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GLOSSARY

Acronym	Signification
ACARS	Aircraft Communications, Addressing and Reporting System
ADAM	Advanced Air Mobility
AR	Augmented Reality

ASSB	All-Solid-State Battery
ATM	Air Traffic Management
CPDLC	Controller Pilot Data Link Communications
DEP	Distributed Electric Propulsion
eVTOL	Electric Vertical Take-Off and Landing
EVE	Eco-friendly air vehicles for multiple operating environments
FSCMs	Full Superconducting Machines
GAs	Graphene Aerogels
HTS	High-Temperature Superconducting
IMs	Induction Machines
Li-ion	Lithium-ion
Li-O2	Lithium-Oxygen
Li-S	Lithium-Sulfur
MaaS	Mobility as a Service
PEM	Proton Exchange Membrane
PMSMs	Permanent Magnet Synchronous Machines
PSR	Primary Surveillance Radar
SOFC	Solid Oxide Fuel Cell
SRMs	Switched Reluctance Machines
SSR	Secondary Surveillance Radar
TRL	Technology Readiness Level
UTM	Unmanned Traffic Management
WFSMs	Wound Field Synchronous Machines

Abstract

This report provides a comprehensive technology portfolio for advancing aircraft and related systems in the domains of **Sustainable Intermodal Mobility (ADAM)** and **Wildfire Fighting (EVE)**. A diverse array of technologies is explored, ranging from aircraft architecture to onboard systems. The portfolio assesses both Current Applicability/TRL and future potential of these technologies for specific use cases. The aim is to inform technology roadmaps and facilitate decision-making in the development of versatile, efficient, and responsive aircraft systems with the aspect of operation.

1. Executive summary

1.1 Introduction

The rapid advancements in aviation technologies offer unprecedented opportunities in various applications, notably in Sustainable Intermodal Mobility and Wildfire Fighting. This report presents a detailed technology portfolio, outlining available and emerging technologies across multiple domains such as aircraft architecture, propulsion systems, onboard systems, and other auxiliary systems like Air Traffic Management (ATM) and maintenance technologies.

The primary objective of this portfolio is to evaluate a broad spectrum of technologies for their capability to serve specific use-cases. The evaluations aim to facilitate informed decision-making and lay the foundation for developing technology roadmaps for overall aviation systems.

Technologies were selected and categorized based on their relevance to the two primary use-cases. The assessment criteria include current applicability/TRL, scalability, and future potential, providing a holistic view that combines both technical and strategic perspectives.

1.2 Brief description of the work performed and results achieved

The technology portfolio was initiated by first identifying the required capabilities at the SoS level, which was further decomposed into functions and means of fulfilling those functions. This decomposition was performed to the Constituent System and Subsystem levels finally identifying key technologies required for each of the use case.

The methodology employed for this report involved a thorough literature review, and technology assessments against predefined criteria. Special focus was given to the two-key use-cases: Sustainable Intermodal Mobility (ADAM) and Wildfire Fighting (EVE).

Key findings point toward several technologies that hold considerable promise in the short and long term. For instance, tiltrotor architectures were found to offer significant advantages in Intermodal Mobility, especially when combined with hybrid powertrain systems. In the field of Aerial Wildfire Suppression, Infrared Cameras and External Buckets were identified as essential tools for effective and rapid response during day and night operations.

The results of these evaluations serve as the basis for the recommendations and technology roadmaps outlined in this report, aiming to guide stakeholders in the selection and development of technologies that offer the most benefits and future potential.

1.3 Deviation from the original objectives

1.3.1 Description of the deviation

During the implementation phase, it was observed that due to the many stakeholders and technologies needed to fulfil the capabilities required by the SoS, a wide variety of literature and expert insight would be required. As such, the timeline for the technology portfolio was adjusted. Furthermore, it was decided to make the technology portfolio a living document throughout the course of the project which can be continuously updated as new requirements and data are identified.

1.3.2 Corrective actions

Given the deviations, the project timeline was adjusted to ensure that all objectives, even if modified, were met without compromising on the quality of outcomes.

2. WORK PERFORMED

2.1 Methodology

2.1.1 Approach

The methodology for constructing this technology portfolio centers on a multi-disciplinary approach. It begins with identifying key use-cases— Sustainable Intermodal Mobility and Wildfire Fighting—around which the technology needs are framed. From there, the capabilities required by the SoS are identified and further decomposed into it functions which can themselves induce other functions. Means of fulfilling those functions were then identified at Constituent System and Subsystem levels which subsequently lead to the identification of technologies. Finally, relevant technologies are selected and categorized based on their ability to serve these use-cases, catalogued in a table format.

2.1.2 Literature Review

An extensive literature review was conducted to gather information on existing and emerging technologies in the aviation and aerospace sectors. Peer-reviewed articles, industry reports, white papers, and expert opinions were consulted to establish the initial technology list.

2.1.3 Technology Selection Criteria

Technologies were evaluated based on a set of predefined criteria:

Relevance to Use-Cases: All technologies were evaluated for their potential impact on the primary use-cases of Intermodal Mobility and Aerial Wildfire Suppression. Technologies that did not have a direct or significant impact were excluded.

Current Applicability/TRL: Technologies were assessed for their current stage of development and readiness for deployment. TRL is a measure used to assess the maturity level of a particular technology. Each technology readiness level represents a different stage in the basic technology development cycle, ranging from basic research to deployment, as seen in Fig. 1.

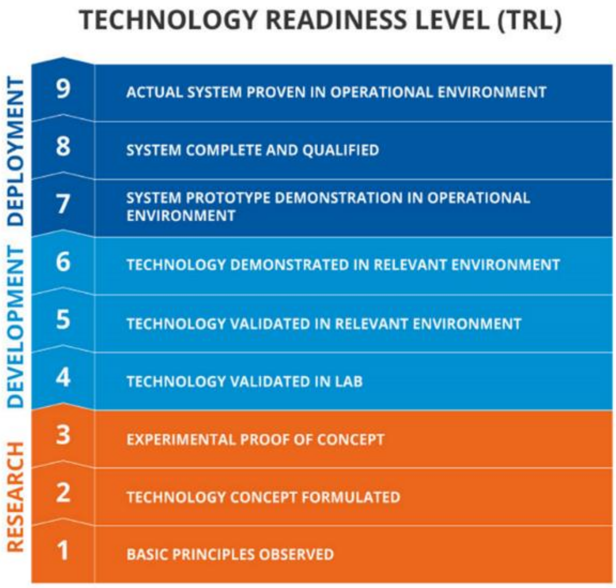

Fig. 1: Technology Readiness Level Standardization [1]

Scalability: The capability of the technology to scale, either in terms of production or in its ability to integrate with existing systems, was a key factor.
Future Potential: Technologies that hold promise for significant advancements or improvements in the future received higher priority.
Energy Efficiency: Given the increasing focus on sustainability, technologies that offer better energy efficiency were given special consideration.
Operational Safety: Technologies that contribute to the safety of the operations, either directly or indirectly, were highly valued.
Cost-Effectiveness: The cost of implementation, maintenance, and operation were also considered.
Availability of Alternatives: Technologies were also evaluated against available alternatives, to determine whether they offer any unique advantages.
Compatibility and Interoperability: Technologies that can be easily integrated with existing systems without requiring extensive modifications were favored.
User Experience: Finally, the ease of use and impact on the end-user experience was also considered, especially for systems directly interacting with passengers or operators.

These evaluation criteria are applied to most of the technologies investigated. However, it's important to note that not all criteria may be relevant for every technology assessment. Some technologies, due to their specific nature, maturity, or singular application, may not have aspects such as scalability or user experience applicable to them.

2.1.4 Assessment Metrics

Based on the technology evaluation, some methods were more favorable than others. However, a qualitative selection was avoided to balance between the exploitation of a mature technology and exploration of a new technology.

2.1.5 Technology Categorization

Technologies were grouped into several categories, such as aircraft systems, like architecture, batteries, onboard systems, and other systems like ATM, vertiports or ground crews to facilitate more focused assessments and discussions.

2.1.6 Validation and Peer Review

The preliminary findings were subjected to validation through peer review, involving both internal team members and external experts to ensure unbiased and accurate assessments.

2.1.7 Limitations

While every effort was made to provide a comprehensive technology assessment, limitations such as time constraints, data availability, and the rapidly evolving nature of some technologies should be noted.

3. TECHNOLOGY PORTFOLIO

3.1 Aircraft Systems

3.1.1 Architecture

The architecture of an aircraft refers to its fundamental design and layout, including how various components and systems are organized and integrated. Different architectures have unique advantages, disadvantages, and best-use scenarios. Four different types of eVTOL architectures are evaluated in this study and represented in Fig. 2. Additionally, two different seaplane architectures are evaluated.

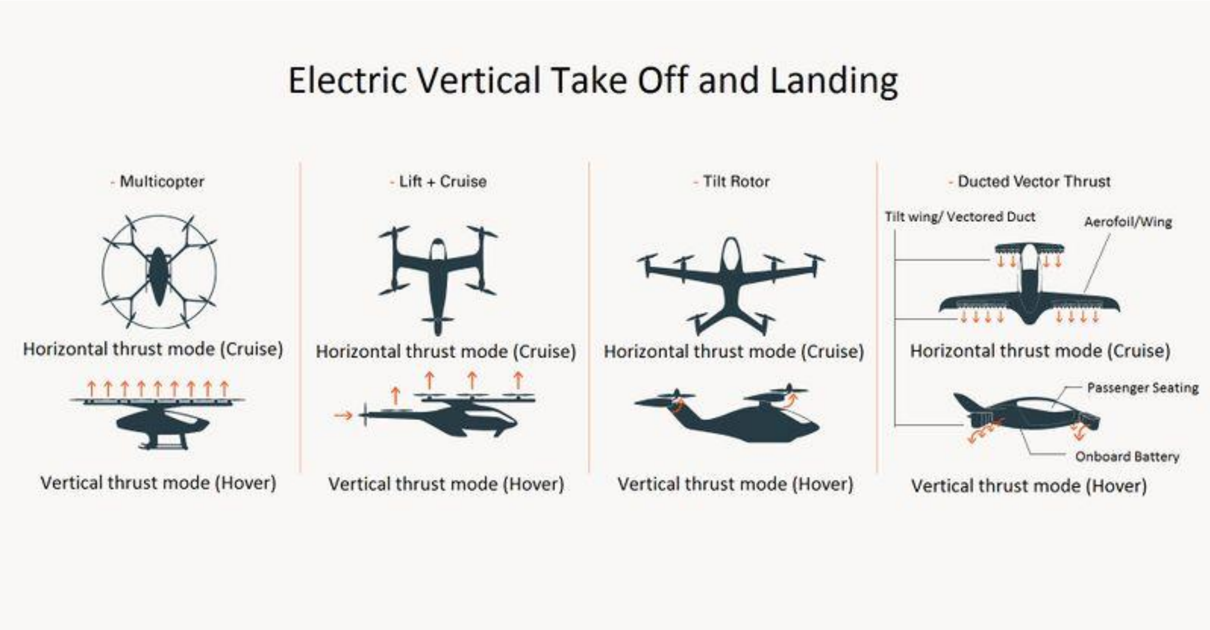

Fig. 2. Different e-VTOL architectures considered in the evaluation [2]

3.1.1.1 Tiltrotor

Capability: Intra/Inter City Travel **Function:** Payload Transport **Tech Group:** Architecture	
Relevance to Use-Cases	High. Mainly applicable to ADAM use case as it is a favorable candidate with its high range. It is also applicable for EVE use case, as it is can reach high speed with high ranges [3].
Current Applicability/TRL	High. High applicability for vertical take-off and landing (VTOL) and high-speed flight, system prototype is demonstrated leading TRL 7. For example, Joby S4 prototypes shown in Fig. 3 have been flying since 2015 [4]
Scalability	Moderate to High. Suitable for a range of applications but limited by size and payload constraints. Some challenges remain in scaling the technology for larger cargo or passenger capacity.
Future Potential	High. Significant advancements in battery technology, rotor efficiency, aerodynamics, and materials could extend applications and improve performance.
Energy Efficiency	Moderate to High. Generally, energy-efficient during forward flight but consumes more energy during vertical take-offs and landings [3]. Hybrid power systems could improve overall efficiency.

Operational Safety	High reliability since even if a rotor fails, the rest can be controlled individually, thus avoiding total failure [5], however pilot training is need for managing the safety of transitions between vertical and horizontal flight [6].
Cost-Effectiveness	Moderate. Initial costs are high due to the complexity of the system. However, its versatility can often justify the costs, depending on the specific use-case.
Availability of Alternatives	Moderate. Alternatives like Lift+Cruise architectures exist and they offer a wider range with intermediate speeds [3].
Compatibility and Interoperability	High compatibility with existing systems, requiring minimal changes to existing infrastructure like air traffic management and vertiports.
User Experience	Provides smooth transitions between different modes of flight, which enhances user comfort and convenience.

Fig. 3: Tilt-rotor Configuration Example (Joby S4-Tilt-rotor eVTOL [4]).

3.1.1.2 Lift+Cruise

Capability: Intra/Inter City Travel **Function:** Payload Transport **Tech Group:** Architecture	
Relevance to Use-Cases	High relevance for Sustainable Intermodal Mobility where smooth transition between VTOL and cruising is required. It has some utility for Aerial Wildfire Suppression, especially in rapid response scenarios.
Current Applicability/TRL	Moderately high TRL with proven capabilities in VTOL and cruising modes. The system prototype is demonstrated in the related environment leading TRL 7 [7].
Scalability	Highly scalable in terms of size and payload, making it a more flexible option for various applications including cargo and passenger transport.
Future Potential	Further development in aerodynamics and materials science could improve efficiency by reducing the drag resulting from lift propulsion system.
Energy Efficiency	A compromise between hover and cruise efficiency however the lift+cruise configuration adds unwanted weight and drag when the systems are not in use [8].

Operational Safety	Distributed Electric Propulsion (DEP) enables the use of multiple propellers for VTOL flight, ensuring safe landing even if several propellers fail [9],however smaller propellers may cause more cascading failures considering bird strikes [6].
Cost-Effectiveness	While initial development and implementation costs may be high, its scalability and range of applications can justify the investment.
Availability of Alternatives	Tiltrotor architectures are the primary alternative but may not offer the same scalability.
Compatibility and Interoperability	High compatibility with existing air traffic management systems and infrastructure. Minimal modifications are needed for integration into current operations.
User Experience	Good user experience due to smoother transitions between flight modes and the potential for greater cabin space and amenities.

(a) (b) (c)

Fig. 4: Lift + Cruise Configuration Examples (a) AeroMobil 5.0-Flying Car. (b) CityAirbus NextGen-eVTOL. (c) Soar-Fuel cell eVTOL [5].

3.1.1.3 Tiltduct

Capability: Intra/Inter City Travel **Function:** Payload Transport **Tech Group:** Architecture	
Relevance to Use-Cases	Moderate to High. Useful for both ADAM and EVE but not specialized for either. However, it is a strong candidate for EVE use case as it provides higher cruise speed than a helicopter or multirotor [10].
Current Applicability/TRL	TRL 6-7 [11] (Some prototypes and operational models, but not as mature as Tiltrotor or Lift+Cruise)
Scalability	Low (Complexity in mechanics and control systems make scaling difficult)
Future Potential	High. As the use of the devices that delay lip separation, such as vortex generators, active flow control, and/or variable lip geometry, adopted by tilt duct vehicles to improve performance, they could fill niche roles where neither Tiltrotor nor Lift+Cruise are suitable in the aspect of noise reduction [10]. The journey of tilt-ducted fan technology began in the 1950s, leading to the creation of prototypes between the 1960s and 1980s [12]. This exploration into aerodynamics and flight control is actively ongoing, promising further advancements in the field as seen in Fig. 5.
Energy Efficiency	Exit vanes provide a potential advantage as they are positioned in the location of high-energy flow, independent of freestream speed. They counteract the pitching moment of the duct about its own axis, potentially eliminating the need for additional power elsewhere on the vehicle. However, ducts contribute a large wetted area, leading to parasite drag which may limit cruise speed and/or efficiency [13].

Operational Safety	Moderate. Tilt duct configurations enhance ground handling safety by reducing risks associated with open rotors, offering a safer environment during ground operations however operational safety concerns include pitch-up moments and flow separations, especially in descending flight conditions, which necessitate careful design and operation to avoid issues like increased power requirements and noise [12].
Cost-Effectiveness	Moderate (Complexity in mechanics could drive up costs, but this may be offset by its unique capabilities)
Availability of Alternatives	High. Tiltrotor, Lift+Cruise offer similar capabilities.
Compatibility and Interoperability	Moderate. It requires specialized infrastructure and control systems, limiting easy integration with current systems.
User Experience	Moderate to High. It offers relatively smooth transitions and ducts have the potential to reduce, shield, and/or redirect noise, which could be a compelling reason to incorporate ducted proprotors [13].

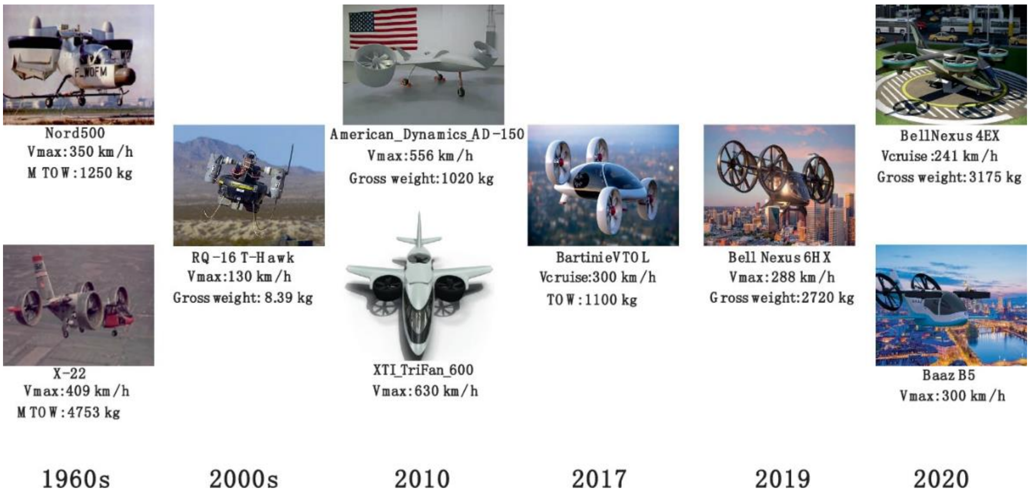

Fig. 5: History of Tilt Duct Configuration Development [12]

3.1.1.4 Multirotor

Capability: **Function:** **Tech Group:** Architecture	
Relevance to Use-Cases	Moderate. More relevant for ADAM due to their low noise and shorter take-off distances [14], however mostly limited by intracity applications. Limited payload capacity and low flight velocity may not be suitable for EVE.
Current Applicability/TRL	High. Widely used in drones, however, intracity mobility system application is completed and approved by the authorities, leading TRL 8 [15].
Scalability	Low to Moderate. Works well for smaller applications; scaling to larger sizes presents engineering challenges.
Future Potential	Moderate to High. Significant research in swarm technology and autonomous flight control, continued advancements in distributed propulsion systems.
Energy Efficiency	Moderate to High. Lower specific energy consumption compared the alternatives [14].
Operational Safety	High. Multiple rotors offer redundancy; well-understood control mechanisms, however smaller propellers may cause more cascading failures considering bird strikes [6].

Cost-Effectiveness	Moderate to High. Lower cost for smaller applications; becomes less cost-effective as scale increases however, the vehicle's overall weight is low due to being wingless therefore it is an economical choice [5].
Availability of Alternatives	High (Tiltrotor, Lift+Cruise, helicopters offer similar VTOL capabilities but different trade-offs)
Compatibility and Interoperability	High (Simpler control systems and infrastructure needs make it easier to integrate)
User Experience	High. Low noise and shorter take-off enhance user experience.

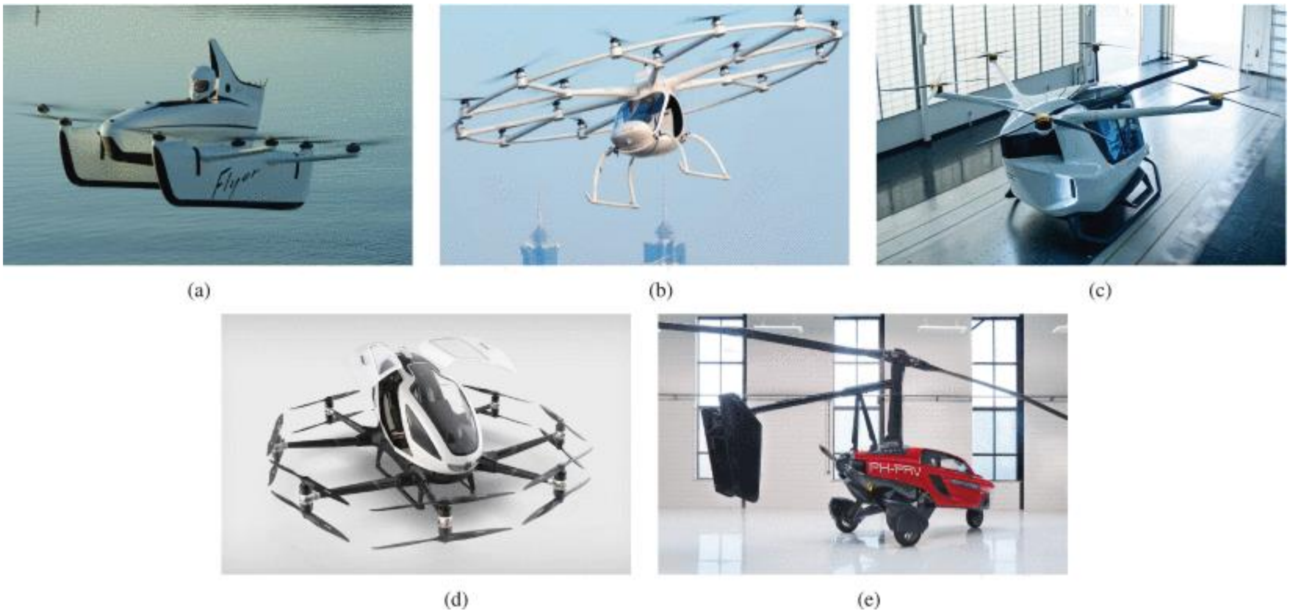

Fig. 6: Multirotor Configuration Examples (a) Kitty Hawk Flyer-Hoverbike. (b) Volocopter 2X-eVTOL. (c) Skai-Fuel cell eVTOL. (d) EHang 216-eVTOL. (e) Pal-V Liberty-Flying Car [5].

3.1.1.5 Floatplane

Capability: Intra/Inter City Travel **Function:** Payload Transport **Tech Group:** Architecture	
Relevance to Use-Cases	Moderate. Relevant for specific Intermodal Mobility scenarios involving water bodies; limited application in Aerial Wildfire Suppression for scooping water however, the response time of seaplanes would generally be quicker as they are usually located closer to the supported location than land planes [16].
Current Applicability/TRL	High (Well-established technology with various commercial and recreational uses, already in production, see Fig. 7)
Scalability	High (Floatplanes exist in a variety of sizes and capacities, including those that can carry cargo or multiple passengers)
Future Potential	Moderate (Mostly incremental improvements expected; electric propulsion is an area of active research)
Energy Efficiency	Moderate. They are generally smaller and have lower aerodynamic performance compared to other types of seaplanes [16].
Operational Safety	Moderate. Landing on a very smooth or wave-less water surface can be dangerous for seaplane pilots due to the difficulty in judging the height of the aircraft. Adverse wave and swell patterns might also affect seaplane operations [16].

Cost-Effectiveness	Moderate (Fuel and maintenance costs are relatively high due to conventional power architecture and high tendency to corrosion)
Availability of Alternatives	Few (Amphibious aircraft and ferries are the main alternatives for the same routes)
Compatibility and Interoperability	Moderate (Requires water-based landing sites; require different handling and maintenance procedures)
User Experience	Moderate. Smooth and scenic rides from the customer perspective however, landing on glassy water presents a uniform mirror-like appearance, making it hard to judge the height of the aircraft, which may require extra training for pilots in proper techniques [16].

Fig. 7: Piper PA-18 N7590K Float Plane Configuration Example

3.1.1.6 Flyingboat

Capability: Intra/Inter City Travel **Function:** Payload Transport **Tech Group:** Architecture	
Relevance to Use-Cases	Moderate (Relevant for specialized Intermodal Mobility applications involving water; some potential for Aerial Wildfire Suppression)
Current Applicability/TRL	High (Well-established, especially for long-haul water routes and for use in remote areas, see Fig. 8)
Scalability	High (Can be designed for different capacities, from small to large passenger and cargo loads)
Future Potential	Moderate (Limited to specific routes; however, development in green technologies may offer new possibilities)
Energy Efficiency	Moderate (Comparable to conventional airplanes, but with a slightly higher drag due to the boat-like fuselage)
Operational Safety	Moderate. Like other seaplanes, flying boats may face challenges related to weather conditions [16].
Cost-Effectiveness	Moderate. The hull must be robust and heavy to withstand water impact [16]; therefore, they are relatively heavier leading higher operational cost, however modern materials can help minimize additional weight.
Availability of Alternatives	Low to Moderate (Floatplanes and ferries can serve as alternatives but may lack some capabilities

Compatibility and Interoperability	Moderate (Requires specialized infrastructure for water landings; generally compatible with existing air traffic systems)
User Experience	Moderate. It also requires pilot trainings due to the same reasons with floatplanes.

Fig. 8: Canadair CL-415 Flying Boat Configuration Example

3.1.2 Wing Types

The type of wings an aircraft possesses significantly impacts its aerodynamic efficiency, range, and overall performance. Different wing types are better suited for particular flight conditions and operational scenarios. The following wing types have been considered for evaluation:

3.1.2.1 Conventional

Capability: Payload Transport **Function:** Generate lift in air **Tech Group:** Wing Types	
Relevance to Use-Cases	High (Applicable to ADAM and EVE)
Current Applicability/TRL	High (Widely used and well-understood technology)
Scalability	Highly scalable from small drones to large commercial aircraft.
Future Potential	Moderate (Mature technology with incremental advancements)
Energy Efficiency	Moderate (Optimized for subsonic speeds but not the most efficient for vertical take-off and landing)
Operational Safety	High (Proven safety record)
Cost-Effectiveness	High (Economical due to extensive existing knowledge and infrastructure)
Availability of Alternatives	High (Various types of wings for specialized use-cases)

Compatibility and Interoperability	High (Widely compatible with existing systems and regulations)

3.1.2.2 Distributed Electric Propulsion

Capability: Payload Transport **Function:** Generate lift in air **Tech Group:** Wing Types	
Relevance to Use-Cases	High (Especially for ADAM)
Current Applicability/TRL	Moderate (Emerging technology with ongoing research, offers the potential for improved aerodynamic performance.)
Scalability	Moderate (Can be adapted for smaller aircraft but still under development for larger ones due to current limitations in electric propulsion)
Future Potential	High (Many ongoing research projects aiming for improved efficiency and capabilities, depending breakthroughs in electric motor and battery technologies.)
Energy Efficiency	High (Specifically designed for better energy utilization)
Operational Safety	Moderate (Still under testing; safety largely unproven)
Cost-Effectiveness	Low (High development and operational costs)
Availability of Alternatives	Few (Unique capabilities but still in the developmental phase)
Compatibility and Interoperability	Moderate (May require new infrastructure and regulations)

3.1.2.3 Strut Braced

Capability: Payload Transport **Function:** Generate lift in air **Tech Group:** Wing Types	
Relevance to Use-Cases	Moderate (Applicable mainly to smaller aircraft for ADAM)
Current Applicability/TRL	High (Well-established for specific aircraft types, common in lighter, general aviation aircraft; offers a balance between aerodynamic efficiency and structural support.)
Scalability	Moderate (Mainly suited for smaller to medium-sized aircraft.)
Future Potential	Low (As the technology is relatively mature, but material advancements could offer improvements.)
Energy Efficiency	Moderate (Optimized for the specific requirements of smaller aircraft)
Operational Safety	High (Proven safety record for the aircraft types it is used on)
Cost-Effectiveness	High (Economical due to simpler construction and materials)
Availability of Alternatives	Many (Other wing types can often fulfill the same roles)
Compatibility and Interoperability	High (Compatible with existing smaller aircraft types)

3.1.2.4 Hydrofoil

Capability: Payload Transport **Function:** Generate lift in water **Tech Group:** Wing Types	
Relevance to Use-Cases	High. Hydrofoil wings are especially beneficial for seaplanes involved in both ADAM and EVE. They can improve take-off and landing performance on water[17].
Current Applicability/TRL	Moderate to High. Hydrofoils are already widely used in marine applications, and the technology is mature enough to be adapted to seaplanes[18].
Scalability	High. Given their importance in facilitating efficient water take-off and landings, hydrofoil wings can be scaled across different sizes and types of seaplanes.
Future Potential	High. The unique benefits of hydrofoil wings in improving energy efficiency and operational effectiveness on water make them a future-proof technology for seaplanes. Also, it could benefit from advancements in materials and hydrodynamic simulations.
Energy Efficiency	High. Hydrofoil wings can significantly reduce drag during water operations, thereby improving fuel or energy efficiency.
Operational Safety	High. They can enhance the stability and control of the seaplane during water-based operations, contributing to operational safety.
Cost-Effectiveness	Moderate to High. Although the initial investment might be higher, the long-term benefits in terms of operational effectiveness and energy savings can justify the costs.
Availability of Alternatives	Moderate. While other wing types can be used, hydrofoils offer unique advantages in water-based operations that are hard to match.
Compatibility and Interoperability	High. If the seaplane is being specifically designed with hydrofoil wings in mind, they can be easily integrated into the design.

3.1.3 Tail Types

The tail configuration of an aircraft plays a crucial role in its stability and control. The design of the tail can influence yaw and pitch characteristics, impacting overall handling and performance. Below are the different types of tail configurations considered for evaluation:

3.1.3.1 V-Tail

Capability: Payload Transport **Function:** Ensure stability **Tech Group:** Tail Types	
Relevance to Use-Cases	Moderate. The V tail configuration can be applied to seaplanes used in Intermodal Mobility and Wildfire Suppression, but it doesn't offer unique advantages for these specific use-cases.
Current Applicability/TRL	High. Primarily found in some general aviation aircraft; reduces drag but can complicate control systems.
Scalability	High. It can be scaled to fit various seaplane sizes effectively.
Future Potential	Moderate. While it's a mature technology, limited advancements expected, though improvements in control algorithms could make it more widespread.
Energy Efficiency	Moderate. It offers good energy efficiency, providing weight reduction (a smaller number of control surfaces) and drag reduction (high aerodynamic efficiency).
Operational Safety	High. The V tail has a proven safety record in aviation.
Cost-Effectiveness	Moderate.

Availability of Alternatives	High. There are several alternative tail configurations available.
Compatibility and Interoperability	Moderate. As the traditional separate rudder and elevators are replaced by two slanted surfaces known as ruddervators, the control system is more complex compared to traditional tail structures.

3.1.3.2 T-Tail

Capability: Payload Transport **Function:** Ensure stability **Tech Group:** Tail Types	
Relevance to Use-Cases	Moderate. Similar to the V tail, the T tail configuration is relevant but doesn't provide unique benefits for Intermodal Mobility and Wildfire Suppression.
Current Applicability/TRL	High. T tails are widely used and well-understood, offers aerodynamic advantages but can lead to specific control issues.
Scalability	High. It's adaptable to various aircraft sizes, well-suited for medium to large aircraft.
Future Potential	Moderate. It's a mature technology with room for improvement, particularly with the development of advanced materials.
Energy Efficiency	Moderate. Offers good energy efficiency, though other tail types may excel in specific scenarios.
Operational Safety	Moderate. Risk of deep stall, requires stiffer fuselage to avoid flutter.
Cost-Effectiveness	Moderate. Potentially lighter due to smaller tails but stiffer fuselage adds additional weight.
Availability of Alternatives	High. Multiple tail configurations are available.
Compatibility and Interoperability	High. Risk of deep stall, requires stiffer fuselage to avoid flutter, potentially additional weight and structural complexity.

3.1.3.3 Conventional

Capability: Payload Transport **Function:** Ensure stability **Tech Group:** Tail Types	
Relevance to Use-Cases	Moderate. Similar to V an T tail configuration.
Current Applicability/TRL	High. Most widespread design, found in everything from small general aviation aircraft to large commercial airliners.
Scalability	High. It's adaptable to various sizes of both eVTOLs and seaplanes by providing predictable and easy-to-control flight experience.
Future Potential	Moderate, mature design with limited scope for revolutionary improvements, but incremental advancements continue.
Energy Efficiency	Moderate. More drag compared to other designs like the T-tail and less resistance to crosswind landings or takeoffs.
Operational Safety	High. Good visibility of control surfaces for inspections.
Cost-Effectiveness	High.

Availability of Alternatives	Moderate. While alternatives exist, the conventional tail remains a strong choice for both types of aircraft.
Compatibility and Interoperability	High. It can integrate easily with existing systems for both eVTOLs and seaplanes.

3.1.3.4 Canard

Capability: Payload Transport **Function:** Ensure stability **Tech Group:** Tail Types	
Relevance to Use-Cases	Low. The canard configuration is less relevant for ADAM and EVE, mainly military applications.
Current Applicability/TRL	Moderate. It's less common than other tail types in aviation, but offers advantages in maneuverability; typically found in experimental and military aircraft
Scalability	Moderate. Primarily used in small to medium-sized aircraft.
Future Potential	High. Ongoing research might improve its effectiveness, specially increased adoption with advancements in aerodynamic modeling and control systems.
Energy Efficiency	Low. Typically, less energy-efficient than other configurations for both eVTOLs and seaplanes.
Operational Safety	Moderate. May have limitations in certain scenarios.
Cost-Effectiveness	Low. Can be costlier to implement and maintain.
Availability of Alternatives	Low. Few alternatives in aviation.
Compatibility and Interoperability	Moderate. Requires specialized design considerations.

3.1.4 Batteries

Battery technology is a cornerstone of electric and hybrid-electric aircraft. The type of battery used impacts the aircraft's range, charging time, and overall performance. Here are the various types of batteries evaluated:

3.1.4.1 Li-Ion (Lithium-ion)

Capability: Payload Transport **Function:** Provide power **Tech Group:** Batteries	
Relevance to Use-Cases	High. Lithium-ion batteries are highly relevant for both eVTOLs and seaplanes in Intermodal Mobility and Wildfire Suppression due to their higher specific power and demonstrated success in electric aviation.
Current Applicability/TRL	High. Li-ion batteries are widely used and well-developed in various industries, including electric aviation, see Pipistrel Alpha Electro, E-Fan X.
Scalability	High. They can be scaled to meet the power requirements of both eVTOLs and seaplanes effectively.
Future Potential	High. Ongoing research aims to improve the energy density of Li-ion batteries, making them even more suitable for aviation applications.
Energy Efficiency	Moderate to High. Li-ion batteries offer good energy efficiency, especially when compared to traditional combustion engines. However, there is room for improvement.

Operational Safety	Moderate. While Li-ion batteries have been used successfully, they are known to pose safety risks, particularly overheating at higher voltages. Safety measures and monitoring systems are necessary to mitigate these risks.
Cost-Effectiveness	High. Li-ion batteries provide a cost-effective solution for electric aviation, especially when considering their widespread availability and proven performance.
Availability of Alternatives	Moderate. While Li-ion batteries are a leading technology, alternatives like solid-state batteries are being developed and may offer advantages in the future.
Compatibility and Interoperability	High. Li-ion batteries can integrate easily with electric propulsion systems commonly used in aviation.
User Experience	High. Li-ion batteries contribute to a quieter and more environmentally friendly flying experience for passengers and operators.

Even though there are certain challenges, such as overheating at higher voltages and the need for advanced cathode and anode materials to address lower specific energy concerns, Li-ion battery technology has achieved specific energy densities over 250 Wh/kg and is currently considered the benchmark for comparison with other potential battery technologies in aviation and automobile applications [19].

3.1.4.2 Li-S (Lithium-Sulfur)

Capability: Payload Transport **Function:** Provide power **Tech Group:** Batteries	
Relevance to Use-Cases	Moderate to High. Li-S batteries offer a promising technology with specific advantages for your eVTOLs and seaplanes. They are particularly relevant when weight and energy density are critical factors.
Current Applicability/TRL	Low to Moderate (TRL 6-7). Experimental stage; offers higher energy density but from limitations such as poor instantaneous power capabilities, high self-discharge and short cycle life, particularly in the presence of high discharge currents [20]. See *Airbus Zephyr* [21].
Scalability	Moderate. Li-S batteries have the potential to scale effectively, but their current application may be limited due to ongoing development.
Future Potential	High if cycle life and stability issues can be resolved. Li-S batteries have the potential to achieve extremely high gravimetric energy capability, making them suitable for applications where weight is crucial. Specially, researches done about the use of Graphene Aerogels (GAs) for Li-S Batteries offer the potential to address several critical challenges in Li-S battery technology, such as increasing sulfur loading and improving cycling stability [22].
Energy Efficiency	High. Li-S batteries offer excellent energy efficiency, with a potential energy density of around 600 Wh/kg.
Operational Safety	Moderate. Li-S batteries may pose certain challenges related to their complex working mechanism and temperature sensitivity. Further research is needed to address these issues.
Cost-Effectiveness	High. Li-S batteries benefit from cheap, abundant, and non-toxic raw materials, which can contribute to cost-effectiveness and environmental friendliness.
Availability of Alternatives	Moderate. While Li-S batteries show promise, they are still in the development phase, and alternatives like Li-ion are more established.
Compatibility and Interoperability	Moderate. Li-S technology may require specific engineering solutions and system adaptations due to its unique characteristics.

User Experience	Moderate. Li-S cells do not require top-up charging when in storage, which is advantageous however, their complex working mechanism may pose challenges in terms of system behavior [20].

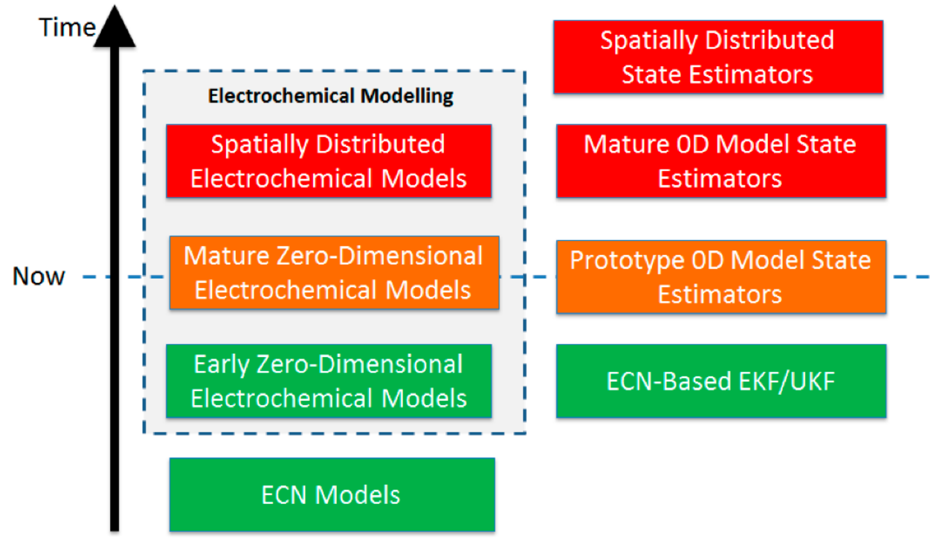

Fig. 9: Anticipated progression for state estimation in Li-S: colors serve as a 'traffic signal' representation of technological preparedness, where green denotes the highest readiness, and red indicates the least readiness [20].

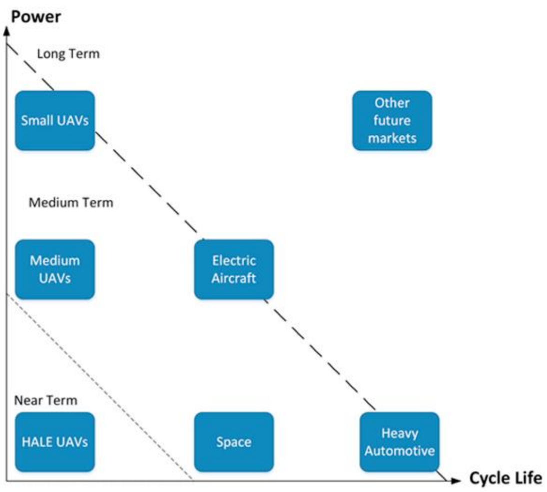

Fig. 10: Applications of Li-S cells compared to enhancements in power, cycle life, and timeframe [20].

Li-S battery technology holds promise, especially in terms of energy density and cost-effectiveness. Its potential applications include high-altitude long-endurance unmanned aerial vehicles (HALE UAVs) with low power and cycle life requirements. The main challenge of these batteries is their longevity, as they tend to fail after around 100 charging cycle [21].

3.1.4.3 Li-O2 (Lithium-Air)

Capability: Payload Transport **Function:** Provide power **Tech Group:** Batteries	
Relevance to Use-Cases	Moderate to High. Li-air batteries offer high specific energy density, making them potentially suitable for aviation applications with weight constraints. However, practical applications are still in the research and development phase.

Current Applicability/TRL	Low. Li-air batteries are currently not in practical use due to several technical challenges, and their technology readiness level is low. Experimental prototypes have demonstrated limited performance.
Scalability	Moderate. Li-air batteries have the potential to scale effectively, but significant research and development efforts are required to overcome existing challenges.
Future Potential	High. Li-air batteries have a theoretical energy density advantage, and research suggests that energy densities of up to 1700 Wh/kg may be achievable in the future (see Fig. 11). Airbus and EADS are considering Li-air batteries for future aircraft [19]. According to, the technology might be market-ready by 2030 [23].
Energy Efficiency	Low. Li-air batteries currently exhibit lower electrical efficiency (around 60% to 70%) compared to other battery chemistries. Improving efficiency is a critical challenge.
Operational Safety	Moderate. Li-air batteries, like other advanced batteries, must address safety concerns, especially as they move toward practical applications.
Cost-Effectiveness	Uncertain. The cost-effectiveness of Li-air batteries is unclear at this stage, as it depends on advancements in technology and economies of scale however, metal-air batteries promise relatively low cost [24].
Availability of Alternatives	Limited. Li-air batteries offer a unique combination of high specific energy density, but alternatives like Li-ion and Li-S batteries are more mature and established. As it is seen in the figure, the State of the Art and expected values for cell energy densities for Li-S and Li-Ion outperform the Li-air batteries.
Compatibility and Interoperability	Moderate. Li-air batteries would need to be designed and integrated into aviation systems, and compatibility with existing systems and safety standards is a consideration.
User Experience	Low maintenance is advantageous however, it is still unclear whether Lithium-Air batteries can be realized as rechargeable systems for electric vehicles [23].

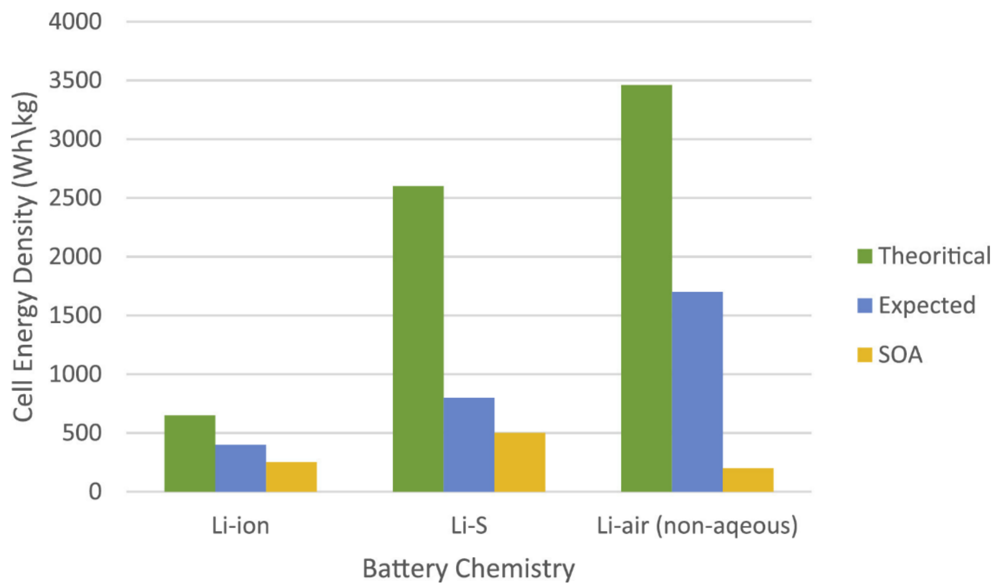

Fig. 11: Cell energy density values of available battery chemistries for aviation applications [19].

Li-air batteries hold promise for aviation applications due to their high theoretical energy density. However, significant technical challenges, including low efficiency and limited cycle life, need to be overcome before practical aviation applications become feasible.

3.1.4.4 ASSB (All-Solid-State Battery)

Capability: Payload Transport **Function:** Provide power **Tech Group:** Batteries	
Relevance to Use-Cases	High. Addresses issues of poor cycle performance, electrolyte leakage, and flammability in current lithium-ion batteries, making them suitable for both intermodal mobility and aerial wildfire suppression.
Current Applicability/TRL	Moderate. Several projects, such as NASA's SABERS project, have demonstrated promising results with solid-state batteries, indicating their viability for real-world applications [19] (TRL of 4-5 or higher).
Scalability	Moderate. Mass production methods are still under development, which may affect scalability.
Future Potential	High. Solid-state batteries offer shorter charging times, higher energy density, and inherent safety, positioning them as the future battery technology for energy storage.
Energy Efficiency	High. Solid-state batteries have higher energy density and shorter charging times, enhancing their energy efficiency.
Operational Safety	High. Inherent safety due to solid electrolytes eliminates issues like electrolyte leakage and flammability.
Cost-Effectiveness	Low, requires 5-10 times more than Li than Li-ion batteries therefore, mass production methods need to be developed, which will impact cost-effectiveness.
Availability of Alternatives	Limited alternatives for addressing the shortcomings of current lithium-ion batteries.
Compatibility and Interoperability	Moderate. Integration into existing systems may require adaptations.
User Experience	High. Shorter charging times and higher energy density offer an improved user experience.

3.1.5 Fuel Cells

Fuel cells offer an alternative to traditional internal combustion engines and batteries, converting chemical energy directly into electricity. They can be particularly useful in hybrid configurations where they serve as range extenders or power backup. Here are the types of fuel cells evaluated:

3.1.5.1 PEM (Proton Exchange Membrane) Fuel Cells

Capability: Payload Transport **Function:** Provide power **Tech Group:** Fuel Cells	
Relevance to Use-Cases	High. It is well-suited for applications where high-power density and rapid response are required, such as automotive and portable devices.
Current Applicability/TRL	Relatively mature technology, with commercial applications like the Toyota Mirai fuel cell vehicle. Several companies are actively producing PEM FC stacks [25].
Scalability	Scalable for a wide range of applications, from small electronic devices to large vehicles.
Future Potential	High. PEM fuel cells have significant potential for future use, especially in automotive and portable applications, with ongoing research to improve efficiency and reduce costs.
Energy Efficiency	High. PEM fuel cells can achieve high energy conversion efficiency when supplied with pure hydrogen, making them energy-efficient for various applications.
Operational Safety	Low to Moderate. Safety concerns are mainly related to hydrogen storage and handling, which require careful management to ensure safety.
Cost-Effectiveness	Low to Moderate. While costs have been decreasing, PEM fuel cells can still be relatively expensive, but ongoing development aims to improve cost-effectiveness.

Availability of Alternatives	Alternatives like lithium-ion batteries exist for many applications, making fuel cells face competition.
Compatibility and Interoperability	Low to Moderate. PEM fuel cells require a hydrogen infrastructure, limiting their compatibility with existing energy systems. Interoperability may be a challenge.
User Experience	Low to Moderate. User experience with PEM fuel cells depends on the availability of hydrogen refueling infrastructure, which can vary by region. However, lower environmental impact when hydrogen is produced using clean methods, as they produce only water vapor as a byproduct.

3.1.5.2 Solid Oxide Fuel Cells (SOFC)

Capability: Payload Transport **Function:** Provide power **Tech Group:** Fuel Cells	
Relevance to Use-Cases	Low. Typically used in stationary power generation due to their lower power density and slower response times. Less relevant for applications with dynamic power demands.
Current Applicability/TRL	Also mature for stationary power generation, with some commercial deployments. However, less mature for mobile applications and aviation.
Scalability	Scalable for stationary power generation but less practical for applications requiring high specific power, like aviation. The specific power density of SOFC is 5-10 times lower than PEM FC. Therefore, it is not expected that they will be used in aviation over the next 10-15 years [25].
Future Potential	Low. SOFCs are well-established for stationary power generation but have limited potential for applications with high specific power requirements.
Energy Efficiency	Moderate to High. SOFCs generally offer good energy conversion efficiency, especially for stationary power generation.
Operational Safety	Moderate. SOFCs are generally safer than some other fuel cell types, with fewer safety concerns related to fuel handling.
Cost-Effectiveness	Low to Moderate. SOFCs may be more cost-effective for stationary applications but may face challenges in mobile and aviation applications.
Availability of Alternatives	Moderate. Alternatives like natural gas generators exist for stationary power generation. SOFCs may face competition from other fuel cell types for specific applications.
Compatibility and Interoperability	Moderate. SOFCs offer more flexibility in terms of fuel options, reducing infrastructure requirements in some cases.
User Experience	Low to Moderate. User experience with SOFCs depends on the application, with mature use cases in stationary power generation but limited relevance for mobile and aviation applications. It is considered environmentally friendly when using clean fuels, but fuel processing and emissions can impact the environment.

PEM Fuel Cells are currently more applicable to a wide range of use cases, with a higher TRL, and offer better scalability for various applications. They are particularly well-suited for mobile and portable devices, as well as automotive applications. SOFCs, while mature for stationary power generation, face challenges in terms of specific power and may not be as relevant for applications with dynamic power requirements like aviation.

3.1.6 Electric and Hybrid Powertrain Systems

Hybrid powertrain systems combine two or more sources of power to improve efficiency and range. They play a pivotal role in achieving a balanced performance in terms of energy usage, operational range, and power output. In this section powertrain structures evaluated based on aircraft type and their TRLs [25]. Here are the types of powertrain systems evaluated:

3.1.6.1 Battery-Powered Full Electric Propulsion Systems for Ultralight Aircraft:

Capability: Payload Transport **Function:** Provide power **Tech Group:** Powertrain Systems	
Future Potential	Battery-powered full electric propulsion systems for ultralight aircraft are already available (TRL-9) and can provide one-hour flight durations. By 2030, it's expected that these systems will achieve at least two-hour flight durations, indicating high future potential.
Current Applicability/TRL	Currently at TRL-9.
Scalability	These systems are suitable for ultralight aircraft with a take-off mass of 600 kg [25] or 650 kg for light sport aeroplanes operated on water [26]. If TRL 9 is considered, the maximum take-off mass can be constrained to 750 kg for very light airplanes [27], among which fully electric vehicles have not yet been extensively explored.
Compatibility and Interoperability	These systems rely on batteries and electric motors, which are well-established technologies.
User Experience	Users can benefit from quieter and environmentally friendly flights.

3.1.6.2 Battery-Powered Full Electric Airplane for 9 Passengers:

Capability: Payload Transport **Function:** Provide power **Tech Group:** Powertrain Systems	
Future Potential	Battery-powered full electric airplanes for 9 passengers are in the development phase (TRL-5), with a maximum range of up to 400-600 km expected by 2030 (TRL-9). This indicates significant future potential.
Current Applicability/TRL	Currently at TRL-5 [23], expected to reach TRL-6-7 before into service time[28].
Scalability	Designed for relatively small aircraft with a maximum take-off weight of 6000 kg.
Compatibility and Interoperability	These systems require charging infrastructure and may require adaptations for larger aircraft.
User Experience	Users can benefit from reduced emissions and operational costs once these aircraft are deployed.

3.1.6.3 Hybrid Electric Propulsion Systems for Commuter Airliners:

Capability: Payload Transport **Function:** Provide power **Tech Group:** Powertrain Systems	
Future Potential	Hybrid electric propulsion systems for commuter airliners with a capacity of up to 19 passengers are expected to be developed in 2025 (TRL-6), offering a range of up to 1000 km. This technology shows potential for short-haul regional flights.
Current Applicability/TRL	Expected to reach TRL-6 by 2025.
Scalability	Suitable for commuter airliners with a maximum take-off weight of up to 7500 kg.
Compatibility and Interoperability	These systems would require advancements in infrastructure and integration.

User Experience	Users could benefit from reduced emissions on short-haul routes.

3.1.6.4 Hybrid Electric Propulsion Systems for Regional Aircraft:

Capability: Payload Transport **Function:** Provide power **Tech Group:** Powertrain Systems	
Future Potential	Hybrid electric propulsion systems for regional aircraft with a capacity of up to 100 passengers, weighing up to 40 t, and a range of up to 4500 km are expected to be developed in 2035-2040 (TRL-6). This technology holds potential for regional air travel.
Current Applicability/TRL	Expected to reach TRL-6 by 2035-2040.
Scalability	Designed for regional aircraft with up to 100 passengers.
Compatibility and Interoperability	Infrastructure development and integration would be necessary.
User Experience	Users could experience more sustainable regional flights.

3.1.6.5 Battery-Powered Full Electric Rotorcraft and VTOL Aircraft:

Capability: Payload Transport **Function:** Provide power **Tech Group:** Powertrain Systems	
Future Potential	Battery-powered full electric rotorcraft and VTOL aircraft are available now (TRL-6), with flight durations of 15-20 minutes. By 2030, these aircraft (TRL-9) are expected to achieve flight durations of 30-35 minutes.
Current Applicability/TRL	Currently at TRL-6, expected to reach TRL-9 by 2030.
Scalability	Suitable for small rotorcraft and VTOL aircraft.
Compatibility and Interoperability	Infrastructure development and battery advancements are necessary.
User Experience	Users could benefit from efficient urban air mobility options.

3.1.6.6 Full Electric Battery-Powered Propulsion Systems for eVTOLs:

Capability: Payload Transport **Function:** Provide power **Tech Group:** Powertrain Systems	
Future Potential	Full electric battery-powered propulsion systems for air taxis are expected to be developed in 2022-2023 (TRL-6), providing flight durations of 15-20 minutes. Hybrid and fuel cell-based systems for such aircraft will be developed later.
Current Applicability/TRL	Expected to reach TRL-6 by 2022-2023.
Scalability	Designed for vertical take-off and landing aircraft (eVTOL) with a maximum take-off weight of 2000 kg.
Compatibility and Interoperability	Infrastructure development and technology integration will be required.
User Experience	Users may experience shorter urban air mobility flights with reduced emissions.

3.1.6.7 Hybrid Electric Propulsion Systems for Rotorcraft:

Capability: Payload Transport **Function:** Provide power **Tech Group:** Powertrain Systems	
Future Potential	Hybrid electric propulsion systems for rotorcraft weighing up to 3000-4000 kg are expected to be developed in 2030-2035 (TRL-6).
Current Applicability/TRL	Expected to reach TRL-6 by 2030-2035.
Scalability	Designed for rotorcraft with specific weight limitations.
Compatibility and Interoperability	Infrastructure and integration challenges would need to be addressed.
User Experience	Users of rotorcraft may benefit from reduced emissions and improved efficiency.

Fuel Cell-Based Propulsion is considered for ultralight aircraft, commuter airliners, rotorcraft, and VTOL aircraft with various TRLs and future development timelines. As the technology is evolving, both academic and commercial resources are being used to investigate the technology. For example, AeroDelft, TU Delft student team, is actively working on the world's first manned liquid hydrogen-powered electric aircraft to promote emission-free aviation while Airbus exploring hydrogen propulsion, where hydrogen is either combusted or converted into electricity via fuel cells, aiming for world's first hydrogen-powered commercial aircraft by 2035. Similarly, ZeroAvia advocates for hydrogen-electric engines as a scalable solution for zero-emission aviation, emphasizing hydrogen's superior energy density and lower costs compared to lithium-ion batteries and aims for hydrogen-powered retrofit of a 19 seaters regional aircraft by 2025.
Moreover, further development needed in electric motors, generators, control systems, power conversion and transmission systems, and energy storage devices.

3.1.7 Electric Motors

Electric motors are the heart of any electric or hybrid-electric aircraft, converting electrical energy into mechanical energy. Their efficiency, power-to-weight ratio, and reliability are critical factors for the overall performance of the aircraft. Here are the types of electric motors evaluated:

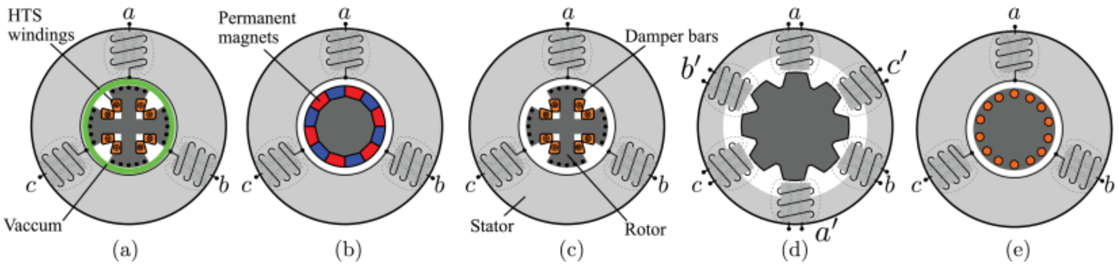

Fig. 12: Representations of different electric motors: HTS: High temperature superconducting machines (a), PMSM: Permanent magnet synchronous machines (b), SRM: Switched reluctance machines (c), WFSM: Wound field synchronous machines (d), IM: Induction Machines (e) [29].

3.1.7.1 High-Temperature Superconducting (HTS) Machines

Capability: Payload Transport **Function:** Convert Energy **Tech Group:** Electric Motors

Relevance to Use-Cases	HTS machines are poised to have a significant impact on the future of aircraft electrification, offering high power density and efficiency. However, their true potential is yet to be fully realized due to challenges in technology maturity.
Current Applicability/TRL	Given the current state of materials and technology, HTS machines are still in the developmental phase and are not expected to be commercialized for aircraft applications for another 20-30 years [29].
Scalability	HTS machines offer scalability up to high power levels but are constrained by limitations in the current state of materials and related technologies.
Future Potential	HTS machines have high future potential but require extensive research and development, especially in materials science and coil manufacturing techniques.
Energy Efficiency	These machines are highly energy-efficient but face challenges in cryogenic losses, particularly in Full Superconducting Machines (FSCMs) due to high ac losses. Research is ongoing to reduce these losses through techniques like striation technology and flux diverters [29].
Operational Safety	Safety is a significant concern, given the complexity of materials and cryogenic temperatures at which HTS conductors operate. Issues such as tape delamination, coil quenching, and electrothermal stresses need to be carefully managed.
Cost-Effectiveness	While the theoretical benefits of HTS machines promise long-term cost-effectiveness, the current high cost of materials and technological limitations hamper immediate economic viability.
Availability of Alternatives	Currently, there are fewer alternatives that offer the same level of power density and efficiency as HTS machines, making them a unique but not yet fully viable option.
Compatibility and Interoperability	The use of cryogenic temperatures and specialized materials poses challenges in integrating HTS machines into existing systems.
User Experience	Given that HTS technology is still under development, its direct impact on the end-user experience is minimal at this point but holds promise for the future.

3.1.7.2 Permanent Magnet Synchronous Machines (PMSMs)

Capability: Payload Transport **Function:** Convert Energy **Tech Group:** Electric Motors	
Relevance to Use-Cases	PMSMs have demonstrated strong potential for aerospace applications due to their high power and torque densities, as well as efficiency. Various organizations, such as Airbus, Rolls Royce, and NASA, have already developed PMSMs for specific aerospace projects.
Current Applicability/TRL	PMSMs are relatively mature, having been implemented in various aerospace projects. However, they still face challenges in magnet operating temperatures and reliability that must be addressed.
Scalability	PMSMs offer robust scalability, with the capacity to meet a range of power requirements for different aerospace applications, from small to large.
Future Potential	With ongoing research, the technology is expected to become more reliable and efficient, making it a strong candidate for broader aerospace applications.
Energy Efficiency	PMSMs are known for their high efficiency, making them an attractive option for energy-intensive aerospace systems.
Operational Safety	While efficient, PMSMs face operational safety concerns, such as uncontrollable magnet fields and possible thermal limits. Proper design measures are necessary to mitigate these risks.

Cost-Effectiveness	The cost-effectiveness of PMSMs is generally favorable due to their high efficiency and power density. However, advanced materials and design could increase costs.
Availability of Alternatives	Few technologies offer a comparable balance of power density, efficiency, and torque, making PMSMs a compelling option in the absence of more reliable alternatives.
Compatibility and Interoperability	PMSMs are generally compatible with existing aerospace technologies but require specific design considerations for optimal performance and safety.
User Experience	As a mature technology, PMSMs offer a strong user experience in terms of efficiency and performance but necessitate attention to operational safety aspects.

3.1.7.3 Switched Reluctance Machines (SRMs)

Capability: Payload Transport **Function:** Convert Energy **Tech Group:** Electric Motors	
Relevance to Use-Cases	Low to Moderate. SRMs have found uses in military aerospace applications, particularly as starter/generators (S/Gs) in aircraft like the Lockheed Martin F-22 and F-35. However, they are not yet widely employed in commercial aircraft [29].
Current Applicability/TRL	SRMs are mature and have been deployed in military aerospace settings. Yet, they haven't been adopted extensively in commercial aircraft, indicating a moderate TRL for those specific applications.
Scalability	SRMs are rugged and operate at high temperatures, making them potentially scalable for various aerospace applications. They are increasingly trending in aerospace use-cases.
Future Potential	With advancements like chamfered-pole, segmented, and modular-rotor designs, SRMs hold promising potential for future aerospace applications, including commercial aircraft.
Energy Efficiency	SRMs generally have lower efficiency levels (around 80%-82%) compared to Permanent Magnet Synchronous Machines (PMSMs). However, novel designs aim to improve this aspect [29].
Operational Safety	The absence of permanent magnets and the rotor's passive nature enhance SRMs' reliability and fault tolerance, especially during power converter failures and under short-circuit conditions.
Cost-Effectiveness	While SRMs are robust and reliable, their manufacturing can become complex and costly if modifications are made to reduce windage losses, for instance, by adding nonmagnetic material between rotor teeth.
Availability of Alternatives	While PMSMs and WFSMs are alternatives, SRMs offer unique advantages in terms of ruggedness, fault tolerance, and operational safety.
Compatibility and Interoperability	SRMs are compatible with existing systems in military aerospace but might need further adaptations for commercial aircraft, especially given the higher power demands.
User Experience	SRMs provide a reliable and rugged system that's beneficial in harsh operating conditions. However, they suffer from high torque ripples, which might be a concern for certain applications.

In summary, SRMs offer a unique set of advantages for aerospace applications, most notably their robustness, high-temperature tolerance, and fault tolerance. However, they face challenges like:

- Lower power and torque densities compared to PMSMs.
- Need for peculiar power converters due to the machine's double-salient structure.
- Risk of high windage losses, which can be mitigated but at the cost of manufacturing complexity.
- Generally limited to operating at full-load conditions, which could necessitate oversizing the machine to meet specific needs.

3.1.7.4 Wound-Field Synchronous Machines (WFSMs)

Capability: Payload Transport **Function:** Convert Energy **Tech Group:** Electric Motors	
Relevance to Use-Cases	WFSMs have been a staple in commercial aircraft for many years, finding application in numerous Boeing and Airbus models. Their use is well-established in starter/generator (S/G) roles.
Current Applicability/TRL	WFSMs are mature technologies, already deployed in several commercial aerospace settings. Their three-stage configuration is a proven design, ensuring fail-safe operation.
Scalability	Due to their large generation capacity and flexible architectures, WFSMs offer excellent scalability options, making them suitable for a wide range of aerospace applications.
Future Potential	The technology is mature but still has room for improvements in rotor cooling, high-speed operation, and excitation systems to be viable for future electrified aircraft.
Energy Efficiency	Traditionally, WFSMs lag behind PMSMs in terms of power density and efficiency. However, recent advancements like the Honeywell designed machine challenge this notion, boasting an efficiency of 98% [30].
Operational Safety	WFSMs excel in fail-safe operation. They are designed to be easily deenergized in the case of faulty conditions, providing an extra layer of safety.
Cost-Effectiveness	The ability to use passive diode bridge rectifiers with significantly lower failure rates can make WFSMs a cost-effective solution, especially when considering long-term operational costs.
Availability of Alternatives	While there are competing technologies like PMSMs and Switched Reluctance Motors (SRMs), WFSMs maintain a unique niche due to their controllability and fail-safe features.
Compatibility and Interoperability	Given their long history in aerospace, WFSMs are highly compatible with existing systems. However, future enhancements are needed to make them suitable for new electrified aircraft.
User Experience	Being a mature technology, the user experience is generally positive, with well-understood operational protocols and maintenance routines.

Even though WFSMs are mature technologies, there are still challenges to overcome:

- Mechanical constraints such as mechanical fatigue, rotor bore stresses, and damper cage thermal expansion need to be addressed.
- Speed limitations not only from the machine itself but also from auxiliary components like brushless exciters and diode rectifiers.
- Rotor cooling to handle the heat generated from the field winding and damper cage is a challenge that needs to be addressed for future electrified aircraft.

3.1.7.5 Induction Machines (IMs)

Capability: Payload Transport **Function:** Convert Energy **Tech Group:** Electric Motors	
Relevance to Use-Cases	Induction Machines are often utilized in industrial settings and are increasingly being considered in aerospace due to their high-speed operation and flux-weakening capabilities. Research funded by NASA has explored their use as starter/generators (S/Gs) in aerospace applications [29].
Current Applicability/TRL	IMs are well-established in industrial applications and have been studied for aerospace S/Gs. They can be considered mature technologies but may need further advancements for specific aerospace applications.

Scalability	These machines are scalable, proven by their commonly use in industrial applications and emerging relevance in aerospace systems.
Future Potential	Innovations like superconducting armature winding could significantly enhance IMs' performance in aerospace applications. Moreover, IMs are also being considered for novel aerospace applications like driving boundary layer ingestion fans. Their high flux-weakening ability and rotor robustness make them a suitable candidate for such high-speed, high-stress applications.
Energy Efficiency	While generally robust, IMs do suffer from high rotor ohmic losses, reducing their overall efficiency. However, specific designs can improve efficiency levels, which can go up to around 96.3% as in the design presented in [31].
Operational Safety	IMs are rugged and safe to operate at high speeds and temperatures. Though not inherently fault-tolerant, they do have fail-safe capabilities since there is no active excitation.
Cost-Effectiveness	Induction Machines are cost-effective due to their robustness, low price, and well-established supply chain.
Availability of Alternatives	IMs serve as an alternative to PMSMs and SRMs, particularly in scenarios requiring high-speed operation and flux-weakening.
Compatibility and Interoperability	They are easily integrated into existing systems but might require a more complicated control system for multiphase modular configurations.
User Experience	Generally positive, given their ruggedness and reliability. However, the power factor and efficiency could be limiting factors.

In summary, IMs offer a blend of ruggedness, high-speed operation, and maturing technology that makes them an increasingly attractive option for aerospace applications. While they do face challenges such as:

- High rotor ohmic losses that affect efficiency.
- Lower torque and power density compared to PMSMs, necessitating a longer stack length for similar performance.
- High starting torque requirements may necessitate power converter oversizing.

Specification	HTSMs	PMSMs	WFSMs	SRMs	IMs
Power density	+	+	neutral	neutral	-
Efficiency	++	++	-	+	-
Robustness and Simplicity	--	neutral	-	++	+
High speed capability	-	neutral	-	++	+
Reliability	-	neutral	+	++	+
Cost	--	neutral	-	++	++
Potential applications	Propulsion generation	Propulsion generation, actuators, fuel pumps, flywheels	Propulsion generation, S/G	Propulsion generation, S/G, taxiing, actuators, fuel pumps, flywheels	S/G, taxiing, fuel pumps, flywheels

Tab. 1: Comparison of the electric motor technologies adopted from [1].

3.1.8 Onboard Systems

Onboard systems are critical for the safe and efficient operation of any aircraft. These systems can range from navigation aids to communication tools to safety mechanisms. Here are the types of onboard systems evaluated:

Use Case	Onboard System	Current Applicability	Scalability	Future Potential	TRL
ADAM, EVE	Very High Frequency Radars	Widely used in commercial and general aviation for navigation and collision avoidance.	Highly adaptable to various aircraft types and operational needs.	Continued evolution with radar technology advancements.	9
ADAM	ADS-B (Automatic Dependent Surveillance–Broadcast)	Becoming a requirement in many airspaces, offers real-time positioning to other aircraft and ground control.	Applicable to all types of aircraft, from small drones to commercial jets.	High; with the integral for the future of integrated air traffic management.	9
ADAM, EVE	TCAS (Traffic Collision Avoidance System)	Mandatory in many larger aircraft, serves as the last line of defense against mid-air collisions.	Generally, for larger, crewed aircraft.	High, especially with data integration across other systems.	9
ADAM, EVE	Lights	Standard across all aircraft for visibility and safety.	Universally applicable.	Low; the technology is mature.	9
ADAM, EVE	Radar	Essential for navigation and weather monitoring.	Varies based on aircraft size and mission requirements.	Moderate, with ongoing improvements in resolution and capabilities.	9
ADAM, EVE	GPS Receivers	Universal in modern aviation.	Universally applicable.	High, as global positioning systems continue to evolve.	9
ADAM, EVE	CPDLC (Controller Pilot Data Link Communications)	Used for non-verbal communication with ATC.	Generally used in larger commercial aircraft.	High, as it reduces the chance of communication errors	8-9
ADAM, EVE	ACARS (Aircraft Communications, Addressing and Reporting System)	Used primarily in commercial aviation.	Generally, for larger and commercial operations.	Moderate; could be replaced or augmented by newer technologies.	9
ADAM, EVE	Inertial Measurement Units	Used for determining the aircraft's velocity, orientation, and gravitational forces, aiding in navigation.	Applicable to all types of aircraft.	High, especially with advancements in sensor technology	9
ADAM, EVE	Wave Detection	Mostly in experimental stages or specialized applications.	Limited; more research needed.	High; important for seaplanes and other water-based aircraft.	3-4

Tab. 2: Onboard Systems Evaluation

3.1.9 Anti-Icing- De-Icing Systems

Anti-icing and de-icing systems are crucial for ensuring the safety and performance of aircraft in a variety of weather conditions. Ice accumulation on wings and other critical parts can significantly degrade the aircraft's aerodynamics, making anti-icing measures essential. Below are the types of anti-icing systems considered:

3.1.9.1 Pneumatic Deicing Boots

Capability: Minimize Maintenance **Function:** Minimize icing **Tech Group:** Anti-Icing- De-Icing Systems	
Technology Description	Inflatable rubber boots on wing edges that can be inflated to remove ice.
Current Applicability/TRL	Mostly found in smaller turboprop aircraft. Expected TRL is 8 since the system complete and qualified. While effective and qualified, the limited scalability makes it less suitable for high-speed aircraft.
Scalability	Limited, not commonly used on high-speed or large aircraft.
Future Potential	Limited to moderate, as the technology is mostly mature but could see minor improvements.

3.1.9.2 Fluid Deicing

Capability: Minimize Maintenance **Function:** Minimize icing **Tech Group:** Anti-Icing- De-Icing Systems	
Technology Description	Fluid, typically glycol-based, is sprayed to prevent and remove ice.
Current Applicability/TRL	Business jets and propeller aircraft. The expected TRL is 7, since system prototype demonstrated in operational environment however; while fluid deicing is used in current systems, environmental regulations and fluid supply limitations lower its TRL.
Scalability	Moderate, can be adapted but with limitations.
Future Potential	Limited due to environmental and supply concerns.

3.1.9.3 Electro-Impulse Deicing

Capability: Minimize Maintenance **Function:** Minimize icing **Tech Group:** Anti-Icing- De-Icing Systems	
Technology Description	Electric impulses break ice apart.
Current Applicability/TRL	Limited applications. The expected TRL is 4-5 since the technology is already validated in the related environment and demonstrates high potentials however it is still in the experimental phase.
Scalability	Moderate.
Future Potential	High, as the technology is still emerging.

3.1.9.4 Bleed Air Systems

Capability: Minimize Maintenance **Function:** Minimize icing **Tech Group:** Anti-Icing- De-Icing Systems	
Technology Description	Hot air from engines is routed through the aircraft to critical areas.

Current Applicability/TRL	Mostly large commercial jets. The expected TRL is 7 as the system prototype is demonstrated however its poor scalability and limited future improvements reduce its TRL.
Scalability	Poor; not suitable for small aircraft.
Future Potential	Limited.

3.1.9.5 Electrothermal Systems

Capability: Minimize Maintenance **Function:** Minimize icing **Tech Group:** Anti-Icing- De-Icing Systems	
Technology Description	Electrothermal systems specifically refer to using electrical energy to generate heat for anti-icing or de-icing. This may involve using resisting heating elements which are embedded or attached to the aircraft's wings or other surfaces prone to icing or using conducting coatings to heat the surface electrically
Current Applicability/TRL	Modern, large aircraft, system is complete and qualified (See Boeing Dreamliner) therefore TRL is 7-8.
Scalability	High.
Future Potential	High.

3.1.9.6 Electro-Mechanical Systems

Capability: Minimize Maintenance **Function:** Minimize icing **Tech Group:** Anti-Icing- De-Icing Systems	
Technology Description	Combined heating and percussive elements to remove the ice [26].
Current Applicability/TRL	Experimental proof-of-concept therefore expected TRL is 3-4.
Scalability	Moderate.
Future Potential	Moderate.

3.1.9.7 Passive (Icephobic Coatings)

Capability: Minimize Maintenance **Function:** Minimize icing **Tech Group:** Anti-Icing- De-Icing Systems	
Technology Description	Coatings that repel ice [32].
Current Applicability/TRL	Component and/or breadboard validated in laboratory environment. Since it is still in the stage of experimental proof-of-concept, the expected TRL is 3-4.
Scalability	High.
Future Potential	High.

3.1.9.8 Microwave Deicing

Capability: Minimize Maintenance **Function:** Minimize icing **Tech Group:** Anti-Icing- De-Icing Systems	
Technology Description	Microwaves heat and remove ice [33].
Current Applicability/TRL	Experimental proof-of-concept, therefore expected TRL is 3-4.
Scalability	Moderate.
Future Potential	High.

Challenges & Future Requirements [34]

- High-fidelity ice prediction tools and experimental methods are required, specifically for AAM vehicles with unique design factors like rotation speeds, Reynolds numbers, and low-noise airfoil designs.
- Ice Protection Systems (IPS) should aim for revolutionary advances in power use and performance capability, particularly as AAM vehicles like eVTOLs have strict power and weight constraints.
- Designing rotor IPS involves multiple competing metrics such as power consumption, rotor balance, and runback refreezing, among others.
- Traditional ice detection systems are insufficient for the unique needs of AAM and need to be tailored to eVTOL and advanced rotorcraft designs.
- Given the power and weight constraints of AAM vehicles, there's a potential role for icephobic coatings to serve as a novel component of IPS.
- Accurate 3D ice shape definitions, effective ice shedding methods, and aerodynamic impact assessments are identified as priority needs for the development of IPS technologies.

3.1.10 Spray Reduction Systems

Spray reduction systems are particularly relevant for seaplanes and amphibious aircraft that take off and land on water. Such systems minimize water spray, which can otherwise affect visibility and aircraft performance. The types of spray reduction systems considered are:

3.1.10.1 Chines or Stub Wings

Capability: Ease of Use **Function:** Minimize visual/performance disruptions **Tech Group:** Spray Reduction Systems	
Technology Description	Chines are the short projections joining the sides to bottom of the aircraft to keep the aircraft stable and structurally more robust by transmitting loads from bottom to sides. They do not extend as the traditional wings extend. Not only they can act like a floatation aid by contributing hydrodynamic lift, they also reduce spray.
Current Applicability/TRL	Generally used in specialized aircraft designed for water landings, like seaplanes. See Fig. 13.
Scalability	Mostly applicable to amphibious aircraft and floatplanes.
Future Potential	Moderate.

Fig. 13: Dornier Seastar with Stub Wings

3.1.10.2 Spray Rails

Capability: Ease of Use **Function:** Minimize visual/performance disruptions **Tech Group:** Spray Reduction Systems	
Technology Description	Spray rails are elongated, often protruding structures attached to the inboard forward portions of the chines of the amphibious aircraft and seaplanes. Their primary function is to redirect and to reduce the amount of water spray thrown into the critical components such as engines and propellers. By doing so, they ensure that water does not compromise visibility, aerodynamic performance, or engine operation during takeoff, landing, and taxiing on water.
Current Applicability/TRL	High. Spray rails are widely employed in many amphibious aircraft and seaplanes. Their design varies depending on the aircraft type and hull configuration, but their fundamental purpose remains consistent across different models there the expected TRL is 9.
Scalability	High. Spray rails can be designed to fit various sizes and types of amphibious aircraft and seaplanes from 2-seater to 4-10-seater amphibian aircraft [35].
Future Potential	Moderate. The concept is mature; however, improvements are expected potentially in the design optimization using CFD and innovation in the materials being used.

3.1.11 Wildfire Detection Systems

In the context of aerial wildfire suppression, effective wildfire detection systems are indispensable. These systems help locate and assess fires, enabling timely and accurate intervention. In aerial detection, vision becomes the primary sense utilized by human spotters. Modern detection methods enhance human capabilities by integrating electronic or optical sensors to detect fire characteristics like heat, light, smoke, flicker, motion, and chemical by-products. These can be combined with human visualization or complemented by automated detection algorithms and computer vision systems. In this section, based on the type of the fire detection characteristics, available technologies are evaluated [36].

3.1.11.1 Infrared Sensors

Evaluation Criteria	Photonic Detectors	Thermal Detectors
Sensitivity level	High	Moderate
Challenges	Requires cooling, complex	Low power consumption
Relevance to Use-Cases	High	High
Current Applicability/TRL	9	8-9
Scalability	Moderate (larger platforms with high complexity due to cooling)	Moderate (small platforms with low sensitivity)
Future Potential	High. With the increasing importance of early wildfire detection and monitoring, the potential for advanced IR sensors is significant. Continuous research might lead to more energy-efficient and compact solutions.	
Energy Efficiency	Low to Moderate	High
Operational Safety	High. IR sensors generally don't have moving parts and are passive, making them safe. However, challenges like saturation can affect data accuracy.	
Cost-Effectiveness	Low	High
Availability of Alternatives	Moderate	Moderate
Compatibility and Interoperability	High. IR sensors can often be integrated into various platforms and systems, from satellites to UAVs. Data from IR can also be used in conjunction with other data sources for comprehensive monitoring.	
User Experience	Moderate. While IR sensors provide crucial data, challenges like motion blur, saturation, and the need for image rectification can impact the user's ability to quickly interpret and act on the data.	

Tab. 3: Comparison between Photonic and Thermal Detectors

3.1.11.2 Multispectral imaging sensors (SEVIRI, ABI, AVHRR, MODIS, VIIRS)

Capability: Surveil Fire **Function:** Detect fire **Tech Group:** Wildfire Detection Systems	
Current Applicability/TRL	Commonly used during daytime operations for wildfire detection and monitoring.
Scalability	Highly adaptable to various aircraft and operational needs.
Future Potential	Moderate; incremental improvements in image quality and processing are likely.

Current Applicability/TRL: Commonly used during daytime operations for wildfire detection and monitoring.
Scalability: Highly adaptable to various aircraft and operational needs.
Future Potential: Moderate; incremental improvements in image quality and processing are likely.

3.1.11.3 Infrared Cameras

Capability: Surveil Fire **Function:** Detect fire **Tech Group:** Wildfire Detection System	
Technology Description	They are used to measure the thermal radiation emitted by the objects in the related environment [37].

	• Near Infrared (NIR)-visible cameras • Short-wave Infrared (SWIR)-visible cameras • Medium-wave Infrared (MWIR) • Long-wave Infrared (LWIR) • Thermal Infrared (TIR)
Relevance to Use-Cases	Aerial Wildfire Suppression- Infrared cameras are highly relevant to aerial wildfire suppression as they can effectively detect and monitor fires day or night. They provide a crucial advantage by identifying the heat signatures of fires, helping firefighting teams respond promptly and efficiently to manage wildfires. Additionally, they can differentiate between flames and solar-heated objects, reducing the chances of false alarms during daytime operations. Intermodal Mobility- Infrared cameras are also relevant to intermodal mobility use cases. They can be employed for monitoring transportation infrastructure, identifying temperature anomalies in critical components, and ensuring the safe and efficient operation of various transport systems, including trains, airplanes, and vehicles.
Current Applicability/TRL	Infrared cameras, including Near Infrared (NIR)-Visible Cameras, Short-Wave Infrared (SWIR)-Visible Cameras, Medium-Wave Infrared (MWIR), Long-Wave Infrared (LWIR), and Thermal Infrared (TIR) cameras, are established technologies with a high TRL. They are widely used in various applications, including aerial fire detection and thermal imaging.
Scalability	Infrared camera systems are scalable and adaptable for use in different platforms, including aerial firefighting aircraft, smaller vehicles, and handheld devices. They can be configured to meet specific operational requirements.
Future Potential	Ongoing research and development efforts aim to enhance the capabilities of infrared cameras, including improving sensitivity, resolution, and the integration of advanced detection algorithms. These continuous advancements may further improve their effectiveness in wildfire suppression and transportation applications.
Energy Efficiency	Infrared cameras are generally energy-efficient, making them suitable for extended use during firefighting missions or transportation inspections without excessive power consumption.
Operational Safety	Infrared cameras enhance operational safety by providing increased visibility and situational awareness. They help reduce risks during firefighting operations by enabling early fire detection and monitoring.
Cost-Effectiveness	The cost-effectiveness of infrared cameras can vary depending on the specific type and features. While high-end models may be relatively expensive, there are more affordable options available for various applications, ensuring cost-effectiveness. Especially CCD cameras.
Availability of Alternatives	While infrared cameras are widely used for thermal imaging, there are alternative thermal imaging technologies and sensors available. However, the effectiveness of infrared cameras in detecting thermal signatures remains a valuable advantage.
Compatibility and Interoperability	Infrared cameras are compatible with various sensors, imaging systems, and data processing tools, allowing for enhanced capabilities and integration with existing systems in both firefighting and transportation applications.
User Experience	Infrared cameras provide a user-friendly experience with real-time thermal imaging that is easy to interpret and use for decision-making. They contribute to a more efficient and effective response in firefighting and transportation scenarios.

3.1.11.4 Optical Cameras (UHDR)

3.1.11.5 Infrared Radar

3.1.11.6 Night Vision Goggles (NVG)

Capability: Surveil Fire **Function:** Detect fire **Tech Group:** Wildfire Detection System	
Technology Description	Image intensifying devices to amplify environment visibility and Near Infrared illumination.
Current Applicability/TRL	The technology is already stable and being used in the related environment for night operations to detect and monitor wildfires. Therefore, the expected TRL is 8-9.
Scalability	Compatible with various cockpit configurations and aircraft types.
Future Potential	Moderate; the technology is mature but could see enhancements in terms of clarity and pilot's view range from 45 degrees to 90 degrees.

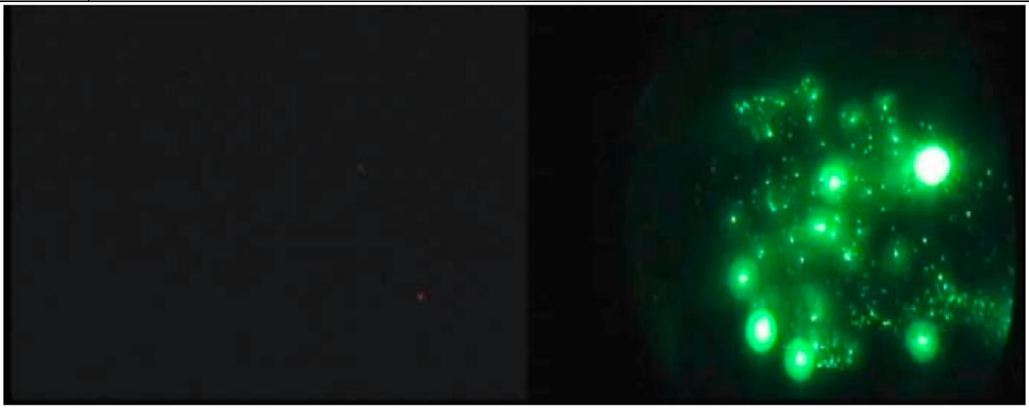

Fig. 14: Left-hand side shows a 'naked eye' image of an active wildfire; right-hand side shows a simultaneously acquired NVG image of the same fire from the same viewpoint [36].

3.1.11.7 Synthetic Vision Systems

Capability: Surveil Fire **Function:** Detect fire **Tech Group:** Wildfire Detection System	
Current Applicability/TRL	Emerging technology providing a 3D view of the terrain, useful for navigation and potentially for fire detection.
Scalability	High scalability as it integrates with existing avionics.
Future Potential	High; this is an emerging field with significant room for advancement, especially in data integration and real-time processing.

3.1.12 Payload Drop Systems (Wildfire Suppression)

Payload drop systems are a critical component for aircraft used in aerial wildfire suppression. They allow for the accurate and efficient deployment of water, fire retardants, or other fire-suppressing substances. Here are the types of payload drop systems considered:

3.1.12.1 Water/Retardant Tank System

Capability: Suppress Fire **Function:** Drop suppressant **Tech Group:** Payload Drop Systems	
Technology Description	It is an external tank that can be mounted beneath or on the wings of an aircraft which can store fire retardant [38]. The retardant is released through a series of doors or outlets, typically located on the belly of the aircraft.

Relevance to Use-Cases	High (Applicable to Aerial Wildfire Suppression)
Current Applicability/TRL	High (Widely used and well-understood technology)
Scalability	High (Can be adapted to various aircraft sizes and purposes)
Future Potential	Moderate (Mature technology with incremental advancements)
Energy Efficiency	Moderate (Efficient for specific missions but may be fuel-intensive)
Operational Safety	High (Proven safety record)
Cost-Effectiveness	High (Economical due to extensive existing knowledge and infrastructure)
Availability of Alternatives	Few (Specialized for wildfire suppression)
Compatibility and Interoperability	High (Widely compatible with existing systems and regulations)
User Experience	Moderate (User experience influenced by the ease of integration)

3.1.12.2 Bucket or Bambi Bucket

Capability: Suppress Fire **Function:** Drop suppressant **Tech Group:** Payload Drop Systems	
Technology Description	It is an external bucket suspended from a helicopter's cargo hook which can be filled with water from natural water sources.
Relevance to Use-Cases	High (Applicable to Aerial Wildfire Suppression)
Current Applicability/TRL	High (Widely used and well-understood technology)
Scalability	Moderate (Adaptable to various helicopter payload capacities)
Future Potential	Moderate (Potential for design and efficiency improvements)
Energy Efficiency	Moderate (Dependent on helicopter type and operation)
Operational Safety	Moderate to High (To ensure safe operations, several factors must be considered, including flight direction, altitude, and speed, which should be adapted based on terrain characteristics and meteorological conditions such as wind speed and direction, gusts, air temperature, and smoke dispersion patterns [2])
Cost-Effectiveness	High (Economical due to extensive existing knowledge)
Availability of Alternatives	Few (Specifically designed for firefighting)
Compatibility and Interoperability	High (Compatible with many helicopter types)
User Experience	Moderate (User experience influenced by the helicopter's capabilities)

3.1.12.3 Hull-Embedded or Fuselage-Mounted Tanks

Capability: Suppress Fire **Function:** Drop suppressant **Tech Group:** Payload Drop Systems

COLOSSUS
COLLABORATIVE SYSTEM OF SYSTEMS

Technology Description	These tanks are integrated into the aircraft's design, offering large capacity for fire retardant storage, pre-loaded before firefighting missions, and released through aircraft belly outlets for efficient delivery.
Relevance to Use-Cases	High (Applicable to Aerial Wildfire Suppression)
Current Applicability/TRL	Moderate to High (In use with potential for further integration)
Scalability	High (Can be integrated into various aircraft sizes)
Future Potential	Moderate (Potential for optimized designs)
Energy Efficiency	Moderate (Depends on aircraft type and tank integration)
Operational Safety	High (Proven safety record)
Cost-Effectiveness	Moderate (Integration costs may vary)
Availability of Alternatives	Few (Integration-specific technology)
Compatibility and Interoperability	High (Can be adapted to different aircraft)
User Experience	Moderate (User experience influenced by aircraft design)

Fig. 15: AT-802F Fire Boss Hull Embedded Design Example

3.1.13 Materials

Selecting the right materials for aircraft construction has a substantial impact on performance, durability, and various operational aspects. Here are some primary options:

3.1.13.1 Composite Sandwich Materials

Capability: Minimize maintenance **Function:** Minimize rust **Tech Group:** Materials	
Relevance to Use-Cases	High. They consist of two high-strength skins and a lighter core, commonly made of foam or lightweight metals. High-performance sandwich structures find applications in aerospace, automotive engineering, and energy absorption due to their structural advantages.
Current Applicability/TRL	Moderate to High. In use with potential for further integration considering the need for experimental and theoretical studies for understanding structural response and performance.
Scalability	Moderate The scalability of sandwich composite structures depends on the chosen fabrication technique and materials. Some methods, like 3D/4D printing, may offer scalability advantages, while others may have limitations. Moreover, the choice of fabrication method depends on the specific material and property requirements for the intended application [39].
Future Potential	High. There is significant future potential for advancements in sandwich composite technology. Ongoing research can lead to improved materials, manufacturing techniques, and performance characteristics.
Energy Efficiency	Moderate. Energy efficiency varies depending on the chosen materials and manufacturing processes. Techniques like injection molding are more energy-efficient, while autoclave processes may consume more energy.
Operational Safety	High (Proven safety record, already being used in fighter aircraft)
Cost-Effectiveness	Moderate. The cost-effectiveness of sandwich composites can vary widely depending on factors like material selection, fabrication method, and application. Some methods like Vacuum-Assisted Resin Infusion may be cost-effective as they reduce the material waste while offering good consistency. However, methods like 3D /4D printing can be less cost-effective for producing large sandwich composite structures even though they offer high design flexibility.
Availability of Alternatives	Moderate. There are alternative materials and structural designs for aerospace applications, but sandwich composites offer unique advantages.
Compatibility and Interoperability	High. Sandwich composite structures can be compatible with various materials and systems. They are designed to meet specific compatibility requirements in aerospace and automotive applications.
User Experience	Moderate. Some manufacturing techniques, like injection molding, are environmentally friendly due to low cost, low energy demands, and closed molds. However, aerospace and automotive industries often favor autoclave processes despite environmental concerns.

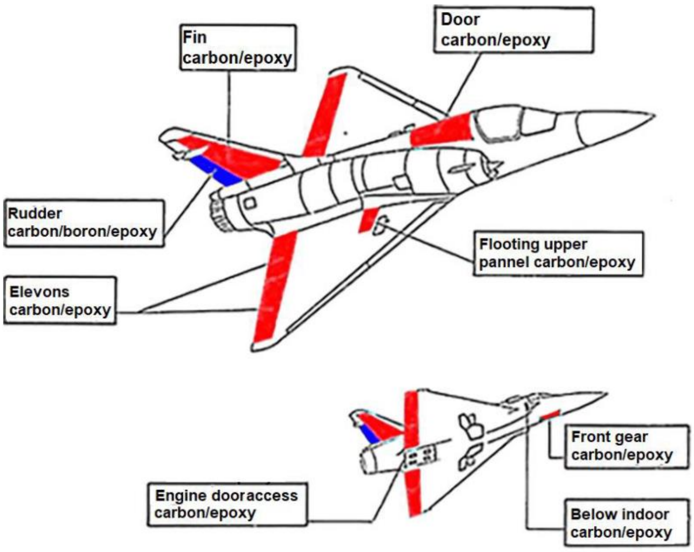

Fig. 16: Carbon-Boron sandwich structure of Dassault Mirage F1 [40]

3.1.13.2 Aluminum Alloys

Capability: Minimize maintenance **Function:** Minimize rust **Tech Group:** Materials	
Relevance to Use-Cases	High. Aluminum alloys have traditionally been widely used in the aircraft industry therefore its use in the design of the different type of aircraft is unquestionable.
Current Applicability/TRL	High. Aluminum alloys have been a popular choice for aircraft due to their excellent strength-to-weight ratio, design flexibility, corrosion resistance, and thermal conductivity.
Scalability	High. Various series of aluminum alloys, such as 7xxx and 2xxx, are used in different aircraft components based on their specific strengths and applications [41].
Future Potential	Moderate. Even though they have been a popular choice, they have limitations like poor strength at elevated temperatures and susceptibility to stress corrosion cracking (SCC). There is a need for more studies focusing on aircraft components, especially those subjected to wear, friction, and high stress, to aid material selection and reduce costs. Exploring the high-temperature capabilities of aluminum alloys can also expand their use in aircraft components.
Energy Efficiency	Moderate to High. Since they have low density, having lightweight contributes to the fuel efficiency. Moreover, since they are easy to shape, manufacturing efficiency is relatively higher compared to the composite materials. However, they have lower strength at elevated temperatures, therefore in high-temperature environments, other materials like titanium and certain advanced composites may offer better energy efficiency due to their ability to retain strength at elevated temperatures.
Operational Safety	High (Proven safety record, high fatigue and corrosion resistance)
Cost-Effectiveness	High. They are relatively abundant, which helps keep material costs reasonable. Moreover, the ease of manufacturing and processing aluminum alloys contributes to cost-effectiveness.
Availability of Alternatives	Moderate to High. While aluminum alloys have been a dominant choice in aerospace applications, there is a growing availability of alternative materials. Advanced composite

	materials, such as carbon fiber-reinforced plastics (CFRP), are increasingly being used in aerospace to replace aluminum in certain components. These alternatives offer specific advantages, such as reduced weight and increased strength, making them attractive for applications where maximizing performance is critical.
Compatibility and Interoperability	High. Aluminum alloys are highly compatible with existing aerospace systems and infrastructure. Their long history of use in the aerospace industry has led to the development of standardized manufacturing processes, testing procedures, and maintenance protocols.
User Experience	High. Aluminum alloys have a long history of use in aerospace, and their properties are well-understood. This familiarity and predictability contribute to a positive user experience. Aircraft designers, engineers, and manufacturers are accustomed to working with aluminum alloys, which simplifies the design and production processes. Additionally, aluminum alloys are relatively easy to inspect and maintain, which enhances the user experience for maintenance crews.

3.1.14 Hull Types for Seaplanes

The design of a seaplane's hull is crucial for its performance on water, affecting aspects like buoyancy, stability, and hydrodynamic efficiency.

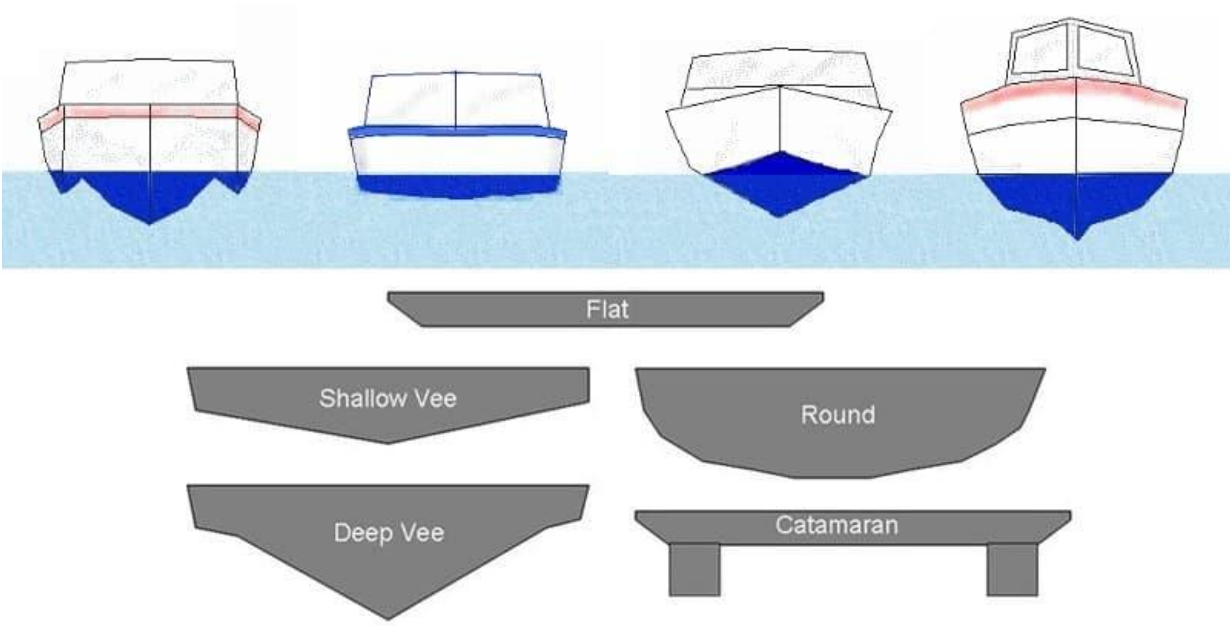

Fig. 17: Possible types of Hull Design [42]

Seaplanes come in various hull types, each with its own set of characteristics. Flat-bottom boats are cost-effective and easy to plane but offer a rough ride in choppy waters and less stability. Vee-bottom boats provide a smoother ride in rough conditions but demand more power. However, it is a well-established technology and relatively efficient for take-off and landings. Round-bottom boats move effortlessly at slow speeds but can be prone to rolling. Multi-hull designs like catamarans offer exceptional stability, reduced seasickness, and ease of piloting, making them popular for charters [42] however it is a niche technology therefore the future potential is limited. The choice of hull type depends on factors like intended use, stability requirements, and maneuverability considerations in seaplane design.

3.2 Other Systems

These systems are auxiliary yet integral to the main aircraft operations, affecting both Air Traffic Management (ATM) and various maintenance technologies.

3.2.1 Air Traffic Management (ATM) and Unmanned Traffic Management (UTM)

ATM and UTM are essential components of modern aviation systems. For effective management, secure and clear communication is crucial. In this section, only the technology description and its current availability are discussed for radios and radars as most of the technologies are in the mature state and deployed in the related environments.

3.2.1.1 Communication Systems

In ATM and UTM various types of communication systems are used to ensure effective communication and coordination between ground and aircraft or aircraft to aircraft. Below are the primary types of systems used for both voice and non-voice communication:

Communication System	Frequency Range	Usage	Characteristics	TRL
Very High Frequency (VHF) Radios	118-137 MHz [43]	Mainstay of pilot-to- Air Traffic Control (ATC) and Flight Service Station (FSS) voice communications [43]	Line-of-sight communication, clear and reliable signals over shorter distances	9
High Frequency (HF) Radios	3-30 MHz [43]	Used for long-distance communication, especially over oceanic and polar routes [43]	Can communicate over thousands of kilometers, subject to atmospheric conditions and interference	9
Ultra-High Frequency (UHF) Radios	225-400 MHz [43]	Primarily used by military aviation for air-to-air and air-to-ground communication [43]	Higher frequency allows for more compact antenna designs and greater bandwidth	9
Satellite Communication (SATCOM) Systems	N/A	Used for communication with aircraft flying over remote areas	Global coverage, used for both voice and data communication with higher data transfer rate	9
Data Link Communication Systems	N/A	Used for transmitting non-voice messages between aircraft and ATC centers	Can send pre-formatted messages, flight plans, and other essential information	9

Tab. 4: Evaluation of possible communication systems

Based on the study done by NASA [44], VHF and satellite communications hold the most promise for Air-to-Ground communication in the ATM-UTM environment.

3.2.1.2 Surveillance Technologies

Surveillance technologies play a crucial role in ATC by accurately and reliably determining aircraft locations, influencing separation distances and airspace utilization efficiency by serving as the eyes of the system, providing situational awareness and facilitating collision avoidance.

Use Case	Technology	Means	Feature	TRL
ADAM, EVE	Primary Surveillance Radar (PSR)	Detects and displays aircraft positions by sending out radio waves that bounce back upon hitting an object.	It does not rely on the aircraft's onboard systems however it does not provide identity or	9

			altitude [45].Expensive compared to SSR.	
ADAM	Secondary Surveillance Radar (SSR) • Mode S (Selective) • Automatic Dependent Surveillance-Broadcast (ADS-B)	Interacts with an aircraft's transponder to receive additional information such as altitude, aircraft identification, and other data [45].	- Provides an air-to-ground data link (Mode S) [46]. - Broadcasts position and velocity information which is automatically transmitted periodically (at least once every second) without flight crew or operator (ADS-B)[47].	9
ADAM, EVE	Terminal Doppler Weather Radar	Monitors weather conditions to provide pilots and air traffic controllers with weather information [48].	Helps in route planning and avoiding severe weather conditions.	9
ADAM, EVE	Multilateration Systems	Uses multiple low-level receiving stations to triangulate aircraft positions based on transponder signals.	Enhances surveillance in areas where other radar systems may have limited coverage, mainly for 'very wide area' applications.	9
ADAM, EVE	Automatic Dependent Surveillance-Contract (ADS-C)	Allows air traffic controllers to track aircraft positions via satellite communications.	Useful for monitoring aircraft in oceanic and remote airspace, mainly fitted to long range air transport aircraft [45].	9

Tab. 5: Evaluation of possible surveillance technologies

3.2.2 Vertiport Systems

Vertiports are specialized landing pads or areas designed for vertical take-off and landing (VTOL) aircraft. Given the increasing prominence of VTOLs and eVTOLs in advanced air mobility and other applications, vertiports will play a significant role in future transportation networks. As the concept of AAM is still being under development and the regulations regarding the design of vertiports are relatively restricted, in this section, the necessary components will be provided with the regulatory needs. First, the regulatory standards are provided:

Regulatory Standards:

Controlling Dimension (CD) (FAA): Longest distance between two outermost opposite points on the aircraft [49].

D-value (EASA): Diameter of the smallest circle that surrounds the VTOL aircraft projection [50].

FAA and EASA Classifications: Both classify VTOL as small helicopters with an MTOW of less than 3175 kg, but have different regulations for vertiport dimensions [51].

TLOF (Touchdown and Liftoff) Pads

A load-bearing area designated for the takeoff and landing of VTOL aircraft. The size and shape (often circular for better pilot recognition in urban environments) are determined based on specific aircraft dimensions, referred to as the CD or the D-value [51].

FATO (Final Approach and Take-Off) Area

An area clear of obstructions, used for the final approach and takeoff of aircraft. It should be designed to accommodate the specific dimensions of the aircraft it serves [51].

Safety Area

An area that extends outward from the FATO, providing additional space for safety considerations [51].

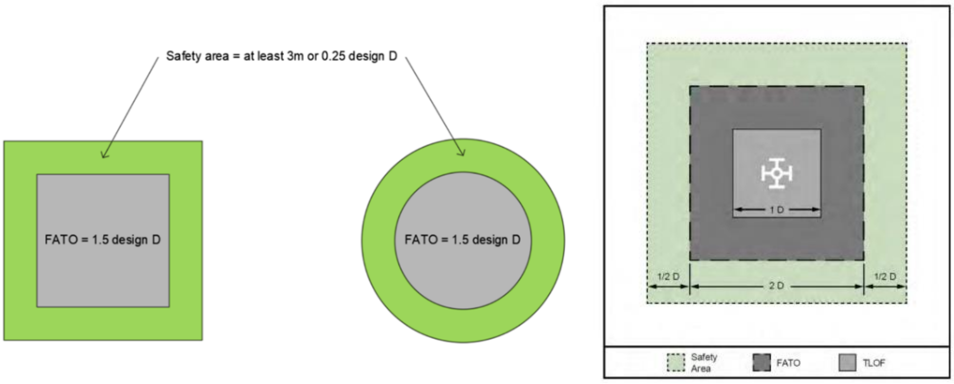

Fig. 18: EASA and FAA Standards for FATO and Safety Area [50,49]

Gates
Areas designated for aircraft parking, passenger embarkation/disembarkation, and possibly recharging.
Taxiways
Paths used for the taxiing of aircraft, with dimensions based on the size and type of aircraft operations.
Induction Paths
Induction paths are designated pathways for aircraft to follow as they approach or leave the vertiport, ensuring organized and safe aircraft movements [51].

There can be several types of vertiport layouts based on the vertiport sizing regulations as shown below.

	Layout 1	Layout 2	Layout 3
Vertiport Layouts	Linear Topology	Satellite Topology	Pier Topology
Description	Efficient for thin and long spaces.	Suitable for a square or circle space.	Intermediate form between linear and satellite topology.
TLOF Pads	Arranged in a row, each can take the role of a gate.	One or more TLOF pads surrounded by several gates.	Separates the area of the TLOF and the gate.
Space Requirements	Needs additional space in other than takeoff and landing directions.	Constraints in taking off and landing in the direction of the gate.	Shares one taxiway, may require two or more taxiways for efficiency.
Advantages	Efficient for narrow, elongated spaces such as along a seaside or a riverside. Simple arrangement.	High gate utilization because the length of the taxiways is constant.	Wider takeoff and landing angles at the TLOF pad and can accommodate a large number of gates.
Constraints	Necessary to secure additional space in accordance with the approach/departure surface and path regulations.	Constraints in taking off and landing in the direction of the gate and in integrating with the existing infrastructure.	Aircraft turnaround times may be extended, and the gate area may be congested. Needs advanced air traffic control system.

Tab. 6: Possible vertiport layout comparison

3.2.3 Seaports Systems

Seaports are vital infrastructures for seaplanes and other water-based transport systems. They serve as the main points for embarkation, disembarkation, refueling, and other essential operations. Seaplane bases or seaports can be considered as a beach or a planned infrastructure based on the need. Considering the unique needs of seaplanes and floating aircraft, several key technologies and components make up the seaport systems:

3.2.3.1 Docking Facilities

- Floating Docks
  Floating docks are platforms that float on the water's surface and are anchored to the seabed. They are used for easy access to seaplanes for passengers, crew, and maintenance personnel. They can be adjusted with the tide and water level changes, providing a stable platform [52].
- Stationary Docks
  Fixed docks are built on piles and they are stationary since they do not move with the tide or water level. They are preferable where the locations have minimal tidal variation [52]. They can support additional infrastructure such as fueling stations and maintenance equipment.
- Ramps
  They are used for moving the seaplanes out of the water for maintenance and inspections. They are easy to facilitate and used for quick and easy movement of seaplanes between water and land.
- Mooring Buoys
  Mooring buoys are anchored floating devices to which seaplanes can be securely tied. They are used for parking of seaplanes in water. They are cost effective and space-efficient when the shoreline infrastructure does not provide enough space.
- Slipways/Slips
  Slipways or slips allow seaplanes to be pulled completely out of the water and they are used for maintenance, storage, and protection from water and weather elements. The main advantage is reducing exposure to saltwater corrosion and facilitating inspections and maintenance.

In conclusion, the design and operation of seaplane docking facilities are influenced by several critical factors. The architectural design of seaplanes, particularly the positioning of their wings, necessitates specific docking configurations. For example, hull planes, which have a distinct design, are typically oriented to nose-in to the dock, making slipways or beaches more suitable alternatives for docking. Sufficient maneuvering space is also very important to ensure the safe and efficient operation of seaplanes within the docking area, therefore docking layout is crucial. Additionally, the natural tendency of seaplanes to align with the wind direction, known as *weathervaning*, is a crucial consideration in the design and layout of docking facilities [52]. Addressing these factors ensures the efficient, safe, and effective operation of seaplane bases, contributing to enhanced aviation operations and safety standards.

3.2.4 Maintenance: Dry Docking Technologies

The need for periodic maintenance, repair, and overhaul (MRO) operations is critical in the aerospace industry, particularly for seaplanes and other specialized aircraft that come into contact with corrosive elements such as saltwater. Dry docking technologies provide a controlled environment for these operations. Here are some key technologies in dry docking:

3.2.4.1 Hangar

A hangar is fundamentally essential for the effective maintenance and storage of seaplanes. It serves the dual purpose of providing a safe environment to carry out essential repairs and maintenance, as well as providing a protective shelter for the aircraft, shielding them from potential damage from extreme weather conditions. However, the unique design of seaplanes, particularly their higher height compared to conventional wheeled aircraft, poses a significant challenge. With limited door openings and interior space, standard hangars may not be suitable for housing seaplanes, necessitating the need for specialized solutions.

Fig. 19: Maintenance operations outdoors due to unfit in the hangar [52]

One such solution is hangars specifically designed for seaplane use. These hangars can be built with raised door openings and expanded interior space to comfortably accommodate the larger size of float aircraft. This customization ensures that seaplanes can be easily accommodated for maintenance operations and storage without the limitations imposed by traditional hangar designs.

In addition to custom-designed hangars, floating hangars offer an innovative and practical solution to seaplane storage and maintenance challenges. Floating hangars positioned over water provide seaplanes with direct and obstruction-free access to the body of water, eliminating height restriction and accessibility issues. This design allows seaplanes to move smoothly in and out of the hangar, enabling efficient maintenance operations and safe storage.

Fig. 20: Floating dock attached with ramp and rail system representation [52]

3.2.4.2 Lifting and Handling Equipment

- Winch System: A motorized pulley and cable system used to lift seaplanes out of the water, offering controlled, mounted on a dock or onshore.
- Ramp: An inclined plane from water to land that allows easy movement of seaplanes for maintenance, repair or storage, with a simple and cost-effective design suitable for various seaplane sizes.
- Crane: A large machine used to move heavy objects, used to lift seaplanes out of the water and place them on maintenance platforms or dry storage areas, enabling the transportation of heavy and large seaplanes even in limited space.

- Cradle: A supporting frame or stand that provides a stable and secure platform for performing maintenance and repairs on seaplanes, ensuring their safety and security during maintenance operations.

3.2.5 Maintenance: Inspection Technologies

Composite materials are increasingly being used in modern aircraft designs for their high strength-to-weight ratio and corrosion resistance. However, they require specialized inspection technologies to ensure their integrity and safety. An extensive comparison is adopted from an FAA report [53] and represented below for the current available non-destructive inspection technologies.

Method	Technology Description	Advantages	Disadvantages
Visual Inspection	A basic inspection method where the surface is visually inspected for any discontinuities or defects.	Inexpensive Highly portable Immediate results Minimum training required Minimum part preparation	Surface discontinuities only Generally large discontinuities Misinterpretation of scratches
Dye Penetrant Inspection	A type of inspection where a colored dye is applied to the surface to reveal defects.	Portable Inexpensive Sensitive to very small discontinuities 30 min. or less to accomplish Minimum skill required	Locate surface defects only Rough or porous surfaces interfere with test Part preparation required High degree of cleanliness required Direct visual detection of results required
Magnetic Particle Inspection	A method that uses magnetic fields to detect surface and near-surface defects in ferromagnetic materials.	Can be portable Inexpensive Sensitive to small discontinuities Immediate results Moderate skill required Detects surface and subsurface discontinuities Relatively fast	Surface must be accessible Rough surfaces interfere with test Part preparation required Semi-directional requiring general orientation of field to discontinuity Ferro-magnetic materials only Part must be demagnetized after test
Eddy Current Inspection	Uses electromagnetic induction to detect flaws in conductive materials.	Portable Detects surface and subsurface discontinuities Moderate speed Immediate results Sensitive to small discontinuities Thickness sensitive Can detect many variables	Surface must be accessible to probe Rough surfaces interfere with test Electrically conductive materials Skill and training required Time consuming for large areas
Ultrasonic Inspection	Employs high-frequency sound waves to detect imperfections or changes in properties within the materials.	Portable Inexpensive Sensitive to very small discontinuities Immediate results Little part preparation Wide range of materials and thickness can be inspected	Surface must be accessible to probe Rough surfaces interfere with test Highly sensitive to sound beam - discontinuity orientation

			High degree of skill required to set up and interpret
X-Ray Radiography	Uses X-rays to view the internal structure to detect any internal flaws or anomalies.	Detects surface and internal flaws Can inspect hidden areas, Permanent test record obtained Minimum part preparation	Safety hazard, Very expensive (slow process), Highly directional, sensitive to flaw orientation High degree of skill and experience required for exposure and interpretation Depth of discontinuity not indicated
Isotope Radiography	Similar to X-ray radiography but uses radioactive isotopes to detect internal flaws.	Portable Less expensive than X-ray Detects surface and internal flaws Can inspect hidden areas Permanent test record obtained Minimum part preparation	Safety hazard Must conform to Federal and State regulations for handling and use Highly directional, sensitive to flaw orientation High degree of skill and experience required for exposure and interpretation Depth of discontinuity not indicated
Thermographic Inspection	Utilizes thermal energy to identify flaws, with abnormalities in temperature indicating defects, especially when materials resist heat flow[53]	Non-contact method Can inspect large areas quickly Can detect subsurface defects	Requires expensive equipment Interpretation of results may require expertise Surface conditions can affect results
Acoustic Emission Testing	An NDI technique where sensors detect ultrasonic pulses emitted from materials under various stresses, identifying and locating flaws like cracks and corrosion[53]	Can detect active flaws and damage in real-time Non-destructive	Requires specialized equipment and expertise May be affected by ambient noise
Shearography	Uses lasers to provide real-time strain measurements on stressed parts, aiding in the rapid detection of defects and anomalies in structures like aircraft components [53]	Optical method non-contact Can detect subsurface defects	Requires specialized equipment Surface conditions can affect results[53]

Tab. 7: Evaluation of Different Inspection Technologies adopted from.

3.2.6 Ground Crews: Wildfire Support Technologies

As part of a comprehensive approach to aerial wildfire suppression, ground crews play a vital role in containing and eliminating fires. While aircraft can drop water and fire retardants from above, ground crews are needed to create firebreaks, control smaller fires, and perform clean-up activities.

- Fire Engines: They are equipped with water tanks and hoses to directly fight fires. They can navigate through rough terrains and provide immediate response.
- Bulldozers: They are used to create firebreaks by clearing vegetation and other potential fuel for the fire.
- Hand Tools: Ground crew uses various hand tools, including shovels, mattocks, and rakes, are used to create firebreaks, remove fuel sources, and perform other essential tasks [54].
- Water Trucks: They are used to supply water to fire engines in areas where water sources are scarce.
- Fire Hose Systems: They include hoses, nozzles, and other equipment used to deliver water or fire retardant to the fire. They can be part of a fire engine or a standalone system.

3.2.7 Wildfire Detection and Monitoring – Satellite Technologies

3.2.7.1 Multispectral Imaging Sensors

Capability: Surveil Fire **Function:** Detect Fire **Tech Group:** Satellite Technologies	
Current Applicability/TRL	Used for early detection of wildfires, as well as mapping and monitoring fire progression.
Scalability	Applicable to both small and large-scale fire events.
Future Potential	High. Evolving technology can capture more detailed data at quicker intervals.

Satellite technologies, especially Multispectral Imaging Sensors, have emerged as pivotal tools in wildfire monitoring. Multispectral imaging involves capturing image data within specific wavelength ranges across the electromagnetic spectrum. The wavelengths may be separated by filters or by the use of instruments that are sensitive to particular wavelengths, including light from frequencies beyond the visible light range, such as infrared. These sensors are currently used for the early detection of wildfires and are instrumental in mapping and monitoring the progression of these fires. Their scalability makes them applicable to both small and large-scale fire events [55].

3.2.8 Wildfire Detection and Monitoring – Terrestrial Systems

Terrestrial systems for wildfire detection and monitoring are essential complements to aerial and satellite-based systems. They provide ground-level data, which is crucial for immediate response and management.

- Optical Cameras: These are essential for real-time monitoring. High-resolution optical cameras can capture detailed images of fire lines, helping responders understand the fire's behavior and direction. However, they are only suitable for the daytime operations.
- Infrared Radars: Infrared radars are especially valuable during nighttime or when smoke obscures the view. They detect heat rather than light, allowing them to identify fire hotspots and monitor the spread of the fire even in challenging visibility conditions.

The detailed evaluation of the technologies is represented in section 3.1.11.

3.2.9 Mobility as a Service Provider

Mobility as a Service (MaaS) is a service providing a shift from personally-owned modes of transportation towards mobility solutions. This is enabled by combining transportation services from public and private transportation providers through a unified gateway. This technology is mainly relevant to ADAM use case to enable door-to-door travel considering multiple stakeholders. Below, the main enabling components of MaaS is shown:

- Website: A platform for users to plan their trips and make payments.
- Application: Mobile applications to provide on the go access to platforms.
- Chatbot Services: A service to provide real time assistance
- AR Navigation: A service to improve user experience by overlaying directional arrows and other navigational cues on real-world imagery.

3.2.10 Alternate Transport Modes

Alternate Transport Modes play a crucial role in an integrated multimodal mobility system. They offer different advantages and limitations that can complement the use of aircraft for specific travel needs. The future of multimodal mobility lies in integrating these various modes for a smooth, efficient, and versatile transport experience.

- Airlines: For longer distances, offering fast and efficient travel across cities, or countries.
- Trains: For longer distances, offering fast and efficient travel across cities, or countries.
- Subways: For medium-range distances, offering flexibility and can be tailored to customer needs.
- Bus: For medium-range distances, offering flexibility and can be tailored to customer needs.
- Taxi: For medium-range distances, offering flexibility and can be tailored to customer needs.
- Car: For medium-range distances, offering flexibility and can be tailored to customer needs.
- Walking: For short distances, basic form of transportation.
- Ride-Sharing: Platforms like Uber and Lyft, offering flexible, on-demand transportation.
- Bicycles/E-Bikes: For short to medium distances, offering ecofriendly and cost-efficient solution.

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4. Conclusion and Outlook

This report offers a comprehensive analysis of the aviation sector's future, emphasizing the transformative potential of emerging aircraft architectures and the technologies that enable them. The report identifies available technologies for two primary use-cases: Sustainable Intermodal Mobility (ADAM) and Wildfire Fighting (EVE). ADAM emphasizes the need for integrated multimodal transport solutions, while EVE highlights the importance of rapid response capabilities in wildfire scenarios.

In the domain of eVTOLs, the report evaluates four distinct architectures, each with its unique advantages and best-use scenarios. The tiltrotor and Lift+Cruise configurations emerge as frontrunners in the eVTOL space. Their versatility, scalability, and high TRLs indicate that they're nearing real-world applicability. The Joby S4 tiltrotor eVTOL, operational since 2015, exemplifies the potential and maturity of such designs. On the other hand, seaplanes are assessed with two architectures, with flying boats with high-mounted wings emerging as a promising design. They offer unique advantages in specific intermodal mobility scenarios, especially in water-rich environments. Their ability to quickly respond in wildfire scenarios by scooping water provides a distinct edge over traditional aircraft.

Technological advancements play a pivotal role in enabling these aircraft designs. The report delves into a spectrum of battery technologies, from the established Li-Ion batteries to the promising Li-S and ASSB technologies. These batteries, with their varying energy densities and efficiencies, are crucial for powering the next generation of aircraft. Furthermore, ensuring the safety and performance of aircraft in various weather conditions, the report evaluates several anti-icing systems, such as pneumatic deicing boots and fluid deicing. These systems prevent ice accumulation on critical aircraft surfaces, ensuring safe operations.

In the context of aerial wildfire suppression, effective wildfire detection systems are indispensable. These systems, integrating electronic or optical sensors, enhance human capabilities, enabling rapid and accurate intervention.

In conclusion, this report offers a comprehensive collection of available technologies enabling the operations for both use cases. The emphasis on specific use-cases, combined with detailed insights into aircraft architectures and the technologies enabling them, aims to provide a clear direction for stakeholders. Both eVTOLs and seaplanes, powered by advanced battery technologies and fuel cells, are set to play significant roles in 4D mobility and aerial wildfire suppression. As the industry moves forward, continued research, collaboration, and innovation will be pivotal in realizing the full potential of these technologies, ensuring a sustainable, efficient, and versatile future for aviation.

5. References

[1] *The European Commission's science and knowledge service. Joint Research Centre (JRC),* [Publications Office of the European Union], [Luxembourg], 2019, 1 online resource.

[2] MIT Technology Roadmapping, "WorldWide eVTOL," URL: https://roadmaps.mit.edu/index.php/WorldWide_eVTOL.

[3] Kadhiresan, A. R. and Duffy, M. J., "Conceptual Design and Mission Analysis for eVTOL Urban Air Mobility Flight Vehicle Configurations," *AIAA Aviation 2019 Forum,* AIAA Aviation 2019 Forum, Dallas, Texas, American Institute of Aeronautics and Astronautics, Reston, Virginia, 2019.
doi: 10.2514/6.2019-2873

[4] Vertical Flight Society, "Joby Aviation S4 2.0 (pre-production prototype)," URL: https://evtol.news/joby-s4.

[5] Swaminathan, N., Reddy, S. R. P., RajaShekara, K., and Haran, K. S., "Flying Cars and eVTOLs—Technology Advancements, Powertrain Architectures, and Design," *IEEE Transactions on Transportation Electrification*, Vol. 8, No. 4, 2022, pp. 4105–4117.
doi: 10.1109/TTE.2022.3172960

[6] Courtin, C. and Hansman, R. J., "Safety Considerations in Emerging Electric Aircraft Architectures," *2018 Aviation Technology, Integration, and Operations Conference,* 2018 Aviation Technology, Integration, and Operations Conference, Atlanta, Georgia, American Institute of Aeronautics and Astronautics, Reston, Virginia, 2018.
doi: 10.2514/6.2018-4149

[7] Airbus, "CityAirbus NextGen - Fully-electric and integrated urban air mobility," URL: https://www.airbus.com/en/innovation/low-carbon-aviation/urban-air-mobility/cityairbus-nextgen.

[8] Bacchini, A., Cestino, E., van Magill, B., and Verstraete, D., "Impact of lift propeller drag on the performance of eVTOL lift+cruise aircraft," *Aerospace Science and Technology*, Vol. 109, 2021, p. 106429.
doi: 10.1016/j.ast.2020.106429

[9] Vertical Flight Society, "Wisk Aero Cora (Generation 5)," URL: https://evtol.news/kitty-hawk-cora/.

[10] Whiteside, S. and Pollard, B. (eds.), *Conceptual Design of a Tiltduct Reference Vehicle for Urban Air Mobility*, 2022.

[11] Vertical Flight Society, "Baaz B5," URL: https://evtol.news/baaz-production-model.

[12] Zhang, J., Liu, Y., Jiang, T., and Zheng, Y., "Conceptual Design and System Level Analysis of Tilt-Duct eVTOL Aircraft," *The Proceedings of the 2021 Asia-Pacific International Symposium on Aerospace Technology (APISAT 2021), Volume 1,* edited by S. Lee, C. Han, J.-Y. Choi, S. Kim and J. H. Kim, Springer Nature Singapore, Singapore, 2023, pp. 189–198.

[13] Johnson, W., "A Quiet Helicopter for Air Taxi Operations," *Aeromechanics for Advanced Vertical Flight Technical Meeting*, 2020.

[14] B. SAEED, "An Assessment of Current and On-The-Horizon eVTOL Technologies for a Flying Car," 2022.

[15] Volocopter, "WE AIM TO LAUNCH UAM FIRST - A new dimension of urban mobility," URL: https://www.volocopter.com/urban-air-mobility/.

[16] Denz, T., Smith, S., and Shrestha, R., "Seaplane Economics: A Quantitative Cost Comparison of Seaplanes and Land Planes for Sea Base Operations," 2007.

[17] Adu-Gyamfi, B. A. and Good, C., "Electric aviation: A review of concepts and enabling technologies," *Transportation Engineering*, Vol. 9, 2022, p. 100134.
doi: 10.1016/j.treng.2022.100134

[18] Fotouhi, A., Auger, D., O'Neill, L., Cleaver, T., and Walus, S., "Lithium-Sulfur Battery Technology Readiness and Applications—A Review," *Energies*, Vol. 10, No. 12, 2017, p. 1937.
doi: 10.3390/en10121937

[19] Service, R. F., "Lithium-sulfur batteries poised for leap," *Science*, Vol. 359, No. 6380, 2018, pp. 1080–1081. doi: 10.1126/science.359.6380.1080

[20] Sultanov, F., Mentbayeva, A., Kalybekkyzy, S., Zhaisanova, A., Myung, S.-T., et al., "Advances of graphene-based aerogels and their modifications in lithium-sulfur batteries," *Carbon*, Vol. 201, 2023, pp. 679–702. doi: 10.1016/j.carbon.2022.09.069

[21] Thielmann, A., Sauer, A., Isenmann, R., and Wietschel, M., *Technologie-Roadmap Energiespeicher für die Elektromobilität 2030*, 2012.

[22] Kwak, W.-J., Rosy, Sharon, D., Xia, C., Kim, H., et al., "Lithium-Oxygen Batteries and Related Systems: Potential, Status, and Future," *Chemical reviews*, Vol. 120, No. 14, 2020, pp. 6626–6683. doi: 10.1021/acs.chemrev.9b00609

[23] *Roadmap for the Technological Development of Hybrid Electric and Full-Electric Propulsion Systems of Aircrafts,* IEEE, 2019.

[24] Rendón, M. A., Sánchez R., C. D., Gallo M., J., and Anzai, A. H., "Aircraft Hybrid-Electric Propulsion: Development Trends, Challenges and Opportunities," *Journal of Control, Automation and Electrical Systems*, Vol. 32, No. 5, 2021, pp. 1244–1268. doi: 10.1007/s40313-021-00740-x

[25] Sayed, E., Abdalmagid, M., Pietrini, G., Sa'adeh, N.-M., Callegaro, A. D., et al., "Review of Electric Machines in More-/Hybrid-/Turbo-Electric Aircraft," *IEEE Transactions on Transportation Electrification*, Vol. 7, No. 4, 2021, pp. 2976–3005. doi: 10.1109/TTE.2021.3089605

[26] Wang, Y., Nuzzo, S., Zhang, H., Zhao, W., Gerada, C., et al., "Challenges and Opportunities for Wound Field Synchronous Generators in Future More Electric Aircraft," *IEEE Transactions on Transportation Electrification*, Vol. 6, No. 4, 2020, pp. 1466–1477. doi: 10.1109/TTE.2020.2980189

[27] Smith, A. C., Iacchetti, M. F., and Tuohy, P. M., "Feasibility study of an induction motor rim drive for an aircraft boundary-layer-ingestion fan," *The Journal of Engineering*, Vol. 2019, No. 17, 2019, pp. 4506–4510. doi: 10.1049/joe.2018.8044

[28] Ma, L., Zhang, Z., Gao, L., Liu, Y., and Hu, H., "Bio-Inspired Icephobic Coatings for Aircraft Icing Mitigation: A Critical Review," *Progress in Adhesion and Adhesives,* edited by K. L. Mittal, Wiley, 2021, pp. 171–201.

[29] Feher, L. and Thumm, M., "Design of Avionic Microwave De-/Anti-Icing Systems," *Advances in Microwave and Radio Frequency Processing,* edited by M. Willert-Porada, Springer Berlin Heidelberg, Berlin, Heidelberg, 2006, pp. 695–702.

[30] Kreeger, R. E., Broeren, A. P., Chen, R.-C., and Struk, P. M., "Aircraft Icing Analysis of Alternatives," *AIAA AVIATION 2022 Forum,* AIAA AVIATION 2022 Forum, Chicago, IL & Virtual, American Institute of Aeronautics and Astronautics, Reston, Virginia, 2022. doi: 10.2514/6.2022-4024

[31] Bahulekar, S., "Effect of Spray Rails on Takeoof Performance of Amphibian Aircraft," Doctoral Dissertations and Master's Theses, 2022.

[32] Allison, R. S., Johnston, J. M., Craig, G., and Jennings, S., "Airborne Optical and Thermal Remote Sensing for Wildfire Detection and Monitoring," *Sensors (Basel, Switzerland)*, Vol. 16, No. 8, 2016. doi: 10.3390/s16081310

[33] Barmpoutis, P., Papaioannou, P., Dimitropoulos, K., and Grammalidis, N., "A Review on Early Forest Fire Detection Systems Using Optical Remote Sensing," *Sensors (Basel, Switzerland)*, Vol. 20, No. 22, 2020. doi: 10.3390/s20226442

[34] *16th Australian International Aerospace Congress*.

[35] Kausar, A., Ahmad, I., Rakha, S. A., Eisa, M. H., and Diallo, A., "State-Of-The-Art of Sandwich Composite Structures: Manufacturing—to—High Performance Applications," *Journal of Composites Science*, Vol. 7, No. 3, 2023, p. 102. doi: 10.3390/jcs7030102

[36] Bil, C., Ravindran, A. R., Walsh, M., Leung, C., Tan, C. Y., et al. (eds.), *Aerial Bushfire Quencher: C-17 Conversion for Fire Fighting Operations*, 2015.

[37] Dwivedi, P., Siddiquee, A. N., and Maheshwari, S., "Issues and Requirements for Aluminum Alloys Used in Aircraft Components: State of the Art," *Russian Journal of Non-Ferrous Metals*, Vol. 62, No. 2, 2021, pp. 212–225.
doi: 10.3103/S1067821221020048

[38] Riley, C., "Understanding The Different Types Of Boat Hulls," URL: https://www.boatsafe.com/types-boat-hulls/.

[39] U.S. Department of Transportation, Federal Aviation Administration, "Data Link Communications," 2017.

[40] Ponchak, D. S., Apaza, R. D., Wichgers, J. M., Haynes, B., and Roy, A., "A study of future communications concepts and technologies for the National Airspace System-part IV," *2015 IEEE Aerospace Conference,* 2015 IEEE Aerospace Conference, Big Sky, MT, 3/7/2015 - 3/14/2015, IEEE, 2015, pp. 1–13.
doi: 10.1109/AERO.2015.7118934

[41] International Civil Aviation Organization, Asia and Pacific, "Guidance Material on Comparison of Surveillance Technologies (GMST)," 2007.

[42] MIT Lincoln Laboratory Air Traffic Control, "Celebrating 50 Years of Research and Innovation," 2022.

[43] Richards, W. R., O'Brien, K., and Miller, D. C., "Air Traffic Surveillance Technology: Transition from Radar Surveillance to Automatic Dependent Surveillance-Broadcast (ADS-B)," *Boeing Aero Magazine*, 2023, URL: https://www.boeing.com/commercial/aeromagazine/articles/qtr_02_10/2/.

[44] MIT Lincoln Laboratory, "Air Traffic Control Research and Innovation," 2021.

[45] Robert Bassey, "Engineering Brief No. 105, Vertiport Design," 2022.

[46] European Union Aviation Safety Agency (EASA), "Prototype Technical Design Specifications for Vertiports," 2022.

[47] Ahn, B. and Hwang, H.-Y., "Design Criteria and Accommodating Capacity Analysis of Vertiports for Urban Air Mobility and Its Application at Gimpo Airport in Korea," *Applied Sciences*, Vol. 12, No. 12, 2022, p. 6077.
doi: 10.3390/app12126077

[48] Quilty, S. M., *Practices in Preserving and Developing Public-Use Seaplane Bases,* Transportation Research Board, Washington, D.C., 2015.

[49] Federal Aviation Administration, "AC 43.13-1B - Acceptable Methods, Techniques, and Practices - Aircraft Inspection and Repair [Large AC. This includes Change 1.]," 1998.

[50] Scottish Government, "Fire & Rescue Service Wildfire Operational Guidance," URL: https://www.gov.scot/publications/fire-rescue-service-wildfire-operational-guidance/.

[51] NASA, "The Big and Small of Fire in Africa," URL: https://www.earthdata.nasa.gov/learn/articles/africa-fires.