December 2022

Washington Electric Airport Feasibility Study

Prepared by University of Washington, Department of Civil and Environmental Engineering

ASSESSMENT OF ELECTRIC UTILITY CAPACITY TO DELIVER ELECTRICITY FOR ELECTRIC AVIATION AT PAINE FIELD AND GRANT COUNTY INTERNATIONAL AIRPORT

by

Steffen Coenen, MS Student
Civil and Environmental Engineering

Daniel Malarkey, Senior Research Scientist
Sustainable Transportation Lab

Don MacKenzie, Associate Professor
Civil and Environmental Engineering

Department of Civil and Environmental Engineering
University of Washington

Seattle, Washington

Washington State Transportation Center (TRAC)
University of Washington, Box 354802
University District Building
1107 NE 45th Street, Suite 535
Seattle, Washington 98105-4631

Washington State Department of Transportation Technical Monitor
John MacArthur

Prepared for

The State of Washington
Department of Transportation
Roger Millar, Secretary

1. REPORT NO. WA-RD 918.1	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE Assessment of Electric Utility Capacity to Deliver Electricity for Electric Aviation at Paine Field and Grant County International Airport		5. REPORT DATE October 2022 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Steffen Coenen, Daniel Malarkey, Don MacKenzie		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Sustainable Transportation Lab, Department of Civil Engineering, Box 352700, More Hall, 3760 E. Stevens Way NE, Seattle, WA 98195.		10. WORK UNIT NO. 11. CONTRACT OR GRANT NO. Agreement 1461, Task 58
12. SPONSORING AGENCY NAME AND ADDRESS Research Office Washington State Department of Transportation Transportation Building, MS 47372 Olympia, Washington 98504-7372 Project Manager: Jon Peterson, 360-705-7499		13. TYPE OF REPORT AND PERIOD COVERED Final Research Report 14. SPONSORING AGENCY CODE
15. SUPPLEMENTARY NOTES		

16. ABSTRACT

Advances in battery-powered electric motor systems, lightweight materials, and aircraft design have resulted in the development of new electric aircraft that could gradually replace conventional fuel-powered aircraft for certain use cases in the coming years. In addition, a whole new category of electric vertical takeoff and landing aircraft has seen billions of dollars of new investment with the goal of serving an entirely new urban air mobility market that would allow for fast trips within congested metro areas.

This study developed methods to estimate plausible future energy and power demand for electric aircraft operations at regional airports to determine whether the electric grid near two regional airports, Paine Field and Grant County International Airport, have the capacity to serve the potential energy (MWh) and peak power (MW) needs of electric aircraft operations over the next one to two decades. Our method has three parts: assumptions on flight operations growth, technical feasibility to serve these flights with electric aircraft, and actual adoption of electric aircraft to serve feasible trips.

We found that the electric utilities serving these two airports have enough electric capacity at the neighboring substations to meet the demand for electricity over the next decade, given the capacities reported by the local utilities. Experience gained in the first decade of commercial electric aircraft deployment at these airports will help inform future analysis as to whether local grid capacity will eventually impede the growth of electric aircraft charging.

Lastly, this report presents recommendations on how regional airports can prepare for electric aviation.

17. KEY WORDS		18. DISTRIBUTION STATEMENT	
Electric aviation, electricity, projection, electric vertical take-off and landing, eVTOL, Paine Field, Grant County International Airport		No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22616	
19. SECURITY CLASSIF. (of this report)	20. SECURITY CLASSIF. (of this page)	21. NO. OF PAGES	22. PRICE
None	None		

TECHNICAL REPORT DOCUMENTATION PAGE

Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Washington State Department of Transportation. This report does not constitute a standard, specification, or regulation.

Contents

Tables

Figures

Executive Summary

New aircraft designs that combine high-performance batteries and electric motors with lightweight, fixed-wing airframes may provide lower total costs of ownership and perform similar to or better than existing liquid-fueled, prop-driven aircraft for some commercial uses. The potential for improved economic performance of electric fixed-wing aircraft for trips under 500 miles could allow for new passenger and cargo air service between regional airports and hub airports that today's conventional aircraft cannot serve economically.

In addition, a whole new category of electric vertical takeoff and landing aircraft has seen billions of dollars of new investment with the goal of serving an entirely new urban air mobility market that would allow for fast trips within congested metro areas.

After the introduction of jets into commercial air service, it took 15 years for them to compose over 80 percent of the active commercial fleet. Whether electric aircraft achieve widespread adoption quickly in 10 years or slowly over 40 years will depend on the success of their manufacturers in managing five risks:

- Technology – Do the aircraft fly safely and economically?
- Certification – Are regulators convinced the products are airworthy?
- Infrastructure – Are there places to take off, land, and charge, and are there systems to manage high flight volumes?
- Operations – Do electric aircraft operators have the experience and capital to operate safely and succeed commercially?
- Socio-cultural – Does the public see the widespread adoption of electric aircraft as serving the public interest?

This study addressed one dimension of the infrastructure risk. We developed methods to estimate plausible future energy and power demand for electric aircraft operations at regional airports to determine whether the electric grid near two regional airports, Paine Field and Grant County International Airport, have the capacity to serve the potential energy (MWh) and peak power (MW) needs of electric aircraft operations over the next one to two decades.

We found that the electric utilities serving these two airports have enough electric capacity at the neighboring substations to meet the demand for electricity over the next decade, given the capacities reported by the local utilities. As part of their regular integrated resource planning process, both the Snohomish County and Grant County public utility districts (PUDs) forecast future demand for electricity, including demand from the electrification of passenger vehicles. The utilities don't have electric aviation in their forecasts. However, Snohomish PUD has accounted for growth in demand from electric vehicles, and even with that growth it will have capacity to serve Paine Field in the early years of electric aviation. Grant County PUD has surplus electricity and can accommodate significant increases in demand. Experience gained in the first decade of commercial electric aircraft deployment at these airports will help inform future analysis as to whether local grid capacity will eventually constrain the growth of electric aircraft charging. Meeting the charging requirements for electric aviation will require utility service upgrades and investments on-site at airports transformers, rectifiers, and charging gear, as shown in the figure below.

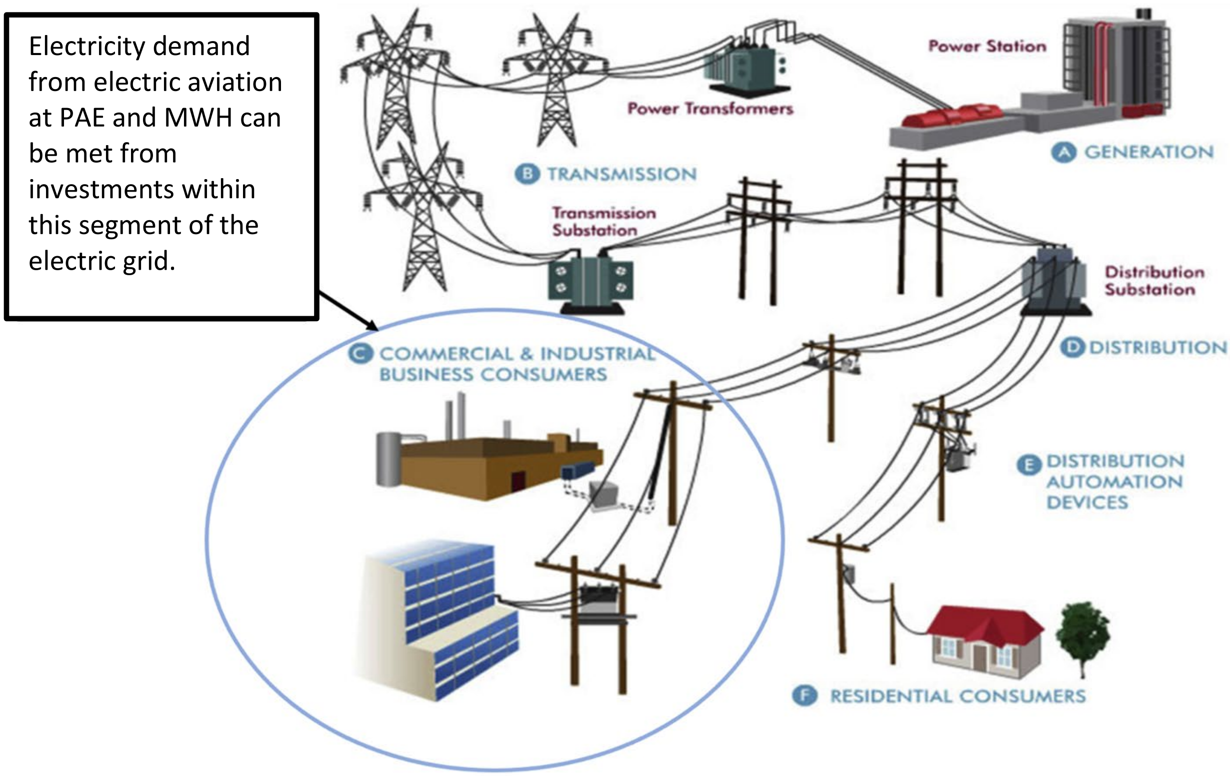


FIGURE ES. THE TARGET GRID SEGMENT FOR INVESTMENTS TO MEET CHARGING DEMAND FROM ELECTRIC AIRCRAFT IN THE FIRST DECADE.

Regional airports can prepare for electric aviation by doing the following:

- Tracking industry developments as different models of electric aircraft gain certification.
- Engaging with emerging electric aviation charging networks regarding their interest and ability to provide service at local airports.
- Tracking state and federal clean energy grant opportunities.
- Encouraging local flight schools to consider electric training aircraft as a lower cost alternative to traditional liquid-fueled airplanes.

I. Introduction

Aviation companies are using advances in battery-powered, electric motor systems, lightweight materials, and aircraft design to develop and build a variety of new electric aircraft that could replace many conventional prop-driven aircraft in commercial use (Schwab et al. 2021). With projected improvements in the underlying technologies, electric aircraft may also eventually replace some travel now served by jet aircraft. New electric aircraft designs could also serve an entirely new market for urban air mobility, providing short trip service within urban areas that avoids bottlenecks in ground transportation. In the face of tight climate action goals and large airport hubs facing capacity constraints, electric aircraft serving regional airports could help respond to increased travel demand for air travel both between and within large metropolitan areas.

Numerous studies have explored the potential of electric and hybrid-electric aviation to reduce the noise, local pollution, and greenhouse gas emissions from conventional aviation operations (e.g., Riboldi et al. 2020; WSP 2020). Electric aircraft produce fewer emissions and less noise than comparably sized conventional aircraft. In addition to reducing negative externalities, electric aviation has some performance advantages relative to conventional aircraft that could grow the aviation market (WSP 2020; Mäenpää et al., 2021). This holds especially true with respect to novel technologies, including electric vertical take-off and landing, or eVTOL, aircraft (Goyal et al. 2018; Cohen et al. 2021). Multiple companies founded in the last decade are pursuing the design, construction, and certification of novel eVTOL aircraft to allow urban air mobility (Schwab et al. 2021). Seeley et al. (2020) argued that "the cost advantages of electric propulsion systems are going to completely disrupt the current aviation market and allow more point-to-point journeys."

Global demand for aviation will increase as a result of increased access to commercial flights for a larger share of the world's population and more frequent trips by current flyers within developed countries (Gössling and Humpe 2020). While aviation contributes 2.4 percent of global CO_2 emissions, growth in demand for global flight operations makes aviation one of the fastest growing sources of CO_2 emissions (Hasan et al. 2021; WWF 2022). In addition, many large airport hubs are approaching capacity constraints (Reichmuth et al. 2011; FAA 2015). Coupled with increased regional travel demand, capacity constraints at major hubs creates opportunities for regional short-haul air travel with zero-emission electric aircraft.

Given this potential for growth in regional aviation activity and the lead time needed to provide additional electric capacity at any given site (Reuters 2021), planners need to assess the potential energy and power needs at airports and understand how these demands may grow in the coming years. Increased demand for electricity for aviation will occur just as the United States undertakes a major shift from the use of fossil fuels to clean electricity for ground transportation, space heating, and some industrial processes (Larson, et al. 2021). In this project we developed a framework for estimating future energy (annual megawatt hours (MWh)) and power (average and peak megawatts (MW)) demand for electric aviation at regional airports and compared that to the existing and future capacity of the electric grid serving airports.

Several states and regions have explored the opportunities for electrified regional air travel. This includes work done in Colorado (Schwab et al. 2021) and the NASA Regional Air Mobility report

(NASA 2021). In 2018, the Washington State Department of Transportation's (WSDOT) Aviation Division was tasked by the state's legislature to explore electric aircraft service in Washington. The work resulted in WSDOT's "Washington Electric Aircraft Feasibility Study" (WSP 2020), published in November 2020, which highlighted the potential impact of the electrification of regional aircraft on commercial aviation. The report also set goals for aviation electrification, which included recommended timelines for the deployment of charging infrastructure at commercial airports; these were by 2030 for aircraft of up to 10 to 15 passengers, by 2040 for general aviation, and by 2050 for all aircraft.

In Washington State, aviation operations are highly concentrated at Seattle-Tacoma International Airport (SeaTac), with about 90 percent of all annual enplanements in Washington counted there (WSDOT 2022). However, SeaTac is close to reaching its maximum capacity (Chan 2021), given geographic constraints on expansion. Spatially diversifying commercial enplanements in Washington to different airports could alleviate some of these capacity constraints. Ultimately, electrification could result in new aircraft operations aligned with climate goals that increase utilization of regional airports other than SeaTac and airports not currently providing passenger service.

These opportunities highlight the importance of assessing potential charging demands for electric aircraft at airports that could feasibly serve as regional nodes in an electric aviation network. Our case studies therefore focused on the potential energy demand from electric aviation at two mid-size airports in Washington that are candidates for increased operations from electric aircraft: Paine Field/Snohomish County Airport (PAE) and Grant County International Airport (MWH).

The main purpose of this project was to develop and demonstrate methods to estimate plausible future energy and power demand for electric aircraft operations. Our research explored whether the electric grids near Paine Field and Grant County International Airport have the capacity to serve the potential energy (MWh) and peak power (MW) needs of electric aircraft operations over the next one to two decades. We also reviewed some of the prototypical electric aircraft in 2022 and identified opportunities for airports to help accelerate the transition to electric aircraft.

The intended audience of this report is state policymakers and airport managers who want to prepare their facilities to meet the requirements of an emerging class of electric aircraft customers. The findings may also be of interest to planners at electric utilities that will be asked to serve large increases in electricity capacity needs and staff at air carriers who want to better understand the markets for electric aircraft and charging solutions.

The report begins with a review of the opportunities for growth as well as the risks to broad-scale deployment of electric aircraft. We then review the performance attributes of a set of prototypical electric aircraft that are either on the market or in the late stages of design and certification. We group these prototypes into categories that we could match to existing data on aircraft operations at the two study airports. We also review the technologies available to charge these aircraft and the emerging business models to provide charging services at airports. We then provide brief profiles of Paine Field and Grant County International Airport and the electric utilities that serve them. Chapter V describes the details of our method for estimating future demand and is the most technical chapter in the report. The next chapter summarizes the results, and we wrap up with recommendations on the steps that policymakers and airports can take to accelerate the deployment of electric aircraft and a conclusion.

Our method of estimating future electricity demand has three parts: assumptions about flight operations growth, assumptions about the progress of the technical feasibility of electric aircraft to serve these flights, and assumptions about actual adoption of electric aircraft to serve feasible trips. In our methods chapter we discuss the empirical basis for each of the key assumptions in our forecast model. Our key findings were that, while electricity demand could rise substantially over time, during the first decade of adoption, utility companies can serve the energy and power needs of electric aviation with available capacity at existing substations close to the airports in our case studies. The actual charging experience at Washington airports during the first decade of deployment will provide much-needed information to allow for better forecasts of future electric demand than our current estimates.

Our forecasts of demand from electric aircraft over the next two decades had wide ranges. In this report we use the terms "scenarios," "forecasts," "projections," and "estimates" interchangeably, although in other contexts the word "forecast" carries connotations of greater precision than the words "scenario" or "estimate." This study did not have access to data about the charging patterns of electric aircraft that are in regular commercial use, as those data do not yet exist. Our estimates in this report are derived from published specifications from aircraft and chargers not yet deployed at scale, calculations derived from physical first principles, and evidence from electric automobile charging. Our forecasts of electricity usage therefore include a wide range of plausible scenarios for electricity demand over the next 20 years.

Notwithstanding this uncertainly, we expect that the two airports in this study can meet their charging needs in the next decade from the electricity available at their neighboring substations. After that, the lessons of the first decade of deployment will help determine when new substation, transmission, or generation capacity may be needed.

II. Factors that will Influence the Pace of Adoption of Electric Aircraft

Investments in electric aircraft companies provide one indicator of the size of the potential market that electric aircraft could serve. Deloitte (2022) reported that in 2021 companies designing eVTOL aircraft raised $5.8 billion in investment and that 350 companies worldwide were working on approximately 600 eVTOL concepts. Fixed-wing electric aircraft have not attracted as much attention and investment as eVTOL but have nevertheless seen a surge of innovation and new market offerings. Existing aircraft manufacturers such as Pipistrel and Diamond, as well as new companies such as Eviation and Bye, are introducing electric aircraft to serve short- and medium-haul trips. However, investor interest and excitement about the prospects for electric aircraft do not ensure their rapid adoption. The last 150 years of technology adoption shows that process can happen quickly or take many decades. Electric aviation confronts a specific set of risks that could impede its rapid growth. In this chapter we briefly review the historic adoption rates of new aviation and consumer technologies to provide a framework for modeling new technology growth and then turn to the specific risks confronting the companies working to build and sell electric aircraft and their services.

Technology Adoption Rates

The classic theory of technology diffusion (Rogers, 1995) is that new technologies spread in the shape of a bell curve and that the customers at each stage differ. A small number of innovators go first, followed by early adopters, then early majority, late majority, and laggards. The adoption of smart phones, starting with Apple's first iPhone in 2007, followed this pattern, and most adults alive in the U.S. today can place themselves somewhere along this bell curve by thinking back to when they started carrying a computer with an Internet connection in their pocket. The cumulative distribution of the blue bell curve in Figure 1 results in an S-curve that measures the market share of new technology, as shown by the yellow curve.

This technology diffusion model has played out in aviation (Kar et al, 2010). The adoption of early jets into the airline fleet took 15 years and followed the familiar S-curve shown in Figure 2 that the technology diffusion model would predict. More recently, regional jets with 50 to 90 seats began commercial deployments in the early 1990s and were in widespread use by the mid-2000s, a 12-year diffusion cycle. The now familiar winglets on jets from Aviation Partners Boeing that help reduce fuel consumption also followed an S-shaped curve during the first decade of the 2000s. These three aviation examples saw S-shaped curves with an adoption cycle that spread over 8 to 15 years. The question for those planning airport facilities is whether commercial aircraft owners and general aviation pilots will adopt electric aircraft at a similar pace.

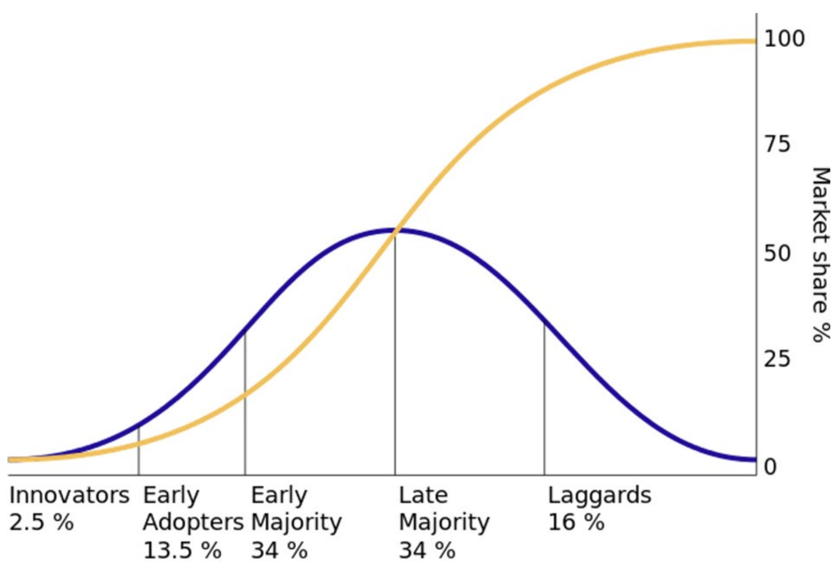


FIGURE 1. MODEL FOR DIFFUSION OF NEW TECHNOLOGIES

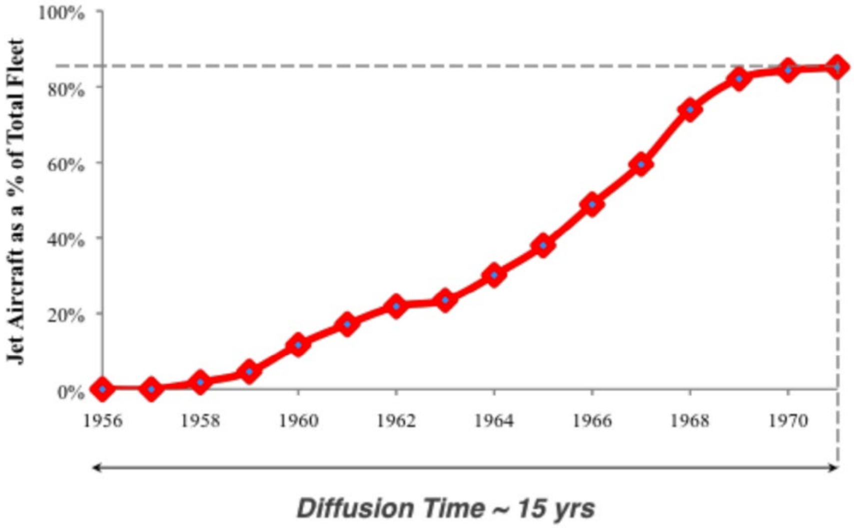
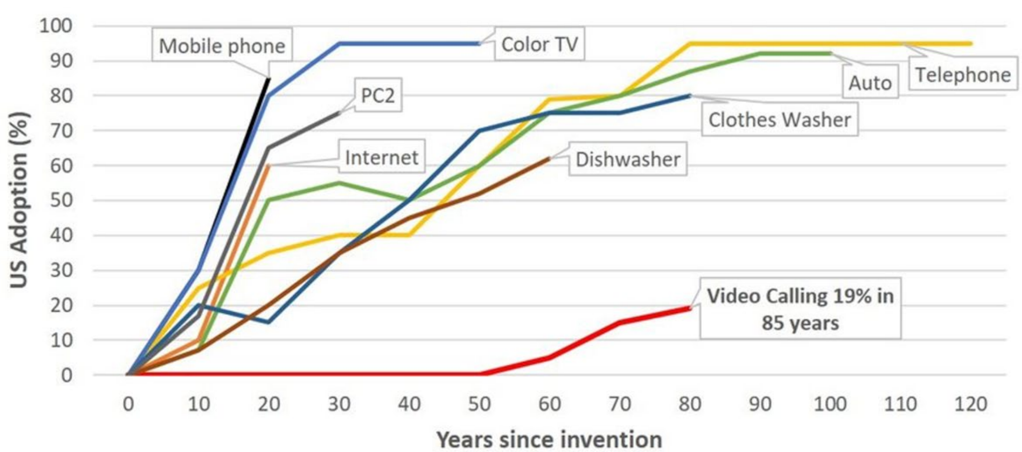


FIGURE 2. DIFFUSION OF EARLY JETS INTO THE AIRLINE FLEET (FROM ATA DATA VIA KAR ET AL. (2010))

Looking at the diffusion of technology in the consumer market, we can see that some innovations can take many decades to reach high levels of market penetration. Figure 3 shows many familiar household consumer technologies and the shapes of their diffusion curves. During the twentieth century technologies such as color TVs, dishwashers, clothes washers, and autos took 40 to 100 years to reach widespread adoption in households. The diffusion patterns have been more rapid with recent technologies such as mobile phones, Internet access, and home computers, reflecting a quickening of the pace of innovation and adoption. However, what is especially striking in Figure 3 is the long, slow diffusion of video calling technology, which was first introduced by AT&T Bell Labs as a subscription service in the 1920s. It wasn't until the COVID-19 pandemic of 2020, 100 years later, that video conferencing became ubiquitous for consumers and businesses. Whether electric aircraft follow the rapid adoption path of regional jets and winglets, or the long, drawn-out path of video conferencing will depend on how the industry manages its risks.



Source: David C. Evans, B*ottlenecks: Aligning UX Design with User Psychology,* 2017

FIGURE 3. ADOPTION RATES OF CONSUMER TECHNOLOGIES

Risks to Widespread Deployment of Electric Aircraft

If electric aircraft are adopted rapidly and widely, then regional airport managers will need to make investments in charging capacity. By the same token, airport managers want to avoid installing expensive equipment that is rarely or never used, so it's worth considering the risks to widespread deployment. Head (2021) provided a useful framework for thinking about the risks of electric aircraft adoption, which are summarized in Table 1. We used this framework to score the risks for fixed-wing and eVTOL aircraft on a three-point scale, and as described below, we found that while eVTOL designs could serve large new markets, they also carry more risks than fixed-wing aircraft.

TABLE 1. RISKS TO DEPLOYMENT OF ELECTRIC AIRCRAFT

Risk	eVTOL	Fixed-Wing
Technical	High	Moderate
Certification	High	Moderate
Infrastructure	High	Low
Operations	High	Moderate
Sociocultural	High	Low

Sources: Head (2021) and authors

Technology Risk

Building and operating safe and reliable eVTOL aircraft present daunting technical challenges. The aerodynamics of vertical lift are complex, especially as aircraft transition between hovering and wing-borne flight. Propulsion, energy storage, flight controls, and autonomous operations all present their own difficulties in creating a safe and functional aircraft. The technical challenges extend beyond building a viable prototype to include scaling production up to build a large enough number of aircraft to lower the unit costs, so the aircraft are financially viable in a commercial operation. Manufacturers must achieve safe and reliable aircraft performance and low production costs.

Technology risk is lower for fixed-wing aircraft because they can utilize knowledge developed for existing airframes and technologies. Indeed, aircraft such as the Pipistrel Alpha Electro are built around an existing airframe by replacing the liquid-fueled engine and fuel tank with electric motors and batteries. Fixed-wing electric aircraft still need to solve the technical challenges of battery performance and safety, integrating a complete electric powertrain, and providing safe and convenient charging options, but this is a shorter list of design challenges than that confronted by the developers of eVTOLs. For this reason, for technical risk we scored fixed-wing aircraft as moderate and eVTOLs as high.

Certification Risk

Gaining approval from the FAA to use a new airframe design to carry passengers is difficult and time-consuming. Federal regulators need to be convinced that designs employing new technologies are safe enough for the flying public, which means reviewing proof that any potential failure point is sufficiently robust alone and in combination with other aircraft elements to offer a safe flight. The FAA requires manufacturers to conduct ground and flight tests to evaluate the suitability of a new aircraft to provide passenger service. The FAA website on airworthiness certification (FAA) reports that approval of a new aircraft type to carry passengers can take between five and nine years. The crashes of two 737 MAX passenger jets within one year of certification increased pressure on the FAA to conduct yet more thorough and careful certification reviews. At the same time, the agency does not want to create overly burdensome regulatory roadblocks to promising new technologies. To better balance the tension between safety and timely deployment of new aircraft, the FAA in May 2022 announced that the agency was "modifying its regulatory approach" to providing airworthiness certificates for eVTOLs (Patterson, 2022). Although the FAA has promised that the changes will not introduce new delays, the industry must wait to see how this change in certification processes will affect the timelines for aircraft that were in the queue under the previous approach. At a minimum, the sudden change in the certification process for eVTOLs will increase the perceptions of uncertainty associated with gaining FAA approval (Hirschberg, 2022).

Because electric fixed-wing aircraft are similar to aircraft already certified as airworthy by the FAA, we judged them to have less certification risk than eVTOLs and scored the certification risks as moderate. Certainly, new battery and motor technologies on fixed-wing aircraft will require careful review by regulators, but the close resemblance to existing airframes, flight controls, and aerodynamics should make it easier and quicker to certify fixed-wing electric aircraft than eVTOLs, which we scored as having a higher risk for certification.

Infrastructure Risk

Two types of infrastructure are needed for electric aircraft to serve commercial and general aviation: ground infrastructure and airspace management systems. Piloted electric aircraft will use existing facilities, and today's voice-based air traffic control (ATC) system will allow them to fly into many established airports, many of which have excess capacity to serve more aircraft operations. Airports will need to add charging infrastructure, and this project showed that, at least for our case study airports, the electricity requirements for charging can be met from the local utilities' existing substations near the airports.

By contrast, even modest scaling of urban air mobility operations using eVTOLs will require significant new infrastructure investments. Cities will need well-designed vertiports in convenient locations to serve popular routes. Mims (2022) reviewed the challenges of building and permitting vertiports in existing cities; these included noise, lack of air space not already claimed by nearby airports, and the need to retrofit structures to accommodate the weight and size of electric aircraft, passengers, and charging gear. In addition, vertical-take-off-and-landing sites must be relatively free of surrounding structures now and in the future, which could require the purchase of expensive air rights in urban centers. Moreover, the projected high levels of operations using eVTOL could overwhelm existing air traffic control systems, requiring new regulatory approaches to managing air space. For these reasons, we scored infrastructure risk for eVTOL as high, in contrast to low for electric fixed-wing aircraft that will use existing airports.

Operations Risk

Manufacturing and operations have separated into separate businesses in the modern aviation industry. In the early 20th century, Boeing both manufactured airplanes and ran an airline, but by 1934 those businesses separated, and the air carrier business became United Airlines. Several eVTOL developers are following the early Boeing model to both build and fly their aircraft, which involves two distinct, complex business enterprises, each demanding specialized expertise. Although there are some synergies, operating both businesses requires more human resources and capital, as the companies must design, build, certify, and scale production of innovative aircraft while also executing marketing plans, developing customer-facing booking systems, and standing up other hardware, software, and personnel systems required for delivering passenger and cargo service. By contrast, the leading fixed-wing electric aircraft manufacturers are focused on building and not operating their aircraft. Those commercial air services that already fly passengers and cargo and that are planning to adopt electric aircraft will have plenty to learn about how to deliver safe and reliable services using electricity, but that learning will happen in companies with a track record of service using existing aviation technologies. We judged the operations risk as moderate for the early adopters of electric fixed-wing aircraft but certainly lower than the operations risk of some of the eVTOL companies.

Sociocultural Risk

If electric aircraft replace existing fixed-wing operations with significantly quieter and cleaner vehicles, public sentiment is unlikely to shift against them even if those electric flights are more frequent than their fuel-powered predecessors. However, the public may react negatively to eVTOLs flying over densely populated metro areas. In many communities, eVTOLs will have to overcome the negative associations created by helicopters and drones, which are viewed by some as noisy, disruptive, and invasive. As Head (2021) noted, “To secure the necessary permissions for urban air mobility operations and infrastructure, proponents will need to persuade a broad range of stakeholders that eVTOL aircraft will benefit the community at large, not just the privileged few.” The manufacturers of eVTOLs promise much quieter operations than helicopters, but the category carries higher potential for public opposition than that of fixed-wing electrics.

We reviewed these five categories of risk to underscore the uncertainty inherent in any forecast about the pace of adoption of electric aircraft. Electric aircraft companies seeking investor funding have acknowledged these risks and have developed narratives about how they can overcome them. These companies can manage their own technology development and aircraft production risk, but for at least three of the five risk categories, key obstacles to widespread adoption lie beyond the direct control of the companies developing electric aircraft.

III. Electric Aircraft Technologies Entering the Market

Aircraft Types

To project future charging demand, we need to understand how much energy different electric aircraft can store, how quickly they charge, and how far they can fly. Table 2 summarizes the prototypical aircraft we used to model future energy demand and the public data we found about their peak power demand, maximum range, and cruise speed. We grouped the aircraft into operations categories that allowed us to use existing FAA data on aircraft operations to make projections.

TABLE 2. REPRESENTATIVE ELECTRIC AIRCRAFT ENTERING THE U.S. AVIATION MARKET*

Operation category	Category of available electric aircraft	Model(s)		General information	Power demand [kW]	Max. range [mi]	Cruise speed [mi/hr]	Source
General Aviation (local and itinerant)	**2-seat fixed-wing trainer**	Pipistrel	Alpha Electro	- First introduced in 2015 - Optimized for local flights - Received FAA Special Airworthiness Certificate in 2018	50 (cruise) 60 (peak)	-	-	Pipistrel
		Bye Aerospace	eFlyer 2	- First flight in 2018 - FAA certification targeted for end of 2022	110	253	83	Bye Aerospace, FutureFlight
eVTOL	**4-seat eVTOL commuter**	Joby Aviation		- 1 pilot, 4 riders - 6 motors - Targeting FAA Part 135 Air Carrier Certificate	-	150	117	Joby Aviation
		Wisk Aero	Wisk Cora	- Designed to (eventually) be autonomous - 12 independent rotors	-	62	100	Wisk, Electric VTOL News

Air Taxi	**9-seat fixed-wing commuter**	Eviation	Alice (Commuter version)	- First flight in Sep. 2022 - 2,500 lb. maximum payload - 2 motors with 640 kW peak power each	1,280 (peak)	506	289	Eviation

* Compiled from publicly available information; dash (-) indicates no information could be found.

Our main criteria for selecting these aircraft were the availability of public performance data and our ability to map them to existing categories of operations. In the case of eVTOLs, which did not correspond to an existing operating category, our single criterion was the availability of performance data. For the general aviation and eVTOL categories with two aircraft, we averaged them for modeling purposes.

General Aviation

In the general aviation category, we selected a pair of two-seat, fixed-wing aircraft, shown in Figure 4. The Alpha Electro from Pipistrel and the eFlyer 2 from Bye both are targeting the market for training new pilots. These planes are designed to offer flight schools lower operating and maintenance costs, and the approximately 60-minute flight time per charge matches the length of a typical instructional flight. Bye predicts that its eFlyer trainer will reduce the flight operations cost to one-fifth that of the gas-powered legacy fleet at flight schools. These aircraft seek to replace a training fleet of 11,000 conventional aircraft that averages almost 50 years old (Bye).

The planes are similar in size to a Cessna 150 two-seater, which is lighter and smaller than the average general aviation aircraft. Using smaller aircraft may bias our analysis to underestimate the charging requirements in this segment, but we addressed that potential bias by testing a wide range of future growth rates. These planes represent the early entrants into the general aviation market, and because they can potentially lower total cost of ownership for flight schools, they may see early uptake in that segment of the market.

FIGURE 4. PIPISTREL TWO-SEAT TRAINER
SOURCE: PIPISTREL WEBSITE.

FIGURE 5. BYE TWO-SEAT TRAINER
SOURCE: BYE WEBSITE.

ELECTRIC VERTICAL TAKEOFF AND LANDING

In the eVTOL category, we used data from Joby and Wisk. Both of these aircraft use propellers to take off and land vertically like a helicopter and then shift to using their fixed wing to provide lift when the aircraft moves horizontally through space. Electric energy use is highest during the takeoff and landing phases. This category does not exist in the existing airport data, so we used a different modeling approach, as discussed in Chapter V.

FIGURE 6. JOBY AND WISK ELECTRIC VERTICAL TAKEOFF AND LANDING AIRCRAFT
SOURCE: JOBY AND WISK WEBSITES.

Air Taxi

Air taxis provide interregional travel for passengers and cargo and represent a promising market for electric airplanes. For this category we used the performance information from the Eviation Alice, a new airframe design that can be configured for a pilot, co-pilot, and nine passengers or as a cargo plane. It has range of 500 miles and a cruise speed of 289 miles per hour, and it had its first test flight in September 2022. Notwithstanding the successful first flight, Eviation CEO Greg Davis said in an interview with *The Seattle Times* that certification to carry passengers would be delayed until 2027 to integrate new batteries and other design changes. Alice has a lightweight fuselage, and its novel shape is designed to provide additional lift to supplement the lift provided by the wings. Eviation claims significantly lower operating costs for the Alice. In August 2021, Eviation signed an agreement with DHL to sell 12 of the aircraft to provide cargo services, and in 2022 it announced a deal to sell 75 Alices to Massachusetts-based Cape Air.

FIGURE 7. EVIATION ALICE NINE-SEAT AIR TAXI

Charging Technologies

Electric aircraft manufacturers have largely adopted the charging standards developed for electric automobiles and trucks. The auto industry has two standards for the plugs used to fast-charge electric road vehicles (CHAdeMO and CCS Combo), with a third proprietary standard used by Tesla. The industry is also working to develop a higher power standard (Megawatt Charging System, MCS) plug that could deliver up to 3.75 MW of electricity. Like automobiles, aircraft may adopt a wide range of power levels for charging.

Level 1

Level 1 chargers use a standard 120-volt AC plug, and the vehicle has an onboard rectifier that converts the alternating current (AC) to direct current (DC) to charge the battery. Level 1 provides approximately 1 kilowatt of power and is too slow for most commercial aircraft uses. However, for private electric aircraft that are stored in hangars with existing 120-volt service, Level 1 may be a viable option for slow charging between infrequent flights.

Level 2

Level 2 chargers use a 240-volt AC circuit and can provide up to 20 kilowatts of power. Like the Level 1 chargers, Level 2 uses an onboard rectifier to convert the AC to DC for battery charging. These chargers have sufficient power to charge the two-seat trainers from Pipistrel and Bye. The aviation industry is developing different form factors for delivering this charging service. Some early chargers are mounted on hangar walls with long cords to charge aircraft either inside or at the hangar door. Others have developed rolling carts with charging plugs that are tethered to a long 240-volt power cord, which allows the charger to serve multiple aircraft locations.

DCFC

Direct current-fast charge (DCFC) systems can deliver from 20 kW to 350 kW of power. These devices convert alternating current to high-voltage direct current off the aircraft to quickly deliver high amounts of energy to the aircraft batteries. This is the technology required for timely charging of eVTOLs and air taxis. DCFC power is delivered using either a CCS Combo or CHAdeMO plug. Our modeling assumed that aircraft could charge up to a peak of 350kW.

As with Level 2 chargers, operators are experimenting with different form factors to make it easy to serve multiple aircraft. To make the economics of DCFC work, they need high utilization, so designers are using power allocation electronics to allow two airplanes to charge using the same rectifier. This requires a stationary charging area at an airport where planes go to charge for between 30 and 60 minutes. An alternative approach is a mobile battery truck that can drive to where aircraft are parked and charge them while they sit idle. This is even more expensive than stationary fast charging, but with high utilization it could make sense for some airports.

MCS

The National Renewable Energy Lab is working with industry partners to develop a new charging standard known as the Megawatt Charging System (MCS), which could charge at up to 3.75 MW to enable heavy-duty trucks, ships, and aircraft to charge quickly and safely. Industry partners are developing prototype chargers that are being tested, and the eventual result will be a standard that allows very rapid charging of high-energy aircraft, but this standard is still under development.

Aircraft Charging Networks

In the automotive sector, specialized firms that operate DCFC networks have emerged to meet the needs of electric car owners. These firms specialize in the design, delivery, and operation of charging networks and typically lease land at locations convenient for vehicle charging. Similar networks are likely to emerge for electric aircraft. Beta Technologies has ambitions to provide DCFC service at airports and has identified 60 sites as part of a network of charging locations to support electric aircraft. Beta is providing DCFC charging with up to 350 kW of power using either CHAdeMO or CCS Combo plugs in combinations of two, four, or eight plugs. Beta plans to adopt the MCS standard once it has been established.

Companies like Beta may be potential partners for regional airports looking to add charging services without taking on the responsibility of adding aircraft charging as a new line of business. Beta works with the local utility to bring in a separate meter and designs, installs, and operates the charging station on an airport property. Beta has several approaches to covering the capital costs of new charging infrastructure at airports. In some locations, the airports or fixed-base operators cover the full capital costs of installing the equipment, while in areas with high enough projected demand Beta may put up some or all the required capital and recover those capital costs with fees for charging.

IV. Airport profiles

Locations

The project sponsors at WSDOT asked our research team to focus on two regional airports, Paine Field and Grant County International Airport. Our goal was that the methods we developed for estimating future charging demand at these two facilities could be applied to other regional airports to forecast charging demand as the market for electric aviation grows.

Paine Field is located in the greater Seattle area approximately 23 miles north of Seattle (Figure 7). It serves as the manufacturing and testing center for Boeing's widebody aircraft, including the 787, 777, and 767. Paine Field also is home to a large general aviation community. Commercial air service by Alaska Airlines was launched at Paine Field in March 2019 to help relieve some of the congestion at SeaTac, the region's main airport hub.

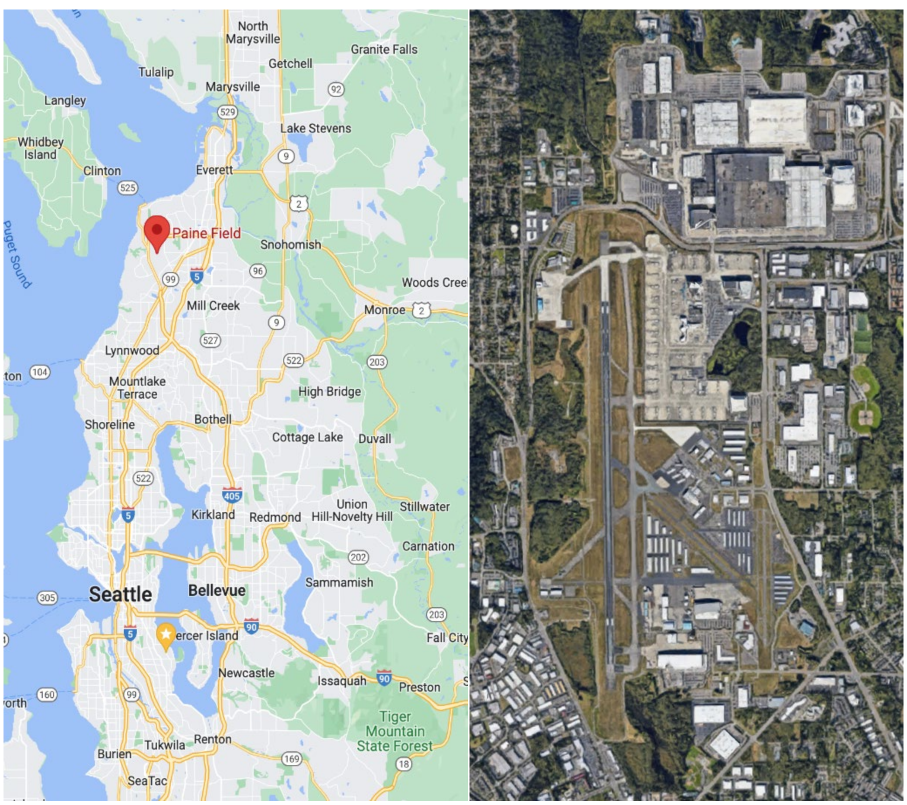


FIGURE 8 PAINE FIELD/SNOHOMISH COUNTY AIRPORT (PAE)
Source: Google Maps

Grant County International Airport is situated in rural, central Washington, approximately 140 miles (230 km) east of SeaTac (see Figure 8). It boasts one of the largest airfields in the United States; its five runways can accept takeoff and landings by the largest aircraft in the world. The airport has good weather for flying and is used frequently for military and commercial test flights, as well as training and general aviation. The airport does not currently have any regularly scheduled commercial flight service.

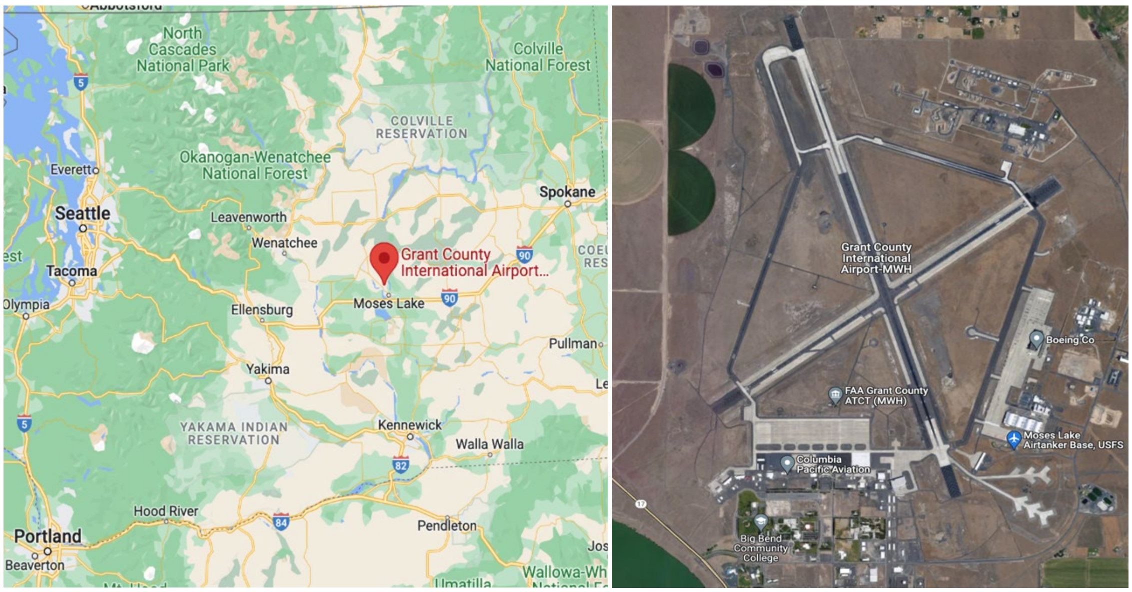


FIGURE 8. GRANT COUNTY INTERNATIONAL AIRPORT (MWH)
SOURCE: GOOGLE MAPS

Operations

Figure 9 shows the numbers of aircraft operations at the airports for the years 2015-2021, grouped by category. Paine Field served more operations on a total basis (nearly 140,000 in 2021), while Grant County International Airport had a more diversified spectrum of operation categories. At Paine Field, general aviation operations (local and itinerant) made up more than 94 percent of all airport operations, with air carrier being the third most frequent category. There was little military operation activity at Paine Field. At Grant County International Airport, general aviation comprised about 58 percent of all operations. In comparison to Paine Field, Grant had a substantially higher portion of air taxi operations, and military activity accounted for nearly 16 percent.

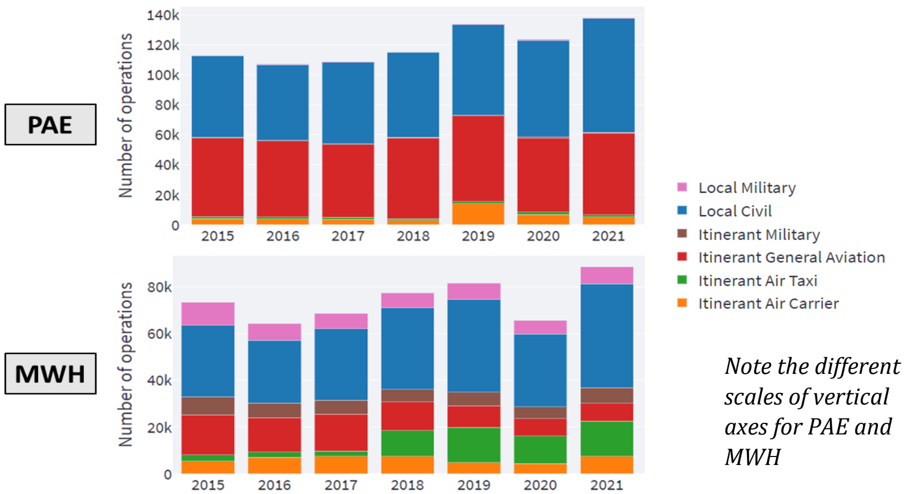
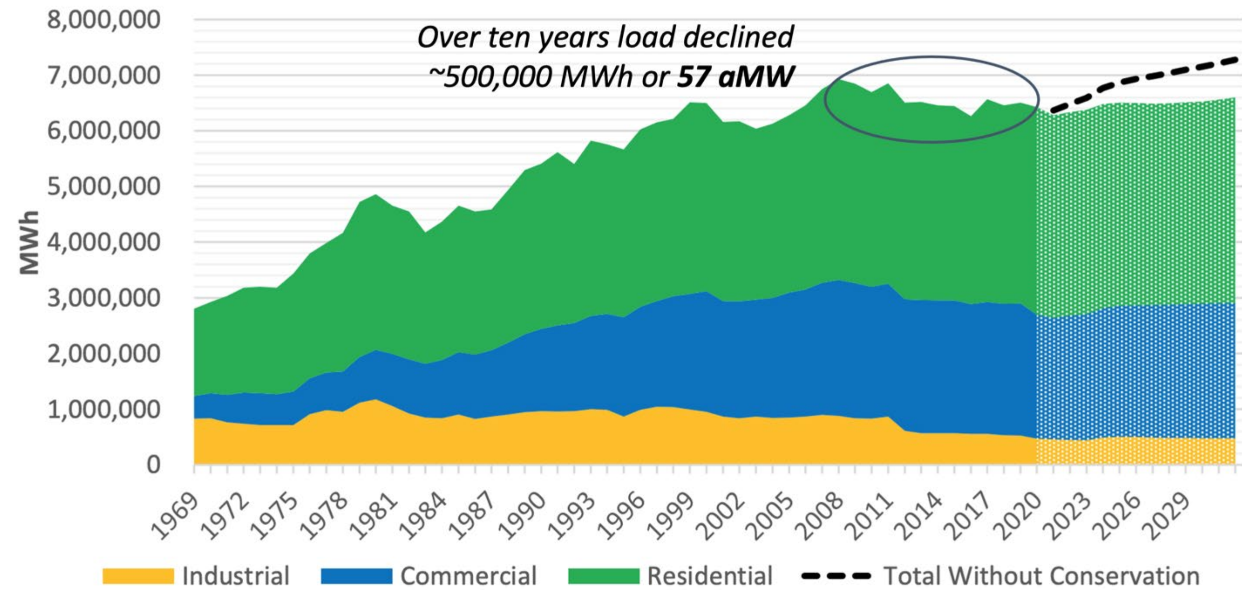


Figure 9. Numbers of aircraft operations at Paine Field (PAE) and Grant County International Airport (MWH): 2015-2021

This study focused on the ability of local utilities to meet the projected demand for electricity from electric aviation at the system level and at substations adjacent to the airports. For the systems perspective, we looked to the integrated resource plans for each utility which presented information on historic and projected energy use and described how the utility planned to meet future demand. Figure 10, from the Snohomish Public Utility District (SNOPUD) 2021 Integrated Resource Plan (SNOPUD, 2021), shows that since 2007 annual electricity demand has dropped by approximately 57 average megawatts. For the next decade, energy demand is not projected to regain the peak of 2007, in part because of energy conservation measures. From a system energy perspective, SNOPUD has seen a decline in average energy use and projects that electricity load will remain relatively flat. The SNOPUD system forecast accounts for the growth in electric vehicles by incorporating the results of a 2017 joint study entitled the "Economic and Grid Impacts of Plug-In Electric Vehicle Adoption in Washington and Oregon." Since that study was published, state and federal policies have created new incentives for buyers to adopt electric vehicles, and those policy changes, combined with recent consumer behavior and the steady growth of EV models on the market, may cause utilities to revise their electricity demand forecasts. However, at this time the best available information on future electricity demand is in SNOPUD's integrated resource plan.



Source: Snohomish PUD, *2021 Integrated Resource Plan*, Figure 2-4

FIGURE 90. HISTORIC AND PROJECTED SYSTEM LOAD AT SNOPUD

Grant County PUD has seen significant growth in demand for electricity in the last 20 years. Figure 11, from its 2020 Integrated Resource Plan, shows that its load increased by 300 average megawatts over 20 years, as large commercial and industrial customers took advantage of its abundant and low-cost hydropower. The PUD's Integrated Resource Plan (Grant PUD, 2020) anticipates an acceleration of demand that could add another 350 megawatts in a decade. Grant County's low-cost power attracted widespread interest from the cryptocurrency industry, which prompted the PUD to adopt new higher rates for those customers to account for the regulatory, business, and concentration risks associated with serving that particular group of customers. Lower rates and substantial additional energy capacity remain available for agriculture, manufacturing, and other commercial uses that align with the county's economic development goals.

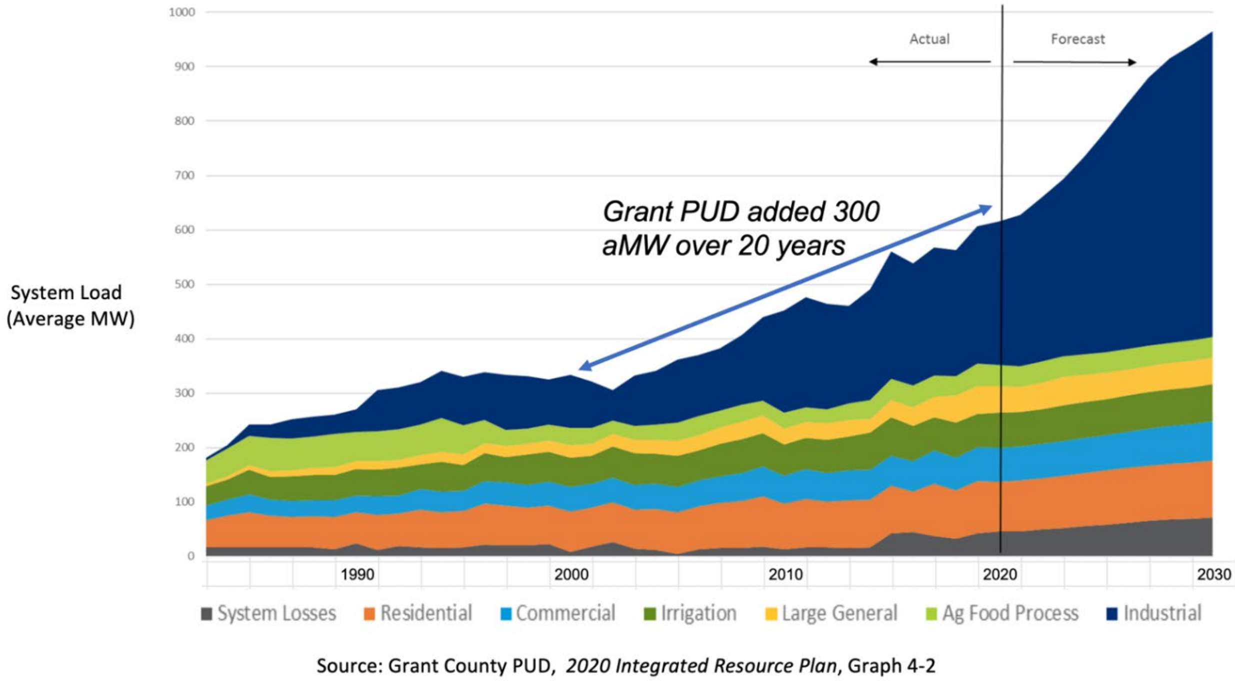


FIGURE 11. HISTORIC AND PROJECTED SYSTEM LOAD AT GRANT COUNTY PUD

We spoke with planning engineers at both PUDs regarding their ability to serve additional demand at the airport and learned that adding between 2.5 and 10 MW peak electrical capacity at a new commercial meter to allow for aircraft charging would not place any special burden on the utility. Adding power at this level is done in the normal course of business and would not require special planning efforts, and the energy could be provided from nearby substations close to the airports' buildings and hangars. Staff from the utilities and airports noted that both facilities have ready access to one or more utility substations that have sufficient electrical capacity available to meet incremental demand in this range. Additional peak power demand above 10 MW could require more planning but would not present a significant obstacle should that level of capacity be needed.

V. Modeling the Growth of Electric Aircraft

Data to Support Scenario Development

The FAA defines operation categories for tracking purposes (Federal Aviation Administration n.d.). Three of these categories represent viable, near-term markets for electric aircraft:

- Local Civil: Operations performed by civil (private or commercial, non-military) aircraft that operate to or from the same airport within a 20-miles radius of the airport.
- Itinerant General Aviation (GA): Operations performed by all civil aircraft, except air carriers or air taxis, that land at an airport arriving from outside the airport area or depart from an airport and leave the airport area.

- Itinerant Air Taxi (AT): Operations performed by all aircraft with a 60-seat maximum or 18,000 lb. payload maximum capacity, carrying passengers or cargo for hire, that land at an airport arriving from outside the airport area, or depart from an airport and leave the airport area.

In addition, we defined a fourth category, eVTOL , as follows:

- eVTOL: Operations of electric aircraft with the ability to take-off and land vertically, used for urban air mobility applications. This is not an FAA-defined operating category at this time.

We excluded the FAA Air Carrier and Military categories because they involve either long-haul passenger trips or military uses that presently lack any all-electric alternative to conventional, liquid-fueled aircraft in the development pipeline. Table 2 shows how we mapped our set of prototypical electric aircraft to these categories.

Forecast Methods

Potential future electricity demand at the two study airports was estimated for the different operation categories and different aircraft electrification scenarios. This section describes the dimensions of analysis and the underlying approaches and sources to quantify them. Given the nascent stage of the electric aircraft market, multiple estimates relied on assumptions informed by the authors' domain knowledge and general literature review, rather than observed charging behavior.

Dimensions of Analysis

- <u>Airport (a):</u> The analysis was conducted for two Washington airports: Paine Field/Snohomish County Airport (PAE) and Grant County International Airport (MWH) at Moses Lake.
- <u>Operation category (c):</u> The electricity demand was estimated for each of the considered flight operation categories listed above. Each category featured unique distributions of aircraft size and typical flight ranges, which affected the electric power demand. One operation was either a take-off or a landing at the respective airport.
- <u>Number of operations growth scenario (o):</u> Three growth scenarios for the numbers of operations for each operation category and at each airport were considered in this analysis (low, medium, and high). The scenarios were based on projections presented in WSDOT's "Washington Electric Aircraft Feasibility Study" (WA EAFS) from 2020 (WSP 2020). The associated growth rates ranged from, on average, 1.9 percent (low growth) to 3.3 percent (high growth) for general aviation, and from 5.0 percent to 8.0 percent for the air taxi category, varying by the year. Because the Local Civil category was not explicitly included in the WA EAFS, the General Aviation growth rates were used for this category.

The electrification of the existing airport operations was assumed to comprise two processes:

- Feasibility rate scenario (f): The technical feasibility to serve aircraft use cases with electric aircraft could develop at different possible paces. The three assumed scenarios varied by both the temporal lag until technical feasibility to start ramping up and the speed of that process.
- Adoption rate scenario (a): The adoption of electric aircraft on routes for which electric aircraft are technically feasible was also assumed to progress at different rates. The adoption rate was intended to capture both the temporal lag induced by aircraft operators, owners, and airlines for adopting such electric aircraft and the time it would take for the whole aircraft fleet to convert, based on electric aircraft adoption speed. The fact that this fleet turnover could take a considerable time and is largely uncertain is discussed in more detail below.
- Time (year) (t): This was the year for which the estimation of electricity demand was made. The growth rates in the WA EAFS are projected until the year 2039, so we stopped our scenario estimates in the year 2040.

Electricity Eemand Estimation

The chosen combination of the analysis dimensions' possible values determines the estimated total annual energy demand $E_{A,c,o,f,a,t}$ (in MWh) for electric aircraft operations. For the three operation categories existing today (Local Civil, Itinerant GA, Itinerant AT), the estimate is the result of the following calculation:

$$E_{A,c,o,f,a,t} = \frac{1}{2} \times (number\ of\ operations)_{A,c,o,t} \times (feasibility\ rate)_{c,f,t} \times (adoption\ rate)_{c,a,t} \times E_c^{flight} \quad (1)$$

Here, E_c^{flight} corresponds to the energy demand (in kWh) for one average flight (different for each operation category), calculated as the product of average power demand and flight duration:

$$E_c^{flight} = (average\ aircraft\ power\ demand)_c \times (average\ flight\ range)_c \ / \ (average\ cruise\ speed)_c \quad (2)$$

The factor $\frac{1}{2}$ in equation (1) stems from the fact that each electric aircraft needs to only be recharged for each take-off, which is very well approximated by half the number of operations (take-offs and landings).

From the total annual energy demand, the average power demand $P_{A,c,o,f,a,t}^{average}$ (in kW) can be derived as follows:

$$P_{A,c,o,f,a,t}^{average} = E_{A,c,o,f,a,t} \ / \ (365 \times 24\ hours) \quad (3)$$

For utility providers and the airports as electricity rate payers, the peak power demand or capacity (in MW) is relevant to prepare for substantial increases in demand and to provide sufficient electrical service. To obtain an estimate for the peak power demand $P^{peak}_{A,c,o,f,a,t}$, the average power demand is multiplied with a seasonality factor (capturing the higher number of flight operations in the summer months than in winter), a charging curve factor, and a factor representing the daily charging pattern:

$$P^{peak}_{A,c,o,f,a,t} = P^{average}_{A,c,o,f,a,t} \times (seasonality\ of\ operations)_{A,c} \times (charging\ curve\ factor) \times 24\ hours\ /\ (charging\ window) \quad (4)$$

eVTOL operations do not exist today, meaning that we could not use the same methodology for eVTOL as for the existing airport operations. Instead, we estimated the number of potential annual eVTOL trips from Paine Field to the SeaTac airport based on the existing travel volume from the area around Paine Field (land area within a 10-mile radius) to SeaTac (estimated to be around 1.1 million trips/year, based on the annual number of passengers at SeaTac and the percentage of the Washington population that lives in the Paine Field catchment area). For the initial eVTOL market, we assumed that only residents with an annual household income of $200,000 or more would be willing to take an eVTOL aircraft to travel from Paine Field to SeaTac because those high-income households would be willing to pay for the time savings provided by an eVTOL. We used these households' share of all households and high-income households' increased propensity for air travel (23 percent of air travelers have an income of $100,000 or more per year, representing only 15 percent of all Americans); see Brandon (2013) to calculate the share of trips between Paine Field and SeaTac that are from high-income households. Assuming Joby Aviation's estimate of an average occupancy of 2.3 passengers per trip (Joby Aviation 2021), we yielded a potential market size of about 215,000 annual eVTOL flights between Paine Field and SeaTac (both ways). The segmentation of eVTOL estimates into different growth scenarios was based on the assumptions of (1) a temporal lag until the maximum growth rate is achieved (operations growth), (2) a year in which regulatory certification for eVTOL operations is achieved (feasibility), and (3) a maximum achievable market share of the potential market size (adoption).

The specific assumptions are listed in Table 3. As described earlier, we did not forecast eVTOL flights from Grant County International Airport to SeaTac under the assumption that such flights would be captured in our forecast of the electrification of the existing air taxi category. All input variables used in the above equations are summarized in Table 3.

TABLE 3. ASSUMPTIONS FOR EVTOL GROWTH SCENARIOS

Analysis	No. of ops.	Feasibility	Adoption

dimension	growth		
Parameter	Years until maximum growth (t_0 in Eq. 5)	Start year for eVTOL ops.	Share of potential market
Low	10	2040	35%
Medium	8	2035	50%
High	5	2030	85%

A visual representation of the combined methodology for existing airport operations and the new eVTOL operations is provided in Figure 12.

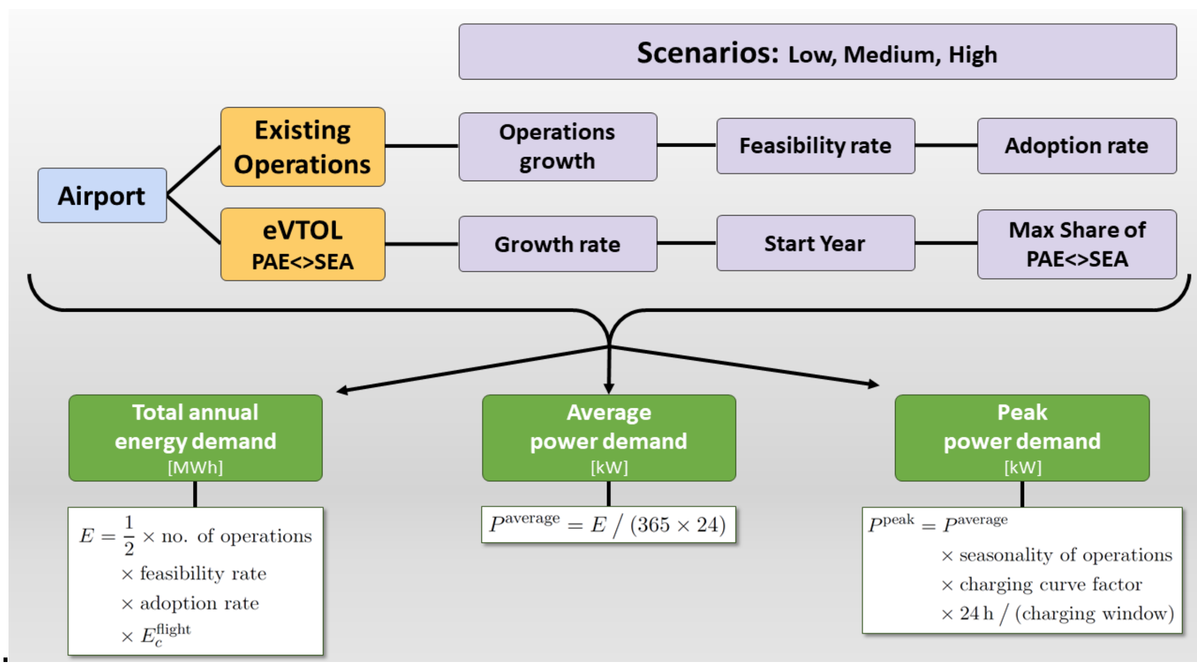


FIGURE 2. SUMMARY SCHEMA OF FORECASTING METHOD

The underlying assumptions for each of these inputs were as follows:

- $(number\ of\ operations)_{A,c,o,t}$: The numbers of operations at each airport and for each operation category were derived from the three-year average of the numbers of operations between 2019 and 2021. These numbers were taken from the FAA's Operations Network

OPSNET, which reports counts of airport operations as recorded by the Air Traffic Activity System (ATADS) (Federal Aviation Administration n.d.). For each year starting with 2023, the growth rates found in the WA EAFS (WSP 2020) were applied to the previous year's numbers of operations, for each of the three growth rate scenarios. We used the 2019-2021 average as the baseline because the COVID-19 pandemic caused a substantial disruption in the trend in operations at the two studied airports, especially in 2020 (-20 percent total operations at Grant County International Airport and -10 percent at Paine Field, with a rebound in 2021 to numbers above the pre-pandemic values).

- $(feasibility\ rate)_{c,f,t}$: We estimated the technical feasibility of electric aircraft to serve existing aviation operations by using a combination of estimates of battery technology improvements (currently the most constraining factor for electric aviation (Viswanathan et al. 2022)) and a frequency distribution of flight distances for single-engine and multi-engine aircraft. In research and industry, a variety of estimates exists for technological advancement in battery technology. With a typical maximum achievable energy density of around 200 Wh/kg today, projections range from a 20 percent increase in energy density by 2030 (Reuters 2022) to potentially more than 600 Wh/kg that year on the high end of estimates (Viswanathan et al. 2022). In addition, there is uncertainty among experts as to which battery chemistries are the most promising in terms of energy density potential (Gao et al. 2021). For the medium scenario, we used a projection of a linear 50 percent increase in battery energy density over 10 years (slow scenario: 30 percent, fast: 70 percent). This would improve the electric range of single-engine (multi-engine) aircraft from about 250 mi (506 mi) today to an estimated 400 mi (810 mi) in 2035 (and to 348 and 703 mi in the slow scenario, and to 478 and 966 mi in the fast scenario for single- and multi-engine aircraft, respectively). We further assumed certification of appropriate electric aircraft for general aviation and air taxi flights by 2026 (slow: 2028, fast: 2024), and thus no electric flight operations before that. Lacking any more recent, complete data on typical distances of flights (by operation category), we leveraged a 2001 NASA study to estimate flight lengths (in miles) of single-engine and multi-engine aircraft (Long et al. 2001). Assuming that the flight distance distribution (Weibull-shaped) has not changed substantially since then, the share of technically feasible flight operations for electric aircraft is given by the integral under the Weibull distribution of flight distances until the maximum achievable flight range in each year. We assigned air taxi operations the multi-engine range trends and used the single-engine projections for general aviation flights (local civil and itinerant GA). Following this methodology, Table 4 shows the resulting years in which the feasibility rate would reach a threshold of 95 percent of all flight operations. Figure 13 depicts the estimated feasibility rate in the medium scenario. Here, certification was assumed to occur in 2026, and the majority of flight operations were found to be feasible immediately because of the Weibull-shape of the distribution of flight distances.

TABLE 4. ASSUMPTIONS ABOUT PERFORMANCE, FEASIBILITY, AND ADOPTION OF ELECTRIC AIRCRAFT

Operation category	Year in which **feasibility** reaches 95%			Year in which **adoption** reaches 95%			**Average aircraft power demand**	**Average flight range**	**Average cruise speed**	E_c^{flight}
	Fast	Medium	Slow	Fast	Medium	Slow	**[kW]**	**[mi]**	**[mi/hr]**	**[kWh]**
Local Civil	2043	2052	>2052	2035	2040	2047	80	63	83	61
Itinerant GA	2043	2052	>2052	2037	2044	2051	110	253	83	335
Itinerant AT	2029	2032	2038	2037	2044	2051	680	350	289	822
eVTOL (PAE)	-	-	-	-	-	-	200	40	108	74

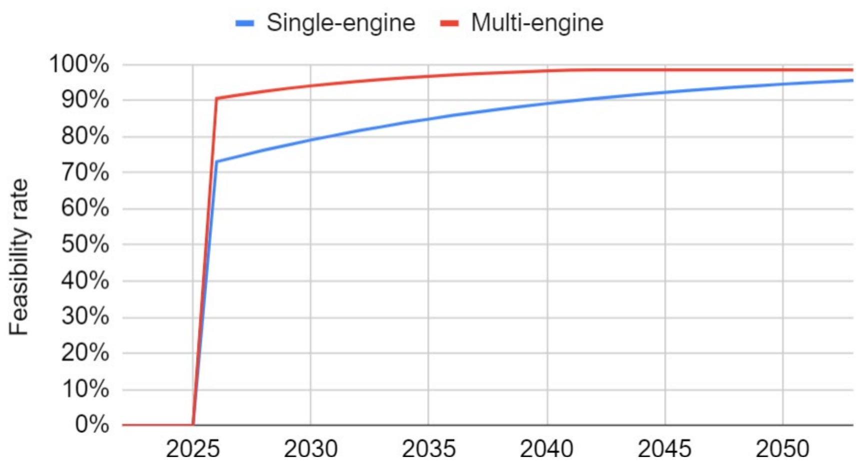
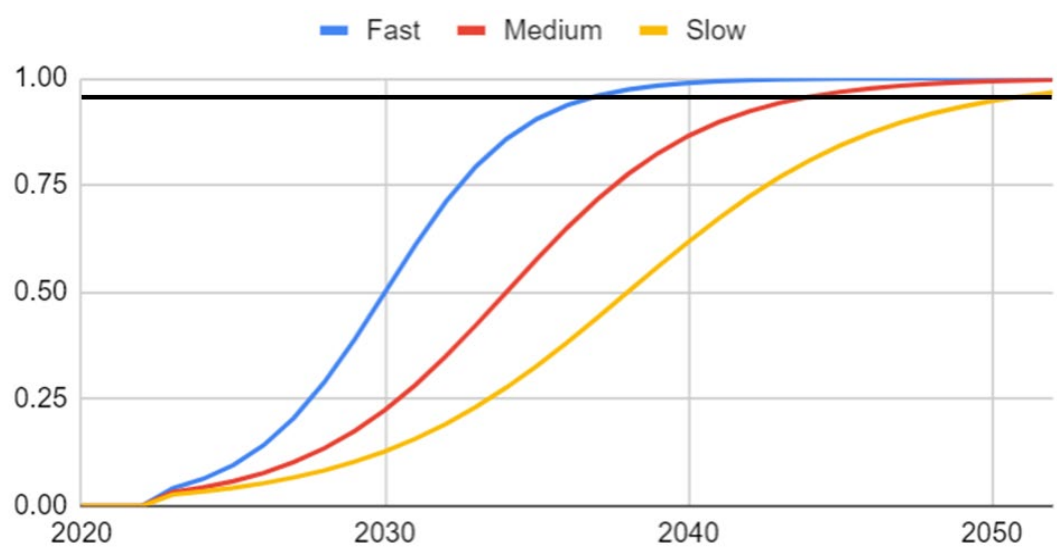


FIGURE 3. SHARE OF FLIGHT OPERATIONS THAT ELECTRIC AIRCRAFT COULD FEASIBLY SERVE OVER TIME

- $(adoption\ rate)_{c,a,t}$: The penetration of electric aircraft on the aviation market was assumed to follow an S-shaped adoption curve, as has been observed and modeled in many cases of new vehicle technologies before (e.g., Zoepf and Heywood 2012). The adoption rate of existing aircraft operations was estimated by using the logistic function

$$p(t) = \frac{1}{1+e^{-g\times(t-2022-t_0)}}, \quad (5)$$

where g determines the maximum growth rate and t_0 is the temporal lag (years from 2022 until the rate reaches 50 percent). The two variables g and t_0 were assumed to reasonably capture the large level of uncertainty around how soon and how quickly the electric aviation market will replace conventional aircraft. Table 4 lists the years in which the adoption rates were assumed to reach 95 percent (thus an almost complete market penetration) under the different scenarios (fast, medium, slow). The adoption of electric aircraft on flights that could be feasibly served by electric was assumed to be driven by multiple factors, most of which are highly uncertain. Regulation could determine how quickly public aircraft fleets or flight schools will have to transition to electric aircraft. Private aircraft for general aviation have historically had very slow turnover rates (the FAA estimates the average age of active GA aircraft at about 40 years (Harrison 2018)), since owners tend to stick with the working aircraft, especially when they only use them infrequently. Higher upfront purchase prices for electric aircraft might also slow the rate of adoption of such aircraft, as the potential cost savings from operations and maintenance would not outweigh the price premium as quickly. In general, even with accelerated adoption of electric aircraft, it would take time for the entire fleet to turn over. Our estimated adoption rates thus represent a large span of possible developments, with 95 percent adoption levels reached as early as 2035 (Local Civil, fast scenario) or 2051 (GA and AT, slow scenario), as shown in Table 4. Figure 14 shows the resulting adoption rate curves, by way of example, for the General Aviation category.



A 95 percent threshold is shown with the black horizontal line. The intersections of the curve correspond with the years shown in Table 4.

FIGURE 4. ADOPTION CURVES FOR ELECTRIC AIRCRAFT IN GENERAL AVIATION OPERATIONS

- $(average\ aircraft\ power\ demand)_c$, $(average\ flight\ range)_c$, $(average\ cruise\ speed)_c$: The average power demand, flight range, and cruise speed during one typical flight were estimated separately for each operation category. The estimate relied on publicly available data on the different electric aircraft (that are commercially available or still under development), assigned to the operation categories in which they would realistically be used (see Table 2). For instance, the Pipistrel Alpha Electro can be used for GA purposes (local and itinerant), whereas the Eviation Alice, as a nine-seat commuter, will serve Itinerant Air Taxi trips. In addition, for the flight range and cruise speed, estimates were revised and confirmed by using findings from NASA's Small Aircraft Transportation System Demand Model study from 2001 (Long et al. 2001). The average aircraft power demand for air taxi services was estimated at 680 kW, combining information on peak power capabilities of the Eviation Alice and a similar electric aircraft model (Bye Aerospace eFlyer 800, take-off power demand of 750 kW (Lincoln 2022), as well as the Eviation Alice's planned battery capacity (820 kWh). The values found and used for the subsequent electricity demand estimates are also shown in Table 4. While each quantity assumes values varying greatly from one flight and aircraft model to the next, we emphasize that the average of these variables' individual values for all annual operations will determine the annual energy demand and thus the desired outcome variable.

The assumptions for the three input variables used for the calculation of the peak power demand were as follows:

- $seasonality\ of\ operations$*:* The seasonality was calculated by using past numbers of operations (for 2015-2021, taken from the FAA's OPSNET data) at both studied airports. Peak monthly operations were typically found in July and were about 70 percent higher than the annual average monthly operations.

- $charging\ curve\ factor$*:* The recharging cycle of an electric battery does not follow a linear increase in the battery's state-of-charge (SOC) over time. Instead, charging power tapers towards the end of the charging cycle (Trivedi et al. 2018). On the basis of the available literature (Battery University 2021) as well as data found by automotive battery testers (InsideEVs 2021a), the peak charging power of an average direct-current fast charging process is about 80 percent higher than the average over the entire charging process (20 to 80 percent state of charge). Specifically, this value was confirmed in a charging analysis of the 2021 Tesla Model S Plaid road vehicle (350 kW peak power, compared to 137 kW averaged over the charging duration) (InsideEVs 2021b). On the basis of direct communication with electric aircraft manufacturers, the industry appears to be aiming for high-power fast charging of their aircraft in between flight operations (e.g., within one hour at 350 kW peak power), which highlights the importance of considering the charging curve factor as described. We recognize that this assumption further relies on the type and size of battery used and is subject to changes based on future advancements in battery and charging technology.

VI. $charging\ window$*:* The charging pattern of electric aircraft has the potential to significantly determine the potentially required electrical capacity. If all charging on a given day is assumed to be equally distributed over 24 hours, then electrical capacity needs are given by the average power demand. However, if all charging occurs within only eight hours of the day, then the peak power demand effectively triples, since the same amount of energy needs to be transferred to the different aircraft in only a third of the time. The authors deemed eight hours a reasonable assumption, based on a typical workday's duration and direct communication with aircraft manufacturers and airport operators; however, the methodological framework allows for a modification of this parameter to allow users to test different charging patterns. **Findings From Electrification Scenarios**

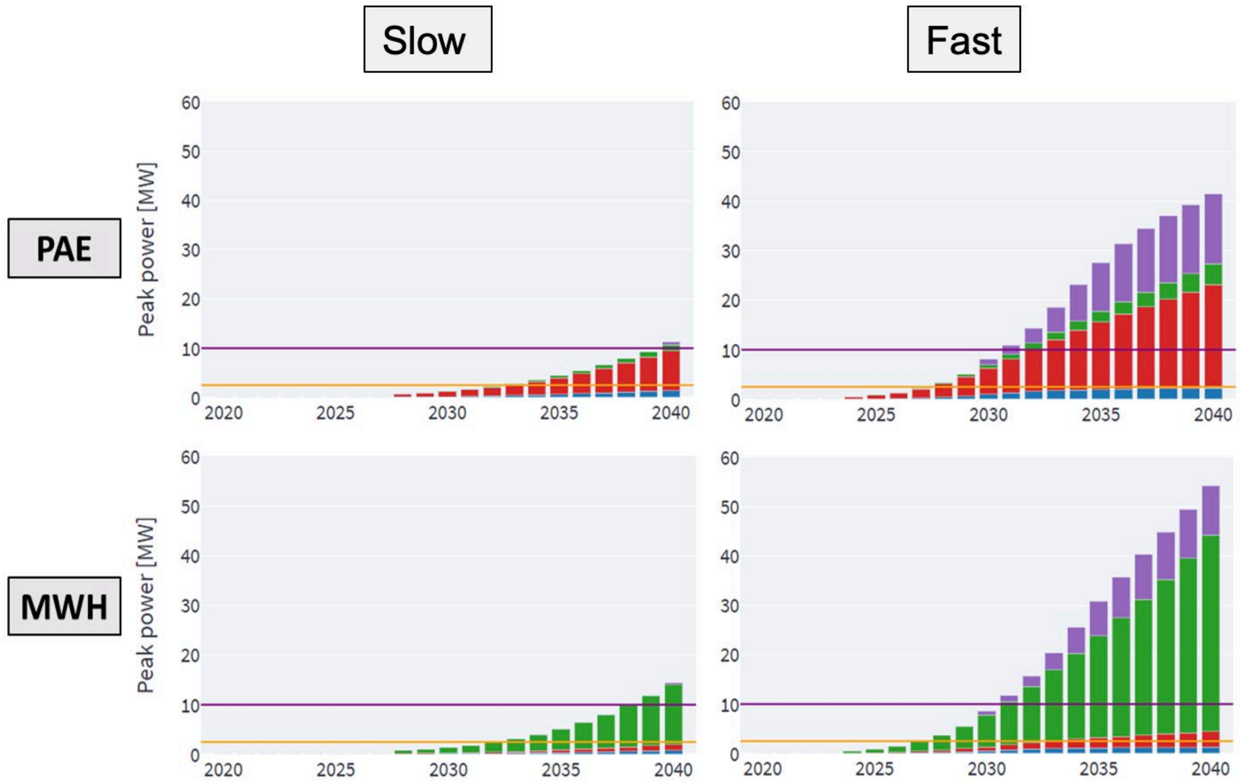
Electricity demand projections

When we translated the projected numbers of operations and various assumptions about the electrification rate of these operations into electricity requirements, the annual energy demands varied greatly, depending on the chosen scenario composition and owing to the uncertainties associated with the nascent stage of the electric aviation market. Using the medium scenarios for operations growth, feasibility rate, and adoption rate, we found that the annual energy demand to support electric flight operations at Paine Field could be as high as 19,000 MWh by 2040. The majority (77 percent) of that can be attributed to general aviation (10 percent local and 67 percent itinerant) operations, in line with the very high share of GA operations at Paine Field. At Grant County International Airport, air taxi operations accounted for more than 84 percent of the nearly 28,000 MWh of annual electricity demand for 2040 projected in the medium scenario. This was the combined result of AT operations (1) making up for a relatively large portion of projected operations for that year (54 percent) and (2) being associated with considerably larger energy demands for each flight operation because of the typically larger flight distance and higher aircraft power.

Figure 15 shows the annual electricity demands converted into estimates for the peak power demand (in MW), following equations (3) and (4), for all scenarios set to low (shown on the left) and high (right). As can be seen, the estimated peak power demands at the two airports were not projected to exceed 10 MW before 2030, even in the highest of all deployed scenarios. This is relevant for both the local utilities and the respective airport managers because such capacity increments can be provided in the normal course of utility business. After the first electric flight operations have begun, and data and experience have been gathered regarding typical charging practices, electric flight distances, and the suitability of electric aviation for different aviation use cases, planners will be able to make much more informed projections about electricity demand from electric aircraft in the 2030s and beyond.

The pace at which commercial air taxi services at Grant County International Airport start electrifying their fleets will largely determine the overall future electric capacity needs at that airport. Historically, the airport has been heavily utilized for testing new aircraft, equipment, and other technologies (Port of Moses Lake 2022). This could put the facility in a unique position as a forerunner for electric aviation, especially in terms of testing new aircraft.

The extent of eVTOL operations and their electricity demand will largely depend on whether private operators can overcome the risks associated with eVTOL deployment and whether there is sufficient projected demand to warrant investment in eVTOL ground facilities at the Paine Field and SeaTac airports.



The golden and purple horizontal lines denote thresholds of 2.5 and 10 MW, respectively.
Figure 105. Peak power demand (MW) for electric aircraft by operation category

From these results, we can conclude that **the provision of sufficient electrical service down to the substation level at the two studied airports will not likely be the main bottleneck for the adoption of electric aircraft in the next decade**. After that, the electricity needs for electric aviation are highly uncertain, resulting in wide ranges between our low and high estimates. Consistent, detailed, proactive data collection as electric flight operations begin will allow for more informed estimates of electric energy and power demand in the future.

On-Line Electrification Scenario Tool

This project included the development of an interactive tool that is available at https://electric-aviation.streamlit.app/ to explore the electricity demand projections made in this study. The corresponding GitHub repository can be accessed at this link: https://github.com/s-t-lab/WSDOT-Electric-Aviation. The tool utilizes the Python Streamlit package (Streamlit Inc. 2022), allowing users to dynamically update projections based on their chosen scenarios. Figure 16 shows a screenshot of the tool.

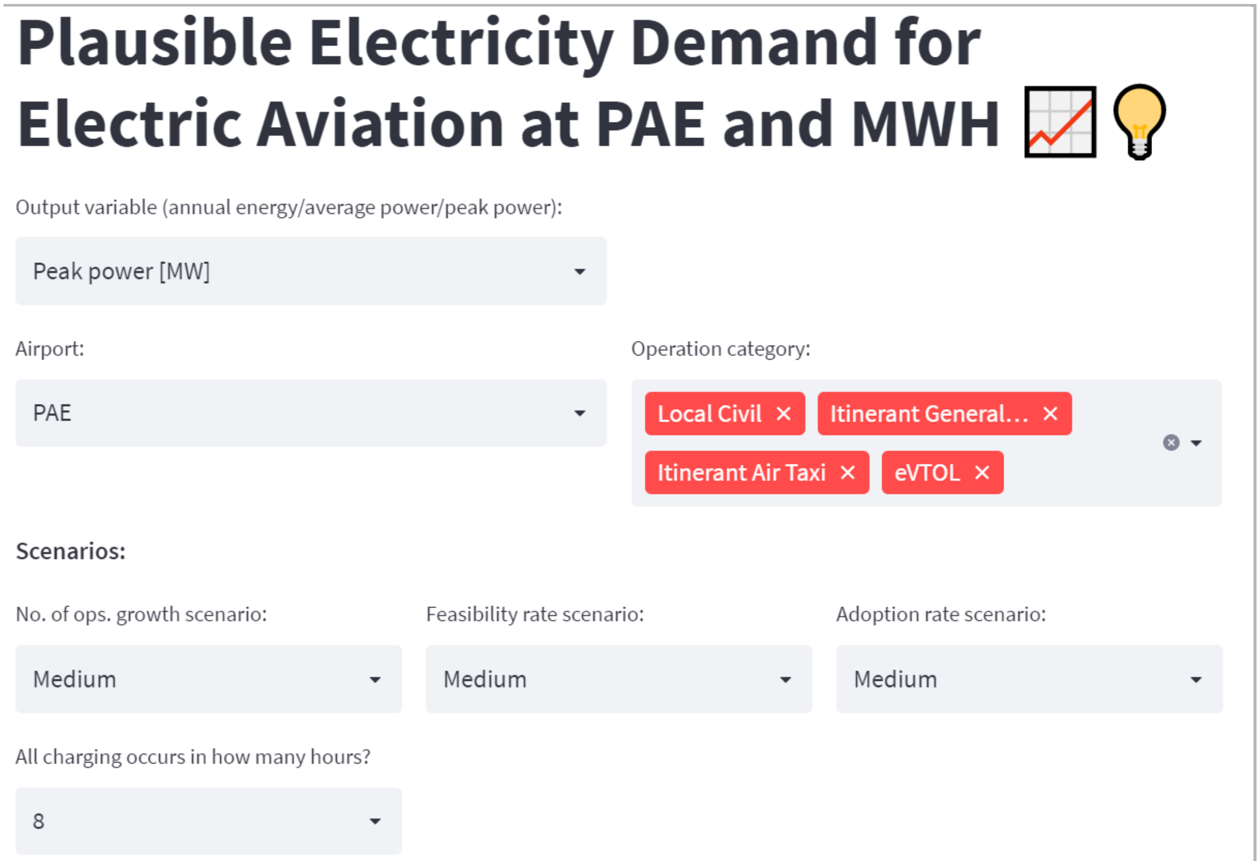


FIGURE 6. SCREENSHOT OF INTERACTIVE ELECTRIFICATION SCENARIO DEVELOPMENT TOOL

VII. Steps Airports Can Take to Support Electric Aviation

Our analysis showed that a lack of access to adequate electric supply from local electric utilities is unlikely to block early adoption of electric aircraft by regional airports. However, regional airports still need to take steps to prepare for aircraft electrification, should it take off. At a minimum, airport managers will want to track the early deployments of electric aircraft at other regional airports and share information about the opportunities and obstacles that emerge as the number of electric aircraft increase.

Airport managers wanting to lead in electrification should begin evaluating options for adding charging stations for electric airplanes as the market ripens. One approach is to engage companies offering network charging services for airplanes such as Beta Technologies, one of the early entrants into the market. Beta and other charging network operators that will target aviation have the domain knowledge to design, build, and operate charging facilities as part of airport ground operations. These companies will develop know-how about engaging the local utility and providing the needed service most cost effectively. Other business models for charging will no doubt emerge. Companies currently in the business of selling aviation fuel may at some point start to offer charging because they understand the local airport facility and can build on existing customer relationships.

In addition to learning about the players and options for providing aviation charging services, airport managers will want to pay attention to state and federal grant opportunities that may emerge for installing charging equipment. Federal and state policies currently provide financial incentives to shift autos and trucks from fossil fuels to electricity. Existing and future legislative programs may make new grant funds available for airports that choose to add charging equipment.

Another promising opportunity for regional airports is to encourage their flight schools to consider the new electric trainers as a cost-effective alternative to liquid-fueled aircraft. The companies marketing these new aircraft promise significant cost savings with modern, up-to-date airplanes. Given the recent shortage of trained pilots for commercial airlines, any effort to lower training costs and increase the supply of pilots would serve the broader aviation industry. Operating a small number of electric trainers would give flight schools and airports early experience in the practical realities of using electric aircraft day to day. Electric trainers to address the pilot shortage may also become a promising area for grants funds.

This project also surfaced unanswered research questions related to forecasting the growth of electric aircraft and their charging requirements. Sharing data about typical charging practices in the different operational categories could better inform future estimates on peak power requirements. A charging station's power requirements will depend strongly on the exact charging patterns for the electric aircraft in use. Private general aviation use cases, such as small airplanes flown for leisure, may adopt relatively slow overnight charging cycles. On the other hand, scheduled flight operations, such as commercial air taxi service or flight schools, will be limited by the availability and capabilities of fast-charging facilities or efficient battery swapping processes. Developing this next level of detail regarding charging patterns will strengthen future forecasts. This study was one of the first efforts to estimate local energy demand from aircraft charging. With more data on the real-world charging experiences of electric aircraft, future forecasts will narrow the range of possible outcomes.

Conclusion

Washington State has long been a leader in aviation and can continue that tradition as the market for electric aviation grows. Increasing demand for air travel and cargo movement, combined with public policy goals to reduce carbon emissions, air, and noise pollution could propel rapid adoption of electric aircraft, but we are still in early days, with few aircraft yet certified for general aviation and none certified to carry passengers. The technology has the potential to transform the aviation industry and stimulate new demand for air travel at regional airports over the next decade. By tracking the pace of adoption and making timely investments in charging infrastructure as demand emerges, Washington's regional airports will help make the transition to cleaner, quieter, lower-cost flight.

Bibliography

Battery University. BU-409: Charging Lithium-Ion. *Battery University*. https://batteryuniversity.com/article/bu-409-charging-lithium-ion. Accessed Jul. 1, 2022.

Boyte-White. The Climate Commitment Act: Washington's Path to Carbon-Neutrality by 2050. https://ecology.wa.gov/Blog/Posts/February-2022/The-Climate-Commitment-Act-Washington-s-Path-to-Ca. Accessed Jun. 20, 2022.

Brandon, J. Airline Travelers Have Higher Household Incomes. http://www.globalonboardpartners.com/airline-travelers-incomes/. Accessed Jul. 21, 2022.

Bye Aerospace. Electric Training Aircraft - EFlyer 2. https://byeaerospace.com/electric-airplane/. Accessed Jun. 25, 2022.

Chan, K. Seattle Looking for Suitable Site to Build Second Major International Airport | Urbanized. *Daily Hive*. https://dailyhive.com/vancouver/seattle-second-international-airport. Accessed Jul. 8, 2022.

Cohen, A. P., S. A. Shaheen, and E. M. Farrar. Urban Air Mobility: History, Ecosystem, Market Potential, and Challenges. *IEEE Transactions on Intelligent Transportation Systems*, Vol. 22, No. 9, 2021, pp. 6074–6087. https://doi.org/10.1109/TITS.2021.3082767.

Deloitte. Advanced Air Mobility – Disrupting the future of mobility. June 2022

Electric VTOL News. Wisk Aero Cora (Generation 5). https://evtol.news/kitty-hawk-cora. Accessed Jul. 21, 2022.

Eviation. Eviation Alice. https://www.eviation.co/. Accessed Jun. 25, 2022.

FAA. FAA Identifies Airport Capacity Constraints and Improvements. https://www.faa.gov/newsroom/faa-identifies-airport-capacity-constraints-and-improvements. Accessed Jul. 21, 2022.

Federal Aviation Administration. OPSNET Reports: Definitions of Variables. https://aspm.faa.gov/aspmhelp/index/OPSNET_Reports__Definitions_of_Variables.html. Accessed Jun. 23, 2022.

Federal Aviation Administration. The Operations Network (OPSNET). https://aspm.faa.gov/opsnet/sys/Airport.asp. Accessed Jun. 9, 2022.

Federal Aviation Administration. Airworthiness Certification https://www.faa.gov/aircraft/air_cert/airworthiness_certification

FLYING Magazine. FAA 'Modifying' Approach to EVTOL Certification. https://www.flyingmag.com/faa-modifying-approach-to-evtol-certification/. Accessed Jul. 1, 2022.

FutureFlight. Bye Aerospace EFlyer. https://www.futureflight.aero/aircraft-program/eflyer. Accessed Jun. 1, 2022.

Gao, M., H. Li, L. Xu, Q. Xue, X. Wang, Y. Bai, and C. Wu. Lithium Metal Batteries for High Energy Density: Fundamental Electrochemistry and Challenges. *Journal of Energy Chemistry*, Vol. 59, 2021, pp. 666–687. https://doi.org/10.1016/j.jechem.2020.11.034.

Gössling, S., and A. Humpe. The Global Scale, Distribution and Growth of Aviation: Implications for Climate Change. *Global Environmental Change*, Vol. 65, 2020, p. 102194. https://doi.org/10.1016/j.gloenvcha.2020.102194.

Goyal, R., C. Reiche, C. Fernando, J. Serrao, S. Kimmel, A. Cohen, and S. Shaheen. *Urban Air Mobility (UAM) Market Study*. Publication HQ-E-DAA-TN65181. 2018.

Grant PUD. Grant PUD - Powering Our Way of Life. *Grant PUD*. https://www.grantpud.org/. Accessed Jun. 23, 2022.

Harrison, E. D. A Methodology for Predicting and Mitigating Loss of Control Incidents for General Aviation Aircraft. Georgia Institute of Technology, Nov 09, 2018.

Hasan, M. A., A. A. Mamun, S. M. Rahman, K. Malik, M. I. U. Al Amran, A. N. Khondaker, O. Reshi, S. P. Tiwari, and F. S. Alismail. Climate Change Mitigation Pathways for the Aviation Sector. *Sustainability*, Vol. 13, No. 7, 2021, p. 3656. https://doi.org/10.3390/su13073656.

Head, E. *eVTOL Basics for Investors*, 2021. https://assets.evtol.com/wp-content/uploads/2021/07/eVTOL-Basics-For-Investors.pdf

Hepperle, M. Electric Flight – Potential and Limitations. 2012.

Hirschberg, *FAA Changes Course on EVTOL Certification,* 2022 https://vtol.org/news/commentary-faa-changes-course-on-evtol-certification

ICAO. Facts and Figures - World Aviation and the World Economy. *International Civil Aviation Organization*. https://www.icao.int/sustainability/pages/facts-figures_worldeconomydata.aspx. Accessed Jul. 2, 2022.

InsideEVs. 2021 Tesla Model S Plaid Fast Charging Analysis (3 Cars Compared). *InsideEVs*. https://insideevs.com/news/549335/three-tesla-plaid-charging-analysis/. Accessed Jul. 21, 2022.

InsideEVs. Tesla Model S Plaid Fast Charging Results Amaze: Analysis. *InsideEVs*. https://insideevs.com/news/515641/tesla-models-plaid-charging-analysis/. Accessed Jul. 2, 2022.

Joby Aviation. Commercializing Aerial Ridesharing - Joby and Reinvent. https://drive.google.com/file/d/1KViIZufQAZ7Q8T7vh79VIuHVW-nZp3CN/view?usp=embed_facebook. Accessed Jul. 1, 2022.

Joby Aviation. Electric Aerial Ridesharing. https://www.jobyaviation.com/. Accessed Jul. 21, 2022.

Kar, R., P. Bonnefoy, and R. J. Hansman. Dynamics of Implementation of Mitigating Measures to Reduce CO2 Emissions from Commercial Aviation. 2010.

Larson E., C. Greig, J. Jenkins, E. Mayfield, A. Pascale, C. Zhang, J. Drossman, R. Williams, S. Pacala, R.Socolow, EJ Baik, R. Birdsey, R. Duke, R. Jones, B. Haley,E. Leslie, K.Paustian, and A. Swan*, Net-Zero America: Potential Pathways, Infrastructure, and Impacts, Final report*, Princeton University, Princeton, NJ, 29 October 2021.

Lincoln, A. Bye Aerospace EFlyer 800 Program Advances. https://byeaerospace.com/bye-aerospace-eflyer-800-program-advances/. Accessed Jul. 21, 2022.

Long, D., D. Lee, J. Johnson, and P. Kostiuk. *A Small Aircraft Transportation System (SATS) Demand Model*. Publication NASA/CR-2001-210874. NASA, Hampton, Virginia, 2001.

Mäenpää, A., H. Kalliomäki, and V. Ampuja. *Potential Impacts of Electric Aviation in the Kvarken Region : Stakeholder Views in 2020*. Vaasan yliopisto, 2021.

Mims, C. The Biggest Problem With Flying Cars Is on the Ground. 2022. https://www.wsj.com/articles/the-biggest-problem-with-flying-cars-is-on-the-ground-11652500850

NASA. *Regional Air Mobility*. 2021.

Patterson, T. *FAA Modifying Approach to EVTOL Certification.* https://www.flyingmag.com/faa-modifying-approach-to-evtol-certification/

Pipistrel. Alpha Electro. https://www.pipistrel-aircraft.com/aircraft/electric-flight/alpha-electro/. Accessed Jun. 25, 2022.

Port of Moses Lake. The Center of Washington Aviation. https://www.portofmoseslake.com/aeronautics/. Accessed Jul. 1, 2022.

Reichmuth, J., P. Berster, and M. C. Gelhausen. Airport Capacity Constraints: Future Avenues for Growth of Global Traffic. *CEAS Aeronautical Journal*, Vol. 2, No. 1, 2011, pp. 21–34. https://doi.org/10.1007/s13272-011-0034-4.

Reuters. EV Rollout Will Require Huge Investments in Strained U.S. Power Grids. *Reuters*, Mar 05, 2021.

Reuters. Tesla Supplier Panasonic Sees 20% Jump in Battery Density by 2030. *Autoblog*. https://www.autoblog.com/2022/07/16/panasonic-battery-energy-density-2030/. Accessed Jul. 21, 2022.

Riboldi, C. E. D., L. Trainelli, L. Mariani, A. Rolando, and F. Salucci. Predicting the Effect of Electric and Hybrid-Electric Aviation on Acoustic Pollution. *Noise Mapping*, Vol. 7, No. 1, 2020, pp. 35–56. https://doi.org/10.1515/noise-2020-0004.

Rogers, Everett. Diffusion of Innovations, 5th Edition. Simon and Schuster. ISBN 978-0-7432-5823-4., 2003.

Schäfer, A., J. B. Heywood, H. D. Jacoby, and I. A. Waitz. *Transportation in a Climate-Constrained World*. MIT Press, Cambridge, MA, USA, 2009.

Schwab, A., A. Thomas, J. Bennett, E. Robertson, and S. Cary. *Electrification of Aircraft: Challenges, Barriers, and Potential Impacts*. Publication NREL/TP-6A20-80220, 1827628, MainId:42423. 2021, p. NREL/TP-6A20-80220, 1827628, MainId:42423.

Seeley, B. A., D. Seeley, and J. Rakas. A Report on the Future of Electric Aviation. 2020. https://doi.org/10.7922/G2BC3WTV.

Snohomish County PUD. Snohomish PUD - Energizing Life in Our Communities. https://www.snopud.com/. Accessed Jun. 23, 2022.

Streamlit Inc. Streamlit. https://streamlit.io/. Accessed Jul. 7, 2022.

Trivedi, N., N. S. Gujar, S. Sarkar, and S. P. S. Pundir. Different Fast Charging Methods and Topologies for EV Charging. 2018.

Viswanathan, V., A. H. Epstein, Y.-M. Chiang, E. Takeuchi, M. Bradley, J. Langford, and M. Winter. The Challenges and Opportunities of Battery-Powered Flight. *Nature*, Vol. 601, No. 7894, 2022, pp. 519–525. https://doi.org/10.1038/s41586-021-04139-1.

Wisk. Wisk | We've Arrived. *Wisk*. https://wisk.aero/. Accessed Jul. 21, 2022.

WSDOT. Aviation - Passengers & Cargo Moved. *Tableau Software*. https://public.tableau.com/views/DEV-CCR-AAW-AV-Passenger/CCR-AAW-AV-Passenger. Accessed Jul. 8, 2022.

WSP. *Washington Electric Aircraft Feasibility Study*. WSDOT Aviation Division, 2020, p. 228.

WWF. Cutting Aviation Pollution. *World Wildlife Fund*. https://www.worldwildlife.org/initiatives/cutting-aviation-pollution. Accessed Jul. 22, 2022.

Zoepf, S., and J. B. Heywood. Characterizations of Deployment Rates in Automotive Technology. *SAE International Journal of Passenger Cars - Electronic and Electrical Systems*, Vol. 5, No. 2, 2012, pp. 541–552. https://doi.org/10.4271/2012-01-1057.