



LUND
UNIVERSITY

LUSA

SCHOOL OF AVIATION

Innovation in Electric Aircraft and eVTOL - The Path Towards an Electrified Future Transport System

Elias Bitar

Bachelor Thesis 15 Credits
Bachelor Programme in Aviation, Later Part
FLYL01
Spring Term 2025

Supervisor: Elna Heimdal Nilsson

Innovation in Electric Aircraft and eVTOL - The Path Towards an Electrified Future Transport System

Elias Bitar

Lund 2025

Bachelor Thesis 15 Credits
Bachelor Programme in Aviation, Later Part
FLYL01
Spring Term 2025
Supervisor: Elna Heimdal Nilsson

Innovation in Electric Aircraft and eVTOL -
The Path Towards an Electrified Future Transport System

Elias Bitar

Number of pages: 24

Keywords:

Electric aircraft, eVTOL, electrified transport, charging infrastructure, future.

Abstract

This thesis examines how innovations in electric aircraft and eVTOL vehicles can contribute to sustainable air travel and transform future transport systems. The research focuses on identifying the most promising technologies and how they could be applied in practice. The study is based on a systematic review of academic literature, case studies and expert interviews from both academia and the aviation industry. Areas explored include battery development, propulsion systems, airframe design and charging infrastructure. The findings show that electric aviation is advancing quickly. eVTOLs have strong potential in urban areas by offering faster, quieter and more environmentally friendly transport. However, challenges such as limited battery capacity, infrastructure demands and safety considerations remain. The study concludes that electric flight can improve access to air travel and play an important role in stabilizing the national electricity grid, but successful implementation will require further development in technology and infrastructure. Future research should focus on battery performance in aviation specific conditions and how to plan smart, integrated charging systems in cities and airports.

© Copyright: Lund University School of Aviation, Faculty of Engineering

Lund University, Lund 2025

Lunds Universitet Trafikflyghögskolan, Lunds tekniska högskola, Lunds universitet, Lund 2025.

Lunds Universitet Trafikflyghögskolan
Lunds tekniska högskola
Lunds universitet
Box 118
221 00 Lund

<http://www.tfhs.lu.se>

Telefon: 0435 – 44 54 00

Lund University School of Aviation
Faculty of Engineering
Lund University
P.O. Box 118
SE-221 00 Lund
Sweden

<http://www.lusa.lu.se>

Telephone: +46 435 44 54 00

Table of content

INTRODUCTION	1
DELIMITATIONS	1
METHODOLOGY	2
PROCEDURE.....	2
PARTICIPANTS	4
INTERVIEWS	4
INSTRUMENTS	4
RESULT	5
ELECTRIC VERTICAL TAKE-OFF & LANDING (EVTOL).....	5
ELECTRIC AIRCRAFT.....	5
PAYLOAD & BATTERIES.....	6
PROPULSION SYSTEM.....	8
AIRFRAME DESIGN	9
INFRASTRUCTURE	11
CASE STUDIES.....	13
DISCUSSION	14
CHALLENGES	14
BATTERIES	15
MISCONCEPTIONS.....	16
INFRASTRUCTURE	17
CASE STUDIES.....	18
FUTURE VISION	19
LIMITATIONS	20
CONCLUSION.....	21
REFERENCES	22
APPENDIX 1	1

Appendix

APPENDIX 1, Interview questions

Introduction

What if your next flight did not need a drop of fuel? As the world deals with climate change, growing cities and the need for cleaner transport, electric aircraft and eVTOLs (Electric Vertical Take-Off and Landing vehicles) have become a possible answer. These new flying technologies could change the way we travel, both in the air and on the ground. Shorter travel times, less noise and emissions are some of the benefits often mentioned. But how close are we really to seeing these changes in everyday life?

Over the last few years, research has focused more and more on electric aviation. Many studies show that electric aircraft, especially smaller ones, can be used for short flights, where battery range is not so much of a problem. For example, Schwab et al. (2020) and Gnadl et al. (2019) explain how small electric aircraft could be used for short trips of up to 450 km. Other researchers, like Cano et al. (2019), talk about the challenges with batteries. Even though battery technology is improving, current batteries still have much less energy density per kilogram than conventional jet fuel. This makes it harder for electric aircraft to fly longer distances and carry more passengers.

In the area of eVTOLs, which are small aircraft that can take off and land vertically, the research shows great potential for use in cities. Kiesewetter et al. (2023) suggest that eVTOLs could help reduce traffic in large cities and be used for many applications like transporting people, emergency services or even package delivery. Other studies look at the best aircraft shapes and designs. Bacchini and Cestino (2019), show how different designs use different amounts of energy, depending on the type of mission.

Even though there is plenty of information available, most earlier studies focus on only one specific part of electric aviation, like batteries or aircraft design. There are not many studies that bring multiple important parts together. Also, many studies include hybrid aircraft or Sustainable Aviation Fuel (SAF), which are not fully electric. This study chooses to look only at fully electric solutions. Another piece missing in earlier research is the use of real world examples and expert opinions. This study includes both, to get a better understanding of the practical challenges and opportunities.

The purpose of this study is to understand how the potential of electric aircraft and eVTOLs could be used to help to improve the transport systems of the future. The research is based on a review of scientific papers, interviews with experts and case studies. The goal is to find out what the most promising technologies are, how they could be used in cities and regional areas and what kind of infrastructure is needed to support them. The study aims to discuss questions like; what are the most important new technologies in electric aviation today? How could electric aircraft and eVTOLs be used to improve other industries, for instance the current electric grid infrastructure? What are the technical-, practical- and planning challenges that still needs to be solved?

This study hopes to add useful knowledge to the field of electric aviation. By focusing on only battery powered solutions and including real life examples, the study gives a clearer picture of where we are today and what is still needed to make electric flight a normal part of everyday life.

Delimitations

There are many different hybrid-electric propulsion systems that also have promising potential. These will however not be discussed in this thesis as the aim of the research concentrates on fully electric options. It is however worth mentioning that research seems to point towards hybrid solutions being implemented as a steppingstone towards an all electric solution.

Control systems and autonomy are other critical components for safe and efficient operation of electric aircraft and eVTOLs. This thesis will intentionally not cover these areas as it would span outside of the research question. Despite this, it is important to highlight the importance of these components as it might have a secondary effect on how urban mobility might look like in the future.

Although there are many different types of eVTOLs and electric aircraft technologies, both of these systems have been regarded as a common subject in the analysis of understanding and envisioning how future transport systems might look like. Separating the systems as individual transport systems might show nuances of how future infrastructure might develop but would also span outside of the scope of this research.

The thesis does intentionally not touch on Air Traffic Control- and Cyber Security areas. Thru out the research it did however become evident that systems today lack a robust and reliable strategy for detecting and mitigating cyberattacks. This leaves a void of vulnerability that would need to be addressed in the future.

Lastly, emissions and the consequences of such are not part of the study.

Methodology

The study has been conducted through a combination of literature reviews, case studies and expert interviews. The literature reviews include scientific articles and reports from the aviation- and engineering industry. Case studies of ongoing projects in electric flight and eVTOL has been analyzed to identify the most promising technological innovations. Interviews with experts from academia and the aviation industry provided further insights into practical challenges and opportunities.

Procedure

The initial work was carried out as a systematic literature review where materials were gathered from LUBsearch. One of the reasons to exclusively use LUBsearch for gathering papers was that the material found was more than sufficient in terms of the number of academic, peer-reviewed articles within the 10-year timeframe chosen. The search was conducted on February 11, 2025. The search terms used (among others) were "electric aircraft", "eVTOL", "Future", "electrified transport" etc. and they were grouped into search blocks according to Table 1. The terms were chosen to reflect the research question to the furthest possible extent. The inclusion criteria chosen was that the sources had to be available in library collection, peer-reviewed and published within the last 10 years. The reason a 10-year timeframe was chosen was that the aviation industry, including technological advancements in battery- and charging technology, has changed significantly over time, therefor a concern that older research might not accurately reflect today's reality was raised.

For the search and screening process, the PRISMA model was used according to Moher et al. (2009). The search yielded 80 results. All titles were read, and several were excluded, including those with a very narrow focus on a specific area of aviation or sustainable energy transportation, as well as articles related to Sustainable Aviation Fuel (SAF) and Hybrid-electric technology. This paper primarily focus on all-electric aircraft and eVTOLs, therefor, including SAF and Hybrid-electric solutions would be outside of the scope of this paper.

45 abstracts were read and 20 articles were selected as the most suitable for the study's purpose. Upon reading the selected articles, it was found that some built on previous research,

therefor some of these earlier studies were also included in the research according to the snowball effect. Several of these articles were older studies, but they were deemed relevant as they often address fundamental technical knowledge that remain constant over time.

In addition to the articles gathered from Lubsearch an additional 5 articles were recommended by the Supervisor of this paper. All of these were partly read and 1 was chosen to be included in the Results.

The 20 selected articles were coded in an attempt to answer the research question. After coding the articles into main topics like Technology and Limitations, as well as sub-topics like Batteries, Aircraft Design and Charging Infrastructure, the work proceeded with summarizing the results that would be relevant to be further analyzed.

The general aim thru out the process was to identify and define certain key areas that would be both measurable and quantifiable. Some examples being if the technology has been tested in actual systems, are they in commercial production or at least planned to be and what the cost-benefit would be with this new and emerging technology.

Table 1. Systematic literature search in accordance with the PRISMA-model.

Lubsearch 20250211	Search Words	Hits	Read Titles	Read Abstracts	Read Articles	Chooses Articles
Search 1	"electric aircraft"	6 486				
Search 2	"eVTOL"	1 998				
Search 3	S1 OR S2	8 347				
Search 4	"future"	8 549 273				
Search 5	"electrified transport"	180				
Search 6	S4 OR S5	8 549 411				
Search 7	"charging infrastructure"	10 395				
Search 8	"sustainable"	2 507 259				
Search 9	"air travel"	62 707				
Search 10	S7 OR S8 or S9	2 578 058				
Search 11	S3 AND S6 AND S10	175				
Inclusion Criterium:	Peer reviewed, Available in Library Collection, Articles published 2010-2015, Exact duplicates removed from the results.	80	80	45	32	20

Participants

Besides the academic journals provided by Lubsearch, initial discussions were made with the Supervisor of thesis in order to define the framework of the study. As part of this work, an interview was conducted with a postdoctoral researcher (Respondent 1) whose expertise includes transnational legislation and civil aviation regulation within the EU, safety standards and risk management. The researcher is currently engaged in a project focusing, among others, on the electrification in aviation and charging infrastructure in airports. The insight and research provided by the academic scholar contributed to the study from an academic point of view.

It was also deemed interesting to have a discussion directly with a manufacturer of electric aircraft in order to understand both the aspects of development as well as the vision for the future from a manufacturing point of view. A Swedish electric aircraft manufacturer was chosen as they have progressed well with their commercial electric aircraft concept.

Interviews

Two expert-interviews were conducted at the finishing stage. The purpose of this was to initially gather specific areas of interest in the field from an academic point of view in order to later confirm or rectify the data gathered at the finishing stage. The participants were selected based on their relevance, experience and availability. The aircraft manufacturer chosen was specifically selected as they have progressed well with their electric aircraft model which spans well beyond the design- and concept phase. The manufacturer is in scale production, expecting to deliver its first aircraft in 2028.

The responses were obtained through scheduled video- or phone conversations in accordance with the participants preference. The interviews lasted approximately 30 minutes each and the questions asked were in accordance with Appendix 1. The audio was recorded with the consent of both participants and relevant parts of the interviews were transcribed into text afterwards.

Relevant parts of the interview used from Respondent 1 was later sent to the respondent for review, prior to being published.

Instruments

To collect data for this study, two primary instruments were utilized; (1) a document analysis of academic journals obtained through Lubsearch and (2) structured interviews conducted via phone and email with an expert and a manufacturer in the field of electric aviation. The academic sources were gathered using specific keyword searches related to electric aircraft technology, development trends and industry adoption.

The structured interview (Appendix 1) was developed by the author of the thesis and included open-ended questions designed to highlight expert opinions on current advancements, technological limitations, regulatory issues and future projections of electric aircraft. The interviews contributed to either verify or dismiss the thoughts and ideas that were intended to be used in the discussion.

In order to measure and quantify the data gathered, it was of importance to gather data both from an academic- as well as a manufacturer point of view. Although the thesis primarily did not aim to make a comparison study this led to a broadening of the data sources.

Result

Electric Vertical Take-off & Landing (eVTOL)

With over half of the world's population living in urban areas, cities are becoming more and more congested. An estimation done by Kiesewetter et. al (2023) suggest that these cities alone produce over 80% of the world GDP. As the cities grow bigger they will face challenges related to congestion and pollution which ultimately might have a negative impact on life quality and the economy. It is therefore imperative that society explores alternative means of transportation besides traditional ground transport in order to mitigate some of negative consequences. One such solution could be the concept Urban Air Mobility (UAM). Some use cases proposed by Kiesewetter et. al (2023) are transport of goods and people in cities, search- and rescue operations, emergency supply deliveries and air ambulance services. UAM could potentially have a transformative effect on the transport system as we know it by reducing travel time thru more direct routes and thereby also reducing congestion and road accidents. This is especially important in areas where current air transport is limited or non-existing (Kiesewetter et. al 2023).

Electric Aircraft

An electric aircraft is an aircraft that uses electric power as its primary source of propulsion, with some- or all of its power coming from electrical energy. Electric aircraft are often classified based on the amount of propulsive energy coming from electricity. There are three commonly used classification; all-electric, hybrid-electric and turboelectric aircraft. Traditional aircraft with internal combustions engines (ICE) use conventional fossil fuels as their only source of energy to propel the aircraft forward. Electric aircraft on the other hand use electricity as the primary source of energy for propulsion. In order to do this they need energy storage systems, like batteries, to power the motors.

According to a study by Schwab et. al, (2020), electric aircraft are undergoing development in various types and applications. The programs are classified into three categories, small, regional, and large aircraft. These are then further split into different types based on the use case with some examples of models currently under development (Schwab et. al, 2020), (Table 1).

Table 1.
Examples of electric aircraft classifications and types (Kiesewetter et al..

Timing	Use case	Description	Model
2020-2025 Near-term	Pilot training	- 1 pilot and 1 passenger	- Pipistrel Velis Electro - Bye Aerospace eFlyer 2 - Rolls Royce Spirit of Innovation
	General aviation: personal or business	- 1-6 passengers - Average flight time: <1 h	- Pipistrel Taurus Electro - Rhyxcon General Aircraft RX4E
	Regional commuter (eVTOL)	- Up to 1 pilot and 4 passengers - Range typically up to 200 miles	- Lilium Jet - Archer Maker - Archer Midnight - Hyundai S-A1 - Joby S4 - Beta ALIA-250 - Airbus CityAirbus
2025-2040 Mid-term	Regional aircraft	- Typical up to 19 passengers - Range typically around 250 miles	- Eviation Alice - Tecnam P-Volt - Aura Aero ERA - Heart Aerospace ES30 - Ampaire Electric EEL ^a - Maeve 01
	Light air cargo	- Maximum payload: 7500 pounds - Custom cargo delivery	- Eviation Alice - Beta ALIA-250c - Aura Aero ERA - Ampaire Electric EEL ^a
2040-2050 Long-term	Large commercial aircraft	- Narrow-body: typically 100-200 passengers, range more than 500 miles - Wide-body: typically 200-400 passengers, range more than 2000 miles	- Wright Spirit - Wright 1 - Boeing Sugar Volt ^a - NASA N3-X ^b - Airbus/Siemens/Rolls-Royce/E-Fan X ^a

Research conducted by Gnadt et. al (2019) indicate that switching from ICE engines to electric propulsion in small aircraft could result in more benefits than switching from turbofans in larger aircraft because of the difference in thermal efficiency. The efficiency offered by electric motors can be as high as 95% with a total system efficiency of 73% (Hepperle et. al, 2012).

According to Liang (2024) it is expected that in the near term future (2025-2040) regional short-haul electric aircraft as well as electric light air cargo vehicles will enter service. Most research seems to point towards regional commuter aircraft being the primary option with scheduled air transport for up to 19 passengers and with a range of around 450 km.

Two commonly used categories related to commercial aircraft are narrow- and wide body aircraft. Narrow body aircraft are primarily used in short- to medium haul operations with around 100-200 passengers and a range of around 900 km. According to the Canadian International Air Transport Association (2019) it is believed that such aircraft partially powered by electricity will be available before 2050. Considering that about 45% of all global flights are under 900 km, this could potentially mean that approximately half of all global flights today are within the range prediction (Schwab et. al, 2021). As wide body aircraft carry 200-400 passengers with a range exceeding 3600 km chances are higher that they will initially be powered by other technologies like turboelectric or Sustainable Aviation Fuel (SAF).

Payload & Batteries

Payload

The payload required for both electric aircraft and eVTOLs will be dependent on the mission they indent to fulfill, both range and payload requirements might differ quite substantially. Asmer et al. (2021) divided the different mission types into five main categories; airport shuttle, intra-city, suburban, mega-city and inter-city.

Airport Shuttle. Short mission range mission, up to 25 km with capacity for payload in order to facilitate up to 4 passengers and extra luggage.

Intra-city. On-demand air-taxi services within urban areas with a range of up to 50 km and 2-4 passengers.

Suburban & Mega-city. Both are quite similar with the exemption of the seat availability. Mega-city mission might require more seats requiring 4-6 passengers. The range is typically 70–100 km.

Inter-city. Any mission greater than 100 km and would likely require a higher passenger number.

Due to the current state in battery density being relatively low, batteries still take up almost half of the total vehicle empty weight in eVTOLs (Smart & Alonso, 2019). The remaining empty weight will be taken up by primarily landing gear, wings, fuselage, hubs and motors. Other systems that did not contribute as much but were still included in the empty weight was recovery systems, seats, air conditioning systems, wiring, and avionics. It was therefor understood that increasing battery energy density from 225 Wh/kg to 400 Wh/kg could significantly reduce gross vehicle weight and thereby increase passenger- and payload capacity.

When comparing total propulsion system weights it was discussed by Chakraborty and Mishra (2023) that an all electric design has the lowest propulsion system weight without any major airframe structure differences when compared to turboelectric and hybrid-electric systems. This in turn results in a lower empty weight and thereby higher payload capacity. The same is noted when considering onboard charging equipment in electric aircraft and eVTOLs. Cox et al., 2023 mentioned that minimal onboard charging equipment was essential to reduce overall weight, enhance system efficiency and performance and increase payload capacity. Stationary off-board charging systems was therefor noted as a more relevant solution in electric aviation.

Batteries

The two segments that require high output power from the battery are takeoff (both electric aircraft and eVTOLs) and landing (eVTOLs). As the battery is discharged the output voltage drops, this results in a higher output current required, especially during landing (Fredericks et. al, 2018). Batteries therefor need to have a higher power density in order to ensure adequate power supply thru out all segments of flight. In order to maximize utilization rates and increase revenue, fast charging or battery swapping are areas that need to be addressed. Advanced battery technology development is therefor of outmost importance for electric aviation.

Lithium Ion Batteries (LIB) were first commercialized in 1991 and contributed to the acceleration of battery density development. According to a study by Wang et. al., (2022), the highest energy density has reached 265 Wh/kg at the cell level, compared to combustible fuel like kerosene which holds an energy density of about 12 000 Wh/kg (Hemighaus et al., 2007). It is however important to emphasize that due to thermal- and battery management systems, as well as packaging at pack level, there is a 30%-40% reduction in energy density from cell to pack (Misra, 2018).

For the coming years NASA has stated a minimum energy density threshold of 750 Wh/kg for electric regional aircraft to be fully implemented (Lvovich & J. Lawson, 2018). This is however beyond the theoretical limitation of Lithium Ion Battery technology according to Cano et Al., (2019). In comparison, an Airbus 320 all-electric aircraft would require an energy density of 800 Wh/kg at pack level (Gnadt et al., 2019). Taking into account Misra's conclusion of energy density loss as batteries get packed, it would require up to 1100 Wh/kg at cell level. In order power the Airbus 320 using technology available today would result in the maximum take-off weight being exceeded by a factor of 38 (Caset et al., 2018). Further studies indicate that commercial narrow body aircraft would require energy densities of 820 Wh/kg and 1280 Wh/kg respective for wide body aircraft (Bills et al., 2020). However, in a study conducted by the National Academy of Science (2016), it was argued that battery technology development would only achieve 400-600 Wh/kg in the next 20 years. These numbers differ significantly from the consensus, which seems to be around 750 Wh/kg.

When comparing battery technologies it is also important to consider battery degradation rates and overall battery life. A battery cycle is the process of charging a rechargeable battery and discharging it as required into a load. A regular cycle life of a commercial Lithium Ion Battery is approximately 2000–3000 cycles. There are other types of batteries that might offer higher cycle life, but might for other reasons not be applicable in electric aviation. Factors such as operating conditions, cell- and pack design, electrolyte and electrodes all contribute to the battery degradation rate.

Solid-state batteries (SSBs), Lithium-Sulfur batteries (LSBs) and Lithium-Air batteries are other types of batteries that show promising development. Combining solid-state electrolyte with lithium metal anode seems to provide energy densities as much as 450 Wh/kg with wider range of temperature allowance and an improved safety performance according to a study (Manthiram & Wang, 2017). It also showed that a theoretical potential of 2600 Wh/kg could be achieved, however with a shorter cycle life than Lithium Ion Batteries. The preliminary results from research done by NASA in 2020 as part of the Solid-state Architecture Batteries for Enhanced Rechargeability and Safety for Electric Aircraft (SABERS) project, indicated a Solid-state battery capable of achieving 1100 Wh/kg at a slightly slower discharge rate (0,4C) and 804 Wh/kg at regular discharge rate (1C) (Viggiano, et al., 2020).

An ultracapacitor, also called a supercapacitor, is another energy storage technology with potential in electric aviation. An ultracapacitor, can store energy between two conducting electrodes without a chemical reaction. It also has a high charging- and discharging rate as well as a power

density of 10 000 Wh/kg with a relatively high cycle life (Misra, 2018). The ultracapacitor has on the other hand limited energy density which does not make it suitable as a primary energy storage system in electric aviation. However, due to its characteristics of high power density it could be used in applications like auxiliary energy storage systems supporting the power required during takeoff and landing with eVTOLs.

In a study comparing electric cars with eVTOL battery systems (Figure. 1), it was noted that eVTOLs will have higher utilization rates, use fast charging to a higher extent, have longer-peak power usage and operate at higher discharge rates than electric cars (Yang et al., 2021).

The study showed that applying electric vehicle battery assessments straight to applications for electric aviation was not suitable. The differences highlighted the need to develop aviation specific batteries in order to meet battery safety- and performance requirements needed for electric aviation. An alternative proposed in the study was battery-swap systems, but this would have to involve close cooperation between battery- and aircraft manufacturers in order to agree on a common standardization. Furthermore, the research also found that due to the much higher utilization- and charging rates with batteries in electric aviation, the batteries would have to be replaced every 3-5 months to ensure safe operation (Yang et al., 2021). Therefore, converting the electric vehicle capacity retention rate, and thereby warranties, were not directly transferable to electric aviation. Similarly, Courtin and Hansman (2018) came to a similar conclusion when noting that there is an uncertainty when it comes to judging how much *useful* energy is contained in a battery at a given state of charge, this would untimely make it difficult to assess the energy reserve required for flight.

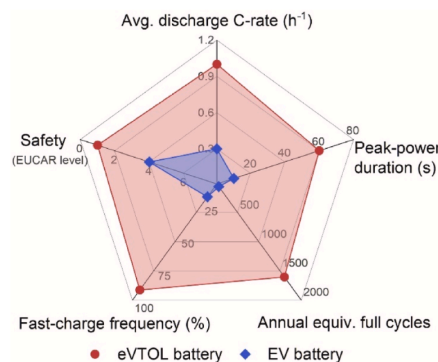


Figure 1. Utilization of eVTOL batteries compared to electric cars (Kiesewetter et al., 2023)

Propulsion system

There are many different and futuristic design-concepts for primarily eVTOLs. Electric aircraft on the other hand seem to follow a more traditional approach with regards to propulsion system design. NASA (2023) and the Vertical Flight Society (2023) has produced a list of reference vehicles and classified them into 2 main categories, namely rotary-wing and fixed-wing. The rotary-wing is then further classified as multi-rotor and rotorcraft designs. Multi-rotor designs (Figure 2a) generate their lift thru multiple propeller units, where as rotorcraft designs (Figure 2b) has a single rotor from primary lift generation. Fixed-wing designs are further classified as lift+cruise, tilt-wing and tilt-rotor. Lift+cruise (Figure 2c) features two individual propulsion systems, one is for lift and the other for forward thrust. Both tilt-rotor (Figure 2d) and tilt-wing (Figure 2e) designs use vectored thrust, this allows the thrust to be directed in different directions which results in a single

propulsion system able to provide thrust for vertical takeoff and landings as well as forward thrust in cruise.

Vehicle performance is greatly affected by the choice of rotor configuration. Research modeling vertical takeoff, transition to cruise and the cruise phase, has indicated that a rotary wing design consumes 40% of the total mission energy for VTOL, 29% in the transition and 31% in cruise. The fixed wing approach on the other hand used 23% for VTOL, 73% in the transition and only 4% in cruise (Senkans et al., 2021). Similar conclusions were drawn earlier by Bacchini and Cestino (2019) where the results showed that multi-rotor designs would require the least energy for short trips (7km) and tilt-rotor designs would require the least energy for longer trips (30-100 km).

Another consideration that was discovered was the importance of lift-to-drag ratio and disc-loading. A high lift-to-drag ratio on the fixed wing design resulted in higher cruise efficiency as less energy from the batteries could be used to generate the same amount of lift. Having better hover efficiency thru lower disc-loading meant that rotary-wing designs could spend less energy on VTOL and transitions phases. The conclusion was therefor that lift-to-drag ratio is more important to fixed-wing aircraft and disk-loading is more important to rotary-wing designs. The design concept will therefor be dependent on the mission profile. Fixed-wing design could potentially be favorable for intra-city and airport shuttle services, where as rotary-wing designs could be used for inter-city applications.

With regards to safety, the literature does not seem to differentiate between the different propulsion designs and there is no clear distinction. Research comparing the overall safety of conceptual propulsion design concepts and conventional commercial aircraft, found that quad-rotor, side-by-side with tilt-wing and lift+cruise designs, all were several orders of magnitude less reliable than commercial aircraft (Darmstadt, 2019). Other safety aspects as autonomy, birdstrikes, thermal runaway and power failure were discussed by Courtin and Hansman (2018). The study showed that there was no significant differences between the different rotor configurations in the most cases, except for fly-by-wire systems which yielded higher safety risk and birdstrikes which were difficult to predict.

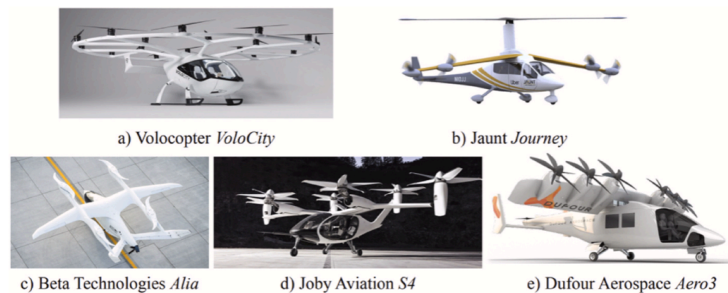


Figure 2a-e. Examples of different propulsion design concepts (Kiesewetter et al., 2023)

Airframe design

Designing the airframe has a significant effect on the overall performance in electric aviation. There are currently many different conceptual designs from both private- and industry leading manufacturers like NASA and Airbus. The industry seem however to agree on two airframe design concepts; Distributed Propulsion (DP) and Boundary Layer Ingestion (BLI).

Distributed propulsion system (DPS)

This design concept uses multiple small electric motors to accelerate airflow over the wing. This is a significant design difference from conventional design approaches where 1-4 larger engines produce the entire thrust vector required for flight. NASA has developed a program named SCEPTOR where they utilize the most common DPS technique; Leading-Edge Asynchronous Propellers Technology (LEAPTech). One example is the NASA X-57 DPS aircraft (Figure 3). This concept uses 14 smaller propellers which are placed evenly along the leading edge of the wing (Wang, 2022). The airflow generated over the wing by the smaller propellers significantly increases the dynamic pressure and thereby increases the lift generated by the wing. This is especially true at low airspeeds where the airflow over the wing otherwise gets disturbed by a high angle of attack.

Boundary layer ingestion (BLI)

The boundary layer on an aircraft is the slow moving air along the body of the aircraft. The boundary layer causes airframe induced drag and thereby reduces momentum and airspeed (Martínez Fernández & Smith, 2020). On conventional commercial aircraft, the engines are normally placed under the wings, away from the body in order to avoid slow- and disturbed moving air to ingest into the engines as this could have a negative effect on propulsion and the overall system performance. By embedding the engine inlet into the aircraft body, the slower moving air can then pass thru fans and eventually generate the required thrust. Higher propulsive force can then be generated using less power as the velocity of the the air coming from the boundary layer is slower. Thru BLI the parasite drag is then reduced as the need for big engines under the wings is no longer required and the overall aircraft efficiency is increased.

One example of an aircraft that combines DPS and BLI is the Airbus E-thrust concept (Figure 4) that has been developed together with Rolls Royce and Cranfield University (Green Car Congress, 2021).

Configuration

As mentioned earlier, the propulsion configuration - fixed or rotor - will have an effect not only on the propulsion itself but also on the overall airframe design. Fixed-wing designs will allow for longer range and higher speeds due to their inherent nature of naturally generating dynamic lift over the wing. Rotor-wing designs on the other hand have better VTOL capabilities as well as better maneuverability. On the other hand, the lift that is generated by the rotors require more energy and produce more drag which results in less range and payload capabilities.

When comparing the mass required for each configuration, Ugwueze et al. (2022) found that at a set range of 100 km, rotary-wing designs are 33% heavier due to increased battery mass, while fixed-wing designs have a 35% greater structural mass. They therefor came to the same conclusion as Bacchini and Cestino (2019), that rotary-wing designs were better suited for intra-city travel while the fixed- wing approach was better suited for inter-city and regional applications. Figure 5 shows how range is affected as a factor of payload and how a wing design as compared to a rotor-design in most cases equals higher range.



Figure 3. NASA X-57 DPS aircraft (Apostolidis, 2024)



Figure 4. Airbus E-thrust concept (Apostolidis, 2024)

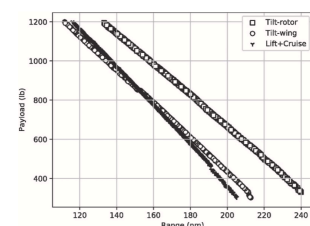


Figure 5. Range as a factor of payload between different configurations (Kiesewetter et al., 2023)

Infrastructure

When it comes to infrastructure related to primarily Urban Air Mobility (UAM), these can be categorized into the main categories; vertihub, vertiport and vertistop (Figure 6). Vertihub is an infrastructure for aircraft maintenance and repair. It is mostly located in the outskirts of cities in suburban areas. Vertiport is a location that serves passengers and cargo to board and disembark. A vertiport is typically placed inside the cities to facilitate easy access for passengers. They can be placed on top of building that have the necessary infrastructure for recharging. Vertistop is a location in-between two vertiports that provides access to other already established ground transports. These could have a few charging pads and would ideally be located between cities.

Research in UAM infrastructure has shown that established urban areas like cities may not have enough space to accommodate large building like vertiports. Instead smaller recharging points could support longer trips in larger areas (Rimjha et al., 2021). Studies also show that choosing the best location for these types of infrastructure depends on multiple factors such as noise pollution, land use patterns (geographical and topological), traffic demand, aircraft design and configuration, charging options and weather patterns (Mendonca et al., 2022). As mentioned previously, the propulsion- and airframe configuration, payload and range capabilities also determine possible infrastructure locations.



Figure 6. UAM infrastructure categories (Kiesewetter et al., 2023)

Researchers have made attempts to determine the optimal location of UAM infrastructure using various different methods. What stands as a common theme seems to be that there are many different variables that have to be taken into account in order to come to a conclusion, some of which might be unpredictable or otherwise variable to an extent where they can not necessarily be modeled, for example weather and the risk of birdstrikes.

Two studies that have made an attempt is Bulusu et al., (2021) and Jeong et al., (2021). The former approached the question by a method to minimizing trip time and maximizing traffic demand. They measured distance as a cost function on a trip from origin to destination thru an algorithm named facility location problems (FLP). They then used machine learning to cluster the vertiport locations by choosing a trip length of 30 min, 4 passengers and assuming the flight paths are straight. They did however not take noise requirements, weather conditions and propulsion configuration into consideration. The later study approached the dilemma from a different view. They produced a way to select a route between vertiports which used noise pollution as a priority. They clustered high demand data using systems like Aviation Environmental Design tools (AEDT) and selected the locations if it included noise priority areas. A third study also focusing on fleet noise during VTOL with fixed-wing designs looked at two scenarios where one was using current helipads located inside the city and the other scenario where hubs were located outside of the city. It revealed that using current helipads inside the city would exceed the noise limit set by the FAA (50 dB) while using the hubs outside of the city would keep the noise level below the same threshold. The conclusion was that route planning is of high importance when it comes to noise pollution in

order to make air-taxi service a viable solution (Glaab et al., 2019). Noise pollution, although important, is however only one of many factors needed to be taken into account when selecting an optimum infrastructure location for UAM applications.

Electric Chargers

The range and size of electric aircraft as well as turnaround time and battery technology will all be deciding factors when it comes to the charging requirements for electric aircraft. As previously mentioned, electric vehicle battery charging is not directly transferable to electric aircraft battery charging, however it is estimated that in the near-term, small electric aircraft (1-4 passengers) will have a similar power level required as electric vehicles, a few hundred kilowatts. The fast charging technology used today could therefore be used as an initial solution for small aircraft, according to Schwab et al., (2021).

As the demand for air travel increases so does the need for range- and passenger capacity, megawatt power levels will therefore eventually become necessary. It is estimated that the peak charging demand for an all-electric regional aircraft with a battery capacity of 800 kWh, would require a 2 MW charging station in order to meet the turnaround time required (Schefer et al., 2020). This by far exceeds the capabilities of today's electric vehicle charging station standards.

In a study made by Schwab et al., (2021) they wanted to assess the total electrical demand for an airport to charge five electric aircraft with the following preconditions: constant power of 3 MW over the entire flight profile (excluding takeoff and landing) and 1,5h travel time (requiring 4,5 MWh). In order to have the aircraft recharged up to the required State of Charge (SOC) within a 30 minute turnaround time, it would require a capacity of 9 MW. Having five aircraft charging at the same time would therefore require an electrical connection of the airport of 45 MW which is an enormous amount of power required for today's European airports, especially for the smaller regions.

Avinor, which is responsible for 43 airports and the joint air navigation service for the Norwegian civilian and military aviation sector, has together with Luftfartstilsynet published a proposal to the introduction of electric aircraft in aviation. In this, it is estimated that the total charging demand when implementing fast charging at small airports will be 1-10 MW (Avinor & Luftfartstilsynet, 2020). The solution to the power distribution issue does not seem to just lie with the amount of power required. Multi-megawatt fast charging options for heavy-duty vehicles were investigated by the Austrian Institute of Technology (2022). The results showed that connecting multi-megawatt charging equipment (< 1 MW) to the current power grid will have a negative impact on low voltage grids. The risk discussed were the chances of causing high currents and thereby creating power grid instability. A proposed solution was to connect the chargers to at least 1 kilo volt (kV) distribution grid (Makoschitz, 2022).

The Nordic Energy Research has proposed three different options in order to avoid causing disturbances on the local and national power grid; direct charging from the power grid, swappable batteries or batteries and the local power grid (Skytte et al., 2023). They argue that airports have, through the investment in stationary or swappable batteries, the possibility to direct the energy consumption to periods with either high renewable electricity production or low electricity prices. By doing so, airports could both increase security of supply and support the sustainable transition of energy systems. The current state of the national electricity grid would not be able to handle a rapid deployment of electric aircraft chargers supporting regional aviation. The study therefore also mentions that battery storage can provide the flexibility required, through strategic charging, to decrease the need to import the national grid capacity. The concept is described as "smart charging" and is already being used on electric vehicles by both private individuals and electricity providers. One of the limiting factors mentioned is the need for logistic planning in order to assure enough power in

line with the scheduled departure times. The conclusion was that the increase in power production and consumption will require that the current power grid is improved in order to meet future demands. Furthermore, consumers will need to implement smart consumption patterns in order to stabilize the national power grid.

Case Studies

Case Study 1

This study was made by Apostolidis et al., (2024) and looks at how inter-island flight operations are currently performed between the ABC Islands (Aruba, Bonaire and Curaçao) and how electric flight operations compare to conventional operations. Prior to this there was a second study made that outlined a timeline for the introduction of electric inter-island flying in the Dutch Caribbean where the last of the three scenarios was used in the research. Phase one (2026) include three electric aircraft with nine seats, phase two (2030) three 19-seat aircraft will be added with 50% of the flights being electric compared to 2019 levels. Lastly, phase 3 (2035) three 9-seat aircraft and three 19-seat aircraft will be added to fully replace the fleet that is currently flying between the ABC Islands (Driessen et al., 2021).

The hub for all inter-island traffic is Curaçao and flights between Aruba and Bonaire are operated thru this hub. There are no seasonality effects as the schedule is fixed thru out the year. The fleet consists of 3 DHC-6 Twin Otters (19 passengers), 2 BN-2 Islanders (8 passengers) and 3 Saab 340B aircraft (34 passengers).

The study is focused on the Eviation Alice and the Heart Aerospace aircraft (9-19 passengers). As both aircraft were still under production during the study only the announced specifications and performance characteristics of the two aircraft could be used and other unknown values were either calculated or assumed.

According to the authors, one of the main research objectives was to identify the amount of energy needed to fly the inter-island routes as well as assessing if the charging is possible in the desired turnaround time. In order to calculate some of the data required, they set up a model that took flight distance, climb- and approach angles and the expected flight level into consideration. The local climate was also taken into account when calculating a realistic energy consumption in the cruise segment. A capacity of 820 kWh for the Alice and 900 kWh for the ES-19 was assumed. In order to assess the capacity at the battery-end-life, 80% State of Health (SOH) was used, therefor the actual capacity was 656 kWh and 720 kWh respectively. Using 30% of the value as energy reserve yielded even less capacity left for flight.

Charging the electric batteries would take place at the islands between the flights. According to EASA, charging with passengers onboard will depend on proof from the manufacturers that safety will not be compromised. It is therefor currently unknown if it will be allowed and to which extent it might affect the case study. The energy that was needed for flight between the islands was calculated and stipulated in Table 2.

Table 2.

Energy required to fly between the ABC islands using Alice and ES-19 (Apostolidis, 2024)

Mission Route	Aircraft	Energy Required for Mission [kWh]	Total Energy Required [kWh]	Power Required (25 Min Charging) [kW]
CUR-AUA	Alice	256	267	640
	ES-19	295	307	738
AUA-CUR	Alice	321	325	780
	ES-19	368	383	920
CUR-BON	Alice	199	207	498
	ES-19	235	245	588
BON-CUR	Alice	184	192	460
	ES-19	212	221	530

The research conclusion drawn was that "electric concepts have the range, payload capacity, and operational characteristics to complement and eventually replace conventional aircraft when they enter service in the next decade" (Apostolidis et al., 2024). The case study did however also find that electric aviation will require expensive infrastructure investments as well as regulatory approvals that are yet to be trialed.

Case Study 2

The study was performed by the Research Institutes of Sweden (Alfredsson et al., 2022) in order to exemplify how infrastructure models can be applicable in specific use cases and what the result of this would be. The intention is to show if the current air traffic can be electrified (based on historic data), adjust towards a more electrified air traffic and develop new routes using electric aviation. The aircraft modeled is a 19-seat aircraft having a capacity of 800 kWh. This was based on information provided by Heart Aerospace for their ES-19 aircraft as well as modeling of the excited energy consumption used on the route Göteborg Landvetter - Bromma Airport (409 km). With this data the simulation consumed 630 kWh in calm winds using ecoCruise. Adding margin for not having to charge beyond 90% SOC and not discharging below 10% yielded 630 kWh. Worth noting was also that all estimates were based on the knowledge known to date of the study. The intended routes to compare against was flights departing- and arriving to Visby airport during a specific date and a total of 25 flights were simulated.

The conclusion made was that all of the 25 flights were feasible from a range perspective (battery capacity exceeds required energy consumption). Furthermore, in 76% of the cases the turnaround time exceeded the minimum time required to charge to fulfill the energy capacity requirement needed. The flight time on the other hand was in most cases longer using the electric aircraft option, with the exception of one flight.

Alfredsson et al., (2022) noted that since the flight time was generally longer with the electric aircraft option, this would involve later arrivals at the destination as compared to conventional aircraft as well as the need for adjustments in logistics for the airports and reduced charging time as a consequence of the above. The second takeaway was that due to the lower seat capacity on the electric option, more flight would have to be conducted in order to meet the same capacity demand.

Discussion

The electrification of aircraft and the potential that eVTOLs possess could truly change the way we live and move around in and out of cities and countries. Both of these emerging technologies holds tremendous potential if implemented with care and precision. But it will not come without its challenges and concerns to be addressed. The following section will highlight some of the potentials observed and answer the question on how future transport systems might look like thru the implementation of these technologies.

Challenges

As UAM vehicles and electric aircraft continue to develop, we will need to ensure the highest possible safety standards. There is much to learn from the established aviation sector but this is still unexplored territories and will have tackle its own safety concerns which are not necessarily transferable from other industries. The use of automation and centralized control

systems are some questions that will have to be address both from a technological perspective but also from en public concern perspective. As UAMs will operate at significantly lower heights than conventional air transport, certain potential hazards may arise and will have to be address already at the design phase in order to mitigate potential safety issues.

Although this thesis intentionally does not touch on the aspects of air-traffic management systems and potential cyber security issues, it is of outmost importance to highlight the need for further development in these areas in order to take the safety considerations necessary for the successful and secure implementation of UAMs. By using airspace corridors effectively, implement geofencing techniques and protect sensitive areas like schools, hospitals and power plants, this technology has potential to even enhance safety over traditional ground transport.

From a technological standpoint the industry will have to take further safety measures when in comes to the design of power electronics, microelectronics and structural components not only in battery packs but in the entire flying structure. The industry will have to come so far that there is close to zero risk that a UAM or electric aircraft will fall out of the sky due to issues related to failed electronics, autonomy or cyber security related issues. This would ultimately change the conception of the general public and may have a devastating effect on the implementation of such technology.

Noise pollution is another factor that will have to be carefully considered. The industry will have to consider not only individual aircraft configuration and the noise produced by such but also measure and assess the noise levels based on a fleet of vehicles operating simultaneously. From the research made in this paper, no information was found that studied the topic of cumulative noise from multiple vehicles. This could be of the natural reason that the technology is still in its development stage and simulating such scenarios could be difficult prior to implementation. However, it is important to highlight that noise might have an effect on how routes are planned, which in turn will create a domino effect on where the infrastructure can be placed, hence affecting range, trip time and the energy required to fulfill a mission. This could lead to a slowdown in the development of UAM application until battery technology has come further, providing higher battery densities capable of handling longer trips than initially modeled.

Batteries

Some of the issues related to batteries that are not discussed as much are for instance the fact that the weight of a battery does not change as is depletes, it remains approximately the same independent of battery level. One of the benefits is that the weight of the aircraft remains constant thru out the flight which does not only simplify range- and payload calculations but also means the maximum landing weight is no longer a factor as an aircraft's takeoff weight never can exceed its landing weight, given there are no other structural limitations hindering this. The negative impact on the other hand is that the power demand to drive the vehicle forward does not decrease over time as it does with conventional aircraft as they consume fuel and thereby reduce weight thru out the flight. Design considerations will therefor have to be made in order to stay within all structural design parameters.

Battery life time will ultimately depend on the chemistry and technology used in batteries. The current batteries that are being commercialized typically has a lifetime that is represented either by the number or charge cycles or the amount of capacity left when fully charged. A typical number for regular Lithium Ion Batteries (LIB) batteries are 1000 cycles or 80% State of Health (SOH). The validity of these numbers and wether they are transferable to electric aviation seems however to be debatable. Some arguments seem to point towards the fact that the aircraft will have to carry the

useless weight of the battery despite not being able to use it to its full extent. This is however also true for conventional Internal Combustion Engines (ICE), as they age bearings and other components lose their precision, residues and combusted material coats the internals of the engine resulting in a lower efficiency and higher fuel burn. From a battery perspective it therefore becomes increasingly important to find an optimum capacity limit in order to ensure safety as well as efficiency. It is also important to highlight the fact that batteries in UAMs and electric aircraft will have a much higher utilization-rate than electric vehicles as they will fast charge more frequently as the use case is significantly higher. Similarly, the discharge rate will be much higher due to the inherent nature of higher power demand in takeoff and landing. For example if an aircraft battery would be charged 5 times per day and the lifetime expectancy is 1000 cycles, that would mean that the battery would have to be replaced every 200 days. There are however some mitigating factors that will be discussed further in the analysis.

Battery swapping is a strategy that often arises when reading about electrification in general. From other industries like the car industry we can see that it was an idea that was tried but never got a strong foothold and was later not implemented, Tesla and other car brands trials this approach without success. One of the arguments used is that it would shorten the required time needed to otherwise charge an integrated battery pack. This might hold true but the question is not as simple as it might initially seem. Implementing such technology would require many different industries and stakeholders to cooperate in a joint effort. Manufacturers of both aircraft and batteries, as well as regulators and airport facilitators would have to develop components, techniques and procedures in order for battery swapping to become a viable solution. The first step would be to design the aircraft to be able to facilitate a removable battery that not only meets all safety standards and is safe to handle but also easy enough to be done in just a few minutes. The second step would be to find a standardization where preferably all aircraft models are able to use the same type of battery. Valuable time would otherwise be lost finding the right battery for a specific aircraft as well as unloading the old and inserting the new. The question that arises is whether there is any time gained in such usage when the option could have been to simply plug in the aircraft and start charging it as soon as it arrived at the gate. Worthwhile is also the fact that it would require a substantial investment in infrastructure as robots probably would have to be used for the swapping phase to assure enough precision and spare batteries would have to be allocated to each airport to account for disruptions or battery failures. From a manufacturing point of view, battery swapping would likely imply added weight in the aircraft as components like quick connectors would have to be integrated as well as added framing of the aircraft body in order to withstand the weight of a single battery. Today's aircraft contain the fuel in the wings and the underbelly, spreading the weight distribution along a bigger area and hence require less structural integrity compared to having a single swappable battery contained in one place. One of the benefits with swappable batteries however is that it would help stabilize the national grid and improve battery lifetime as batteries could facilitate smart charging. Charging at night when the electricity price is regularly lower and the demand is less would help stabilize the grid. It would also mean that the batteries can be charged slower which improves battery life. Likewise, having more spare batteries than otherwise required would also mean less cycles per battery.

Misconceptions

As battery density continues to improve there is still one question that needs to be addressed. Given the fact that the energy required to travel a fixed distance remains constant and with the energy density of about 250 Wh/kg, a battery would require about 50 times more energy than the

same amount of energy contained in kerosene (12 000 Wh/kg). This would result in the need to add more batteries in order to meet the same efficiency, adding more weight results in a higher energy demand to fulfill the same mission, necessitating even more batteries and then the cycle continues. Adding to this is the fact that batteries maintain their weight as they are being consumed so even when the battery is almost fully depleted it would still have to carry the burden of its own weight. Unlike conventional fuel which is being used and converted to either thrust and heat, lowers the aircraft total weight throughout the flight and thereby requiring less energy as the flight progresses.

One of the misconceptions on the other hand related to the ratio between kerosene and electricity is the fact that the industry tends to compare them 1:1 forgetting that the whole drivetrain efficiency has to be taken into account. Given the energy density above, the ratio starts at 1:48 (250 Wh/kg / 12 000 Wh/kg), this is a number often used by skeptics when discussing the efficiency of electric aviation. However, the efficiency of an internal combustion engine is roughly 28% compared to that of an electric engine which has about 90% efficiency. This parameter in itself reduced the ratio from 1:48 to 1:15. Provided the industry can continue to develop battery densities in accordance with the prediction, a battery with 600 Wh/kg would bring the ratio further back to 1:6,2. Lastly, utilizing airframe design improvements like DPS and BLI could improve aerodynamics by as much as a factor of 4 resulting in the ratio between kerosene and electric to become only 1:1,5. This ratio is important to remember as the industry compares the different solutions to each other. Continued development in battery chemistry, electric motors and aircraft design could mean that the industry can meet the above potential.

One mitigating factor that could be implemented related to battery charging is to use multiple charging cables instead of a singular. As the power required to fast-charge an electric aircraft battery the charging cable and adapters will have to be very robust and thereby potentially too heavy for a person to handle. Using multiple charging cables connected to different parts of the battery pack could be a mitigation to this problem. Similarly to how conventional aircraft are fueled today where sometimes two fuel hoses are connected to the aircraft in order to refuel at a faster rate for aircraft that require a large amount of fuel. However this approach would require even more investments in infrastructure than with a single cable and charging standards would have to be reviewed.

Infrastructure

Many of the solutions proposed would require the need to invest heavily in upgrading either the national grid or the electricity infrastructure leading up to the airports and vertiports. However another solution could be to use local energy generation- and storage instead. By using solar panels and stationary batteries only the infrastructure within the airport site would need upgrading. Solar panels could be placed on hangar roofs and other otherwise unused space at an airport. For instance at airports with multiple runways where there is often widespread areas of flat grass between the runways could be an ideal place to deploy solar panels that could generate enough electricity to run the airport sustainably as well as charge stationary batteries and swappable batteries during the day to be used at night. This approach would not only relieve the burden on the national grid but also balance out the supply and demand of the same.

Smart charging is another technique that holds great potential and to some extent works similar to a solar panel / battery storage solution as described above. As commercial aircraft usually are parked during the night, this means that the parking time exceeds the time otherwise needed to charge. Using smart charging by either charging at a slower rate to increase battery life time or to avoid high peak currents on the grid has a double sided effect. It not only retains battery health but

also spreads the energy demand evenly throughout the day, resulting in a more predictable energy demand on national scale as well as a more stable electricity price for all. By intelligently controlling the charging one could also take into account the battery SOC, chemistry, thermal management and other environmental conditions. Knowing when a flight will depart, intelligent charging could make sure that the battery is finished charging only when it is expected to be used and not earlier. As batteries generally degrade faster at a fully charged level this would mean that the battery is kept at a healthier SOC longer as well as it is preconditioned just in time before it is intended to be used. All of these factors extend battery life, leading to less batteries having to be deployed which in turn has a positive effect on the environment and safety. It is also worth noting that smart charging would probably be best utilized by using the battery swapping option even though it could be used in both scenarios.

After having interviewed an electric aircraft manufacturer which is currently developing their electric platform, it became evident that as a manufacturer they intend- and to some extent already are engaged in discussions with airport authorities and local legislators to find an infrastructure solution that not only solves some of the challenges from an operator perspective but also benefits the individual airport. A surprising fact that the literature review did not touch on but the manufacturer confirmed was that airports and facilitators approach the idea of electric aviation with curiosity and interest despite the heavy investments in infrastructure required. The reason being that airport managers realize that a shift towards more sustainable air travel is happening and thereby an investment in new technology will be required, irrelevant of which technology it will be. Electric aviation seems - according to the manufacture - to be a more interesting technology over hybrid solutions from an airport management point of view.

Case studies

The two case studies offer insight into how electric aviation might actually work beyond theory and from a practical perspective. Both cases seem quite positive at first as they show that current electric aircraft concepts have both enough range and performance for short distance routes, especially in isolated or regional areas like the ABC islands and Visby. But when analyzed further it appeared that both cases have deeper challenges, especially when considering longterm and large scale expansion.

In the example of the ABC islands the flights are short, predictable and repetitive which is an ideal use case for electric aircraft. But even under ideal situations battery health and charging times still limit flexibility, unless used in combination with smart charging and integration. The ABC island operation is already tight in a small network with just a few aircraft, what would happen in a busier system with more unpredictable schedules or weather delays? Furthermore, the study does not touch on how charging logistics would work if there are delays or if there is technical issues with the charging infrastructure. What kind of redundant systems and backups would the airports need both from a practical and regulatory perspective?

The Visby study also highlights some interesting points. It confirmed that the flights are technically possible, but as electric aircraft are expected to carry less passengers per flight, more departures might possibly be needed to transport the same amount of passengers as today. This has a consequence on more than just adjusted departure- and arrival times. It will most likely also have an affect on the air traffic congestion as well as the amount of workforce needed both in terms of flight crew but also ground staff at the airports.

Based on the above, electric aviation might change how we should think about fleet management and cost efficiency. We might have to shift our strategies in how we organize air

traffic. Smaller and more frequent flights might be required instead of fewer larger ones which in turn will have an affect on how regional airports operate. One idea that came to mind was that instead of completely replacing conventional aircraft with electric alternatives one-to-one, maybe the electric option could become part of a new kind of system, something more integrated with trains, buses and other local transport which is already part of our trasport infrastructure. Especially bringing in eVTOLs in the equation, society could develop a more decentralized transport network where small electric aircraft connect smaller cities to city hubs instead of large airports. This would make airports more like local mobility hubs rather than large traditional departure terminals.

Instead of just seeing these case studies as proof that electric aviation works for short routes, I think it is more valuable to view them as early simulations of what future challenges might look like. They help to identify where the limits are, not just in terms of technology, but in how our current systems are structured. To really succeed, we will probably need to rethink operations, infrastructure, regulations and also passenger expectations. When analyzed in a deeper meaning, these case studies show that electric aviation is not just about plugging in a new aircraft, it might mean redesigning the whole system from the ground up.

Future vision

In order to answer the second part of the research question on how future transport systems might look like through the implementation of the above technologies is a rather difficult task. There is no clear answer to that question as it will depend on many different factors. It is difficult to predict how technology will evolve in the coming years and which path we decide to embark on. Furthermore, regulators will have to approve and oversee the regulations required for such deployment. Large investments in infrastructure will be needed and the thrust and approval of the society and individuals will have to be gained prior to UAM vehicles and electric aircraft are in full use. However, the following part will discuss future possibilities in an attempt to shape a vision of the future and imagine how future transport systems might look like.

The potential that UAM has on our society is almost infinite. The way we move around in and around cities could be completely different in 50 years as compared to today. From other industries like the car industry we have already seen a swift away from combustable propulsion towards electric. The change came faster than most expected and it rapidly changed the way we look at fueling and charging. When owning an electric car, having to stop by a petrol station to refuel before picking up the kids at school or after work is no longer a factor. Simply plugging in an electric car after arriving at home and finding it fully charged and ready to go in the morning is something society soon will take for granted. Shifting from one technology to another often happens faster than we imagine as exponential development is inherently difficult to predict and understand. The same happened in 2006 when the first iPhone was launched, almost overnight the world had changed and after a year most people could not image their daily life without a smartphone. Many times, we as individuals and as a society do not always know what we want and need before we have actually seen and experienced it. The same will most like be true with electric aviation and UAMs.

Imagine a future where no longer anyone owns a car, simply because it is not needed. What if you could hail a drone thru an app on your phone that arrived at your location within minutes to take you to your desired location. The ride would be smooth, uninterrupted and autonomously controlled. You as a passenger could watch a movie, make the needed phone calls or simply enjoy the view without the need to sit in a traffic jam on ground in a fossil fueled car. Road congestion

would no longer be a factor, parking lots could be rebuilt to green and flourishing parks and the cost to own and drive a car would be just as unlikely as owning a Sony Ericsson or Motorola of the past.

The integration of UAM systems could easily be integrated into existing transportation networks or completely new networks could be built. New ventures like tunneling and automated ground transport within the tunnels could potentially be connected to vertiports in the outskirts of a city to provide a seamless travel experience. The benefit would be less noise pollution by UAMs and more stops along the way within the city. On-demand UAM services will however be relatively sensitive to fluctuation in demand. People tend to follow certain living patterns which are similar to each other. Most people need to go to school or jobs in the morning and get home in the afternoon. UAM services will have to take this into consideration. One solution could be increased level of ride-sharing in high peak demands such as in the morning and afternoon. The benefit of such would be a lower cost of traveling as the price is split. To some extent the demand can be predicted and modeled. As an example, you could link your working schedule to an app that knows at what date and time you will be requiring transport. A centralized coordination system could then create expected schedules, allocate vehicles and execute smart charging principles in order to meet the expected demand. Similarly, should you plan at vacation and need transport to and from the airport, the system would know beforehand and make sure there is transport available.

Over the past years there has been a rapid increase of e-commerce, this has also increased the expectations for rapid delivery rates. UAMs could play a role in solving some of the issues that the global supply chains are facing today. Integrating UAMs into supplying cargo and food deliveries could potentially serve two industries, both the transport of people and goods. This would in turn alleviate the pressure on ground transportation, yielding the same benefits on ground as described earlier. Deploying cargo shuttles or potentially using UAMs to carry passengers and cargo at the same time could be a viable solution to circumnavigate the challenges in supply chains we are seeing today. Besides the benefits of faster delivery times, such a solution could bring other unexpected benefits. Isolated communities would not have to wait much longer for their deliveries, people living in isolated areas would have the possibility to work and attend schools in places that were not possible before. This in turn would increase job creation and further support both urban- and national growth and economy.

There are as many challenges as there are potentials with the evolving technology of UAMs and electric aircraft. However the implementation of such will depend on many variables and might end up being more complex than expected. "The unique characteristics of aviation, that are manned or unmanned, should never be overlooked" (respondent 1).

Limitations

The study was primarily carried out as a literature review of the past and current state of electric technology related to aircraft and eVTOLs. Based on this fact a timeframe of 10 years was chosen but despite this it became evident that some facts did not match today's reality and might because of the same reason not be valid for much longer. Factorial figures like battery density and range might change over time, however comparison values between conventional and electric alternatives holds true for longer.

Both electric aircraft and eVTOLs have been studied in this thesis and to some extent placed in the same category. Both the infrastructure needed for implementation as well as the use case is however different between the two. The values and ideas presented in the paper are common for both emerging technologies. However, separating these technologies and studying them individually could yield other interesting results.

This study did not take into account subjects like control systems and autonomy, air traffic control- and cyber security as well as emissions. Taken all of these topics into account would bring the research outside of its scope. However, it is relatively unclear if any of these could have contributed to a different answer to the research question. Especially questions related to autonomy and acceptance among humans to adapt to- and use technologies like unmanned self-flying vehicles.

The research does not touch on the political- and regulatory requirements needed in order for electric aircraft and eVTOLs to be implemented. This could potentially create a bottleneck effect in the implementation and could therefore affect the timeframe to future adoption as well as hinder current development in battery technology.

Conclusion

This study has shown that the rapid development of electric aircraft and eVTOL technology has a strong potential to reshape future transport systems. Innovations in battery chemistry, propulsion systems and airframe design are bringing electric aviation closer to operational usage, especially for short-range routes. The integration of these technologies into urban and regional areas could significantly reduce carbon emissions, noise pollution and the reliance on fossil fuel which could offer a viable path toward sustainable mobility.

The implications of the findings are many. UAMs using eVTOLs can reduce road congestion and shorten travel times, especially in populated cities. Similarly, regional electric aircraft could make remote areas more accessible, creating new opportunities for economic development and connectivity. Furthermore, the electrification of air transport aligns well with renewable energy systems where airports and vertiports can adopt smart charging strategies that reduce stress on national power grids.

Despite all the promises, challenges remain. Battery energy density must improve to support longer ranges and higher payloads and infrastructure must develop to handle higher charging demands. Electric motor development as well as airframe designs and noise management will be critical factors in determining how quickly these technologies can be scaled.

Future research should focus on battery performance with aviation specific conditions, optimal infrastructure placement based on urban planning restrictions and the cumulative noise impact of multiple UAM vehicle operations. These are key steps toward transitioning from prototype to widespread deployment.

In conclusion, while full electrification of air transport will take time, this thesis highlights that with the right innovation, investment and mindset, electric aviation has the potential to fundamentally change how we move around, more sustainably, efficiently and inclusively.

References

* Reference as part of the literature search.

- *Adu-Gyamfi, B. A., & Good, C. (2022). Electric aviation: A review of concepts and enabling technologies. *Transportation Engineering*, 9, 100134.
<https://doi.org/10.1016/j.treng.2022.100134>
- *Alfredsson, H., Nyman, J., Joborn, M., Staack, I., & Petit, O. (2022). *Infrastrukturmodellering för storskalig introduktion av elflyg och flygtrafikledning (MODELflyg)*. RISE Rapport.
- *Apostolidis, A., Donckers, S., Peijnenburg, D., & Stamoulis, K. P. (2024). Electric aircraft operations: An interisland mobility case study. *Aerospace*, 11(3), 170.
<https://doi.org/10.3390/aerospace11030170>
- Avinor, & Luftfartstilsynet. (2020). *Forslag til program for introduksjon av elektrifiserte fly i kommersiell luftfart*.
<https://luftfartstilsynet.no/globalassets/dokumenter/andre-dokumenter/forslag-til-program-for-introduksjon-av-elektrifiserte-fly-i-kommersiell-luftfart.pdf>
- Bacchini, A., & Cestino, E. (2019). Electric VTOL configurations comparison. *Aerospace*, 6(3), 26.
<https://doi.org/10.3390/aerospace6030026>
- Bills, A., Sripad, S., Fredericks, W. L., Singh, M., & Viswanathan, V. (2020). Performance metrics required of next-generation batteries to electrify commercial aircraft. *ACS Energy Letters*, 5(2), 663–668.
<https://doi.org/10.1021/acsenergylett.9b02574>
- Cano, P., Yu, A., Lu, J., & Chen, Z. (2019). Automotive Li-ion batteries: Current status and future perspectives. *Electrochemical Energy Reviews*, 2(1), 1–28.
<https://doi.org/10.1007/s41918-018-0022-z>
- Caset, F., Boussauw, K., & Storme, T. (2018). Meet & fly: Sustainable transport academics and the elephant in the room. *Journal of Transport Geography*, 70, 64–67.
<https://doi.org/10.1016/j.jtrangeo.2018.05.020>
- Chakraborty, I., & Mishra, A. A. (2023). Sizing and analysis of a lift-plus-cruise aircraft with electrified propulsion. *Journal of Aircraft*, 60(3), 747–765.
<https://doi.org/10.2514/1.C037044>
- Courtin, C., & Hansman, R. J. (2018). Safety considerations in emerging electric aircraft architectures. In *2018 Aviation Technology, Integration, and Operations Conference*.
<https://doi.org/10.2514/6.2018-4149>
- Darmstadt, P. R., et al. (2019). *Hazards Analysis and Failure Modes and Effects Criticality Analysis (FMECA) of Four Concept Vehicle Propulsion Systems*.
- Driessen, C., & Hak, M. (2021). *Roadmap electric flight in the Kingdom of The Netherlands*. Ministerie van Infrastructuur en Waterstaat.
<https://open.overheid.nl/repository/ronl-f5b5b66a0570563a5c5051b74919618f7ea39468/1/pdf/bijlage-2-roadmap-electric-flight-naco-nlr-report.pdf>
- EADS. (2013). EADS demonstrating electric and hybrid aviation propulsion; innovative distributed propulsion series hybrid. *Green Car Congress*.
<https://www.greencarcongress.com/2013/06/eads-20130617.html>
- *Fei, Y. (2024). Materials challenges in the development of all-electric aircraft. *E3S Web of Conferences*, 553, 02023.
<https://doi.org/10.1051/e3sconf/202455302023>

- Fredericks, W. L., Sripad, S., Bower, G. C., & Viswanathan, V. (2018). Performance metrics required of next-generation batteries to electrify vertical takeoff and landing (VTOL) aircraft. *ACS Energy Letters*, 3(12), 2989–2994.
<https://doi.org/10.1021/acsenergylett.8b02195>
- Glaab, P., Wieland, F., Santos, M., Sharma, R., Tamburro, R., & Lee, P. U. (2019). Simulating fleet noise for notional UAM vehicles and operations in New York. In *2019 IEEE/AIAA 38th Digital Avionics Systems Conference (DASC)* (pp. 1–10).
<https://doi.org/10.1109/DASC43569.2019.9081670>
- Gnadt, A. R., Speth, R. L., Sabnis, J. S., & Barrett, S. R. H. (2019). Technical and environmental assessment of all-electric 180-passenger commercial aircraft. *Progress in Aerospace Sciences*, 105, 1–30.
<https://doi.org/10.1016/j.paerosci.2018.11.002>
- Hepperle, M. (2012). *Electric flight—Potential and limitations* (Tech. Rep. STO-MP-AVT-209). German Aerospace Center.
- International Air Transport Association. (2019). *Aircraft technology roadmap to 2050*. Montreal, QC, Canada.
- Jeong, J., So, M., & Hwang, H.-Y. (2021). Selection of vertiports using K-means algorithm and noise analyses for urban air mobility (UAM) in the Seoul metropolitan area. *Applied Sciences*, 11(12), 5729.
<https://doi.org/10.3390/app11125729>
- *Kiesewetter, L., Shakib, K. H., Singh, P., Rahman, M., Khandelwal, B., Kumar, S., & Shah, K. (2023). A holistic review of the current state of research on aircraft design concepts and consideration for advanced air mobility applications. *Progress in Aerospace Sciences*, 142, 100949.
<https://doi.org/10.1016/j.paerosci.2023.100949>
- *Liang, Y., Mouli, G. R. C., & Bauer, P. (2024). Charging technology for electric aircraft: State of the art, trends, and challenges. *IEEE Transactions on Transportation Electrification*, 10(3), 6761–6788.
<https://doi.org/10.1109/TTE.2023.3333536>
- *Liu, M., Hao, H., Sun, X., Qu, X., Wang, K., Qian, Y., Hao, X., Xun, D., Geng, J., Dou, H., Deng, Y., Du, S., Liu, Z., & Zhao, F. (2024). Exploring the key technologies needed for the commercialization of electric flying cars: A levelized cost and profitability analysis. *Energy*, 303, 131991.
<https://doi.org/10.1016/j.energy.2024.131991>
- Makoschitz, M. (2022). Key aspects to enable multi-megawatt fast charging.
<https://link.springer.com/article/10.1007/s00502-022-01037-w#Sec5>
- Manthiram, A., Yu, X., & Wang, S. (2017). Lithium battery chemistries enabled by solid-state electrolytes. *Nature Reviews Materials*, 2(4), 1–16.
<https://doi.org/10.1038/natrevmats.2016.103>
- Martínez Fernández, A., & Smith, H. (2020). Effect of a fuselage boundary layer ingesting propulsor on airframe forces and moments. *Aerospace Science and Technology*, 100, 105808.
<https://doi.org/10.1016/j.ast.2020.105808>
- Misra, A. (2018). Energy storage for electrified aircraft: The need for better batteries, fuel cells, and supercapacitors. *IEEE Electrification Magazine*, 6(3), 54–61.
<https://doi.org/10.1109/mele.2018.2849922>

- Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G. (2009). Preferred reporting items for reviews and meta-analyses: The PRISMA statement. *Public Library of Science*, 6(7).
<https://doi.org/10.1371/journal.pone.0018769>
- *Muhammad Yeasir Arafat, & Pan, S. (2024). Urban air mobility communications and networking: Recent advances, techniques, and challenges. *Drones*, 8(12), 702.
<https://doi.org/10.3390/drones8120702>
- National Academies of Sciences, Engineering, and Medicine. (2016). *Commercial aircraft propulsion and energy systems research: Reducing global carbon emissions*. The National Academies Press.
<https://doi.org/10.17226/23490>
- Rimjha, M., Hotle, S., Trani, A., Hinze, N., & Smith, J. C. (2021). Urban air mobility demand estimation for airport access: A Los Angeles international airport case study. In *2021 Integrated Communications Navigation and Surveillance Conference (ICNS)* (pp. 1–15).
<https://doi.org/10.1109/ICNS52807.2021.9441659>
- Schwab, A., Thomas, A., Bennett, J., Robertson, E., & Cary, S. (2021). *Electrification of aircraft: Challenges, barriers, and potential impacts* (Tech. Rep. NREL/TP-6A20-80220). National Renewable Energy Lab.
<https://docs.nrel.gov/docs/fy22osti/80220.pdf>
- Senkans, E., Skuhersky, M., & Kish, B. (2021). A first-principle power and energy model for eVTOL vehicles. In *AIAA AVIATION 2021 FORUM* (p. 3169).
<https://doi.org/10.2514/6.2021-3169>
- *Schefer, H., Fauth, L., Kopp, T. H., Mallwitz, R., Friebe, J., & Kurrat, M. (2020). Discussion on electric power supply systems for all electric aircraft. *IEEE Access*, 8, 84188–84216.
<https://doi.org/10.1109/ACCESS.2020.2991804>
- *Skytte, K., Vølstad, M. L., & Stiler, D. S. (2023). Overview of electricity and energy capacity for the establishment of electric aviation routes in the Nordic region.
<https://doi.org/10.6027/wp2023:5.1403-2511>
- Smart, J. T., & Alonso, J. J. (2019). Primary weight estimation for eVTOLs via explicit analysis and surrogate regression. In *AIAA Aviation 2019 Forum*.
<https://doi.org/10.2514/6.2019-3679>
- Ugwueze, O., Statheros, T., Horri, N., Innocente, M., & Bromfield, M. (2022). Investigation of a mission-based sizing method for electric VTOL aircraft preliminary design. In *AIAA SCITECH 2022 Forum* (p. 1931).
<https://doi.org/10.2514/6.2022-1931>
- Viggiano, R., et al. (2020). *Solid-state architecture batteries for enhanced rechargeability and safety for electric aircraft*. NASA.
https://ntrs.nasa.gov/api/citations/20205008150/downloads/Rocco_Viggiano_-_CAS_SABERS_PRIIME_2020_Presentation_-_20205008150.pdf
- Wang, CY., Liu, T., Yang, XG. et al. Fast charging of energy-dense lithium-ion batteries. *Nature* 611(7936), 1–6. (2022).
<https://doi.org/10.1038/s41586-022-05281-0>
- Wang, K., Zhou, Z., Fan, Z., & Guo, J. (2021). Aerodynamic design of tractor propeller for high-performance distributed electric propulsion aircraft. *Chinese Journal of Aeronautics*, 34(10), 20–35.
<https://doi.org/10.1016/j.cja.2021.01.008>
- Yang, X.-G., Liu, T., Ge, S., Rountree, E., & Wang, C.-Y. (2021). Challenges and key requirements of batteries for electric vertical takeoff and landing aircraft. *Joule*, 5(7), 1644–1659.
<https://doi.org/10.1016/j.joule.2021.05.001>

Appendix 1

Interview questions provided to respondent 1 and the aircraft manufacturer.

* Aircraft manufacturer specific question.

Could you provide a brief summary about yourself and your field of expertise?

“When you look at the whole electric-air network, aircraft, charging stations and flight paths - which complex surprises might we run into?”

“How could easy access to eVTOL taxis and short haul electric flights change how we live in and move around our cities?”

“What can electric aviation learn from the rapid growth of electric cars and sustainable energy technology like solar panels and battery storage, and what might those industries learn back from aviation?”

“If flying becomes as easy as hailing a taxi, how could that change our ideas of personal freedom and fairness in who gets to travel?”

“What major changes, or risks, could a fully electric, autonomous air fleet bring to society?”

“How should we plan for battery end-of-life, recycling, second-use storage or material recovery - to keep electric aviation viable longterm?”

“What new safety systems or backup designs are needed to make battery-powered aircraft and eVTOLs as reliable as today’s aircraft?”

“How will vertiports need to connect with trains, buses and roads to make door-to-door electric-air travel smooth?”

”Regarding autonomous flying vehicles, how should we look at liability when the human factor is no longer a factor?”

”How are you approaching the integration of electric aircraft into existing aviation infrastructure and ecosystems (airports, charging, maintenance etc.)?”*

”How do you as a manufacturer balance tradeoffs between aircraft range, payload and battery weight in your current and future designs?”*

”Thinking half a century into the future, how do you envision the future?”