phase-system, due to increased pump power and larger pipe diameter [58]. Additionally, liquid cooling systems are heavier than direct air cooling systems due to the higher density of the fluid. Liquid cooling systems are more compact as fans or air ducts are not required and they have a lower pressure drop. The pressure drop is defined as the difference between the inlet pressure and the outlet pressure of the fluid. It represents the pressure that the system must overcome so that the fluid can flow through the cooling system including cooling lines and a heat exchanger to reject the heat to the ambient air. It affects the size and flow rate of the pump (in the case of a liquid cooling system) or of the fans (in the case of an air cooling systems) [46].
Typically, cold plates are placed between or below the cells in a stack of pouch and prismatic cells [71]. Cylindrical cells can be also cooled using a cold plate at the top (or bottom) due to the significantly higher thermal conductivity in the axial direction compared to the radial direction [72]. Alternatively, cooling tubes can be attached to the side surface or thermal conductive structures can be employed [63, 73]. For pouch cells tab cooling can be applied. The tabs are electrically conductive connected with the large surface area of the pouch cell and given that the majority of the heat is generated in the tabs, it is reasonable to apply cooling there [74].

2.4.4. Pump two-phase systems (P2P)

The process of a P2P consists of evaporation and condensation. The liquid should be partly in a supercooled state to avoid cavitation in the pump. A

TAB 2. Comparison of different heat transfer technologies [57–62]

	Direct Air	Liquid	PCM	SHX	P2P
Efficiency	Low	High	High	Medium	High
Integration	Easy	Moderate	Easy	Moderate	Difficult
Temperature drop	Small	Large	Large	Large at high altitude	Large
Temperature distribution	Uneven	Even	Even	Even at high altitude	Even
Maintenance	Easy	Difficult	Easy	Difficult	Difficult
Cost	Low	High	Low	Moderate	High
Challenges	Noise	Leakage	Leakage, slow response, supercooling	Availability of cooled air during take-off, leakage	Overheat, vibration
Weight	Light	Heavy	Very heavy	Moderate	Moderate

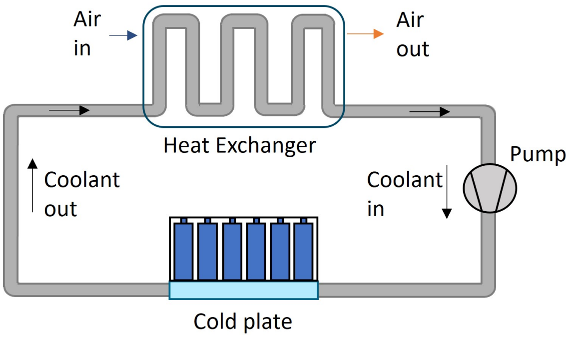

FIG 7. Liquid cooling design [63, 64]

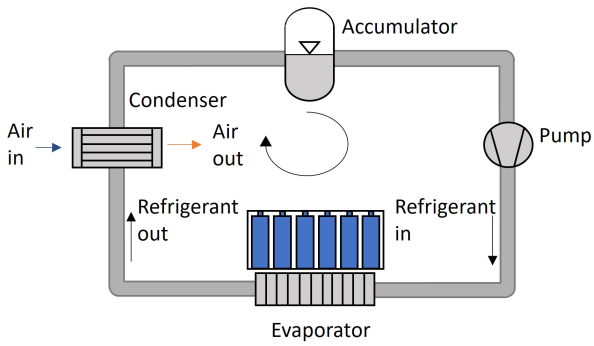

FIG 8. Pump two-phase system design [60, 77]

phase-change from liquid to vapour occurs during the absorption of heat. Afterwards, the fluid removes the heat in the condenser and returns to the liquid phase, repeating the cycle [75].
Compared to single-phase systems, two-phase system demonstrate enhanced heat transfer performance and reduced power consumption, due to a lower mass flow rate [58].
A P2P may use a mechanical pump instead of a capillary pump due to higher effectiveness. However, vibration of this system is a challenge affecting the performance [59, 60].
These systems are relatively simple to manufacture, but may need a large accumulator and are at risk of flow instability, leading to pressure drop [61, 76].

2.4.5. Phase-change material (PCM)

PCMs are relatively inexpensive passive systems. The capacity of PCMs to absorb significant quantities of heat enables them to reduce both the maximum temperature and temperature gradients. For instance, the paraffin RT 70HC has a latent heat capacity of 260 kJ/kg and a specific heat capacity of 2 kJ/kgK, in comparison to 1.0 kJ/kgK for air or 4.2 kJ/kgK of water [78]. The thermal conductivity and the specific heat capacity of PCMs can be further improved through the addition of nanomaterial additives. Moreover, PCMs are less complex than liquid cooling systems. Nevertheless, it is important to consider the potential risks associated with leakage and pressure variations during phase transitions, the low thermal conductivity, supercooling, additional weight, and poor thermal stability. As with other passive systems, they are unable to respond in a sufficiently time-efficient manner to rapid changes [25, 79–83].
To further enhance the performance and safety of the module, the PCM can be combined with additives or aerogel, the latter of which demonstrates low density yet strong thermal insulation properties, as presented in the work of Weng et al. [84]. While the PCM would be used for heat storage, the aerogel serves as the insulating material, offering a promising solution to prevent TR propagation.
PCMs have also been shown to be compatible with active systems. In the publication of Zhang et al. [85] it was demonstrated that for a pouch cell module a PCM working in combination with an active liquid cooling system can effectively prevent TR propagation.

2.4.6. Conclusion for BTMS

The following conclusion can be drawn: Direct air is a viable choice for low power applications. Similar to

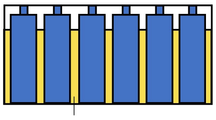

FIG 9. Phase-change material design [64, 65]

air, liquid cooling systems represent a well-established and commercially viable option that can be used with cold plates, tubes or thermal conductive structure. For the future, PCM seems to be a promising solution and may be mixed with additives or aerogel to further increase the performance. The implementation of skin heat exchangers has been demonstrated to have a positive effect on the aircraft performance but can only be considered as an additional cooling system at high altitude. Pump two-phase systems are available in a variety of configurations. Such systems are already applied for the cooling of large data centres. For the application in an aircraft, it is necessary to resolve a number of performance-related issues.

3. METHODOLOGY OF THE DESIGN PROCESS

3.1. Standards for product development processes

The fundamental principles of a product development process were established by Wögerbauer [86] with the following stages:

- clarification of the task,
- development of solution ideas,
- evaluation and improvement of the solution,
- generation of documents for the manufacturing process.

However, Wögerbauer did not adopt a systematic approach for the development, generation and assessment of the solution and their alternatives within this development process. His process was further evolved by Rodenacker [87], Roth et al. [88], Hubka [89], Koller [90] and Pahl and Beitz [91]. The contributions has been used for the development of the VDI 2221, which encompasses the following activities for the product development process:

- clarification of the problem or the task,
- determination of the functions and their structures,
- search for solution principles and their structures,
- assessment and selection of solution concepts,
- subdivision into modules,
- design of the modules,
- integration of the product as a whole as well as
- elaboration of the execution and usage requirements.

In general, a number of iteration steps would be required to achieve a satisfactory solution. It is recommended that the results of each phase are evaluated to facilitate the implementation of improvements at the earliest possible stage. This approach of short iteration cycles has been considered within the V-model of the VDI 2206 [92].
The V-model begins with the requirements for the product from which an initial overall system design has to be derived. This general design is concretised in domain-specific designs, in order to integrate these individual designs into an overall system. The most important part is represented in the assurance of properties in which the solution concept is continuously compared with the initially defined requirements. Ultimately, the product is in most cases more of an interim solution that undergoes further iterations of the macro cycle until the final product is finished.

3.2. Development process adaption

It should be noted that the product development process employed for a given task may differ from the aforementioned examples. According to Abeln [93], the necessary activities are dependent on the sector, the design type, whether a new product is designed or an existing one is improved, and the number of pieces. Therefore, adjustments are necessary and allowed. Consequently, the diagram in FIG. 10 outlines the proposed methodology for the design of a battery pack in line with the VDI 2221, but in a slightly different order [94].
The process starts with the clarification step covering the most significant requirements of the standards which are listed in the left box. The elements of the module resulting from the subdivision step are the cell, the BMS, the BTMS, as well as structural, mechanical and electrical components. The next box depicts the elaboration of solution principles by examining combinations of the aforementioned elements. Finally, the assessment and selection of solution concepts is conducted. This involves defining parallel and series connections between the cells and considering the connections between the BTMS and BMS in the module, as well as the connection of the BTMS to the aircraft level thermal management system. Moreover, the integration concept into the aircraft must be worked out. Iteration steps may be necessary to optimise the pack design before concluding the process with the final concept.
Even though the conduction of the process of this study finishes with two exemplary solutions presented later on, the conduction should be further expanded taking more battery module subelements into account and conducting a more detailed examination on the measures for the requirements, the packaging considerations and the integration concept.
In the following subsections each process step with the applied adaptions will be shortly described.

3.2.1. Clarification

The clarification of the problem or the task includes the identification of the sources of requirements. In

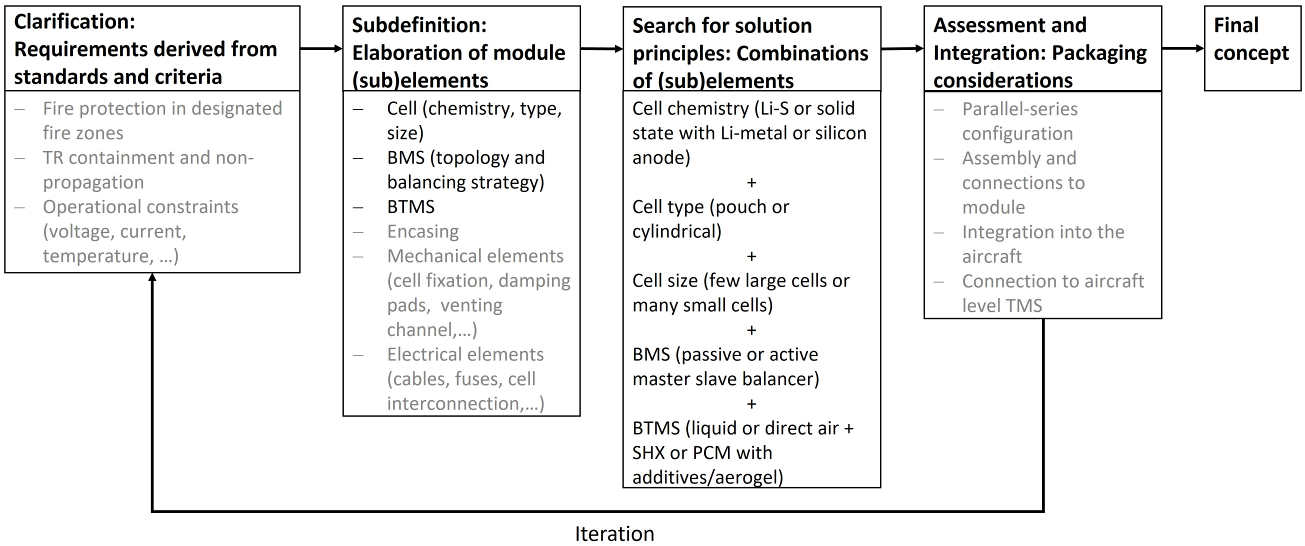

FIG 10. Full battery pack design process of this study (grayed out elements are not in the scope of this studies exemplary conduction of the development process)

general, sources can be divided into three categories: people, products and documents [95]. A broad view of sources of general requirements is given in Feldhusen et al. [96]. Specific requirements for batteries in aviation can be acquired from standards and regulations described in section 2.1.2. Subsequently, the evaluation criteria can be derived from the requirements list. They depend on the application and should be listed in an appropriate way so that responsibilities and measures are clear.

3.2.2. Subdivision into module elements

The subdivision into module elements and their design enables precise comprehension of the elements at an early stage of the design process. These elements should be selected and designed in accordance with the requirements. In this context, it is of particular importance to identify the sensitivities of the requirements with regard to the module elements. This will allow to describe the optimization potential of them.

3.2.3. Search for solution principles

The search for solution principles should result in a list of adequate options for the module elements which have to be combined to concepts in a morphological box for further assessment. The selection of the module elements can depend on the cell type. Moreover, the functionality of a concept may be affected due to negative interaction between two module elements.

3.2.4. Assessment and Integration

The concepts should be compared in order to evaluate the relative merits of each option against one another. This can be achieved through the implementation of a predefined assessment process. Possible assessment processes with different complexities are listed by Feldhusen et al. [96] and Adunka [97]. In general, an assessment process should cover a series of solutions and alternatives, with each of them resulting in advantages and disadvantages for the system. These should be weighted against one another to identify optimal solutions to fulfill the requirements of the product [98–100].
It is of high importance to consider that, despite the expectation of its occurrence is beyond the system boundaries, certain aviation specific risks exist with the potential to affect the product. These are named in the ARP 4761 and include among others lightning, bird strike, icing and leakage of coolant fluids, high temperature air and hydraulic fluids [101].
Finally, the integration of the product includes the stacking of the cells within the module, so that the desired voltage and capacity can be achieved. Additionally, it involves the investigation of connections for the high-voltage cables and the venting channels, as well as the connection between individual modules. Afterwards, the final concept can be further detailed.

4. CONDUCTION

In the following subchapters, an exemplary conduction of the aforementioned product development process for battery packs is presented. Despite the fact that certain requirements are explicitly listed in FIG. 10, they have been waived in the exemplary conduction of the process. Furthermore, structural, mechanical and electrical components have been also waived in the subedfinition step due to their lower impact on the design process or the negligible variation between the options. However, for an accurate assignment of the functions, a complete list of the module elements is required. The assessment and integration step can be conducted only after a sufficient level of detail has been achieved for the concepts.

4.1. Clarification and deriving criteria of the battery module

Possible performance parameters for the assessment of batteries are outlined by Suárez et al. [102,103] and Link et al. [7]. Combined with the criteria of TAB. 1 and 2 the evaluation of the design solutions is based on the five criteria illustrated in the legend of FIG. 11 and 12. The chosen criteria are: safety, performance, life cycle cost and reliability, resilience and ease of integration are chosen [7, 102, 103].
Safety is a crucial criterion which takes into account features to prevent cell failure due to excessive temperature, current and/or voltage. The term resilience is used to describe the ability of a system to withstand pressure, temperature and forces. It ensures stable operation of the battery. Performance is defined as the gravimetric and volumetric energy density of the system. This criterion is crucial to meet the range and the weight limit of the electric aircraft. The life cycle cost and reliability of a system is determined by the capital cost and operational cost, the cycle life and the effort required for manufacturing and maintenance. Lastly, the ease of integration is evaluated which considers the stacking of the cells, the assembly of the module elements, and the encasing. Moreover, for the assembly to a battery pack the system level thermal management system, the fire extinguishing system, and a proper integration concept into the aircraft must be considered.

4.2. Subdivision into module elements

In FIG. 11 a pool of options for the elements of the battery module design is compiled. For each option the color indicates whether the option has a positive or negative impact on each criterion. These options are addressed in the following section.

4.3. Exemplary solutions and outlook

From the variety of options that can be derived from FIG. 11, two promising design combinations are exemplary illustrated in FIG. 12. In both cases, a passive balancing master-slave BMS topology is selected, expected to be the optimal choice in terms of cost-effectiveness and cooling capabilities. The cells are made of a solid-state electrolyte and lithium anode. In the design (a), a stack of large pouch cells is cooled using a tab cooler due to the majority of the heat being generated in the tabs. The pouch-cell module contains a small number of large cells, resulting in a higher energy density and a less complex design reducing integration and maintenance effort in comparison to the cylindrical-cell module in FIG. 12 (b). The high number of cylindrical cells increases maintenance and integration efforts. However, the design (b) is expected to be safer due to the safety features of cylindrical cells at cell level, less expensive due to the longer cycle life and to demonstrate a higher level of resilience. A cold plate at the bottom of the cylindrical cells is used because of the significantly higher thermal conductivity in axial direction for that cell type. Prismatic cells are not considered due to their insufficient gravimetric and volumetric energy density.

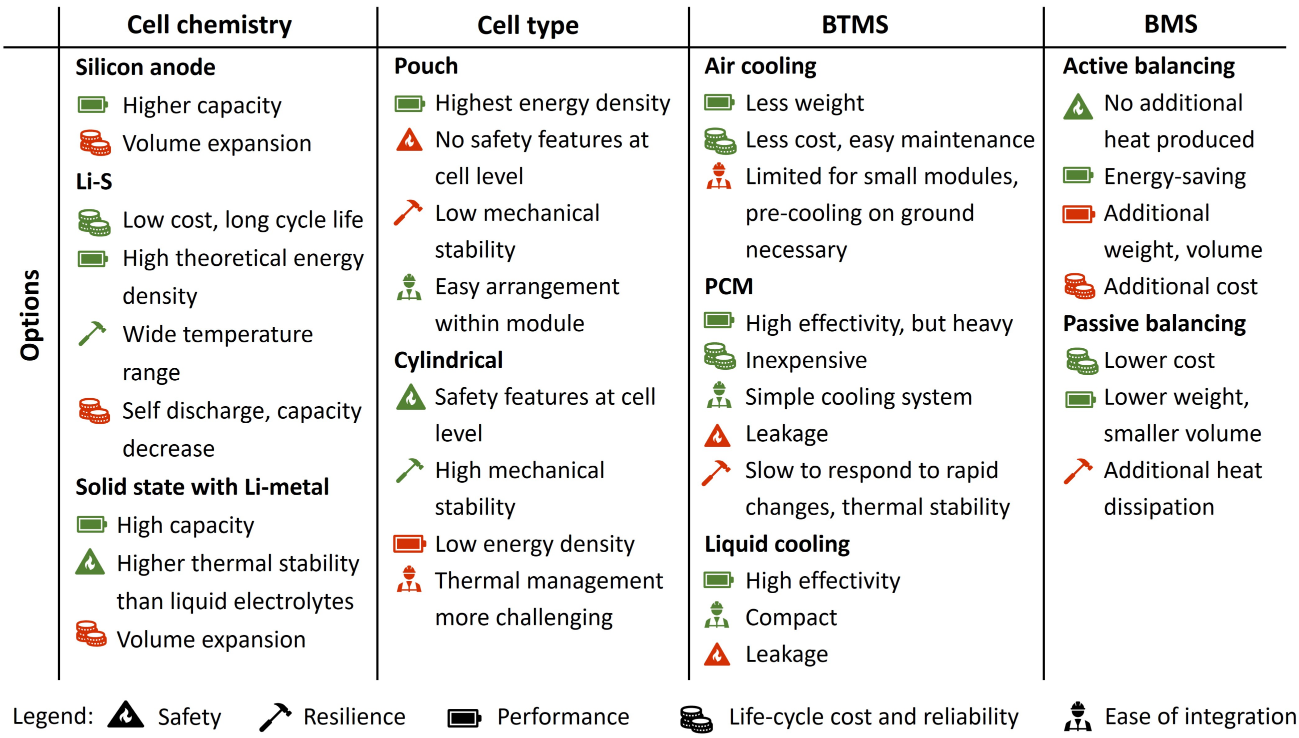

FIG 11. Options for the module design. The legend is provided in FIG. 12. Green indicates a positive effect and red indicates a negative effect.

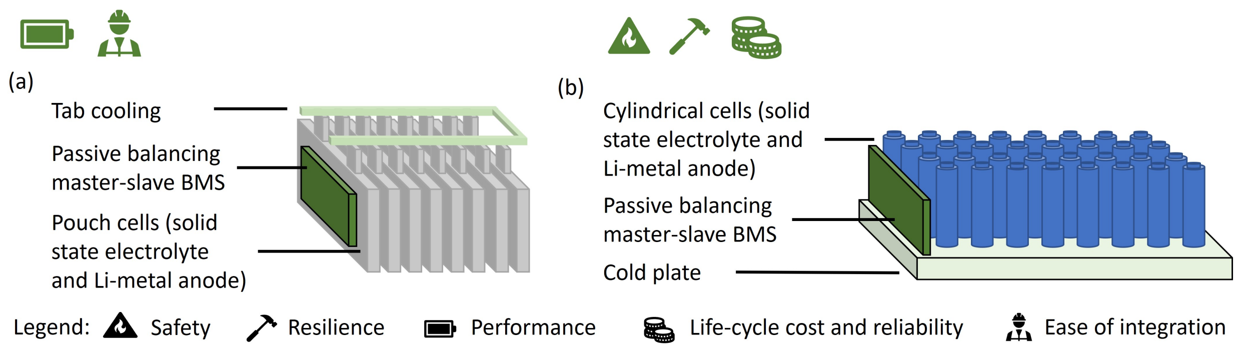

FIG 12. Two promising solutions resulting from the search for solution principles: (a) Pouch cells with tab cooling and (b) cylindrical cells with cold plate at bottom. The green symbol at the top of the options indicates which of the criterion is met more effectively.

Alternatives to the two design combinations can be derived from FIG. 11. As previously stated, new cell chemistries will be required, but the precise properties are not yet fully understood. The solid-state electrolyte and lithium-metal anode can be replaced with a silicon anode or with a Li-S cathode. While Li-S still has to prove its ability to achieve the stated high energy density, the silicon anode may prove to be a competitive alternative to the current solution, if a method for dealing with the volume changes is established. However, it must be noted, that the high performance of Li-metal in combination with the high safety of solid-state electrolytes has yet to be proven. The passive balancing system may be sufficient, if a successful matching process of the cells is implemented. In that case, cells that have undergone a preliminary selection process are utilized, with only those that exhibit similarities being employed. This can save a cost-intensive active balancing system. However, if the heat generated by the cells as a result of inadequate balancing exceeds a certain threshold, the deployment of an active balancing system may be necessary.
Furthermore, two alternative cooling systems are proposed. Firstly, a direct air cooling system may reduce weight, cost and maintenance effort but is limited to small modules. Additionally, pre-cooling on ground may be required to maintain the operative temperature range. Secondly, the PCM is a promising solution for future applications due to its simplicity, low cost, and high effectiveness. Further development is expected as combinations with additives and aerogels are tested. Of the BTMS options outlined in the document, only the pump two-phase cooling system has been excluded, as it requires further investigation regarding its performance concerns.

5. CONCLUSIONS

This paper provides an overview of the SOTA in battery packaging, discussing the most important elements and their influence on the final design. The evaluation of them resulted in the following conclusions:

- While pouch and cylindrical cells are promising cell types for aviation, the properties of cell chemistries that are expected to be used in future applications are currently uncertain. If the specified values for the energy density are achieved, the possibility of electrically driven short range aircraft may be feasible within the next decade.
- The selection of a BMS is a relatively straightforward one, besides the choice between active and passive balancing. It has to be evaluated whether the energy saved through an active balancing system is sufficient to offset the system cost.
- The heat transfer technologies with a high TRL have been discussed in this context. While SOTA solutions, such as liquid cooling and air cooling, are widely in use, they may be incapable of meeting the demands of future applications. Two-phase solutions, like PCM and P2P are still in development and may prove to be a suitable approach. In particular, the effectivity and the impact on energy density require further investigation.

Overall, the design will be primarily driven by the TR containment and non-propagation strategy and the energy density.
The design of the pack may differ depending on the relative importance assigned to each criterion and the requirements of a specific application. These have been defined as safety, performance, resilience, ease of integration as well as life-cycle cost and reliability. It has to be decided in advance which of the aforementioned factors are of greater critical importance for the final design.
Although the design process assessed here is qualitative and only a top-level example, to enable an initial estimation of the final results, it delivers guidance for future design studies. However, a more comprehensive and quantitative study of specific design combinations must be conducted including electrical, mechanical and structural elements. This will facilitate the assessment of detailed results and an investigation into the suitability of the system for a specific aircraft design.

Contact address:

alperen.altun@dlr.de

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