Estimating Electrical Energy and Capacity Demand for Regional Electric Flight Operations at Two Mid-Size Airports in Washington

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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 the face of tight climate action goals and large airport hubs facing capacity constraints, electric aircraft at regional airports could help respond to increased regional travel demands. In this paper, we develop a framework for estimating future energy (annual MWh) and power (average and peak MW) demand for electric aviation at regional airports. We apply our modeling framework to two mid-size case study airports in Washington: Paine Field/Snohomish County Airport and Grant County International Airport. 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. The results reveal that, while electricity demand could rise substantially over time, during the first decade of adoption utility companies are expected to be able to serve the energy and power needs of electric aviation with available capacity at existing substations close to the airports in our case studies.

Keywords: transportation electrification, electric aviation, energy demand, peak power

INTRODUCTION

Aviation serves people's desire and need to travel over long distances, including transcontinentally, reducing travel times drastically compared to alternative modes of transportation. Global demand for aviation is expected to increase in the coming years (*1*), as a result of increased access to commercial flights for a larger share of the world's population as well as more frequent flyers mostly in developed countries (*2*). Although still comprising a relatively small share of global emissions, flight operations are one of the fastest growing sources of climate-damaging CO_2 emissions (*3*, *4*).

Constrained by the laws of physics and the chemistry of liquid fuels, fossil-fuel hydrocarbons are hard to beat in terms of the energy density (both per mass and per volume) required for long-haul flights (*5*). However, in recent years, several companies (newly formed and existing) have pursued the development of electric aircraft, designed to serve certain aviation market segments (*6*). In addition, many large airport hubs are approaching capacity constraints (*7*, *8*). Coupled with increased regional travel demand, as well as the fact that a significant share of flight operations are short- to mid-haul (*9*), this opens opportunities for more regionalized air travel with new 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 (*10*), planners need to assess the potential energy and power needs at airports and understand how these demands may grow in the coming years. In this paper, we develop a framework for estimating future energy (annual Megawatt-hours, MWh) and power (average and peak Megawatt, MW) demand for electric aviation at regional airports.

In light of Washington State's historic leadership position in the aerospace industry and strict climate action goals (*11*), the state has evaluated the economic and environmental opportunities of electric aviation (*12*). In Washington, aviation operations are highly concentrated at Seattle-Tacoma International Airport (SeaTac), with about 90% of all annual enplanements in Washington counted there (*13*). However, SeaTac is close to its maximum capacity (*14*), given geographic constraints on expansion. Spatially diversifying commercial enplanements in Washington to different airports could alleviate some of these capacity constraints. Moreover, utilizing electric aircraft for flights with a distance that allows electrification could result in new aircraft operations aligned with climate goals (*15*). We thus apply our modeling framework to two mid-size case study airports in Washington: Paine Field/Snohomish County Airport (PAE) and Grant County International Airport (MWH[1]).

THE CONTEXT OF ELECTRIC AVIATION

The electric aircraft market

Numerous studies have explored the potential of electric and hybrid-electric aviation to reduce impacts such as noise, local pollution, and greenhouse gas emissions from conventional aviation operations (*12*, *16*, *17*). Electric aircraft have no direct emissions and generally produce less noise compared to comparably-sized conventional aircraft (*16*).

In addition, electric aviation has performance advantages relative to conventional aircraft that could expand the aviation market (*12*, *18*). This holds especially true with respect to novel technologies, including electric vertical take-off and landing (eVTOL) aircraft (*19*, *20*). Multiple companies founded in the last decade are pursuing the design, construction, and certification of novel eVTOL aircraft allowing for urban air mobility

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[1] The 3-letter airport code being MWH should not be confused with energy demand units of MWh.

(*6*). Seeley et al. note that "the cost advantages of electric propulsion systems are going to completely disrupt the current aviation market and allow more point to point journeys" (*21*).

Scope of this paper

For this study, we focus on fully-electric aircraft, which are constrained to use on certain types of flights, due to limited range. The Federal Aviation Administration (FAA) defines operation categories for tracking purposes (*22*). Three of these categories represent viable 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 for hire by all aircraft with a 60-seat or 18,000 lb-payload maximum capacity, that land at an airport arriving from outside the airport area, or depart from an airport and leave the airport area (following the definition in the FAA's Operations Network OPSNET (*23*)).

In addition, we define a fourth eVTOL category 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 chose to treat eVTOL operations as their own category, due to their novelty and unique aircraft design, technology, and power requirements.

We exclude the FAA Air Carrier and Military categories because they involve long-haul passenger trips or military uses that presently lack any electric alternatives. This is predominantly due to fundamental physical constraints, since an electric aircraft's range is proportional to the mass ratio of its battery to its total gross weight (*24*). **Table 1** includes examples of available electric aircraft on the market that can serve the four aircraft operation categories amenable to electrification. In regards to the air taxi category, this includes, but is not limited to, the 9-seat Eviation Alice that is currently under development as a commuter plane, with its first flight in 2022 using two 640 kW engines designed to power the aircraft over an electric range of up to 500 miles (*25*). This aircraft could feasibly serve certain commercial air taxi services. The way in which the seating capacity of electric aircraft models in the air taxi segment could be different than of conventional aircraft in that segment and thus impact the number of required flights for a given demand was not considered in this work.

As of November 2022, no electric aircraft has passed all regulatory requirements for a complete certification for commercial use cases; however, the FAA has recently announced a shift in its regulatory approach, aiming to minimize delays in eVTOL certification processes (*26*).

This study does not address the engineering design associated with installing adequate charging ports for recharging aircraft batteries. It rather evaluates the electric power and energy needs as measured at the utility meter for supporting electric aircraft and whether local utilities have sufficient capacity at the substations adjacent to the airports.

TABLE 1 Overview of representative electric aircraft available for different use cases, compiled from publicly available information. Where there is a dash (-), no information could be found.

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)	-	-	(*27*)
		Bye Aerospace	eFlyer 2	- First flight in 2018 - FAA certification targeted for end of 2022	110	253	83	(*28*, *29*)
eVTOL	**4-seat eVTOL commuter**	Joby Aviation		- 1 pilot, 4 riders - 6 motors - Targeting FAA Part 135 Air Carrier Certificate	-	150	117	(*30*)
		Wisk Aero	Wisk Cora	- Designed to (eventually) be autonomous - 12 independent rotors	-	62	100	(*31*, *32*)
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	(*25*)

Regional airports as potential future electric aviation hubs

Several states and regions have been exploring the opportunities for electrified regional air travel. This includes work done in Colorado (*6*), Utah (*33*), as well as the NASA Regional Air Mobility report (*34*). 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" (*12*) from 2020, which stresses the potential impact of the electrification of regional aircraft on commercial aviation. The report also set goals for aviation electrification, which include the provision of charging infrastructure at commercial airports for aircraft up to 10-15 passengers by 2030, for general aviation by 2040, and for all aircraft by 2050. These goals highlight the importance of assessing potential charging demands for electric aircraft at airports that could feasibly serve as regional hubs for electric aviation.

In this study, we analyze the potential for two mid-size airports in Washington to serve future electric aviation operations: Paine Field/Snohomish County Airport and Grant County International Airport, at Moses Lake. Paine Field is located in the Greater Seattle Area approximately 32 miles (51 km) north of Washington's largest airport (SeaTac). Grant County International Airport is situated in rural and central Washington, approximately 140 miles (230 km) east of SeaTac, and is used frequently for military and commercial flight test programs.

Paine Field lies in the service area of the Snohomish County Public Utility District (*35*), and Grant County International Airport is served by the Grant County Public Utility District (*36*). While the Snohomish County Public Utility District explicitly estimated and accounted for a rising adoption and power demand from electric cars and trucks in their integrated resource plan (*37*), the Grant County Public Utility District did not do so. However, as a rural county, Grant County lags the state as a whole in electric vehicle adoption (*38*). Upon conversation with systems planning engineers at both utilities and research on available capacity increments, it became apparent that both utilities are able to rather easily provide capacity increments to either of the two airports in the range of 2.5-10 MW peak electrical capacity. Such increments would not require long-term planning efforts and could be provided from nearby substations in close proximity to the airport's buildings and hangars. Both airports are located well within one mile from at least one utility substation, which have sufficient electrical capacity available (based on internal communication with both utility districts).

Research question

The research question for this study can be formulated as follows: To what extent does the electric grid near Paine Field and Grant County International Airport have the capacity to serve the potential energy (MWh) and peak power (MW) needs of early electric aircraft operations in the next one to two decades? The respective findings can be very useful for the airports and their managers directly, for utilities (that, for very large projected capacity needs, might require longer planning horizons), and air carriers (which are interested in understanding the market's overall technical needs and their feasibility).

We will proceed by presenting our methods and data sources, followed by a presentation and discussion of the relevant results. The paper closes by putting this study's findings into a broader perspective and discussing the implications they could have on electric aviation at regional airports.

DATA AND METHODS

Dimensions of analysis

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

The six different analysis dimensions, along with their possible values, are the following:

- Airport: $A \in \{PAE, MWH\}$
- Operation category: $c \in \{Local\ Civil, Itinerant\ General\ Aviation, Itinerant\ Air\ Taxi, eVTOL\}$
- Number of operations growth scenario: $o \in \{low, medium, high\}$
- Feasibility rate scenario: $f \in \{slow, medium, fast\}$
- Adoption rate scenario: $a \in \{slow, medium, fast\}$
- Time (year): $t \in \{2023, 2024, \dots, 2040\}$

Details are listed below. The corresponding indices (A, c, o, f, a, t) are used to signify which quantity depends on which analysis dimension(s).

Airport (A): The analysis is conducted for the two different Washington airports, PAE and MWH.

Operation category (c): The electricity demand is estimated for each of the four operation categories listed earlier. Each category features unique distributions of aircraft size and typical flight ranges, which impact the electric power demand. One operation is either a take-off or a landing at the respective airport.

Number of operations growth scenario (o): We use three growth scenarios for the numbers of operations for each operation category and at each airport (low, medium, and high). The scenarios are based on projections presented in WSDOT's "Washington Electric Aircraft Feasibility Study" (WA EAFS) (*12*). The associated growth rates range from, on average, 1.9% (low growth) to 3.3% (high growth) for general aviation, and from 5.0% to 8.0% for the air taxi category, varying by the year. Since 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 existing airport operations is assumed to comprise two processes:

Feasibility rate scenario (f): The technological feasibility to serve aircraft use cases with electric aircraft is assumed to be able to develop at different possible paces. The three assumed scenarios vary by both the temporal lag for technological feasibility to start ramping up as well as the speed of that process.

Adoption rate scenario (a): The adoption of electric aircraft on routes for which electric aircraft are technologically available is also assumed to progress at different possible paces. The adoption rate is intended to capture both the temporal lag induced by aircraft operators, owners, and airlines for adopting such electric aircraft and the time it takes for the whole aircraft fleet to turn over, based on electric aircraft adoption speed. The fact that this replacement of older aircraft by new aircraft can take a considerable time and is largely uncertain is discussed in more detail below.

Time (year) (t): This is the year for which the estimation of electricity demand is made. The growth rates in the WA EAFS are projected until the year 2039, so we stop our scenario estimates in 2040.

Electricity demand 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:

$$\begin{aligned} E_{A,c,o,f,a,t} = \tfrac{1}{2} &\times (number\ of\ operations)_{A,c,o,t} \\ &\times (feasibility\ rate)_{c,f,t} \times (adoption\ rate)_{c,a,t} \\ &\times E_c^{flight} \end{aligned} \tag{1}$$

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:

$$\begin{aligned} E_c^{flight} = &(average\ aircraft\ power\ demand)_c \\ &\times (average\ flight\ range)_c\ /\ (average\ cruise\ speed)_c \end{aligned} \tag{2}$$

The factor $\frac{1}{2}$ in equation (1) stems from the fact that each electric aircraft needs 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 $P^{average}_{A,c,o,f,a,t}$ (in kW) can be derived as follows:

$$P^{average}_{A,c,o,f,a,t} = E_{A,c,o,f,a,t} \;/\; (365 \times 24\ hours) \tag{3}$$

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 bigger number of flight operations in the summer months compared to winter), a charging curve factor, and a factor representing the daily charging pattern:

$$P^{peak}_{A,c,o,f,a,t} = P^{average}_{A,c,o,f,a,t} \times (seasonality\ of\ operations)_{A,c} \tag{4}$$

$$\times\, (charging\ curve\ factor)\ \times 24\ hours \;/\; (charging\ window)$$

No eVTOL operations exist as of today, meaning that we cannot leverage the same methodology for eVTOL as for the existing airport operations. Instead, we estimate 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 assume that only residents with an annual household income of $200,000 or more will be willing to take an eVTOL aircraft to travel from Paine Field to SeaTac. This (rather strong) assumption is motivated by the observations made in the on-road electric vehicle market, which, in its early phase, saw strong overrepresentation of affluent households and environmentally conscious individuals (*39*). In the eVTOL case, companies face high development and certification costs which may further increase prices charged to initial users. We leverage these households' share of all households and high-income households' increased propensity for air travel (23% of air travelers have income of $100,000 or more per year, representing only 15% of all Americans (*40*)) 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 (*41*), we yield 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 is 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 2**. We do not include eVTOL flights from Grant County International Airport to SeaTac under the assumption that such flights will be captured in our estimates of the electrification of the existing air taxi category.

A visual representation of the combined methodology for existing airport operations and the new eVTOL operations is provided in **Figure 1**. All input variables used in the above equations are defined in **Table 3** and will be further described below. All references to miles (mi) in this paper imply the use of the statute mile, as opposed to the nautical mile.

TABLE 2 Assumptions behind the different eVTOL scenarios. Using these assumptions, a logistic curve as outlined in Eq. 5 is created, representing the adopted market share of the total potential market size of about 215,000 trips between Paine Field and SeaTac.

Analysis dimension	**No. of ops. growth**	**Feasibility**	**Adoption**
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%

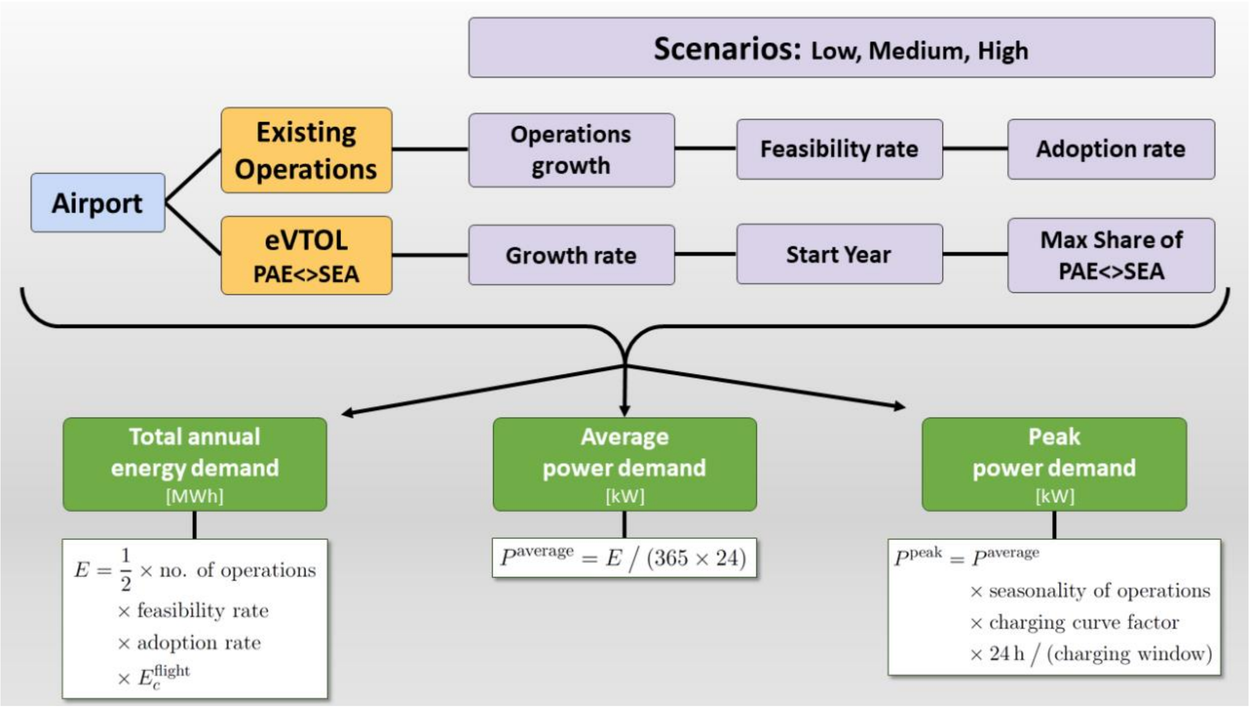

FIGURE 1 Schema of the utilized methodology.

TABLE 3 Input variables and the dimensions of analysis they vary along (indices). The lower three variables are used to convert the projected average power demand into a peak power demand.

Input variable	Description	Possible values/unit
$(number\ of\ operations)_{A,c,o,t}$	The number of operations (take-offs and landings) projected in different growth scenarios for the different operation categories	Absolute number of annual flight operations
$(feasibility\ rate)_{c,f,t}$	The percentage of all operations that are technically feasible to electrify with appropriate electric aircraft	0-100%
$(adoption\ rate)_{c,a,t}$	The percentage of all technically feasible operations that will actually be electrified, i.e. the rate at which electric aircraft are used for feasible trips	0-100%
$(average\ aircraft\ power\ demand)_{c}$	Assumed operation category-averaged aircraft power demand averaged over a typical flight	kW
$(average\ flight\ range)_{c}$	Assumed typical operation category-averaged flight range	mi
$(average\ cruise\ speed)_{c}$	Assumed typical operation category-averaged cruise speed	mi/hr
$seasonality\ of\ operations$	Ratio of peak vs. average monthly number of operations	1.7
$charging\ curve\ factor$	Ratio of peak to average charging power during one typical charging process (since charging power tapers towards the end of a charging cycle)	1.8
$charging\ window$	The number of hours during a day in which all charging events of that day (hypothetically) occur	2, 4, 6, 8, …, 24 hours

The underlying assumptions and sources for each of these inputs are:

1. $(number\ of\ operations)_{A,c,o,t}$: The number of operations at each airport and for each operation category are taken from the FAA's Operations Network OPSNET (*23*). For each year starting with 2023, the growth rates found in the WA EAFS (*12*) were applied to the previous year's numbers of operations, for each of the three growth rate scenarios. We use the 2019-2021 average as the baseline because the Covid-19 pandemic has caused a substantial disruption in the trend in operations at the two studied airports, especially in 2020 (-20% total operations at Grant County International Airport, -10% at Paine Field, with a rebound in 2021 to numbers above the pre-pandemic values).
2. $(feasibility\ rate)_{c,f,t}$: We estimate the technological feasibility of electric aircraft to serve existing aviation operations using a combination of estimates of battery technology improvements

(the most constraining factor for electric aviation (*42*)) and a frequency distribution of flight distances for single-engine and multi-engine aircraft. In research and industry, there exists a variety of estimates for the technological advancement in battery technology. With a maximum achievable energy density of around 200 Wh/kg (Watt-hours per kilogram) today, projections range from a 20% increase in energy density by 2030 (*43*) to potentially more than 600 Wh/kg that year (*42*). In addition, there is uncertainty among experts as to which battery chemistries have the highest energy density potential (*44*). For the medium scenario, we use a projection of a linear 50% increase in battery energy density over 10 years (slow scenario: 30%, fast: 70%). This would improve the electric range of single-engine (multi-engine) aircraft from about 250 mi (506 mi) today (see **Table 1**) to an estimated 400 mi (810 mi) in 2035. We further assume 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 leverage a 2001 NASA study to estimate flight lengths (in miles) of single-engine and multi-engine aircraft (*9*). Assuming the flight distance distributions (Weibull-shaped) did not change 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 assign air taxi operations the multi-engine range trends and use the single-engine projections for general aviation flights (Local Civil and Itinerant GA). Following this methodology, **Figure 2** depicts the estimated feasibility rate in the medium scenario. Here, certification is assumed to occur in 2026, and the majority of flight operations are found to be feasible immediately, due to the Weibull-shape of the distribution of flight distances (skewed towards longer distances). **Table 4** shows the years in which the feasibility rate reaches a threshold of 95% of all flight operations.

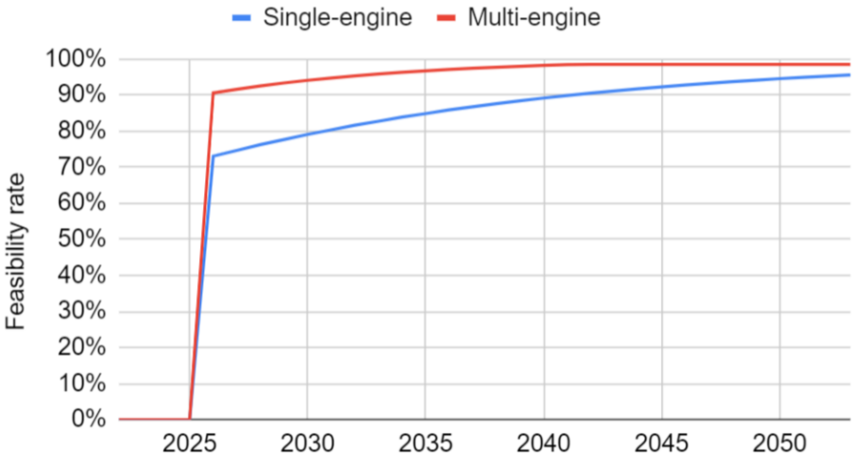

FIGURE 2 The estimated share of single-engine (Local Civil and Itinerant GA) and multi-engine (Air Taxi) flight operations that could feasibly be served using electric aircraft, used as the “feasibility rate” in this study, in the medium scenario.

3. $(adoption\ rate)_{c,a,t}$: The penetration of electric aircraft on the aviation market is assumed to follow an S-shaped adoption curve, as has been observed and modeled in many cases of new vehicle technologies before (e.g. (*45*)). The adoption rate of existing aircraft operations is thus estimated using the logistic function

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

where g determines the maximum growth rate and t_0 is the temporal lag (years from 2022 until the rate reaches 50%). The two variables 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 at which the adoption rates are assumed to reach 95% (thus an almost complete market penetration), under the different scenarios (fast, medium, slow). The adoption of electric aircraft on flights that can be feasibly served by electric aircraft is assumed to be driven by multiple factors, most of which are highly uncertain. Previous research on the adoption of new aircraft technologies has found varying results. Findings range from as much as 30 years for a 50% turnover of a generic aircraft fleet (*5*) to e.g. only about 10 years for the almost complete adoption of regional jets around the end of the 20th century (*46*). 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 long replacement cycles (the FAA estimates the average age of active GA aircraft at about 40 years, see (*47*) and (*5*)), 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 do not outweigh the price premium very quickly. In general, it should be noted that, even upon accelerated adoption of electric aircraft, it takes time for the entire fleet to turn over. Our estimated adoption rates thus represent a large span of possible developments, with 95% adoption levels reached as early as 2035 (Local Civil, fast scenario) or 2051 (GA and AT, slow scenario), as shown in **Table 4**. **Figure 3** shows the resulting adoption rate curves, by way of example for the General Aviation category.

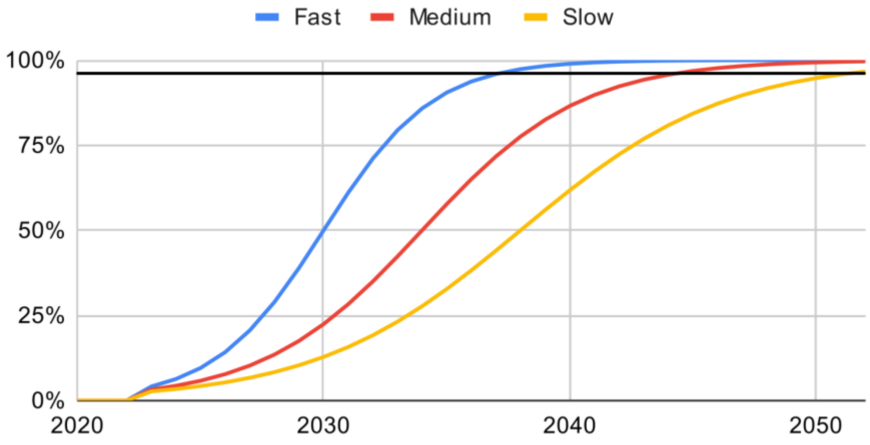

FIGURE 3 The estimated adoption rate curves for the General Aviation operation category, as an example. A 95% threshold is shown with the black horizontal line. The intersections of the curve correspond with the years shown in Table 4.

TABLE 4 Overview of assumptions on the input variables. The years in which the two different electrification rates reach 95% are color-coded, with earlier years being greener and later years redder. The rightmost column (E_c^{flight}) is the result of the three abutting columns.

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

4. $(average\ aircraft\ power\ demand)_c$, $(average\ flight\ range)_c$, $(average\ cruise\ speed)_c$: The average power demand, flight range, and cruise speed during one typical flight are estimated separately for each operation category. The estimates rely on publicly available data on the different electric aircraft (that are commercially available or under development), assigned to the representative operation category they would realistically be used in (see **Table 1**). For instance, the Pipistrel Alpha Electro can be used for GA purposes (local and itinerant), whereas the Eviation Alice will serve Itinerant Air Taxi trips. In addition, for the flight range and cruise speed, estimates are revised and confirmed using findings from the aforementioned NASA study from 2001 (*9*). 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 (*48*)) as well as the Eviation Alice's planned battery capacity (820 kWh). The resulting values used for the subsequent electricity demand estimates are shown in **Table 4**, too. The values were vetted against information in ACRP Research Report 236 (*17*). While each quantity assumes values varying greatly from one flight and aircraft model to the next, we emphasize that it is the average of these variables' individual values for all annual operations that will determine the annual energy demand and thus the desired outcome variable.

The assumptions for the three input variables used to calculate the peak power demand are as follows:

- $seasonality\ of\ operations:$ The seasonality was calculated using past numbers of operations (for 2015-2021, as taken from the FAA's OPSNET data) at both studied airports. Peak monthly operations were typically found in July and were about 70% 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 (*49*). Based on the available literature (*50*) as well as data found by automotive battery testers (*51*), the peak charging power of an average direct-current fast charging process is about 80% higher than the average over the entire charging duration (20-80% SOC). 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) (*52*). Based on direct communication with electric aircraft manufacturers, the industry appears to aim 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 factoring in the charging curve factor as described. We recognize that this assumption further relies on the type and size of the battery used, and is subject to changes based on future advancements in battery and charging technology. However, we assume that charging strategies will be similar to those of electric cars, given the reportedplans of electric aircraft companies to use lithium-ion batteries and prior research that drew comparisons to the battery technology in electric cars (*53*, *54*).

- *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 within 24 hours, then electrical capacity needs are given by the average power demand. If all charging at a given airport, however, occurs within only 8 hours of the day, then the peak power demand (for charging the electric aircraft) 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 deem 8 hours a reasonable assumption, based on a typical work day's duration and direct communication with aircraft manufacturers and airport operators. This method assumes that aircraft operations and charging session initiations are uniformly distributed within the charging window. The methodological framework allows for a modification of this parameter in order to allow the user to test different charging patterns.

Interactive tool

This publication comes with an interactive tool that was made available under 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 (*55*), allowing users to dynamically update the projections based on the chosen scenarios. **Figure 4** shows a screenshot of the tool.

Plausible Electricity Demand for Electric Aviation at PAE and MWH 📈 💡

Output variable (annual energy/average power/peak power): Peak power [MW]

Airport: PAE

Operation category: Local Civil ✕ Itinerant General... ✕ Itinerant Air Taxi ✕ eVTOL ✕

Scenarios:

No. of ops. growth scenario: Medium

Feasibility rate scenario: Medium

Adoption rate scenario: Medium

All charging occurs in how many hours? 8

FIGURE 4 Screenshot of the interactive tool published along with this paper. The screenshot shows the drop-down menus that can be used by the viewer to determine the specific scenario.

RESULTS AND DISCUSSION

Airport operations

Figure 5 shows the numbers of operations at the two studied airports for the years 2015-2021, grouped by operation category. While Paine Field is serving more operations on a total basis (nearly 140,000 in 2021), Grant County International Airport has a much more diversified spectrum of operation categories.

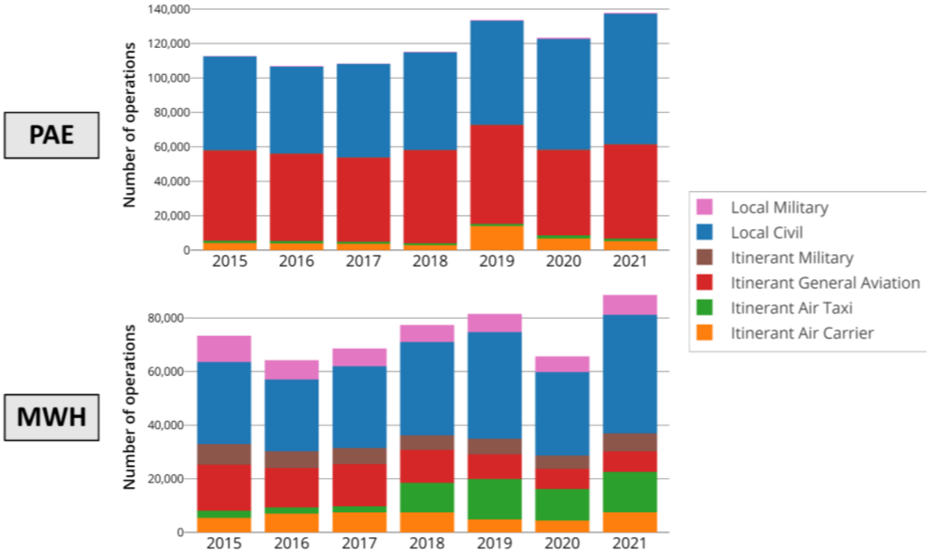

FIGURE 5 The numbers of operations at Paine Field (PAE) and Grant County International Airport (MWH) in the years 2015-2021, by operation category. Note the different vertical axes for PAE and MWH.

For the estimates of future numbers of operations, the growth rates found in the WA EAFS study were used and applied to the 2019-2021 averages. For eVTOL, depending on the chosen feasibility scenario, operations only commence in 2030, 2035, or 2040 (see **Table 2**). Under the three different growth scenarios (based on the WA EAFS), the total number of operations in the three existing airport operation categories (Local Civil, Itinerant GA, Itinerant AT) increases from about 122,000 to between 169,000 (low estimate), 180,000 (medium), or 214,000 (high) at Paine Field by 2040. eVTOL, in our estimates, has the potential to account for up to about 180,000 flights by 2040, though subject to significant regulatory and technological uncertainties. At Grant County International Airport, estimates for the total number of operations in 2040 range from about 103,000 (low) to 157,000 (high), a large increase from about 60,000 in 2019-2021. This increase is largely due to relatively high projected growth rates for the air taxi segment, which could increase from about 14,000 to nearly 95,000 annual operations by 2040.

Electricity demand projections

When translating the projected numbers of operations and various assumptions about the electrification rate of these operations into electricity requirements, the annual energy demands are found to vary greatly, depending on the chosen scenario composition and owing to the large uncertainty associated with the nascent stage of the electric aviation market. Using the medium scenarios for the operations growth, feasibility rate, and adoption rate, 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%) of that can be attributed to general aviation (10% local and 67% itinerant) operations, in line with the very high share of GA operations at Paine Field. At Grant County International Airport, air taxi operations account for more than 84% of the nearly 28,000 MWh of annual electricity demand in 2040 projected in the medium scenario. This is the combined result of AT operations (1) making up for a relatively large portion of projected operations for that year (54%) and (2) being associated with considerably larger energy demands for each flight operation, due to the typically larger flight distance and bigger airplane power demands (see **Tables 1 and 4**).

Figure 6 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 there, the estimated peak power demands at the two airports are not expected to exceed 10 MW before 2030, even in the highest of all deployed scenarios. This is relevant for the local utility companies as well as the respective airport managers, as 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 was gathered around 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 amount to which commercial air taxi services at Grant County International Airport will start electrifying their airplane fleets will largely determine the overall future electrical capacity needs at that airport. Historically, the airport has been heavily utilized for testing new aircraft, equipment, and other technologies (*56*). This could put the facility in a unique position to be 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 Washington's priorities in terms of the development of commercial air mobility services from Paine Field to SeaTac.

At this point, we can conclude that the provision of sufficient electrical service down to the substation level at the two studied airports will not inhibit the adoption of electric aircraft in the coming years. The potentially required capacity increments are available at nearby substations and would not induce infrastructure investments aside from ordinary costs including line extension charges or for transformers. Since such costs are part of every capacity project, they would furthermore only impact the capital costs of the project and not the utility's electricity rate. Beyond the next 10 years, the electricity needs for electric aviation are difficult to forecast with today's knowledge resulting in wide ranges between our low and high estimates. Data collection after electric flight operations begin will allow for more informed estimates of electric energy and power demand in the future.

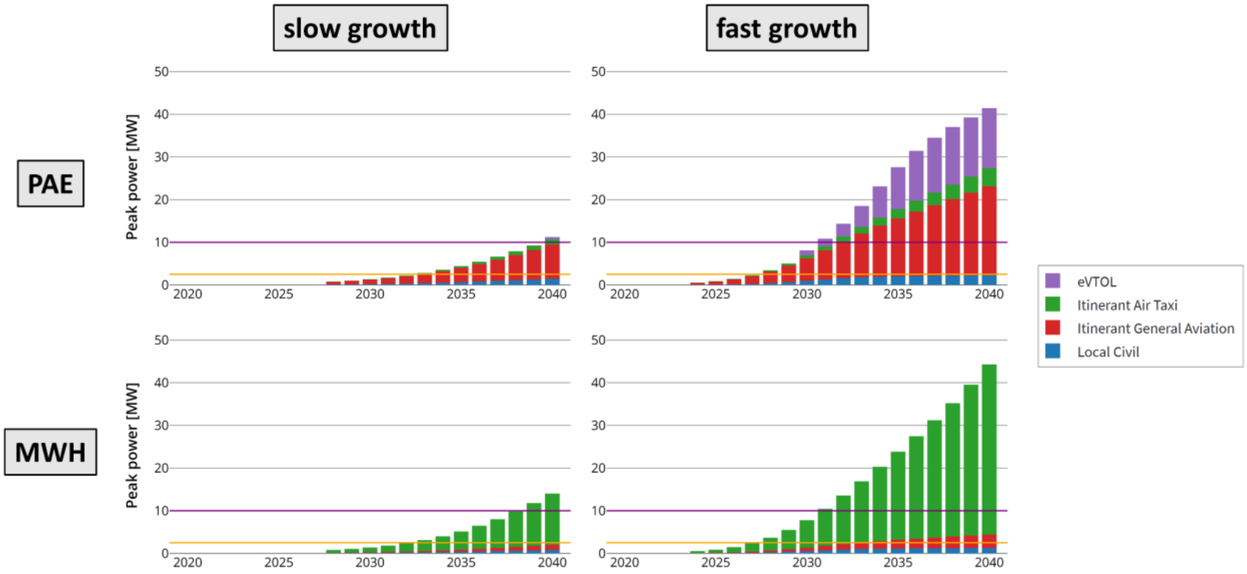

FIGURE 6 The estimated peak power demands (in MW) for electric aircraft operations at Paine Field (PAE) and Grant County International Airport (MWH), by operation category. Shown are a low (left) and a high (right) scenario for electric aviation, with all three scenarios (number of operations growth, feasibility, and adoption) assumed to be either low or high. The golden and purple horizontal lines denote thresholds of 2.5 and 10 MW, respectively.

IMPLICATIONS FOR SUPPORTING ELECTRIC AVIATION

The framework model presented in this paper allows for the efficient calculation of potential future energy demand at any regional airport, constrained by the availability of data on historic operations and plausible future growth rates.

The findings represent the first quantitative estimation of potential future electricity needs for electric aviation operations at Washington airports, both in terms of annual energy demand as well as peak power requirements. The results show that utility companies at the two studied airports can serve the increase in electrical demand induced by electric aviation in the coming decade, using available grid capacity at nearby substations. The methodological framework can easily be applied to different airports across the United States, based on their mix of aircraft operations and expected electrification rates.

There are a variety of future research opportunities related to forecasting the growth of electric aircraft and their charging requirements. It would be useful to develop a comprehensive fleet turnover model that captures the relationship between adoption of electric aircraft and phasing out conventional airplanes, considering the typical use cases of such aircraft and different incentive systems for owners and operators to switch to electric aircraft. Updating the model's parameters with data from actual charging behavior of electric aircraft in the different use cases will help reduce uncertainty in the model.

ACKNOWLEDGMENTS

The authors would like to thank and acknowledge the WSDOT Research Office for funding this project and the support of the WSDOT Aviation Division for helping to connect with the electric aviation industry.

AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: Steffen Coenen: review of electric aviation market and available electric aircraft, method conception and execution, conducting interviews with airports and industry leaders, draft manuscript preparation; Daniel Malarkey: conducting interviews with airports and industry leaders, eVTOL methodology, manuscript editing; Don MacKenzie: study conception, manuscript editing. All authors reviewed the results and approved the final version of the manuscript.

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