OLYMPIA REGIONAL
AIRPORT
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Olympia Regional Airport

DRAFT APPENDIX 5-1
EMERGING TECHNOLOGIES

5. Emerging Technologies

A.1 INTRODUCTION

The aviation industry has traditionally relied on fossil fuels as the primary energy source for aircraft propulsion, leading to significant carbon dioxide (CO2) emissions and environmental concerns. As the global awareness of climate change and its associated impacts grows, there is an increasing need to transition to more sustainable and environmentally friendly forms of air transportation. In response to this pressing challenge, researchers and industry stakeholders have turned their attention to electric and hydrogen-powered aircraft and SAF as potential alternatives to conventional fossil fuel-based aircraft. Industry advances are rapidly occurring and data in this appendix may have changed after spring 2024.

A.2. ELECTRIC AVIATION

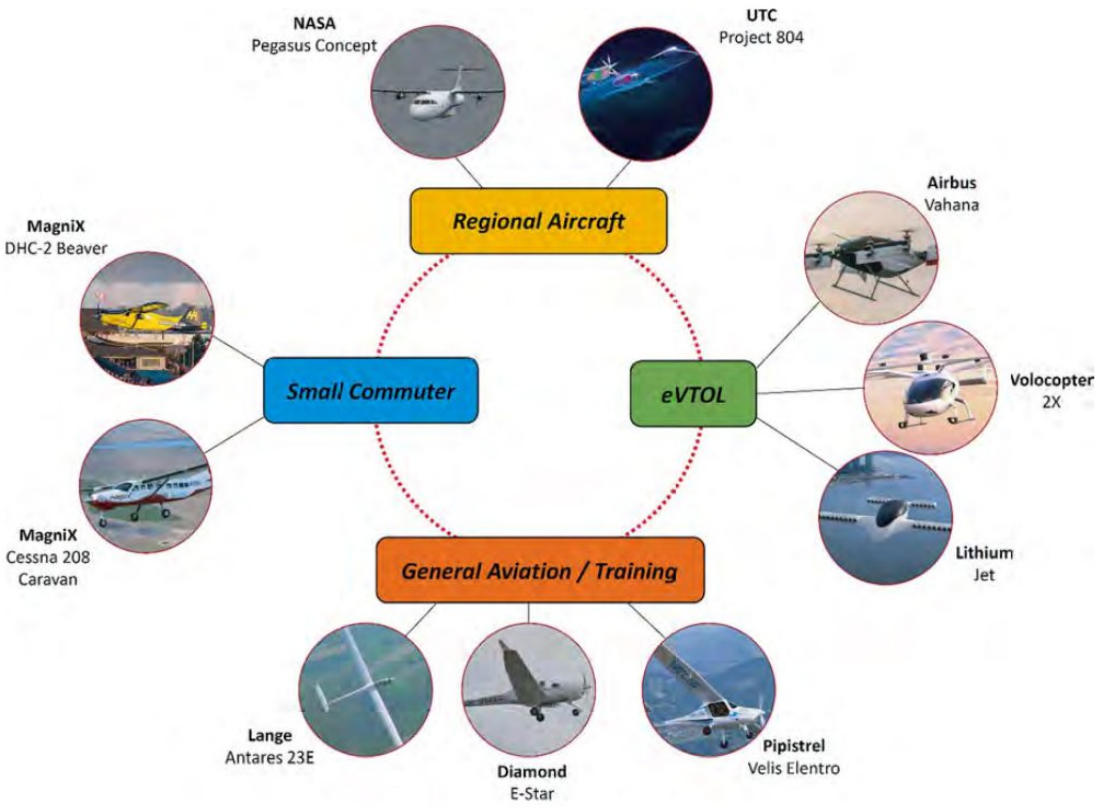
Electric aviation encompasses various aircraft types and applications involving the electrification of propulsion and aircraft control. Electrification can manifest as either fully electric systems or hybrid electric solutions. Furthermore, electric aircraft offer the flexibility of manned flight, remote control, or complete autonomy. These aircraft can be designed for conventional takeoff and landing (CTOL) or VTOL operations.

A.3. ELECTRIC AIRCRAFT

Electric aircraft employ electric motors as their primary means of propulsion, departing from conventional combustion engines. These aircraft depend on electric energy stored in batteries or generated via onboard power mechanisms like fuel cells or hybrid systems. The classification of electric aircraft can be divided into two principal categories: all-electric aircraft and hybrid-electric aircraft.

All-electric aircraft exclusively utilize electric motors for propulsion, relying entirely on electrical energy. They commonly incorporate high-capacity batteries for energy storage. These aircraft are engineered to function without emitting direct emissions, resulting in a notable decrease in greenhouse gases and local air pollutants when contrasted with conventional aircraft.

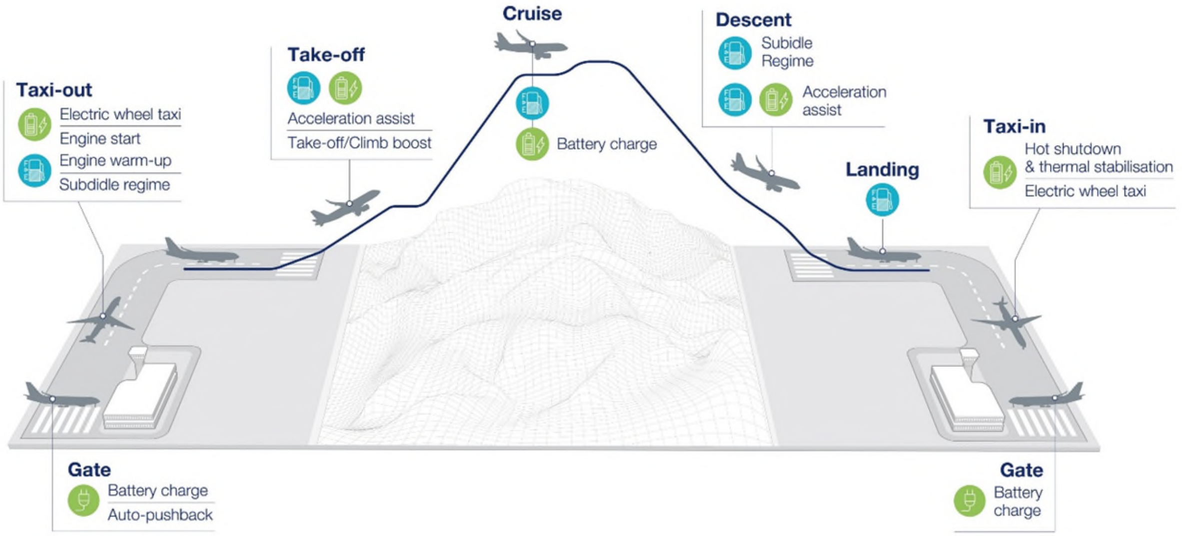
Figure A-1: Examples of Electric Aircraft



Source: ACRP Research Report 236 2022.

Some electric aircraft use hybrid propulsion systems that combine electric motors with internal combustion engines or gas turbines. The combustion engine generates electricity to power the electric motors or directly assists in propulsion. Hybrid setups allow for the strategic usage of electricity and aviation fuels, combined or alternatively, which brings benefits such as enhanced efficiency, decreased fuel usage, and reduced emissions compared to standard aircraft. This setup provides flexibility, especially for longer flights or larger aircraft, where battery energy density might still be limited. According to Airbus, aircraft hybridization can reduce fuel consumption by up to 5%.

Figure A-2: Hybrid Aircraft During Flight Phases



Source: Airbus – Hybrid and Electric Flight 2023.

Though electric aviation is in its early stages, electric aircraft technology is swiftly progressing, propelled by breakthroughs in battery technology, electric motor efficiency, and power management systems. These advancements pave the way for extended flight ranges, enhanced performance, and greater commercial feasibility of electric aircraft.

A.4. BATTERY TECHNOLOGY

Electric aircraft battery technology is a critical component in the development and widespread adoption of electric propulsion systems for aviation. Advancements in battery technology are essential to overcome energy storage limitations, increasing the range and endurance of electric aircraft, and enhancing their overall performance.

A.5. ENERGY & POWER DENSITY

One of the critical challenges in electric aircraft battery technology is achieving high energy density, which determines the amount of energy that can be stored in a given volume or weight. Higher energy density batteries would enable electric aircraft to have longer flight ranges and support the operation of larger aircraft. While significant progress has been made, current battery technologies, such as lithium-ion batteries, still need to catch up to the energy density of aviation fuels. Ongoing research and development efforts focus on improving the energy density of batteries through novel materials, cell chemistries, and structural designs.

Power density is another crucial aspect of electric aircraft batteries. It refers to the ability of a battery to deliver high power outputs quickly, enabling rapid acceleration, climb rates, and maneuverability. Electric aircraft require batteries with high power density to meet the demands of takeoff, climb, and other high-power operations. Current battery technologies have made considerable strides in power density, but further improvements are necessary to enhance the performance of electric aircraft and ensure efficient power delivery during critical flight phases.

A.6. SAFETY & ENVIRONMENTAL CONSIDERATIONS

Safety considerations are paramount in electric aircraft battery technology. Lithium-ion batteries, while widely used in various applications, have inherent safety risks due to their chemistry. The potential for thermal runaway, leading to fires or explosions, requires stringent safety measures, including robust battery management systems, thermal management, and structural protection. Continued research focuses on enhancing battery safety, developing new chemistries, and implementing advanced safety features to mitigate risks and ensure the reliable operation of electric aircraft.

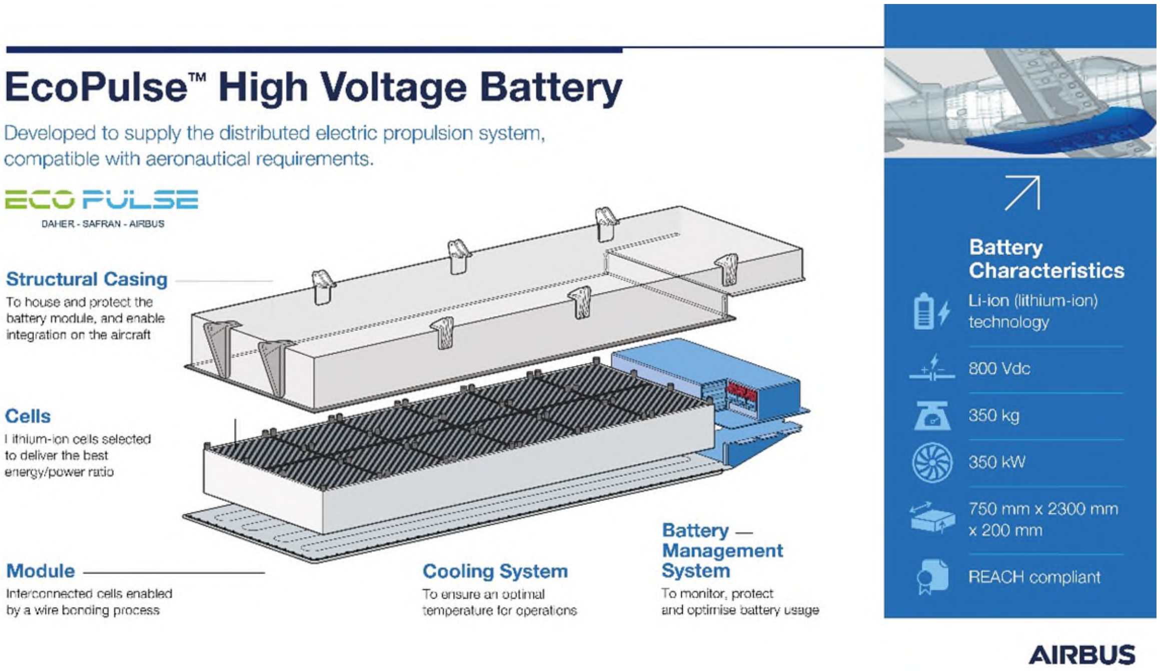
Battery production and end-of-life management present environmental considerations. The extraction of raw materials, manufacturing processes, and disposal of batteries can have ecological impacts. It is crucial to develop sustainable and environmentally responsible practices throughout the lifecycle of batteries, including recycling and reuse strategies. Research into alternative battery chemistries, such as solid-state batteries, holds promise in reducing the environmental footprint and addressing resource limitations associated with current battery technologies.

A.7. BATTERY RESEARCH & DEVELOPMENT

Several emerging battery technologies show potential for electric aircraft applications. Solid-state batteries, for example, offer higher energy density, improved safety, and potentially faster charging times compared to traditional lithium-ion batteries. Other research focuses on alternative materials, such as lithium-sulfur or lithium-air, which can potentially provide even higher energy densities. However, these technologies are still in the early stages of development and face challenges related to scalability, manufacturing costs, and cycle life.

Electric aircraft battery technology is a critical area of research and development for the aviation industry. Advancements in energy density, power density, and safety are necessary to overcome the limitations of current battery technologies. Collaboration between researchers, manufacturers, and regulatory bodies is crucial to drive innovation, establish safety standards, and create a sustainable ecosystem for electric aircraft battery technology. With ongoing advancements and investment, electric aircraft batteries have the potential to revolutionize aviation.

Figure A-3: Advanced Electric Aircraft Battery Technology by Airbus



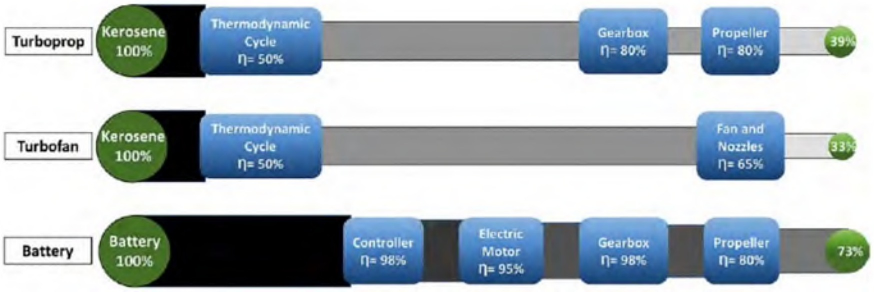
Source: Airbus – EcoPulse High Voltage Battery 2022.

A.8. ELECTRIC AIRCRAFT ENERGY EFFICIENCY

Electric aircraft offer several advantages in terms of energy efficiency compared to conventional aircraft. The inherent efficiency of electric propulsion systems, regenerative braking, aerodynamic optimization, weight reduction, advanced energy management systems, heat recovery, and mission-specific efficiency contribute to improved overall energy efficiency.

Electric aircraft propulsion systems, particularly electric motors, offer higher efficiency than internal combustion engines. Electric motors can convert electrical energy into mechanical energy with greater efficiency, resulting in less energy loss during propulsion. Electric motors have an approximate efficiency of 70% compared to about 39% efficiency of combustion engines. This efficiency advantage contributes to reduced energy consumption and improved overall energy efficiency of electric aircraft.

Figure A-4: Powertrain Efficiency Comparison



Source: ACRP Research Report 236 2022.

Electric aircraft can incorporate regenerative braking systems that recover and store energy during deceleration and landing. When an electric aircraft applies brakes, the electric motors can act as generators, converting kinetic energy into electrical energy that can be stored in the aircraft's batteries. This energy recovery mechanism enhances overall energy efficiency by reusing energy that would otherwise be dissipated as heat in traditional braking systems.

Due to the scalability of components, electric aircraft can take advantage of their design flexibility to optimize aerodynamics, further enhancing energy efficiency. By reducing drag through streamlined shapes, optimized wing designs, and innovative airframe configurations, electric aircraft can minimize energy losses caused by air resistance. Improved aerodynamics contribute to reduced energy consumption and improved flight efficiency.

Electric aircraft benefit from weight reductions due to the elimination of heavy components such as fuel tanks, combustion engines, and associated systems. Lighter aircraft require less energy for propulsion, resulting in improved energy efficiency. Additionally, the absence of fuel onboard eliminates the need for fuel transfer systems and associated energy losses, further contributing to enhanced efficiency.

Electric aircraft employ advanced energy management systems to optimize energy consumption throughout the flight. These systems monitor and control the power distribution between propulsion, avionics, and other onboard systems, ensuring efficient energy utilization based on flight conditions and operational requirements. Electric aircraft can optimize energy efficiency and extend flight range by dynamically managing energy flows.

Electric aircraft can leverage waste heat generated by the electrical propulsion system for various purposes, such as cabin heating, de-icing, or powering auxiliary systems. Heat recovery systems minimize energy waste and improve overall system efficiency. Additionally, effective thermal management systems ensure that batteries and other critical components operate within optimal temperature ranges, preventing energy losses due to thermal inefficiencies.

Electric aircraft can be optimized for specific missions, enabling efficient operations tailored to the aircraft's intended use. Short-range electric aircraft, for example, can be designed with specific battery capacities optimized for frequent takeoff and landing cycles, maximizing efficiency for regional or urban air mobility applications. By tailoring the aircraft to its mission profile, electric aircraft can achieve higher energy efficiency for specific operational scenarios.

Electric aircraft have the potential to leverage renewable energy sources for charging or powering onboard systems. Integrating renewable energy, such as solar or wind power, into the charging infrastructure or directly into the aircraft's power system can further enhance electric aircraft's sustainability and energy efficiency.

Figure 5-5: Airbus Zephyr: Solar-powered Electric Aircraft

Source: Airbus – Zephyr 2013.

Continued research and development efforts focused on battery technology, aerodynamics, and system optimization will further enhance the energy efficiency of electric aircraft.

A.8.1. ELECTRIC AIRCRAFT USE CASES

Electric aircraft have a wide range of potential use cases across various sectors. As electric propulsion technology advances, these aircraft are being explored for commercial and non-commercial purposes. Some prominent use cases for electric aircraft are urban air mobility (UAM), regional air travel, training and pilot education, air cargo and logistics, sightseeing and recreational flights, research and development, environmental monitoring and surveillance, and humanitarian and emergency response.

- **Urban Air Mobility (UAM):** Electric aircraft can be used for short-distance transportation within urban areas, offering a sustainable alternative to traditional ground transportation. These aircraft, often referred to as electric vertical takeoff and landing (eVTOL) vehicles, can provide efficient and fast transportation for commuters, reducing congestion and travel times.

Figure A-6: Urban Air Mobility Concept

Source: Eve Air Mobility – Urban Air Mobility 2022.

- **Regional Air Travel:** Electric aircraft have the potential to revolutionize regional air travel by offering quieter and more environmentally friendly alternatives to conventional aircraft. Shorthaul routes between neighboring cities or remote areas can benefit from the lower operating costs and reduced carbon emissions of electric aircraft.

- **Training and Pilot Education:** Electric aircraft can be utilized for flight training and pilot education purposes. Their quieter operation and reduced maintenance costs make them attractive options for flight schools and training centers. Electric aircraft provide aspiring pilots with hands-on experience in eco-friendly aviation and promote sustainable practices in the industry.

- **Air Cargo and Logistics:** Electric aircraft can play a significant role in the air cargo and logistics industry. Electric cargo planes offer the potential for efficient, low-cost, and eco-friendly transportation of goods over short to medium distances. They can contribute to reducing emissions associated with transporting goods and help meet sustainability targets in the logistics sector.

- **Sightseeing and Recreational Flights:** Electric aircraft can provide unique experiences for tourists and aviation enthusiasts. These aircraft offer quiet operations, zero emissions, and a smoother flying experience, enhancing the pleasure and comfort of sightseeing flights. Electric seaplanes can also enable eco-friendly recreational flights over lakes, rivers, and coastal areas.

- **Research and Development:** Electric aircraft serve as testbeds for research and development in the aviation industry. They provide a platform to explore new technologies, battery systems, aerodynamics, and propulsion systems. Electric aircraft research supports advancements in energy storage, power management, and other critical areas, benefiting the broader aviation sector.

- **Environmental Monitoring and Surveillance:** Electric aircraft can be utilized for environmental monitoring and surveillance missions. With their ability to operate quietly and for extended durations, electric aircraft can gather data on air quality, wildlife habitats, and other environmental parameters without disturbing sensitive ecosystems. They can aid in ecological research, climate monitoring, and conservation efforts.

- **Humanitarian and Emergency Response:** Electric aircraft can be valuable assets in humanitarian and emergency response operations. Their ability to take off and land in confined spaces and their lower operating costs make them suitable for delivering supplies, conducting aerial surveys, and supporting disaster management efforts in remote or hard-to-reach areas.

- **Personal and Recreational Use:** Electric aircraft can also cater to personal flying enthusiasts and recreational pilots. Electric-powered aircraft, including general aviation aircraft, ultralight aircraft, and recreational gliders, offer a sustainable and enjoyable flying experience for individuals passionate about aviation.

It's important to note that while electric aircraft technology is advancing rapidly, some use cases may still be in the experimental or early adoption stages. Regulatory frameworks, infrastructure development, and further advancements in battery technology are essential to realizing the full potential of electric aircraft across these use cases.

Table 5-1: Example Electric Aircraft Configurations and Use Cases

	Conventional Takeoff and Landing				Vertical Takeoff and Landing	
Configuration	Small All-Electric Tube & Wing	Small All-Electric Tube & Wing	Commuter All-Electric Tube & Wing	Regional Hybrid-Electric Tube & Wing	All-Electric Multi Copter	All-Electric Tilt Rotor
Capacity	1 Pilot + 1 Passenger	1 Pilot + 3 Passenger	2 Pilot + 9 Passenger	2 Pilot + 39 Passenger	2 Passengers	1 pilot + 4 passengers
Range	1 hr.+ reserve (Circuits) 45 min + reserve (Cross country)	4 hours / 420 miles	650 miles	700 miles	25 miles	60 miles
Cruise Speed	98 mph	190 mph	300 mph	280 mph	81 mph	150 mph
Power Requirement	1 motor 60 kW	1 motor 105 kWh	3 motors 260 kWh each	2 Parallel-hybrid engines 2MW each	16 motors 152 kW	4 Motors 200 kW
Energy Storage	Batteries (21 kWh)	Batteries (120 kWh)	Batteries (900 kWh)	Jet Fuel Batteries (800 kWh)	Battery (30 kWh)	Battery (130 kWh)
Charging	Swap battery 45 min @ 20 kW 1 hr. 5 min @ 14 kW 1 hr. 40 min @ 10 kW 6 hr. @ 3 kW	45 min @ 60 kW 1 hr. 35 min @ 24 kW 3 hr. 45 min @ 10 kW	30 min for 1 hr. flight @ 400 kW 45 min for 1.5 hr. flight @ 400 kW	Unspecified Assumed fast charger @ 600 kW	2 hr. @ fast charge	35% Capacity in 7 min @ 600 kW
Example	Pipistrel Alpha Electro	Bye Aerospace Sunflyer / eflyer 4	Eviation Alice	UTC Project 804	Beijing Yi-Hang Creation	Bell Nexus 4EX / Joby S4
Use Case	Flight-Training Operations	Recreational Air Taxi Operations	Commuter Operations Air Cargo Operations	Regional Airline Operations	Air Taxi Operations	Air Taxi Operations

Source: ACRP Research Report 236 2022.

A.9. ELECTRIC AIRCRAFT POWER MANAGEMENT AND GENERATION

Electric aviation power management and power generation are fundamental to the transition toward sustainable flight. In electric aircraft, where propulsion is driven by electric motors, efficient power management is essential to ensure optimal energy usage and system reliability. Power management systems continuously monitor and regulate the flow of electrical energy, allocating it to various systems based on priority and real-time demands. This dynamic allocation ensures that essential functions, such as propulsion and avionics, receive sufficient power while maintaining the overall energy balance. Additionally, electric aviation relies on innovative power generation methods to supply the energy needed for flight. Advanced propulsion systems, such as battery-powered electric motors or hybrid configurations, often integrate power generation capabilities to recharge batteries during flight, making efficient use of regenerative energy. Continued advancements in power electronics, battery technology, and control algorithms will further enhance the capabilities and efficiency of electric aircraft power management systems and generation.

A.10. POWER MANAGEMENT

Electric aircraft power management is critical to ensuring the efficient and reliable operation of these aircraft. Given the limited energy storage capacity of batteries and the varying power demands during different flight phases, effective power management systems are necessary to optimize energy usage and ensure sufficient power for propulsion, avionics, and other onboard systems.

One key consideration is energy flow monitoring and control. Power management systems continuously assess the state of charge of the batteries, the power demand from various systems, and the available power supply. By dynamically managing the energy flow, these systems ensure power is distributed efficiently and prioritize critical systems to maximize operational safety and performance.

Another vital aspect is power distribution and prioritization. Different systems receive power based on their priority and real-time demands. Propulsion systems typically receive the highest priority to maintain safe flight operations. Other systems such as avionics, flight control, climate control, and communication systems are allocated power based on their importance and operational requirements. Efficient power distribution ensures optimal utilization of available energy and enhances overall system reliability.

Load balancing is crucial to prevent power imbalances and ensure the uniform distribution of electrical load across multiple power sources or battery cells. Power management systems monitor individual cells or battery packs and adjust power flow to maintain balanced charging and discharging. Load balancing helps maximize the lifespan and performance of the batteries, avoiding premature degradation and potential safety risks.

Effective thermal management is essential for maintaining optimal performance and longevity of the batteries and other electrical components. Power management systems monitor the temperature of critical components and ensure they operate within safe limits. Active cooling or heating mechanisms may be employed to maintain appropriate temperature ranges. Proper thermal management minimizes energy losses due to thermal inefficiencies and safeguards against thermal-related failures.

Electric aircraft power management systems often incorporate redundancy and fault tolerance measures to ensure continued operation in the event of system failures. Redundant power distribution and control units and backup power sources such as emergency battery packs or auxiliary power units can provide backup power in critical situations. These measures enhance system reliability and reduce the risk of power-related failures.

Power management systems continuously strive to optimize energy usage and improve overall system efficiency. Advanced algorithms, machine learning, and predictive analytics can be employed to analyze historical data, flight conditions, and operational parameters to optimize power distribution and enhance overall energy efficiency. These optimization techniques enable continuous improvement in power management strategies and contribute to extended flight range and reduced energy consumption.

A.11. POWER GENERATION

Electric aircraft power generation refers to the process of producing electrical energy on board an aircraft to power its systems and propulsion. Unlike traditional aircraft, which rely on internal combustion engines for propulsion and electrical power generation, electric aircraft use innovative methods to generate electricity for various components, including electric motors, avionics, lighting, and other systems. This approach is a key aspect of the electric aviation paradigm, contributing to improved efficiency, reduced emissions, and enhanced performance.

Several power generation methods are being explored for electric aircraft. One common approach is using advanced battery systems as the primary power source. These batteries store and supply electrical energy to electric motors for propulsion and other systems. During flight, the batteries can be recharged through regenerative braking or energy recovery mechanisms, where the electric motors act as generators during descent or deceleration, converting kinetic energy back into electrical energy. Battery technology advancements are crucial for increasing energy density, extending flight range, and supporting various aircraft sizes and missions.

Solar panels are another method mounted on the aircraft's surface to convert sunlight directly into electricity. While the energy generated from solar panels is typically insufficient for primary propulsion, it can contribute to powering auxiliary systems, such as avionics or lighting, and help extend the overall endurance of the aircraft. Additionally, in some experimental electric aircraft, small wind turbines are incorporated to generate electricity from the airflow during flight, providing supplementary power to support specific functions.

Thermoelectric generators are also being explored to convert temperature differences into electricity. They could harness waste heat from the aircraft's engines or other heat sources to generate additional power.

Effective electric aircraft power generation systems are designed to balance energy demands, maximize efficiency, and ensure the aircraft's overall performance. The choice of power generation method depends on factors such as the aircraft's mission profile, range, size, and available technology. As electric aviation technology continues to advance, innovations in power generation are essential for realizing the full potential of electric aircraft.

A.12. ELECTRIC AVIATION AIRPORT INFRASTRUCTURE

The development of a robust and widespread charging infrastructure is crucial for the practicality and scalability of electric aircraft. Charging infrastructure needs to support fast charging capabilities to minimize ground time and enable efficient operations. Additionally, the infrastructure should accommodate different battery chemistries, voltage requirements, and aircraft configurations. Collaborative efforts involving governments, airports, and industry stakeholders are essential to address the challenges associated with charging infrastructure development, including grid capacity, power supply stability, and standardization.

The transition towards electric aviation brings forth a host of technological and infrastructural challenges, with the provision of reliable and efficient charging infrastructure ranking among the foremost priorities. Airport electric aircraft charging infrastructure is designed to meet the specific energy requirements of electric aircraft, ensuring their seamless operation within the airport ecosystem. This section provides an in-depth analysis of the various facets of this infrastructure, shedding light on its components, functionalities, integration within airport operations, and its implications for the burgeoning field of electric aviation.

Charging stations form the bedrock of airport electric aircraft charging infrastructure. These strategically located stations are equipped with high-power charging equipment that can efficiently replenish the energy reserves of electric aircraft batteries. In addition to power capacity and voltage specifications, standardized connectors play a pivotal role in streamlining the charging process, ensuring compatibility across diverse electric aircraft models.

An often-underestimated yet vital aspect of this infrastructure is the inclusion of standardized connectors. These connectors are meticulously engineered to match the specific charging ports found on various electric aircraft models. This standardization guarantees seamless compatibility, eliminating the need for cumbersome modifications or adjustments when connecting the aircraft to the charging station. Consequently, it expedites the charging process and enhances overall operational efficiency.

Airport electric aircraft charging infrastructure incorporates standardized charging protocols. These protocols serve as a bridge between the charging station and the aircraft's batteries. By adhering to uniform charging protocols, the infrastructure streamlines the energy transfer process. This not only ensures the safe transfer of electrical energy but also optimizes the efficiency of the charging operation, reducing potential delays and increasing the predictability of charging times.

Safety features constitute a paramount consideration in the design of airport electric aircraft charging infrastructure. These features, including sophisticated sensors and controls, are integrated to prevent potential risks such as overcharging and overheating. By monitoring the charging process and adjusting parameters in real-time, these safety features ensure the secure and reliable operation of the charging infrastructure, safeguarding both the aircraft and the charging station.

The integration of monitoring and management systems within the charging infrastructure introduces a layer of operational intelligence. These systems continuously monitor the charging process, capturing critical data regarding energy transfer and battery health. This real-time oversight empowers operators and maintenance personnel with actionable insights. They can track the progress of charging, identify potential anomalies, and make informed decisions to ensure the optimal health of the aircraft's batteries.

The successful integration of these components and functionalities within airport electric aircraft charging infrastructure ensures the smooth operation of electric aviation and signifies a significant leap toward sustainable aviation practices. By fostering seamless charging processes, enhancing operational efficiency, and contributing to the reduction of carbon emissions, this infrastructure plays a pivotal role in shaping the trajectory of the aviation industry's transition toward electrification.

A.13 AIRPORT POWER MANAGEMENT AND GENERATION

The advent of electric aircraft represents a transformative shift for the aviation industry. This evolution significantly impacts airport power management and generation strategies. As airports prepare to accommodate electric aircraft, they need to reassess and adapt their infrastructure, energy storage, and delivery systems.

As airport energy demands increase, future intelligent software solutions will offer real-time monitoring of power consumption, predict future demands, and optimize energy allocation. This software will also be integrated with flight scheduling systems to ensure aircraft are charged and ready as needed. As airports experience variable power demand throughout the day, smart grid technologies will be vital to dynamically allocate power to different charging points, maximizing efficiency and minimizing grid strain. With the advent of electric vehicles, charge management systems have been developed to manage energy costs for electric vehicles. These systems will have to be further developed and ported over to handle electric aircraft charging and larger electric vehicle fleets.

Given the critical nature of aviation, it's imperative to have backup systems and redundancies. Power interruptions can't be afforded, especially during aircraft charging. Robust backup solutions, including generators and battery storage, are essential to ensure uninterrupted services. Diesel fuel generators are the most commonly used backup energy source due to their size, cost, and simplicity. Battery storage units can be employed to store energy during off-peak times and release it during high demand. Such systems can stabilize power loads, reduce costs, and ensure a consistent energy supply.

Microgrids are a potential solution to offset increased operating costs while maintaining backup power solutions. A microgrid relies on on-site power generation that has the capability to serve as the primary source of energy for the airport. In many scenarios, there can be multiple sources of power generation such as solar, wind, battery storage, and generators. Renewable sources of energy can be used to generate revenue when not needed for airport use.

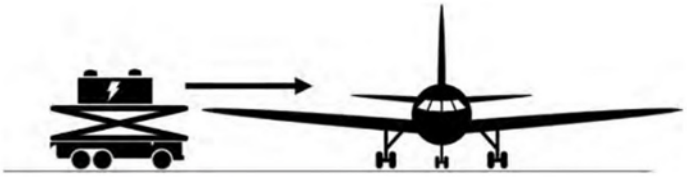
A.14 CHARGING OPTIONS

Three viable options are being considered for providing energy to electric aircraft: battery swapping, mobile charging, and fixed charging stations. Airports have to consider the power requirement, location, and funding of these charging options. Additionally, each option has infrastructure, operations, and safety implications that may affect the feasibility for an airport.

Figure A-7: Electric Aircraft Charging Options

Electric aircraft charging via fixed charging stations.

Electric aircraft charging via a mobile supercharger.



Electric aircraft battery swap.

Source: ACRP Research Report 236 2022.

A.15. FIXED CHARGING STATIONS

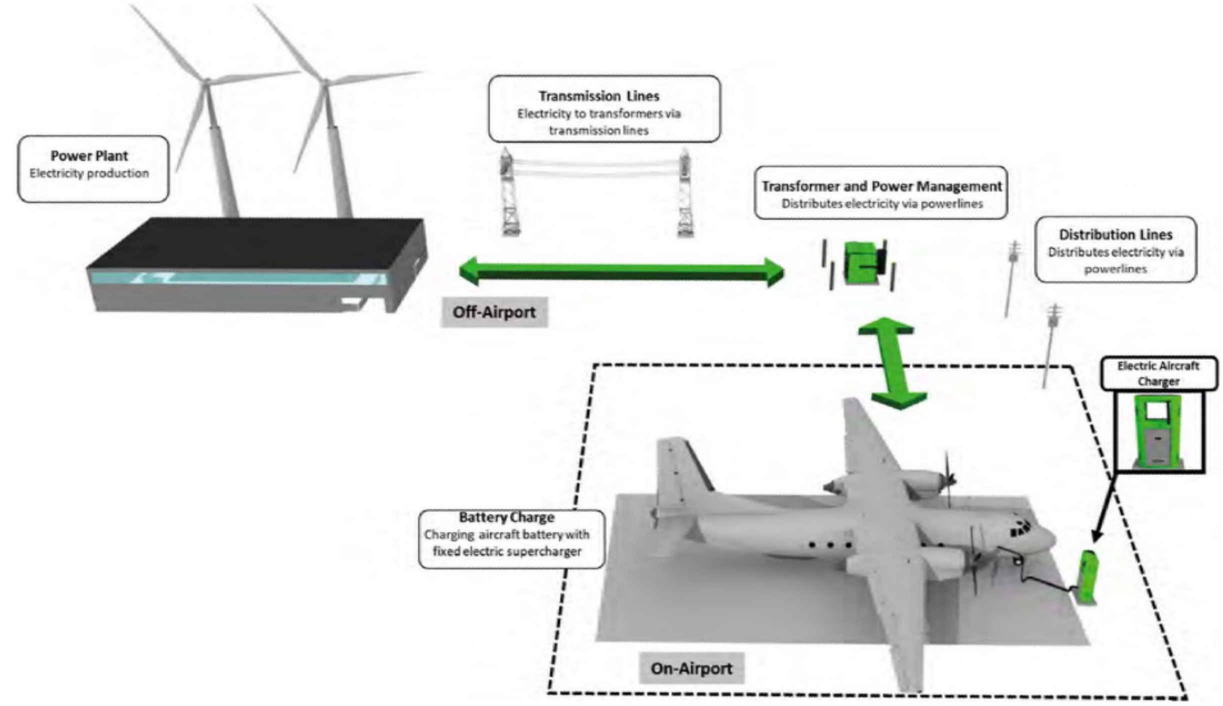
Electric aircraft charging stations represent a critical piece of infrastructure for the developing electric aviation industry. Such stations require substantial investments in high-capacity chargers that can deliver rapid, reliable charging to meet the enormous energy needs of aircraft. In addition, the electrical grid supplying these stations needs to be particularly robust and reliable, with adequate redundancy measures to ensure a constant power supply. Safety is another crucial concern, necessitating fire suppression systems, electrical insulation, and grounding mechanisms, among other safety measures. Advanced monitoring and control systems are also integral for real-time monitoring of the charging process, battery health, and energy usage. Furthermore, standardized connectors and ports must be designed to accommodate a variety of electric aircraft types and ample space must be allocated to house the charging infrastructure, which can be quite extensive. Regulatory compliance, including adherence to aviation and electrical standards, is another prerequisite that can't be overlooked.

The advantages of such permanent charging stations include a high level of consistency and reliability, given their direct connection to the electrical grid. They can offer much higher charging capacities than mobile solutions, translating to quicker turnaround times for electric or hybrid aircraft. Additionally, the scale of these permanent facilities allows for potentially lower operational costs over time, despite higher initial expenditures. These stations can also integrate comprehensive and robust safety measures, and if connected to a grid supplied by renewable energy sources, they could significantly advance the green energy goals of the aviation industry.

However, there are drawbacks to consider. The initial cost of setting up these charging stations is often high, particularly when compared to more flexible but less capable mobile charging solutions. Once installed, these stations lack the flexibility to adapt easily to changing demands or emerging technologies in electric aviation. Their reach is also geographically limited to the airports where they are installed, which might necessitate a broader network of stations for extensive coverage. Operational challenges in managing high power levels and ensuring safety could also be more complex in a permanent setup. Lastly, the dependency on a robust electrical grid makes these stations less suitable for remote or less-developed locations.

As the electric aviation sector evolves, electric aircraft charging stations will likely play a significant role in the ecosystem. They may coexist with other forms of charging solutions like mobile charging trucks to offer a more flexible, efficient, and comprehensive charging infrastructure.

Figure A-8: Electric Aircraft Fixed Charging Station Supply Line



Source: ACRP Research Report 236 2022.

A.16. MOBILE CHARGERS

Electric aircraft mobile truck charging is an innovative concept that seeks to provide charging solutions to electric aircraft in a flexible manner. This approach typically requires specialized trucks equipped with large battery packs or generators, advanced battery management systems, safety equipment, and standardized connectors for interfacing with aircraft. In addition, the system demands a robust network and software infrastructure for real-time monitoring, truck dispatching, and telematics, along with maintenance facilities and skilled technical staff to keep the trucks operational.

One of the significant advantages of mobile truck charging is its flexibility. These trucks can be dispatched to various locations, making them suitable for airports that do not have permanent charging facilities, or that see fluctuating levels of demand. This also lowers the initial capital expenditure for airports, particularly smaller ones, as they may not need to invest in permanent charging infrastructure. Scalability is another benefit; adding more trucks to the fleet is relatively straightforward, allowing for a dynamic allocation of resources based on real-time needs. Furthermore, mobile charging trucks can be deployed quickly, offering a fast way to test the feasibility of electric aviation in new markets or regions.

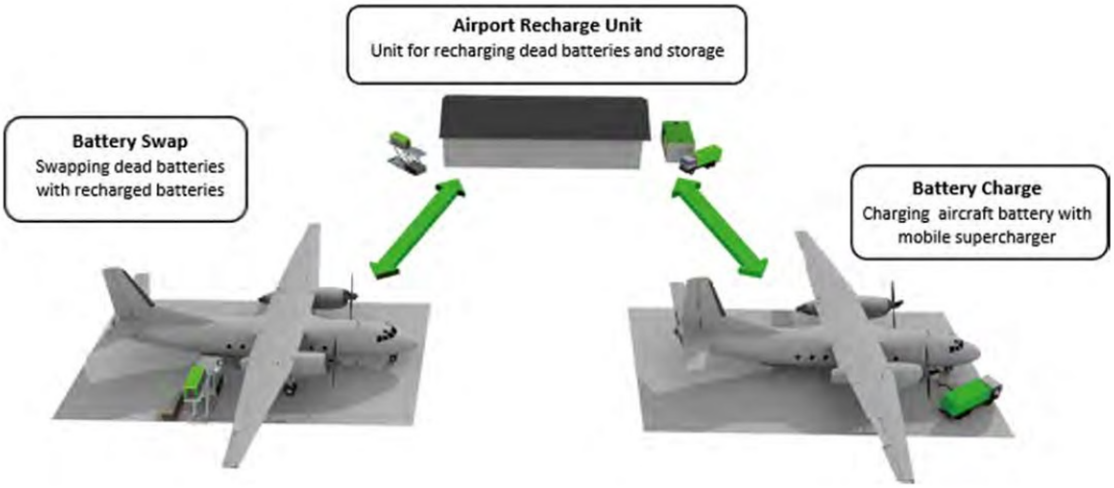
However, there are challenges and downsides to consider. The charging capacity of mobile trucks may be limited compared to permanent stations, which could lead to longer charging times or necessitate multiple trucks for a single aircraft. Operational complexity is another issue, as managing a fleet of mobile chargers involves intricate logistics and coordination. Over time, the operational costs, including maintenance, manpower, and potentially fuel (if the trucks themselves are not electric), could be higher than those for fixed infrastructure. High-traffic airports might also experience logistical challenges and congestion with many trucks navigating the tarmac. Environmental concerns could also arise if the trucks are powered by fossil fuels, partially offsetting the green benefits of electric aircraft. Additionally, the trucks are subject to wear and tear from constant movement, potentially increasing maintenance requirements.

While electric aircraft mobile truck charging offers a promising and flexible approach, particularly in the early stages of electric aviation or at smaller airports, it comes with its own challenges. As the electric aviation sector matures, a hybrid approach that combines both permanent and mobile charging infrastructure may offer the most balanced solution.

A.17. BATTERY SWAPPING

The battery swapping method replaces a spent battery of an aircraft with a fully charged battery. Battery swapping has the potential to reduce turn-around times for aircraft as the wait time for a swap would be less than the time required for charging a battery. Additionally, this method places less peak demand on the electrical grid as opposed to direct aircraft charging. However, battery swapping has its own infrastructure demands. Airports would need to create a battery charging facility that will slowly charge multiple batteries at the same time. While this method may not require the same levels of peak power capacity, it may use more energy overall. Along with infrastructure demands, battery swapping procedures would require regulatory approval as the FAA may consider the process a major repair or alteration. This would greatly reduce the feasibility of the battery-swapping option. Another caveat associated with the battery swapping method is the need for skilled technical staff to swap out batteries. Systems and procedures would have to be put in place to ensure the proper removal of the spent battery and correct installation of the new one.

Figure A-9: Electric Aircraft Mobile Charge and Battery Swapping



Source: ACRP Research Report 236 2022.

A.18. AIRPORT FINANCIAL PLANNING FOR ELECTRIC AIRCRAFT

Airport financial planning for electric aircraft involves strategic considerations and adjustments to accommodate the integration of electric aviation within an airport's operations. This encompasses various aspects of financial planning, including budgeting, revenue generation, cost management, and investment decisions. There are various financial planning elements to consider, such as:

- **Infrastructure Investment:** Airports need to allocate funds to develop and install electric aircraft charging infrastructure. This may include charging stations, power supply upgrades, and related equipment. Collaboration with charging technology providers and manufacturers is essential to determine the costs involved.

- **Charging Infrastructure Upkeep:** Electric aircraft charging infrastructure requires ongoing maintenance and technical support. Budget provisions should be made for regular maintenance, repairs, and updates to ensure the reliability and safety of the charging facilities.

- **Operational Costs:** Electric aircraft operations may have different operational costs compared to traditional aircraft. Airports should analyze and forecast changes in electricity consumption, ground handling procedures, and maintenance practices to accurately budget for electric aircraft operations.

- **Electricity Procurement:** Airports will need to establish agreements for procuring electricity, which may involve negotiations with energy providers. Exploring options for renewable energy sourcing can align with sustainability goals and potentially lead to long-term cost savings.

- **Revenue Generation:** Airports can explore new revenue streams associated with electric aircraft. This might include charging fees for electric aircraft usage, offering maintenance and technical services, or leasing charging infrastructure to aircraft operators.

- **Aircraft Charging Fees:** Airports can implement a fee structure for electric aircraft charging services based on factors such as energy consumption, aircraft size, and charging duration. These fees can contribute to covering infrastructure costs and generating revenue.

- **Incentives and Subsidies:** Airports can research and pursue available incentives, grants, or subsidies provided by governments or aviation industry bodies to support the adoption of electric aviation. These financial incentives can alleviate some of the initial investment costs.

- **Collaboration and Partnerships:** Collaborating with aircraft manufacturers, charging infrastructure providers, airlines, and regulatory bodies can lead to shared financial responsibilities, knowledge exchange, and joint funding opportunities.

- **Financial Analysis and Modeling:** Conducting financial analysis and modeling scenarios specific to electric aircraft operations can help airports understand the potential costs, benefits, and returns on investment associated with integrating electric aviation.

- **Marketing and Promotion:** Allocating funds for marketing and promotional campaigns to attract electric aircraft operators and raise awareness about the airport's commitment to sustainability and innovation.

- **Long-Term Planning:** Airport financial planning should consider the long-term trajectory of electric aviation. Provisions for future infrastructure expansion, technological advancements, and changing market demands should be factored into financial strategies.

- **Risk Assessment:** Assessing financial risks associated with electric aviation, such as changes in technology, market acceptance, or regulatory developments, allows airports to make informed decisions and establish contingency plans.

Airport financial planning for electric aircraft requires a forward-looking approach that balances initial investment costs with long-term sustainability and revenue potential. Strategic financial decisions should align with the airport's overall vision, operational goals, and commitment to advancing sustainable aviation practices.

A.19 HYDROGEN AVIATION

With the aviation industry's continual increase in greenhouse gas emissions, stakeholders are actively looking for solutions to environmental concerns. Along with electric aircraft, studies are being conducted to determine the effectiveness of hydrogen-powered aircraft.

Hydrogen aircraft utilize hydrogen gas as a primary fuel source for propulsion and power generation. Unlike traditional aircraft that rely on fossil fuels, such as jet fuel, hydrogen aircraft use hydrogen gas to power their engines or fuel cells. Hydrogen can be burned in internal combustion engines or used in fuel cells to produce electricity that drives electric motors for propulsion.

Hydrogen aircraft are considered a potential solution for reducing the environmental impact of aviation, as they produce minimal to no greenhouse gas emissions when operated. When hydrogen is burned in an internal combustion engine, the primary emission is water vapor, making it a "zero-emission" fuel when the entire hydrogen production process is powered by renewable energy sources. In fuel cell applications, only water and heat are emitted as byproducts.

Hydrogen aircraft come in various forms, including smaller regional aircraft, unmanned aerial vehicles (drones), and potentially larger commercial aircraft. However, the development and adoption of hydrogen aircraft face challenges such as hydrogen storage, infrastructure, energy density, and production methods. Despite these challenges, research and development efforts are ongoing to make hydrogen aviation a feasible and sustainable alternative for the aviation industry.

A.20. HYDROGEN PROPERTIES AND PRODUCTION

Hydrogen is the lightest and most abundant element in the universe and is often recognized for its potential as a clean energy carrier. Found primarily combined with other elements in nature, like in water (H_2O), it doesn't naturally exist in its elemental state on Earth. In its gaseous form, hydrogen is colorless, odorless, tasteless, and non-toxic. However, it's also highly flammable, which necessitates careful handling. While it boasts a high energy content by weight, surpassing even gasoline, its low volumetric density presents challenges, especially in terms of storage and transport.

Currently, hydrogen production primarily hinges on processes like Steam Methane Reforming (SMR), where natural gas, primarily methane, is reacted with steam under pressure. This process, however, generates carbon emissions. On the cleaner side of production methods, electrolysis stands out. Here, electricity splits water into hydrogen and oxygen, and when this electricity is sourced from renewables, the hydrogen produced is virtually emission-free. Other methods include thermochemical water splitting, which harnesses high temperatures, often from solar energy, to produce hydrogen. Another process is biomass gasification, where agricultural residues are converted into hydrogen and other gases through reactions with steam. Recent research has been delving into biological production, exploring how microorganisms like algae and bacteria can be harnessed to produce hydrogen. Another intriguing avenue is photoelectrochemical water splitting, where sunlight, in conjunction with specialized semiconductors, directly produces the energy required to split water.

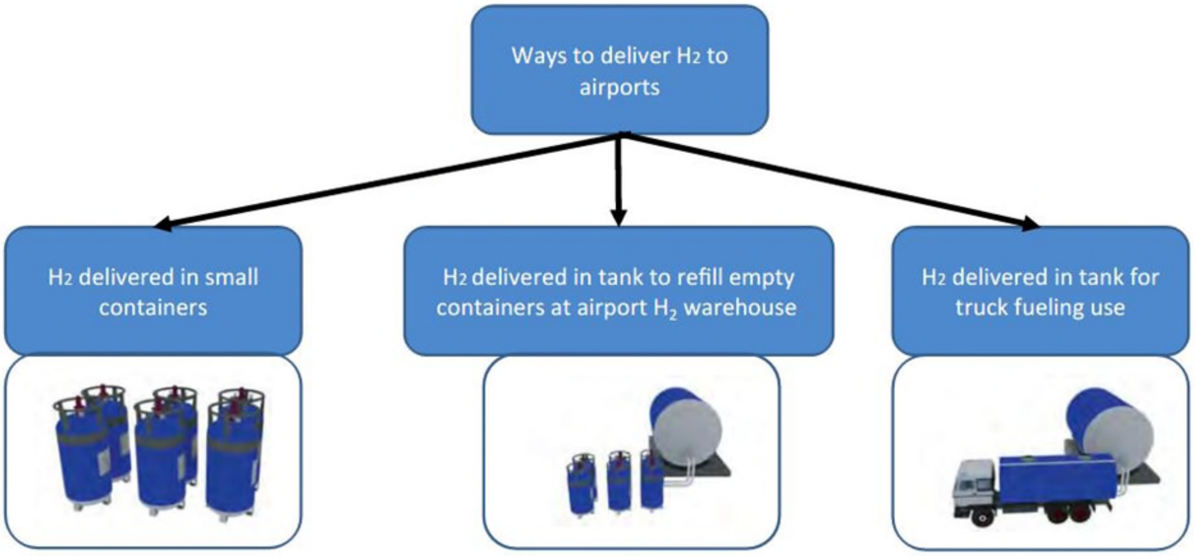
Hydrogen's potential in the renewable energy landscape is significant, though challenges abound. Its storage and transportation require either high-pressure conditions, extremely low temperatures, or containment in a chemically bonded state. Safety concerns, given its flammability, also dictate stringent precautions in its production, storage, and transportation. Furthermore, economic factors, such as the cost of inputs and energy for its production, can influence its viability as an energy carrier. Nonetheless, as the global thrust towards sustainable energy grows, hydrogen's role, especially when derived from clean sources, is set to be pivotal in sectors like transportation, electricity generation, and industry.

A.21. HYDROGEN TRANSPORTATION AND STORAGE

Hydrogen storage and transportation are central concerns in the move towards embracing hydrogen as a pivotal energy source. While hydrogen is abundant and boasts impressive energy content by weight, its low volumetric energy density poses challenges. One common storage method is compressing hydrogen in tanks designed to handle pressures up to 700 bar. Alternatively, hydrogen can be transformed into a cryogenic liquid at approximately -253°C, offering denser storage, albeit with the added energy costs of liquefaction and the necessity for cryogenic containment. Other storage techniques exploit the chemical attributes of hydrogen. For instance, certain metals can form metal hydrides by chemically bonding with hydrogen, allowing for storage at reduced pressures. Moreover, chemical compounds can be engineered to release hydrogen upon undergoing specific reactions, and porous materials, like metal-organic frameworks, can adsorb hydrogen on their surfaces.

Regarding transportation, pipelines are a viable option, reminiscent of the natural gas industry. However, there are challenges tied to the potential for hydrogen embrittlement, which might affect certain pipeline materials. Specialized tanker trucks, equipped to manage either the high pressure of compressed hydrogen or the extreme cold of liquid hydrogen, offer another transportation solution. Railcars or ships, armed with similar storage systems, become feasible for vast distances or substantial quantities. An intriguing alternative to direct hydrogen transport lies in localized production: transporting or sourcing water locally and then generating hydrogen on-the-spot using electrolyzers.

Figure A-10: Hydrogen Delivery



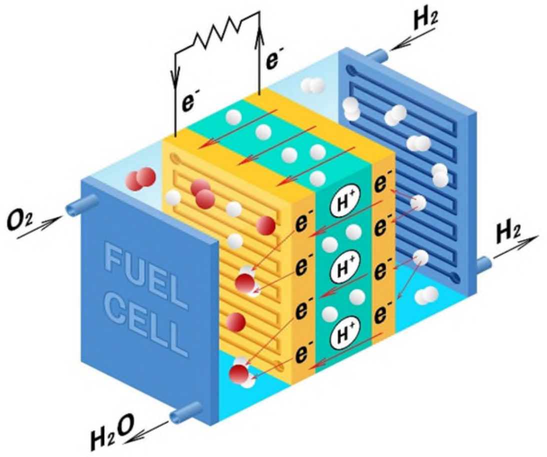
Source: ACRP Research Report 236 2022.

A.21. HYDROGEN FUEL CELLS

Hydrogen fuel cells are devices that generate electricity by converting the chemical energy stored in hydrogen gas and oxygen into water, with the only byproduct being water vapor. This makes them a potentially clean and efficient alternative to traditional internal combustion engines that produce greenhouse gases and other pollutants.

The basic components of a hydrogen fuel cell system include the anode, where hydrogen gas is introduced to the fuel cell, which leads to the splitting of hydrogen molecules into protons and electrons through electrolysis. The cathode introduces oxygen (usually from the air) to the fuel cell, causing oxygen molecules to react with the protons that have traveled through an electrolyte membrane from the anode. The electrolyte membrane allows protons to pass through, blocking electrons and forcing them to travel through an external circuit, creating an electric current that can be used to perform work. This electrical circuit generates an electric current, which can power various devices, such as electric motors in vehicles or electrical systems in buildings. Catalysts at the anode and cathode facilitate the chemical reactions in the fuel cell, making the process more efficient.

Figure A-11: Hydrogen Fuel Cell



Source: Airbus – Hydrogen Fuel Cells, Explained 2020.

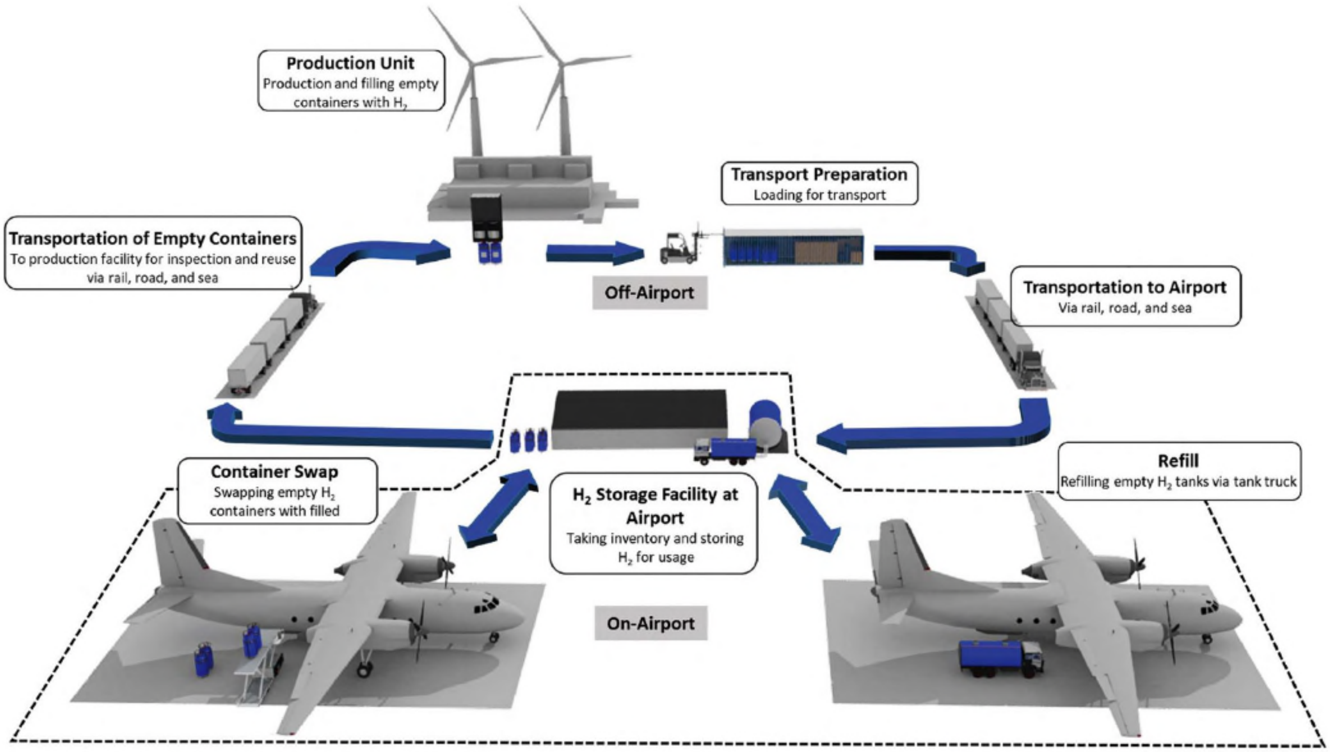
Hydrogen fuel cells have several advantages, including zero emissions since the only byproduct is water vapor. They can be highly efficient, especially when compared to internal combustion engines, which waste a significant portion of fuel energy as heat. Hydrogen's versatility in sourcing, including natural gas, renewable sources like wind and solar power, and even water through electrolysis, makes it potentially sustainable. Refueling a hydrogen fuel cell vehicle is comparable in speed to refueling a conventional gasoline vehicle, unlike battery electric vehicles which usually require longer charging times.

However, there are also challenges and limitations associated with hydrogen fuel cells. The most common method of hydrogen production, SMR, is still largely dependent on fossil fuels. The infrastructure for producing, transporting, and distributing hydrogen is underdeveloped compared to gasoline or electricity, limiting widespread adoption. The cost of hydrogen fuel cells and the associated infrastructure can be expensive. Additionally, hydrogen has a lower energy density by volume compared to gasoline or batteries, affecting the range and storage capacities of hydrogen-powered vehicles.

A.22. HYDROGEN AIRPORT INFRASTRUCTURE

There are many uncertainties associated with hydrogen-fueled aircraft such as the amount of hydrogen needed to fuel various-sized aircraft, fuel tank capacities, and methods of fueling. There are three ways hydrogen aircraft can be fueled: fueling trucks, hydrant systems, and container swapping. Currently, there is no infrastructure that delivers large quantities of hydrogen from production to the airport. However, fueling trucks could serve as a short-term solution. In the long-term horizon, hydrogen hydrant systems and pipelines could emerge at hub airports. The hydrogen container swap option faces a hurdle as it will require FAA approval as the swap might not be considered a minor alteration and would have to be performed by a licensed mechanic.

Figure A-12: Hydrogen Container Swap and Tank Refill Process



Source: ACRP Research Report 236 2022.

A.23. SUSTAINABLE AVIATION FUEL

SAF is a biofuel that is used to power aircraft. SAF has similar properties to conventional jet fuel but with a reduced carbon footprint. Biofuel is a biomass-based synthesized paraffinic kerosene (SPK) that is mixed with conventional jet fuel. While the effectiveness of biofuels varies based on the source of the fuel and the technology used, even a 50-50 blend of biofuel and jet fuel reduces emissions by as much as 50 to 70 percent. Industry experts identify aviation biofuels as one of the key elements in reducing carbon emissions. Recently, Boeing stated that sustainable aviation fuels are the only answer to reducing carbon emissions by 2050.

There are currently five types of SPK used for blending with conventional jet fuel. The hydro-processed esters and fatty acids (HEFA) pathway produces HEFA-SPK, an oil-to-jet platform. FT-SPK, a gas-to-jet platform, involves the gasification of biomass to produce synthetic gas. FT-SPK/A is another product of the gas-to-jet platform but with the addition of bio-based aromatics. The alcohol-to-jet (ATJ) platform, ATJ-SPK, involves the fermentation of sugars to produce alcohol which is then processed into jet fuel. Lastly, the sugar-to-jet platform directly processes sugar to produce SIP-SPK.

Table 3-2: Types of Aviation Biofuel

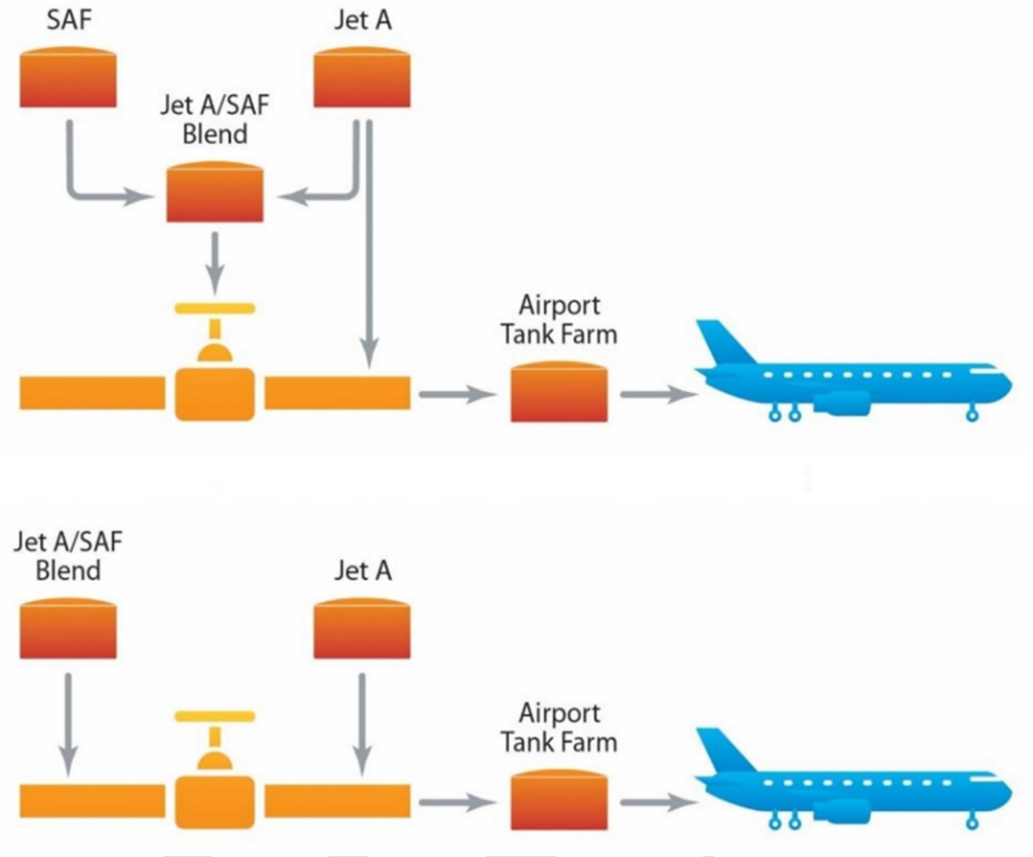
Biofuel	Production Platform
HEFA-SPK	Oil-to-Jet
FT-SPK	Gas-to-Jet
FT-SPK/A	Gas-to-Jet
ATJ-SPK	Alcohol-to-Jet
SIP-SPK	Sugar-to-Jet

Source: Frontiers in Energy Research 2020.

While all these production pathways are approved for developing biofuel and show promise, HEPA-SPK is the only one that is mature technologically and has begun to be commercialized. As such, HEPA-SPK is expected to be the primary aviation biofuel used in the industry for the foreseeable future. However, HEFA-SPK is currently more expensive than conventional jet fuel. Industry experts forecast that biofuels need to meet 2% of annual jet fuel demand to reduce costs enough for a self-sustaining biofuel market. Reaching that level of market share will require billions of dollars in investment for the development of new biofuel refineries. As biofuels gain feasibility, it is forecasted that biofuels will reach 20% of aviation fuel demand by 2040. In the interim, manufacturers are developing aircraft that are able to use biofuel blended with conventional fuel which will reduce greenhouse gas emissions while reducing the reliance on developing technology.

There are currently a few options being considered for SAF blending location options. If quality control is given priority, SAF from a stand-alone facility should be blended with Jet A at a terminal. Another option is to deliver SAF to a terminal that serves an airport. The airport then stores SAF and Jet A in separate tanks and then blends them into a third tank at the desired ratio. The last option is to offload SAF delivered by train or truck into a Jet A storage tank at an airport.

Figure A-13: SAF and Jet A Blending Options



Source: National Renewable Energy Laboratory 2018.

A.24. SUMMARY

Transitioning to alternative power sources, and away from fossil fuels as the primary energy source for aircraft propulsion, is an end goal to a long and scientific process. Climate change, and the impacts of it, have pushed the need for sustainable alternatives to the forefront and into the research and development stages. Ultimately, the shift to more sustainable and environmentally friendly forms of air transportation will be seen in the future, but preparation for that transition has already begun. Airports, specifically, can realize the greatest future benefits by beginning to consider how integration may occur at the airport level and begin gathering information related to the needs associated with future electrical/hydrogen/SAF demand, storage of the particular power source, and how it will be transferred to aircraft in the future at the airport.

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