Transportation Electrification in Washington State: Plans, Trends, Challenges

Steffen Coenen

A thesis
submitted in partial fulfillment of the
requirements for the degree of

Master of Science

University of Washington
2023

Committee:
Don MacKenzie
Edward McCormack

Program Authorized to Offer Degree:
Department of Civil and Environmental Engineering

University of Washington

Abstract

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Chair of the Supervisory Committee:
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Second, in support of the state's efforts, I developed light-duty electric vehicle (EV) registration forecasts by census tract. The developed forecasts are based on Department of Licensing vehicle registration data and a logistic regression model accounting for time trends

and census tract specifics. I concluded that the product, price, and policy trends of the last years are not sufficient to reach the state's EV adoption goals. However, new EV models, falling prices, and federal and state policies may still alter the underlying trends.

Lastly, I led the first effort to quantify future electricity demand for electric aviation at regional airports. I applied the modeling framework to two mid-size airports in Washington: Paine Field/Snohomish County Airport and Grant County International Airport. The method combined estimates of flight range and aircraft power demand with operations growth projections and historic adoption rates of new aviation technologies. The results revealed that 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 studied airports.

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Master of Science in Civil Engineering
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conducted in the
Sustainable Transportation Lab
presented to the
Department of Civil and Environmental Engineering
at the
University of Washington

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Prof. Edward McCormack

Seattle, Washington, United States,
in June 2023

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Kurzdarstellung

Der US-Bundesstaat Washington hat ehrgeizige Ziele zur CO_2-Emissionsreduktion und dem Ausstieg aus Verbrennerfahrzeugen verabschiedet. Um diese Ziele zu erreichen, unternimmt der Bundesstaat erhebliche Anstrengungen, um für die schnelle Elektrifizierung des Mobilitätssektors zu planen, sie vorherzusagen, und ihre Auswirkungen zu addressieren. Diese Arbeit stellt drei Forschungsbeiträge vor, die diesen Prozess konkret unterstützen, und sie unterstreicht damit den Bedarf für und die Fähigkeiten von akademischer Forschung über Grundlagenwissenschaft heraus, Politik zu untersützen.

Der Bundesstaat Washington verfolgt die Entwicklung eines Kartierungs- und Prognosetools zu emissionsfreien Fahrzeugen, um die steigende Zahl an Elektrofahrzeugen und den Ausbau öffentlicher Ladeinfrastruktur zu überblicken. Um die Anschaffung dieses Tools zu unterstützen, habe ich bestehende Tools auf ihre Fähigkeit geprüft und bewertet, bundesstaatliche und lokale Regierungen beim Planen von Infrastruktur für emissionsfreie Fahrzeuge zu helfen. Die Ergebnisse zeigen, dass keines der geprüften Tools alle vom Bundesstaat gesetzten Bedingungen erfüllen kann, weder alleine noch in Kombination. Die Empfehlungen an den Bundesstaat beinhalten verschiedene Optionen zur Beschaffung des Tools.

Zweitens, um die Bestrebungen des Bundesstaates zu unterstützen, habe ich Prognosesn zur Zahl an Elektrofahrzeugen in allen Bezirken Washingtons entwickelt. Die entwickelten Prognosen basieren auf Fahrzeugzulassungsdaten des Washingtoner Department of Licensing und einem logistischen Regressionsmodell, das Zeittrends und Besonderheiten der Bezirke berücksichtigt. Ich kam zu dem Schluss, dass die Produkt-, Preis- und Politiktrends der letzten Jahre nicht ausreichen, um die Ziele des Staates bei der Einführung von Elektrofahrzeugen zu erreichen. Allerdings können neue Elektrofahrzeugmodelle, sinkende Preise sowie Maßnahmen auf Bundes- und Bundesstaatsebene die zugrundeliegenden Trends noch verändern.

Schließlich leitete ich den ersten Versuch, den zukünftigen Strombedarf für elektrische Luftfahrt an Regionalflughäfen zu quantifizieren. Ich habe das Modellierungsframework auf zwei mittelgroße Flughäfen in Washington angewendet: den Paine Field/Snohomish County Airport und den Grant County International Airport. Die Methode kombinierte Schätzungen der Flugreichweite und des Flugzeugenergiebedarfs mit Flugbetriebsprognosen und historischen Einführungsraten neuer Luftfahrttechnologien. Die Ergebnisse zeigten, dass Stromversorgungsunternehmen im ersten Jahrzehnt der Einführung voraussichtlich in der Lage sein werden, den Energie- und Strombedarf für elektrische Luftfahrt mit der verfügbaren Kapazität bestehender Umspannwerke in der Nähe der untersuchten Flughäfen zu decken.

Abbreviations

AFDC	Alternative Fuel Data Center
ANL	Argonne National Laboratory
BEV	Battery-electric vehicle
CO_2	Carbon dioxide
DCFC	Direct current fast charging
DOL	Department of Licensing
EV	Electric vehicle
EVSE	Electric vehicle supply equipment
eVTOL	Electric vertical take-off and landing (aircraft)
FAA	Federal Aviation Administration
GHG	Greenhouse gas
HB	House Bill
kW	Kilowatt
kWh	Kilowatt-hour
MFT	Mapping and Forecasting Tool
mi	(statute) mile
MW	Megawatt
MWh	Megawatt-hour
MWH	Grant County International Airport
NREL	National Renewable Energy Laboratory
PAE	Paine Field/Snohomish County Airport
PHEV	Plug-in hybrid electric vehicle
SAF	Sustainable aviation fuel
SeaTac	Seattle-Tacoma International Airport
U.S.	United States
USDOT	United States Department of Transportation
WA	Washington
WSDOT	Washington State Department of Transportation
ZEV	Zero-emission vehicle

Contents

1 Introduction

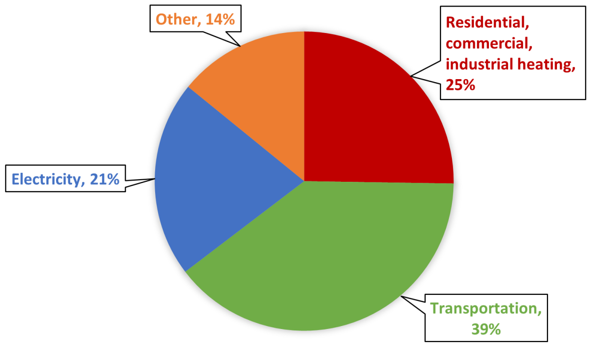
Overwhelming scientific evidence from the past decades has led the international community to formally commit to mitigating global climate change as part of the 2015 Paris Agreement (IPCC 2023; UNFCCC 2015). Since then, many governments around the world, on the national and subnational levels, have passed increasingly ambitious measures to reduce domestic carbon emissions, the main contributor to climate change. In the United States, states have fairly wide competency over their own energy policy (StatePowerProject.org 2023; Higman, Ladislaw, and Tsafos 2021), with the authority to set the course of action for energy provision and consumption. In regards to the transportation sector, California stands out with the unique ability to set emission standards for new vehicles (EPA 2023; CARB 2019), which many states, including Washington, opt to follow (CARB 2022).

As part of that, Washington state has passed binding legislation to completely phase out internal combustion engine vehicles from new vehicle sales by 2035 (Washington State Department of Ecology 2023a; The Seattle Times 2022a). The state has also set a non-binding target of 100% electric vehicle (EV) share of new light-duty vehicle sales by 2030 (Washington State Legislature 2022 Sec. 415, and The Seattle Times 2022b). Additionally, beyond the transportation sector alone, the state also committed to a 45% reduction in greenhouse gas emissions below 1990 levels by 2030 and net-zero emission levels by 2050 (Washington State Department of Ecology 2023c).

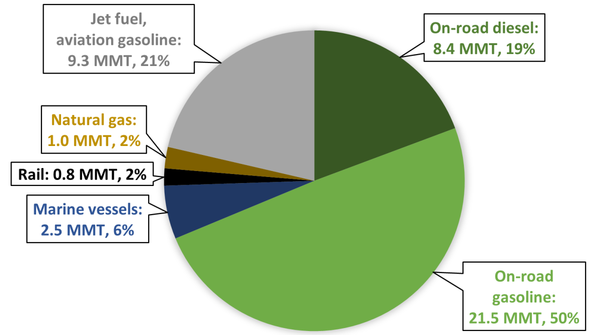
The purportedly strong focus of the Washington state legislature on emission reductions measures targeting the transportation sector can be explained by the high share the sector comprises in all of the state's emissions: Figure 1.1 shows the greenhouse gas emissions in Washington state in recent years[1]. Of the 2019 total emissions of 102.1 million metric tons of CO_2-equivalent (Washington State Department of Ecology 2023b), transportation accounted for 39% – the largest contributing sector. Past greenhouse gas emission inventories confirm this picture (Washington State Department of Ecology 2023b). Figure 1.1(b) stratifies the transportation emissions of 2017 by subsector, revealing that on-road emissions from gasoline and diesel use comprise about 69% of all transportation emissions. The next largest subsector is aviation (usage of both jet fuel and aviation gasoline), with operations at the largest airport in Washington (Seattle-Tacoma International Airport) contributing the most (WSDOT 2022).

The described figures highlight the relevance of addressing the transportation sector's emissions. Washington, over the past few years in specific, has passed ambitious legislation to support the decarbonization of the transportation sector, with a focus on electrification. In 2021, the state legislature passed House Bill 1287 (HB 1287) (Washington State Legislature 2021). This bill

[1] The most recent Washington greenhouse gas inventory showing the share of all emissions by subsector is for 2019. The 2017 data shown in Figure 1.1(b) was used since this was the most recent data showing Washington's transportation emissions by subsector.



(a) Total emissions by sector. Based on 2019 data shown in Washington State Department of Ecology 2023b.



(b) Transportation emissions by subsector. MMT = million metric tons of CO_2-equivalent. Based on 2017 data shown in The Seattle Times 2023.

Figure 1.1: Washington state greenhouse gas emissions.

- mandates the development of a zero-emission vehicle mapping and forecasting tool,
- requires electric utilities to model and account for future load growth from EVs in their service area for their integrated resource plans, and
- changes the building code to require EV charging capability at most new buildings with on-site parking.

Through this bill, the state aims to increase its "preparedness for a zero emissions transportation future" (direct quote from the bill as passed, see Washington State Legislature 2021).

The aviation sector, which in 2017 accounted for about 21% of Washington's transportation emissions (see Figure 1.1, has proven to be one of the toughest-to-decarbonize sectors of the economy (e.g. Gupta and Paliwal 2022). Projections and studies from international aviation organizations (e.g. ICAO 2022), the International Energy Agency (IEA 2022), and the Intergovernmental Panel on Climate Change (IPCC 2023) alike point out the need to transition fuel supply to sustainable aviation fuels (SAFs) to mitigate the bulk of aviation emissions. However:

1. There are high levels of uncertainty behind the lifecycle emission benefits of SAFs (NREL 2022a),
2. It is unclear at this time what the required levels of SAFs can be produced from (NREL 2022a), and
3. Solutions to mitigate or eliminate emissions from certain flight operations exist in the form of electric or hydrogen aircraft (ICCT 2022).

In addition to its climate benefits, electric aircraft also eliminates any local air pollutants (TRB ACRP 2022), which can be a crucial improvement for communities affected by local airport pollution.

The above measures, emission levels, and other considerations highlight the need for appropriate planning for a mobility transition that is driven by vehicle electrification. There is ample uncertainty around future EV adoption, the electricity load needed to charge these vehicles, and how other transportation subsectors can mitigate emissions. Additionally, the state has a natural interest to oversee and track the progress made in this transition. This thesis presents three research contributions that tangibly assist this process. In doing so, the thesis attempts to highlight the need for and capabilities of academic research beyond foundational science to support public policy measures.

Chapter 2 presents each research project's research question and provides additional detail on the overall goal of this thesis. Then, Chapter 3 discusses the first research work, which aimed at guiding the state as to how to reasonably procure the mapping and forecasting tool envisioned in the legislative mandate. Chapter 4 describes a regression-based forecasting model that predicts EV adoption levels by census tract across Washington over the coming years. As the third research contribution, in Chapter 5, this thesis presents a methodological framework that can be used to quantify potential electricity demand from electric aviation for regional flight operations. Finally, Chapter 6 reflects on the individual chapters' findings and discusses potential opportunities for future work.

2 Research question

This thesis is comprised of three main research contributions, each in active support of Washington state's interest in a rapid transportation electrification. Table 2.1 lists the three research questions to be addressed in the respective chapters. More detail is added to each research problem in the respective thesis chapters.

Table 2.1: The three research questions to be answered throughout this thesis.

Chapter	Chapter 3	Chapter 4	Chapter 5
Research question	How can the state plan, monitor, and interpret the progress made in terms of electric vehicle adoption and the public charging infrastructure buildout across the state? What are existing tools' capabilities concerning these requirements?	To what extent can we understand the spatiotemporal heterogeneity in terms of EV adoption across Washington, and what are likely EV adoption rates in different areas of the state over the coming years?	To prepare for electric flight operations and support electric utilities' capacity planning, what are the potential energy and power demands for charging electric aircraft at mid-size airports?

Chapter 3: The first research project presented in this thesis discusses the mapping and forecasting tool mandated by the state legislature through HB 1287. For this project, I reviewed and scored existing zero-emission vehicle infrastructure planning tools to understand if any of them (alone or in combination) can meet the requirements for the state mapping and forecasting tool detailed in the legislative mandate. The research agenda for this project was thus two-fold: It was first important to scope out the required and desired features of the state tool to see how the state can utilize it to track EV adoption and charging station buildout progress. In a second step, as will be discussed in the chapter, the review of existing tools allowed for the identification of suitable procurement options for the state tool, based on the results of the review.

Chapter 4: For the second research effort, traditional analysis and modeling techniques are used to forecast a quantity of interest. In this case, the state of Washington is highly interested to know to what extent it is on track to meet its self-set goals for EV adoption in 2030 and 2035. Hence, the goal of the work presented in that chapter was to predict the EV adoption rate, at a high spatial resolution. In doing so, the analysis revealed striking insights into the composition and spatial distribution of the Washington light-duty EV fleet. The modeling outcomes also have the potential to inform additional analyses on the spatial and temporal distribution of the EV charging demand.

Chapter 5: Lastly, for the third research project, infrastructure preparedness is the guiding principle. State aviation planners, along with electric utilities and airport managers, are interested in understanding potential levels of future electricity demand for electric aviation. For this reason, a bottom-up modeling framework was designed to quantify the annual energy and peak power needs for regional electric flight operations at two Washington airports.

Across the described chapters of this thesis, a common theme is the support of the state's transportation electrification planning efforts. While the first one touches on elements of statewide, comprehensive planning, which includes mapping relevant data and analysis layers in one common tool, the latter two projects can be viewed as possible contributions to that mapping and forecasting tool. As will be discussed further in each respective chapter, results from the two latter projects are useful for the state in determining the speed of electric vehicle adoption (both on-road vehicles and aircraft) and the power needs associated with it. In doing so, this thesis provides exemplary answers to the question of what practical, policy-related knowledge gaps academic research can answer.

3 State electric vehicle infrastructure planning

This chapter presents a research contribution aimed at supporting Washington state's capabilities to oversee, plan, and forecast the ongoing transportation electrification transition. First, an introduction provides an overview of state-level efforts in planning for zero-emission vehicles and their infrastructure. In Section 3.2, the required and desired features for the ZEV mapping and forecasting tool as planned by the state are presented. Section 3.3 discusses recent efforts by other jurisdictions to plan for or forecast ZEV infrastructure. Section 3.4 presents the main research contribution of this chapter: a review of existing tools to plan for and forecast zero-emissions vehicle infrastructure. Lastly, Section 3.5 and 3.6 describe the state's existing mapping platform and our tool procurement recommendations, before I conclude this chapter.

This chapter is based on a research report submitted to the Washington State Department of Transportation (WSDOT). The full report is the result of the contributions from the University of Washington Sustainable Transportation Lab (methods and results discussed in this thesis chapter) and the Washington State University (stakeholder engagement process; not discussed in this chapter). The report is public and can be accessed at https://wsdot.wa.gov/sites/default/files/2022-11/Implementing-ZEV-MFT-Report.pdf. My main contribution lies in the systematic review and scoring of available tools used for zero-emission vehicle infrastructure planning.

3.1 Introduction

A focus in the state's efforts of decarbonizing the transportation sector lies in advancing electric vehicles for the light-duty vehicle sector. As discussed in this thesis' Introduction, this is motivated by the large share of emissions originating from that passenger vehicles (cars and trucks). Beyond that, the state is pursuing the mitigation of emissions from the medium- and heavy-duty vehicle sector (Washington State Department of Ecology 2023d). To achieve the long-term climate goals set by the Washington legislature, including achieving net-zero emission levels by 2050 (Washington State Department of Ecology 2023c), a reduction of non-road transportation emissions (such as rail, aviation, and shipping) will be necessary as well.

For these reasons, the state would like to be in a position to oversee this ongoing transportation decarbonization process. In 2021, the Washington state legislature passed HB 1287 that included direction to WSDOT to develop a Zero-Emission Vehicle Mapping and Forecasting Tool (ZEV-MFT) "to enable coordinated, effective, efficient, and timely deployment of charging and refueling infrastructure necessary to support statewide and local transportation electrification efforts that result in emissions reductions" consistent with state goals (direct quote from the bill as passed, see Washington State Legislature 2021). The ZEV-MFT will allow WSDOT, other state agencies, electric utilities, local governments, and private infrastructure companies to plan infrastructure for zero-emission vehicles and track progress toward meeting emission reduction targets.

The federal infrastructure bill ("Infrastructure Investment and Jobs Act", see 117th Congress 2021) that President Biden signed on November 15, 2021, includes billions of dollars to fund infrastructure for zero-emission vehicles. The ZEV-MFT will help stakeholders plan for these federal funds and deliver value to Washington's citizens by aiding the selection of the best locations for ZEV infrastructure. The tool would help support grant applications, program design, and project development funded by federal programs that include[2]:

- U.S. Department of Transportation (USDOT) electric vehicle formula funds: $5 billion
- USDOT zero emission vehicle discretionary grants: $2.5 million
- USDOT reduction of truck emissions at port facilities: $250 million
- Federal Transit Administration low-no grants for buses and bus facilities: $5.2 billion
- US Department of Energy state energy program formula funds: $500 million
- US Department of Energy alternative fuel public school facilities: $500 million
- Environmental Protection Agency clean school bus program: $5 billion

Furthermore, the tool is intended to assist planning efforts, both on the state and local level. Examples include:

- State agencies (such as WSDOT or the Governor's Office): The tool would allow for tracking the state's progress toward electric vehicle (EV) adoption goals, including the self-set target of 100% electric vehicle share of new light-duty vehicle sales by 2030 (Washington State Legislature 2022)
- Electric utilities: The tool would enable utility companies to quantify potential future electric vehicle charging demand to improve their preparedness in terms of generation, transmission, and distribution capacity
- Local governments (such as city or county councils): The tool would allow local governments to assess their state of transportation electrification, including by comparing themselves to neighboring jurisdictions, and understanding gaps in their ZEV infrastructure.

[2] For a current comprehensive overview of federal funding programs for EV infrastructure, see https://www.transportation.gov/rural/ev/toolkit/ev-infrastructure-funding-and-financing/federal-funding-programs. The Dollar figures shown above represent the total budgeted federal spending for each respective program.

3.2 Mapping and forecasting tool requirements

According to the legislative mandate in HB 1287, the ZEV-MFT shall initially prioritize on-road transportation, maintain the latest data, model charging and refueling infrastructure for light-, medium-, and heavy-duty vehicles, and incorporate WSDOT's traffic data for passenger and freight vehicles (Washington State Legislature 2021). The bill included tiered language of critical ("The tool must ..."), preferred ("The tool must, if feasible..."), and rather optional ("The tool must include, to the extent feasible") features the ZEV-MFT should have (Washington State Legislature 2021), depending on the technical feasibility of implementing such features.

Figure 3.1 shows some of the key requirements for the ZEV-MFT detailed in HB 1287 illustrated. The mapping tool must include data layers of existing conditions shown in the left-hand column which includes the number of registered ZEV vehicles by vehicle class along with the number of their associated charging and refueling stations. The tool must also include the existing road network, traffic levels, population, employment, health, environmental, and socioeconomic data at the level of census tracts.

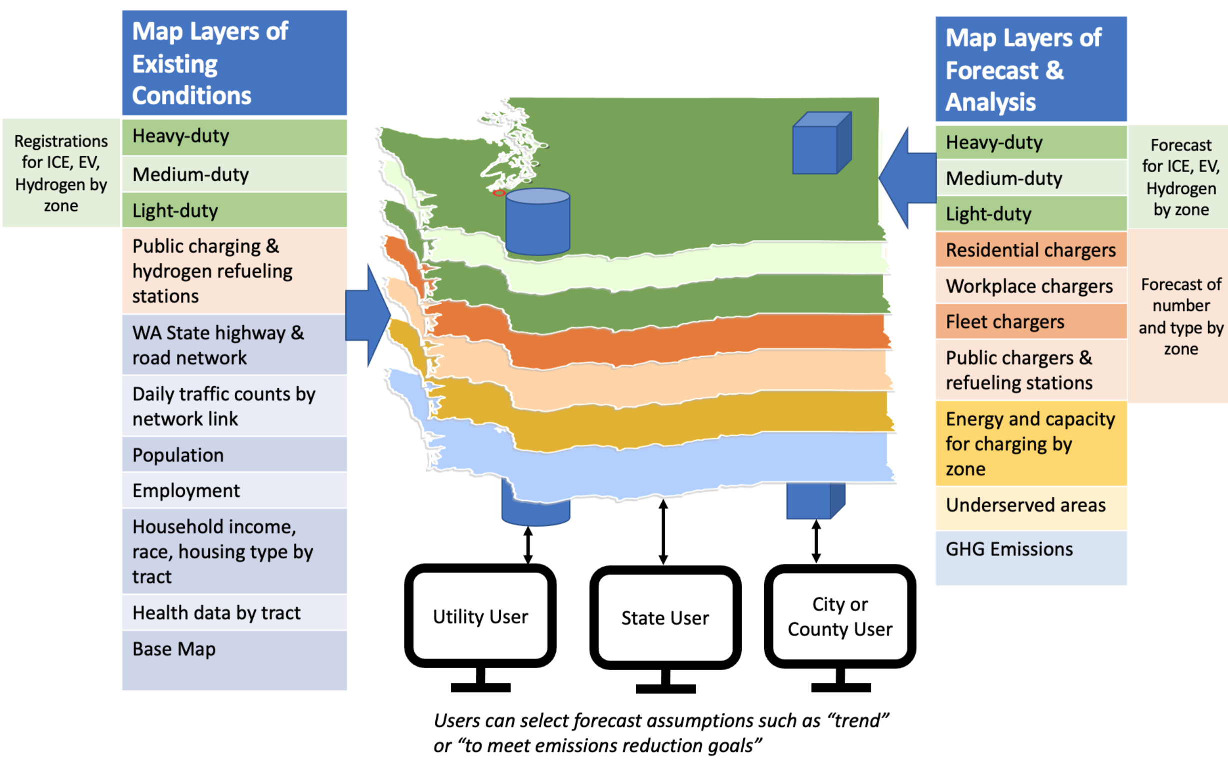


Figure 3.1: Schematic diagram of the mapping and forecasting tool to fulfill the requirements set in HB 1287.

In addition to characterizing present conditions, ZEV-MFT must also forecast future quantities of vehicles and charging and refueling stations along with the electricity needed to serve those stations under different scenarios including a scenario in which the transportation sector meets state goals for greenhouse gas reductions. The tool should allow electric utility users to generate reports on future electric vehicle charging demand to enable effective planning of generation, transmission, and distribution capacity and to aid in the siting of charging facilities. The tool should also allow cities and advocacy groups to analyze existing and projected conditions by subareas to enable timely and equitable distribution of public investments in zero-emission vehicles and charging and refueling stations. The tool should also allow state-level users to evaluate progress toward greenhouse gas reduction goals and provide information on the consequences of potential changes to public policy related to ZEVs.

The Innovative Partnerships Office at WSDOT contracted with the Sustainable Transportation Lab at the University of Washington to address three related research questions:

1. What tools and approaches to forecasting ZEVs and their related infrastructure have California, Oregon, and other jurisdictions used to develop policies and plans?

2. Do any of the existing tools offered in the market have a track record of meeting requirements close to those in HB 1287, either alone or in combination?

3. What options does WSDOT have for meeting the mapping and forecasting requirements of HB 1287 with high confidence and at reasonable cost?

Over ten weeks in the fall of 2021, our research team evaluated 17 tools related to ZEV forecasting and planning and reviewed different studies that estimated future needs for charging and refueling infrastructure. The team also met with leaders in the WSDOT information technology group to discuss their capabilities, experience with GIS platforms, and recommendations for implementing ZEV-MFT.

3.3 Recent studies to plan for ZEV infrastructure needs

Washington's state and provincial partners on the Pacific Coast (California, Oregon, and British Columbia) each issued reports in 2021 that project the need for electric vehicle charging infrastructure within their boundaries. These three studies, along with similar reports from Colorado, the City of Seattle, Princeton University, and a consultant team working on behalf of the three Western states provide a snapshot of the state of practice for mapping and forecasting the demand for ZEV infrastructure in 2021. Table 3.1 lists these studies and the tools used to produce electric vehicle adoption and/or charging needs forecasts.

Several key insights emerge from a review of these reports:

- All of the studies relied primarily on custom analysis to estimate future demand for ZEV infrastructure

- EVI-Pro from National Renewable Energy Laboratory was used by both Oregon and California to forecast infrastructure needed for light-duty vehicles for their reports

- Most of the studies focus on light-duty electric vehicles; California and the consortium of Western states also estimate demand for medium and heavy-duty electric vehicles.

- None of the studies specifically forecast demand for public transit agencies, maritime, or aviation, uses that HB 1287 directs Washington's state agencies to consider as a potential application of the tool.
- Washington's neighbors focused their forecasts on electric rather than hydrogen vehicles. Given current trends, hydrogen will lag behind electricity for on-road uses but hydrogen may gain market share over time for on-road, maritime, and aviation uses.

Table 3.1: Recent ZEV infrastructure needs assessments in western jurisdictions in the U.S. and Canada.

Study	Forecasting tools used
Assembly Bill 2127-Electric Vehicle Charging Infrastructure Assessment Analyzing Charging Needs to Support Zero-Emission Vehicles in 2030, California Energy Commission, July 2021. (Matt Alexander et al. 2021)	EVI-Pro, EVI-RoadTrip, HEVI-LOAD
British Columbia Public Light-Duty Zero-Emission Vehicle Infrastructure Study, Province of British Columbia, May 2021. (CleanBC 2021)	Custom analysis
Colorado charging infrastructure needs to reach electric vehicle goals, International Council on Clean Transportation, February 2021. (Hsu, Slowik, and Lutsey 2021b)	Custom analysis
City charging infrastructure needs to reach electric vehicle goals: The case of Seattle, International Council on Clean Transportation, January 2021. (Hsu, Slowik, and Lutsey 2021a)	Custom analysis
Net-Zero America: Potential Pathways, Infrastructure, and Impacts, E. Larson, et al., Princeton University, October 2021. (Princeton University 2021)	Custom analysis
Transportation Electrification Infrastructure Needs Analysis (TEINA) for Oregon, Kittelson, RMI, HDR and Forth, June 2021. (Kittelson & Associates 2021)	EVI-Pro, Custom analysis
West Coast Clean Transit Corridor Initiative, Interstate 5 Corridor, California, Oregon, Washington. HDR, et al., June 2020. (West Coast Clean Transit Corridor Initiative 2020)	Custom analysis

3.4 Existing mapping and forecasting tools

3.4.1 Overview of existing tools

Table 3.2 below summarizes the names and capabilities of the 17 reviewed existing tools that aim to support ZEV infrastructure planning on the national, state, county, sub-county, city, or sub-city level. This long list of potential tools reflects a high level of innovation and a large number of recent entrants that is typical of an emerging market. National labs and universities are conducting research and developing tools that are making their way into the private market of consulting firms and non-profits that provide planning and program services to state and local governments.

Table 3.2: Overview of existing ZEV forecasting tools.

Tool Sponsor/developer	Key characteristics
BEAM Lawrence Berkeley National Laboratory (LBNL)	• Agent-based, regional transportation model that can site charging infrastructure based on projected per-hour and per-county demand • So far only applied on the scale of a metropolitan region (e.g. San Francisco Bay Area) • Free access to software repository; usage is non-interactive and requires executing software code
Caret Center for Sustainable Energy	• Platform to forecast and evaluate the impacts of different user-defined EV incentive programs • Applied in several incentive programs of states and regions around the world • Proprietary software and modeling approach; online user interface
Charge4All Arup	• Suitability software that identifies high-level prioritization areas for electric vehicle supply equipment (EVSE) and street-level curbside suitability • So far only applied to southern California • Proprietary software and modeling approach; online GIS-based user interface
ChargEVal University of Washington	• Decision support system for public fast-charging EVSE for Washington state • Estimates the potential utilization for a chosen charging location and predicts other key metrics • Free access to software repository; restricted access to online user interface
E-DRIVE M.J. Bradley & Associates, Georgetown Climate Center, Ceres	• Prioritization tool that identifies the suitability of all census tracts in the U.S. for public fast-charging EVSE deployment • Estimates based on user-defined weights applied to several metrics • Free access; online interactive user interface

Table 3.2: (continued)

Tool Sponsor/developer	Key characteristics
Electric Bus Planning Framework M.J. Bradley & Associates	• Framework to determine the capital and operating requirements for the electrification of transit buses, included necessary charging infrastructure • Applied to several public metropolitan transit agencies • Proprietary modeling approach used for consulting to transit agencies; extent and design of user interface not reviewed
Energy Zones Mapping Tool Argonne National Lab (ANL)	• Mapping tool to identify energy resource areas and corridors in the US based on 360 layers that include various demographic and environmental data • Recently added exemplary EVSE models (corridor, urban TNC, rural) that output suitability scores for 250x250m cells • Free access (after registration); online GIS user interface
EV-CB Framework M.J. Bradley & Associates	• Framework to project societal costs and benefits of scenarios of EV adoption and charging patterns • Applied to several states • Proprietary modeling approach used for consulting purposes; spreadsheet-based tool, extent and design of user interface not reviewed
EValuateCO Atlas Public Policy	• Dashboard on the current and past market within the state (EV adoption, demographics, and charging infrastructure) • So far only applied to Colorado • Free access; online dashboard
EVI-X/EVI-Pro National Renewable Energy Laboratory (NREL)	• Comprehensive modeling suite to inform the development of large-scale EVSE deployment on a city level or county level • Applied by California and Oregon for their recent EV charging needs assessments • Proprietary software available under public license; requires executing software code
GIS EV Planning Toolbox UC Davis	• Forecasting tool to provide workplace and public charging demand on a census block group level based on user-defined EV market sizes • Applied by MPOs in California and Pennsylvania/New Jersey • Restricted access to modeling approach; GIS-based user interface

Table 3.2: (continued)

Tool Sponsor/developer	Key characteristics
HEVI-LOAD Lawrence Berkeley National Laboratory (LBNL)	• Model to project regional charging infrastructure needs for public, shared private, and private charging of medium and heavy-duty electric vehicles • Applied in California for their 2030 EV charging needs assessment (for the medium and heavy-duty sector) • Software under development and not available online; extent and design of user interface not reviewed
ILIT M.J. Bradley & Associates, Georgetown Climate Center	• Prioritization tool that identifies the suitability of all census tracts in 14 northeastern states for public fast-charging EVSE deployment • Estimates based on user-defined weights applied to several metrics • Free access; online user interface and an interactive GIS data visualization
PEV-CDM University of Vermont	• Research-focused framework aiming to produce hourly EV charging demands based on real-world travel patterns • Result of research at the University of Vermont, so far only applied to Quebec • Restricted access to software; usage is non-interactive and requires executing software code
REVISE-II Oak Ridge National Laboratory (ORNL)	• Optimization tool on where and when new charging stations should be deployed, including the allocated capacity • So far only reflects inter-city (county-to-county) highway travel • Free access to software repository; usage is mostly non-interactive and requires executing software code
StreetLight Data StreetLight Data	• Data provision software to analyze and rank charger site selections on a city level (or smaller) based on travel, traveler, visibility, and charging load metrics • So far only applied to a city (Santa Clara, CA) • Proprietary software; online user interface
UrbanFootprint UrbanFootprint	• Data provision software to quantify and analyze various impacts of user-defined land use scenarios in cities • No direct forecasts of EV charging demand • Proprietary software; online GIS-based user interface

3.4.2 Method for selecting, evaluating, and scoring existing tools

Tasked to evaluate the capability of these existing commercial and research tools, I began by gathering all relevant tools and frameworks in this field from various sources. The project's scope of work highlighted some of the tools to be considered – namely Caret, EVIX/EVI-Pro, and M.J. Bradley & Associates as a consulting firm. The latter company provides four different relevant tools (E-DRIVE, Electric Bus Planning Framework, EV-CB Framework, ILIT). In addition, EVI-X/EVI-Pro and HEVI-LOAD were used as the primary tools in recent EV infrastructure needs assessments conducted for neighboring states. Literature searches for related keywords (such as electric vehicle charging stations, charging infrastructure, planning, mapping, forecasting etc.) resulted in adding BEAM, Charge4All, GIS EV Planning Toolbox, PEV-CDM, and REVISE-II to the list of tools to be evaluated. Some tools were pointed out to our research team by individuals at WSDOT. This includes the Energy Zones Mapping Tool, EvaluateCO, StreetLight Data, and UrbanFootprint. Lastly, ChargEVal as a relevant tool developed in the Sustainable Transportation Lab was already known to the team.

As an initial approach, I gathered and documented all information on the tools that were available online, including links to websites, tool descriptions, documentations, user guides, associated research papers, repositories with the source code, news articles, as well as any studies that used one or more of the tools. For tools that are freely available online, the direct use of the tools supported the evaluation process further, especially with respect to user-friendliness and how feasible it would be for the general public to use it. Our research team also sought direct conversations with vendors and experts, including lead development staff of EVI-Pro at NREL, representatives for Caret from the Center for Sustainable Energy, as well as staff from the California Energy Commission. Broken down by all individual requirements stated in HB 1287, I finally evaluated each of the tools with respect to these requirements as well as required input and output data in a spreadsheet-based format.

Table 3.3 reports how I scored the tools on their ability to fulfill key characteristics of HB 1287. To provide full transparency and reproducibility of these results, a table with descriptions of what each tool needs to provide to reach one of the three scores in Table 3.3 is provided below. Generally, the scores correspond to the tool fulfilling the stated requirements fully or to a large extent (1, green), only in parts (2, yellow), or not at all (3, red). Specifics on the scoring criteria are presented in the right column of that table.

Table 3.3: Scoring criteria applied to existing tools.

Characteristic	(Specification)	Scoring criteria
Accessible to the general public		(1) The tool is accessible over the internet, user-friendly, and easy-to-use (i.e. it is feasible to be used by the general public). (2) The tool is accessible but not easy-to-use for the general public (3) The tool is only accessible by experts or the developers themselves or it is not easy-to-use (e.g. needs compiling of software).
Transparent, non-proprietary forecasts		(1) The tool is transparent as to how it derives its EV and EVSE projections and forecasts, and there are no proprietary formulations included. (2) The tool's developers provide a high-level explanation of its functionalities, the leveraged methods, and metrics, but it does not allow for a third-person to replicate the tool's exact outputs with the same input data. (3) The tool is not or very poorly documented or the forecasts, if existing, lack explanation how certain numbers are derived.
Applied in Western states		(1) The tool has been applied in Oregon and/or California to support their recent forecasts and/or projections of needed charging infrastructure. (2) The tool has been applied in Oregon and/or California to support EV programs but not forecasts or has only been applied in other states for transportation electrification efforts. (3) The tool has not been applied in the EV instrastructure studies we reviewed.
Commercially ready		(1) The forecast tool has (paying or non-paying) customers and is commercially available as of November 2021. (2) The forecast tool has completed its first stages of development and is available as of November 2021. (3) The tool is not a finished product or doesn't appear to be actively maintained and supported
Includes required WA data	Travel	(1) The tool incorporates travel data (e.g. traffic counts, peak traffic demands) for Washington State, taken from official Washington State sources, into its forecasts and projections. (2) The tool incorporates travel data for Washington State, taken from national data sources. (3) The tool has not been incorporating travel data for Washington State or does not incorporate any traffic data.
	Demographic	(1) The tool incorporates demographic data (e.g. on population density, sex, race, or ethnicity), taken from sources that cover Washington State. (2) The tool incorporates demographic data, taken from sources that do not cover Washington State (e.g. other states' offical data or regional surveys' data). (3) The tool does not incorporate any demographic data.
	Socioeconomic	(1) The tool incorporates socioeconomic data (e.g. on employment, health, household type), taken from sources that cover Washington State. (2) The tool incorporates socioeconomic data, taken from sources that do not cover Washington State (e.g. other states' offical data or regional surveys' data). (3) The tool does not incorporate any socioeconomic data.
	Environmental	(1) The tool incorporates environmental data (e.g. on overall air quality or toxicity, particulate matter), taken from sources that cover Washington State. (2) The tool incorporates environmental data, taken from sources that do not cover Washington State (e.g. other states' offical data or regional surveys' data). (3) The tool does not incorporate any environmental data.

(continued)

Characteristic	(Specification)	Scoring criteria
Includes vehicle types and their respective infrastructure	Light EV	(1) The tool includes the derivation of forecasts and/or projections for light-duty EVs (<10,000 lbs, e.g. passenger cars) and related infrastructure. (2) The tool includes light-duty EVs and/or related infrastructure, but does not produce direct forecasts or projections for their charging infrastructure. (3) The tool does not include light-duty EVs.
	Medium EV	(1) The tool includes the derivation of forecasts and/or projections for medium-duty EVs (10,000-26,000 lbs, e.g. vans or shuttle buses) and related infrastructure. (2) The tool includes medium-duty EVs and/or related infrastructure, but does not produce direct forecasts or projections for their charging infrastructure. (3) The tool does not include medium-duty EVs.
	Heavy EV	(1) The tool includes the derivation of forecasts and/or projections for heavy-duty EVs (>26,000 lbs, e.g. city transit buses, heavy freight trucks, garbage trucks) and related infrastructure. (2) The tool includes heavy-duty EVs and/or related infrastructure, but does not produce direct forecasts or projections for their charging infrastructure. (3) The tool does not include heavy-duty EVs.
	Any hydrogen	(1) The tool includes the derivation of forecasts and/or projections for any type of hydrogen vehicles (light-duty, medium-duty, or heavy-duty) and refueling infrastructure. (2) The tool includes hydrogen vehicles, but does not produce direct forecasts or projections for their refueling infrastructure. (3) The tool does not include hydrogen vehicles.
Subarea demand forecast		(1) The tool forecasts charging demands at a disaggregate geographic level (sub-city, i.e. ZIP code, census tract, or similar) to help find possible future charging station locations. (2) The tool forecasts charging demands at county-level or larger or outputs priority areas (on county-level or finer) for future EVSE based on estimated suitability. (3) The tool does not forecast charging demands.
Forecasts kW & kWh for utility planning		(1) The tool forecasts electricity demand at a disaggregate geographic level (sub-city) for both energy (kWh) and capacity (kW), based on an assessment of the local EV charging needs/demands. (2) The tool forecasts electricity demand only at county-level or coarser or, with some adaptation, the tool allows for the evaluation of electricity demand scenarios. (3) The tool does not forecast electricity demand for local EV charging needs/demands.
Projects ZEV adoption to meet climate goals		(1) The tool projects the level of ZEV adoption required to meet emission reduction goals, both on state level as well as in each utlity service's area. (2) The tool provides some functionality that estimates greenhouse-gas emissions and savings thereof, which could be adopted to project the level of ZEV adoption required to meet emission reduction goals. (3) The tool does not project how large ZEV adoption has to be to meet emission reduction goals.
Includes public transport		(1) The tool includes public transport as part of the transportation electrification efforts. (2) The tool includes public transport to some extent, but does not provide direct or indirect support for its electrification. (3) The tool does not include public transport as part of the transportation electrification efforts.
Includes maritime & aviation		(1) The tool includes maritime transport and aviation as part of the transportation electrification efforts. (2) The tool includes maritime transport and aviation to some extent, but does not provide direct or indirect support for its electrification. (3) The tool does not include maritime transport and aviation as part of the transportation electrification efforts.

3.4.3 Findings on existing tools' capabilities with respect to HB 1287

Table 3.4 evaluates each tool against some of the key requirements identified in HB 1287 and stakeholder conversations. Because of the early stage of the market, all of the currently available tools carry some risk that the sponsoring entity may not support them over time as no clear market leaders have yet emerged. If there were a market leader for forecasting charging infrastructure for light-duty vehicles, it would be EVI-Pro, the tool developed by NREL and used by the states of California and Oregon. But, according to staff at NREL, even this tool has yet to be formally licensed to any entities outside the national labs for commercial use. Moreover, light-duty vehicles are just one of four vehicle types for which HB 1287 requires mapping and forecasting. A quick scan across the rows in Table 3.3 reveals that none of the tools reviewed meet all the requirements of HB 1287 alone or in combination. Most of the tools forecast light-duty electric vehicles and related infrastructure, a few address medium- and heavy-duty electric vehicles, and none of them forecast hydrogen vehicles and refueling infrastructure nor do they forecast maritime and aviation needs.

3.5 WSDOT's existing online mapping platform

WSDOT, in coordination with the state's Office of the Chief Information Officer, has adopted ArcGIS as its standard geographic information system or electronic mapping platform. WSDOT has a license from the firm ESRI to operate the ArcGIS Online system for a wide range of public uses that can be found at https://wsdot.maps.arcgis.com/home/index.html.

Many of the data layers of existing conditions shown on the left side of Figure 3.1 are already available on WSDOT's mapping sites including the state highway network, traffic counts, public health data, city and county boundaries, and population data. Other ArcGIS map layers of existing conditions are readily available from other jurisdictions such as the U.S. Census and the federal Department of Energy. ArcGIS Online is a proven platform for WSDOT and applications like WSDOT's Community Planning Portal are accessed thousands of times each month by planners and analysts in local governments.

Table 3.4: Existing ZEV forecasting tools scored on HB 1287 requirements.

	Accessible to the general public	Non-proprietary forecasts	Applied in Western states	Commercially ready	Includes required WA data				Includes vehicle types and their respective infrastructure				Subarea demand forecast	Forecasts kW & kWh for utilities	Projects ZEV # for climate goals	Includes public transport	Includes maritime & aviation
					Travel	Demographic	Socioeconomic	Environmental	Light EV	Medium EV	Heavy EV	Any hydrogen					
BEAM	3	1	3	2	3	3	3	3	1	3	3	3	2	2	3	2	3
Caret	2	2	2	1	2	2	2	3	1	3	3	3	1	1	2	3	3
Charge4All	2	3	3	1	3	2	2	3	1	3	3	3	2	1	3	3	3
ChargEVal	3	1	2	3	1	3	3	3	1	3	3	3	3	1	3	3	3
E-DRIVE	1	2	3	1	2	1	1	1	1	3	3	3	2	3	3	3	3
Electric Bus Planning Framework	3	1	3	3	3	3	3	3	3	3	2	3	2	2	3	1	3
Energy Zones Mapping Tool	1	2	2	1	2	1	1	1	2	3	3	3	2	2	3	3	3
EV-CB Framework	3	3	3	3	3	3	3	3	2	3	3	3	3	2	2	3	3
EValuateCO	1	3	2	2	3	1	1	3	1	3	3	3	2	2	3	3	3
EVI-X/EVI-Pro	3	2	1	2	3	2	3	3	1	2	2	3	2	2	3	3	3
GIS EV Planning Toolbox	2	2	2	3	3	2	2	3	1	3	3	3	1	1	3	3	3
HEVI-LOAD	3	1	1	2	3	3	3	3	3	1	1	3	2	2	2	1	3
ILIT	1	2	3	1	2	1	1	1	1	3	3	3	2	3	3	3	3
PEV-CDM	3	1	3	3	3	2	2	3	1	3	3	3	1	1	2	3	3
REVISE-II	3	1	3	2	2	3	3	3	1	3	3	3	2	2	3	3	3
StreetLight Data	3	2	3	2	3	2	2	3	1	3	3	3	2	1	3	3	3
UrbanFootprint	1	2	3	1	2	1	1	1	2	3	3	3	2	2	2	2	3

Fullfills requirement...	
fully or mostly.	1
only in parts.	2
not at all.	3

3.6 Procurement options

Our research team identified three options for WSDOT to procure the ZEV-MFT:

- Option 1: Contract for a turnkey solution hosted by the vendor
- Option 2: Host the tool using WSDOT's ArcGIS Online license and contract for the annual forecast layers on the right side of Figure 3.1
- Option 3: Host the tool using WSDOT's ArcGIS Online license and hire new WSDOT staff to generate the annual forecast layers on the right side of Figure 3.1

Our research team compared these options across five evaluative criteria shown in Table 3.5. Option 1 would have the highest vendor costs and the lowest staff costs; Option 3 would have the highest staff costs and the lowest vendor costs. It is difficult to say which option would have the lowest combined vendor and staff costs, and our team did not develop a comprehensive cost plan combining vendor and staff costs across all options. The risk of vendor lock-in and getting stuck with a stranded mapping and forecasting technology is highest with Option 1, though vendor selection criteria could mitigate this risk. Options 2 and 3 can be scored high on the platform's track record given the proven success of ArcGIS Online across state and local government in Washington. As part of technical report submitted to WSDOT as part of this work, our research team recommended Option 2 because it builds on WSDOT's existing ArcGIS Online platform and data sets and then allows WSDOT to periodically contract for forecasts from the country's leading experts on ZEV infrastructure requirements. Our research team acknowledged that Option 1 may prove more attractive to WSDOT, especially if the IT personnel and institutional resources to support Option 2 are scarce.

Table 3.5: Procurement options scored on qualitative evaluative criteria.

Option	Vendor costs	WSDOT staff costs	Vendor lock-in risk	Stranded technology risk	Platform's track record
1: Turnkey	High	Low	High	High	Short
2: Contract for forecasts	Medium	Medium	Low	Low	Long
3: Staff for forecasts	Low	High	Low	Low	Long

In addition to the presented analysis of existing tools that are in partial fulfillment of HB 1287 requirements, our research team developed a cost estimate for the first five years if WSDOT pursued Option 2. The cost estimate for the fiscal years 2023 through 2027 totaled about $8.7 million. Since I did not lead this analysis effort, I do not present this effort in this thesis. However, the interested reader can read about the five-year cost estimates our research team developed in the full report submitted to WSDOT that is linked at the beginning of this chapter. In Washington state's "Plan For Electric Vehicle Infrastructure

Deployment”[3], published in July 2022, $8.5 million were allocated to the state’s Department of Commerce’s budget to oversee the implementation of the ZEV-MFT.

3.7 Conclusion

The Washington state legislature gave WSDOT an unprecedented assignment in HB 1287. There is currently no other state in the U.S. with a publicly accessible online tool available that is as comprehensive as the ZEV-MFT mandated by HB 1287.

None of the existing tools for helping states plan for ZEV infrastructure are capable of providing all of the functionality envisioned in the bill’s description of the mapping and forecasting tool. Fortunately, WSDOT can build on the recent work of its neighboring states and provinces to identify the best practices to forecast charging and refueling infrastructure. WSDOT can also leverage its own experience with online mapping systems to assemble geographic information that is accessible to the public. By making information available to a wide range of stakeholders including utilities, cities, counties, tribes, and community groups, WSDOT’s ZEV-MFT project will help inform more effective public investment decisions as our transportation system shifts away from fossil fuels toward low-carbon alternatives.

[3] This plan is a requirement of the National Electric Vehicle Infrastructure (NEVI) program, which is funded by the federal infrastructure bill of 2021 and comprises the electric vehicle formula funds and discretionary grants, both mentioned earlier in this chapter. The Washington state NEVI plan is available at https://wsdot.wa.gov/sites/default/files/2022-08/Electricvehicle-plan-infastructuredeployment.pdf.

4 Electric vehicle adoption forecasting

This chapter presents a research project aimed at modeling and forecasting light-duty electric vehicle (EV) adoption across Washington at a high geographic resolution (by census tract). The chapter begins with an introduction to the topic, providing background on the current state of EV adoption in Washington. Then, the used data and deployed methodology are described in Section 4.2. Section 4.3 presents and discusses the results of the modeling effort. I conclude this chapter by discussing implications of the results of this project on supporting ongoing EV adoption. I was the leading researcher working on this project, including assembling and processing all data sources, defining and implementing the methodology, and presenting and discussing the results.

4.1 Introduction

WSDOT's Innovative Partnerships Office contracted with the University of Washington's Sustainable Transportation Lab to develop light-duty electric vehicle registration forecasts by census tract for the coming years. This thesis chapter lists and describes the data sources and methodology used for this task, and presents the results obtained from the analysis work. The outcomes of this work can be viewed as a possible contribution (a layer) in the zero-emission vehicle mapping and forecasting tool discussed in the previous chapter. As a noteworthy feature, the modeling is done at the census tract-level, providing high spatial resolution for electric utilities or city planners to analyze future EV adoption uptake on the neighborhood scale. The results can furthermore inform future modeling efforts to understand the home, workplace, and public charging demands induced by the EVs registered in each census tract.

Electric vehicle adoption is increasing in Washington State. EVs comprised 6.7% of all new light-duty vehicle registrations in Washington in the first nine months of 2022 (State of Washington 2022b). They also make up about 1.8% of the current light-duty vehicle stock in Washington (as of September 2022, State of Washington 2022d). While EV adoption rates are increasing, they also vary strongly across the state. King County is home to a quarter (26%) of all of Washington's light-duty vehicles but over half (53%) of the electric vehicles. The flipside of higher EV adoption in King County is low EV adoption in many rural counties. In September 2022, 10% of all census tracts in Washington still had less than 10 EVs registered. This strong geographic heterogeneity in EV adoption across Washington will likely persist until zero-emission vehicle sales mandates force lagging areas to catch up.

The adoption of EVs in the next two decades will be shaped by goals recently set by the Washington legislature: a target of 100% electric vehicle share of new light-duty vehicle sales by 2030 (The Seattle Times 2022b), and a requirement in Washington's Clean Vehicles Program for zero-emission vehicles to make up 100% of new sales starting in model year 2035

(The Seattle Times 2022a). Given the differences in the EV adoption rates by subarea over the last decade, the regulatory requirement of 100% EV sales by 2035 will add constraints to customer preferences in some geographies more severely than others. In addition, EV adoption rates in different subareas will depend on local as well as national policies and incentives.

The forecasts presented in this chapter are based on the EV adoption trends in each respective census tract in Washington over the past 12 years. They do not account for potential future policy interventions including Washington's regulatory ban on the sale of new light-duty vehicles with internal combustion engines in 2035. These forecasts are best understood as likely pathways of EV adoption by census tract if past trends prevail and are most useful for understanding how EV adoption will vary by locale. Whether a particular census tract hits an EV stock share of 20% in ten or thirteen years matters less for planning than knowing that one census tract is forecast to have twice the EV charging demand of another. By projecting plausible estimates of EV adoption by census tract, the forecasts can help state and local governments, electric utilities, property owners, and private charging companies make more informed decisions about where to invest to ensure adequate charging capacity for EV drivers in the future.

4.2 Data and methods

4.2.1 Data sources

This section presents and references the various datasets used to forecast EV adoption across Washington by census tract. Not all of the listed data sources were used to produce the EV forecasts presented in the next chapter, but the datasets were used for model development and the comparison of different model configurations (as presented in Section 4.3.2).

For the purpose of this project, data sources were taken as of September 2022. In the future, the analysis and forecasting framework can be updated using more recent data, especially on the EV and light-duty vehicle registration transactions.

4.2.1.1 Vehicles

The forecasted variable in this work is the electric vehicle market share of all light-duty vehicles, for each step in time and in each census tract in Washington, expressed as either the stock share or sales share. Here, the former describes the share of EVs in the currently registered light-duty vehicle stock (i.e. the vehicles on the road), whereas the latter represents the share of EVs in the new light-duty vehicle sales (i.e. the new vehicles entering the vehicle stock). Both quantities relate to each other. One can translate a forecast of annual new electric vehicle sales into a forecast of the total vehicle stock by using a fleet turnover model that appropriately accounts for vehicle entry to and retirement from the vehicle stock. This is done using Argonne National Laboratory's VISION model, as described in the methodology section.

To derive past vehicle counts by census tracts, publicly available data provided by the Washington State Department of Licensing (DOL) was used that contains vehicle registrations transactions tagged with the respective vehicle's census tract. Each vehicle's identification number (VIN) is stripped to only include the first 10 out of 17 digits, so that specific vehicles cannot be identified from the data. While in similar formats, the data sets from DOL are split between registration transaction records for all light-duty vehicles (State of Washington 2022d) and for electric vehicles only (State of Washington 2022c).[4] For each point in time (month) and for each census tract, a light-duty vehicle count was derived by summing up all new vehicle sales ("Original Registration")[5] and all vehicle registration renewals ("Registration Renewal") over the past one year (365 days)[6]. These vehicle counts represent the currently registered number of light-duty vehicles for a specific point in time (month) and census tract.

Similarly, by summing only over the past one month, a count of new vehicle sales, used vehicle sales, and registration renewals could be derived by counting the "Original Registrations", "Registrations at Time of Transfer", and "Registration Renewals", respectively. By doing so, over 39 million past vehicle registration transaction records were scanned. Vehicle counts for each month prior to 2018 were derived based on population data for each census tract from 2011 to 2017, by scaling the monthly vehicle counts in each census tract in 2018 according to the relative difference between each census tract's population in the years from 2011 to 2017 and in 2018[7].

Using the respective counts for all light-duty vehicles and for EVs only, EV shares could be derived as the quotient of EV count and all light-duty vehicle count: EV share of registered vehicles (EV stock share), EV share of new vehicle sales (EV sales share), EV share of used vehicle sales, and EV share of vehicle registration renewals. Since there are 141 months between January 2011 and September 2022 and 1458 census tracts in Washington[8], 205,578 data points resulted for each of these variables. For the purpose of this project, only the EV stock share and the EV sales share (of new vehicle sales) were used.

4.2.1.2 Gas prices

Historic average Washington gas prices for each month since 2011 were taken from the U.S. Energy Information Administration (U.S. Energy Information Administration 2022). The "Washington All Grades Conventional Retail Gasoline Prices" were used in dollars per gallon, representing monthly average gasoline prices in Washington.

[4] Vehicle registration records are publicly available from January 2020 to September 2022. The UW research team worked with DOL to provide vehicle registration data dating back further than the publicly available dataset. DOL provided the equivalent vehicle registration data going back to January 2017, so that light-duty vehicle counts could be derived from January 2018 to September 2022.

[5] This and the following expressions in quotation marks denote the transaction type data tags used by DOL to denote new vehicle registrations, used vehicle registrations, and registration renewals. For more information on this labeling, see https://data.wa.gov/Transportation/Vehicle-Registration-Transactions-by-Department-of/brw6-jymh under "About this Dataset".

[6] Vehicle registration data for one full year prior to the point in time of interest is required, since passenger vehicle registration renewals are required once per year in Washington.

[7] To do this, population data for the years 2011 through 2017 was taken from the U.S. Census Bureau, as described in Section 4.2.1.5.

[8] As defined in the 2010 U.S. Census Bureau census tract designations (see further below).

4.2.1.3 EV charging stations

Information on the location, type, and quantity of public electric vehicle charging stations was taken from the National Renewable Energy Lab's (NREL) Alternative Fuel Data Center (AFDC) (NREL 2022b). The respective dataset is a record of all public EV charging stations across the United States. Using the stations' geographic location (latitude, longitude), the respective census tract was derived in which the charging station is situated. With this data, the number of all Level 2 and DC fast charging stations was derived for each census tract and month since 2011.

4.2.1.4 EV product variety

The number of available EV models available to consumers was estimated by counting the number of different make/model combinations in Washington at every point in time since 2011. This was done using the same EV registration transactions dataset used to derive EV counts (see above). The data contains entries of each vehicle's make and model, which was used to derive the various make/model combinations (such as Tesla Model 3 or Volkswagen ID.4).

4.2.1.5 Socioeconomic data

Socio-economic data by census tract was taken from the U.S. Census Bureau's American Community Survey (ACS) 5-year estimates for each year from 2011 to 2020 (U.S. Census Bureau 2021). This data is released annually for each census tract. At the time of this project, 2021 ACS data was not yet released; hence, 2020 data was assumed for 2020, 2021, and 2022. This data contains counts of the number of people in each census tract that share certain social, racial, economic, or other properties. Using these counts, the following quantities could be derived from the ACS data: total population, median household income, share of white people, share of people with a Bachelor's degree or higher, and share of people living in single-family units.

4.2.1.6 Census tracts

Information on the shape and number of census tracts across Washington was taken from the U.S. Census Bureau. The bureau changed its census tract designation in 2020, resulting in slightly different numbers of census tracts in Washington due to mergers and splits of neighboring census tracts. The vehicle registration data used to derive census tract-level EV shares is given in the 2020 census tract designation, while all socioeconomic data (from the ACS) prior to 2020 is given in the 2010 census tract designation. A relationship file is used to convert the vehicle counts and derived EV shares into the 2010 census tract designation.[9]

[9] Because Washington grew in the decade from 2010 to 2020, most census tract changes were cases in which a census tract from the 2010 designation was split into two (or more) new census tracts in the 2020 designation. Because of this, our research team decided to express the vehicle counts and EV shares in the 2010 census tract designation. For this, 2020 census tracts were assigned the 2010 census tract that their area predominantly comprised, using the respective census tract relationship file available at https://www.census.gov/geographies/reference-files/time-series/geo/relationship-files.html. There were 1,458 census tracts in the 2010 designation, and 1,784 in the 2020 designation.

In addition, GIS shapefiles of Washington census tracts as provided by the U.S. Census Bureau[10] were used to visualize results on a map.

4.2.2 Methodology

This section describes the methods used to produce census tract-level forecasts of electric vehicle adoption across Washington using vehicle registration data from the Department of Licensing. The chosen methodology projects past EV adoption trends in the different census tracts into the future, with the assumption that both EV sales share and EV stock share (as defined in the previous section) follow an S-shaped technology adoption curve over time as has been observed with most new technology diffusion, including in the automotive sector (Rogers 2003; Zoepf and Heywood 2012).

The monthly, census tract-level EV shares (stock share and sales share) are first analyzed in regards to geographic and temporal trends. The research team used multiple methods of data visualization to illustrate the strong geographic heterogeneity across Washington in terms of EV adoption levels. The team also produced a set of descriptive statistics, which also include the time trend of the number of available EV (BEV and PHEV) models to Washington consumers.

4.2.2.1 General note on forecasting

Niels Bohr, 1922 Nobel laureate in Physics and father of the atomic model is claimed to have said[11]: "Prediction is hard, especially about the future." This catch phrase is a reminder that any forecast of uncertain processes, including the mass market adoption of new technologies, such as electric vehicles, poses challenges. As a general rule, it is hard to rely on out-of-sample predictions which in this case means using the past to project the future. This holds true especially regarding predictions on data points that are farther away from the sample data used to calibrate the forecasting model (here: later years in the forecast). In regards to EV adoption, changes in consumer purchasing behavior, gas prices, product availability, or major policy interventions (and more) could alter EV adoption rates. The forecasts produced by the UW research team rely on the past trends and geographic heterogeneity in EV adoption across the state to develop plausible future adoption scenarios by census tract. Even if they do not turn out to be precisely accurate, they may nonetheless be useful in helping charging networks, state and local governments, and utilities evaluate the relative demand for future charging among different locales. As plausible estimates of future EV adoption, these forecasts can serve as one input in developing plans to ensure local areas will have sufficient capacity from the electric grid and charging stations to meet the projected growth over the next decade.

[10] The shapefiles are available under https://www.census.gov/geographies/mapping-files/time-series/geo/tiger-line-file.html.

[11] https://quoteinvestigator.com/2013/10/20/no-predict/

4.2.2.2 Forecasting model

To produce monthly, census tract-level forecasts of EV adoption in Washington, a logistic regression model with a logit-transformed dependent variable representing the EV market penetration was used. The dependent variable is the electric vehicle share of either new light-duty vehicle sales (sales share) or of the light-duty vehicle stock (stock share). Choosing these two alternative approaches is mainly motivated by the following:

1. Charging infrastructure needs are determined by the number of EVs on the road (stock share)
2. State goals (100% sales share by 2030 or 2035) are defined in terms of the EV sales share

The logistic regression model deployed in this project can be expressed with the following equation:

$$\log\left(\frac{p_{it}}{1-p_{it}}\right) = y_0 + \beta_i + \gamma_t + \epsilon_{it}$$

Here, the indices i and t represent the respective census tract and point in time (month), respectively. Then, p_{it} denotes the EV stock share or sales share (derived from DOL vehicle registration data as described in the previous section). The transformation using the logarithm of the so-called odds $\frac{p_{it}}{1-p_{it}}$ ensures that the dependent variable p_{it} will always assume values between 0 and 1, and move from 0 to 1 as the right hand side of the equation increases. There, y_0 is a constant. The β_i are census tract-specific fixed effects, quantifying each census tract's propensity for EV adoption. Accordingly, the γ_t are time fixed effects, quantifying the general statewide trend towards an increasing EV adoption over time. All these three quantities are parameters whose values are yielded as part of the model fitting process. The ϵ_{it} are the residuals of the model (i.e. the difference between predicted and observed value).

In addition, model runs were conducted that include some or all of the following independent variables:

- Public charging station availability
- Race (share of white/non-white people)
- Education (share of people with college degree)
- Housing type (share of people living in single-family units)
- Median household income
- Gas prices
- EV product variety (no. of available EV models)

In these models, each of the included variables has a model parameter assigned to it whose value is derived as part of the fitting process. The model equation then takes the form

$$\log\left(\frac{p_{it}}{1-p_{it}}\right) = y_0 + \beta_i + \gamma_t + \sum_v \alpha^v x_{it}^v + \epsilon_{it}\,, \tag{4.1}$$

where α^v is the model parameter for variable v (one of the ones listed above) and x_{it}^v is the variable's numeric value in census tract i and in time step t.

The census tract-level fixed effects (β_i) intend to capture the heterogeneity in terms of EV adoption levels observed between census tracts. These effects are assumed to remain constant over time, corresponding to a continuation of the trend that some areas of the state show sooner and faster EV adoption than others. The time fixed effects (γ_t) intend to capture the general statewide rise in EV share over time. These effects are quantified for each step in time in the model fitting process, and then extrapolated into the future based on the observed past trend. Figure 4.1 visualizes the estimated time fixed effects and the function fitted to them. The functional form of a scaled logarithm was chosen due to the found temporal evolution of the time fixed effects. The function fits well to the modeled fixed effects and are projected out until 2035, without accounting for possible disruptions caused by influential policy decisions or other impactful external events. Such events could include abnormal increases in gas prices, which could drive EV adoption, or also an imbalance between EV supply and demand, as could partially be observed since 2022 (Loew 2022; Seekamp 2023). Due to the logarithmic functional form of the fit, the projected time fixed effects flatten out compared to the past. It should be noted that this shape does not translate directly onto the forecasted adoption curve, as the model (Equation 4.1) does not prescribe linearity between the forecasted EV shares (p_{it}) and the time fixed effects (γ_t). This part of the model reflects the assumption of a continuation of past trends in EV adoption. The model used to forecast EV adoption in the state, at this point, is thus not sensitive to specific EV-related policy changes imposed on the federal, state, or local level, including sales incentives or the installation of public or at-home charging infrastructure.

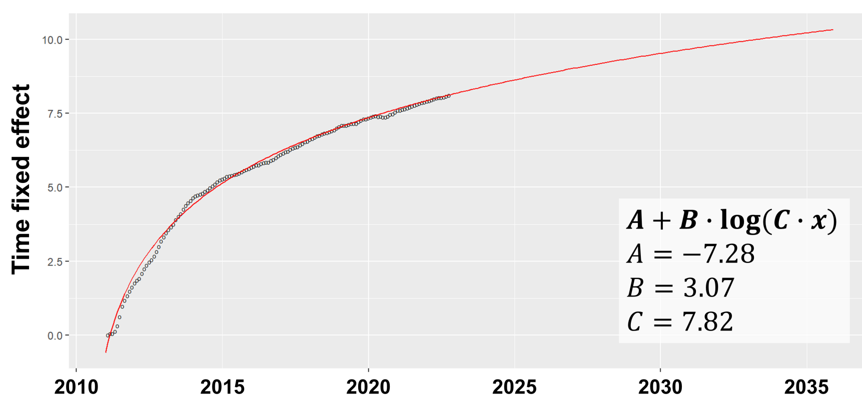


Figure 4.1: Time fixed effects as estimated by the model (black circles), and fitted to with a logarithmic function (red line and functional form with parameters).

This forecasting approach yields two separate forecasts:

1. One forecast of the EV stock share based on the EV stock share as the dependent variable p_{it}
2. One forecast of the EV sales share based on the EV sales share as the dependent variable p_{it}

The two approaches yield census tract-level results for each month from the present through 2035. The results can be examined at the census tract level or aggregated to statewide EV shares using the total light-duty vehicle count in each census tract. In specific, the statewide EV sales or stock share $p_{\mathrm{WA},t}$ can be derived from the census tract-level results using

$$p_{\mathrm{WA},t} = \frac{\sum_i p_{it} \cdot n_{it}}{\sum_i n_{it}}$$

where n_{it} is either the number of all light-duty vehicles or the number of new light-duty vehicle sales in census tract i at time step t.

4.2.2.3 Vehicle stock turnover model

The Argonne National Laboratory (ANL) developed a model to estimate energy use and carbon emission impacts of the adoption of various advanced vehicle technologies, called VISION (Argonne National Laboratory 2022). The model can be used to simulate the turnover of a vehicle fleet (or: stock) given certain market shares of different vehicle technologies over time. To accomplish this, VISION keeps track of the different vehicle vintages and retirement cycles, based on data for the average lifetime of light-duty passenger vehicles and typical dynamics of the used vehicle market.

Using VISION in its current 2022 version, the statewide EV adoption forecast results obtained from the model developed in this project can be converted into the respective alternative quantity:

1. The statewide EV stock shares over time can be converted into statewide EV sales shares that would be required to yield the forecasted stock shares.

2. The statewide EV sales shares over time can be converted into statewide EV stock shares that would result from the forecasted sales shares.

Because VISION is spreadsheet-based and non-programmable, fleet turnover dynamics were not simulated for all 1458 census tracts of the state, but only for the statewide results and for specifically selected census tracts.

4.3 Results

4.3.1 Characterization of the EV fleet across Washington: past and present

Washington state is one of the leading states in the U.S. in terms of electric vehicle adoption (NREL 2022c). Based on the DOL vehicle registration data used in this work, in the first nine months of 2022, the EV share of new light-duty vehicle sales was 6.7%. They also make up about 1.8% of Washington's current light-duty vehicle stock, also see Table 4.1. About 76% of all electric vehicles in Washington are all-electric models (BEVs), with the rest being plug-in hybrids (PHEVs). As of September 2022, all but two Washington census tracts had at least one electric vehicle registered in its light-duty vehicle stock, representing 99.94% of

Washington's population. While 90% of all census tracts have at most 174 registered EVs, the leading tract has 722 EVs registered (in the City of Issaquah). The highest EV share in the light-duty vehicle stock in one census tract is 12.5% (520 of 4,159 light-duty vehicles, in Belltown in the City of Seattle).

Table 4.1: Statewide means and median of census tracts in terms of EV share in Washington's light-duty vehicle stock.

	Statewide mean	Median of census tracts
EVs	1.79%	1.12%
BEVs	1.36%	0.78%
PHEVs	0.43%	0.34%

The statewide distribution of the EV stock share by census tract is visualized in Figure 4.2-4.4. Figure 4.2 shows a map of the EV stock share in Washington's census tracts in 2015 and 2022. As one can see in these maps, the EV share in the vehicle stock substantially increased in the seven years from 2015 to 2022. In 2015, the vast majority of tracts had less than 0.5% EVs registered in their vehicle stock. Only some tracts in the Puget Sound region, most of them in King County, have EV shares of more than 0.5%, with only a handful exceeding 1.79% (the 2022 statewide mean EV stock share). By 2022, EV shares increased in all census tracts, with then 18% (or 259) of all census tracts exceeding an EV share of 3% in the light-duty vehicle stock. 61 tracts have an EV share of 6% or more. These leading tracts are geographically concentrated around Lake Washington and Lake Sammamish in the cities of Seattle, Sammamish, Issaquah, Bellevue, and Mercer Island (in no particular order). Generally, most of the high-adopting tracts are located in the west and northwest of the state, with notable exceptions around Vancouver, the Tri-Cities, and Spokane.

Figure 4.3 shows the distribution of the EV stock share across Washington's census tracts. The chart shows that most census tracts have EV shares of less than 2%. Half of the census tracts in the state have either less than or more than 1.12% EVs in their light-duty vehicle stock. About one third of all census tracts (486) have an EV share that lies above Washington's statewide mean of 1.79%.

Figure 4.4 visualizes the per-county number of EVs, by plotting the number of all light-duty vehicles (of any powertrain) against the share of EVs in the county vehicle stock. Each bar represents one Washington county, and the area of each bar corresponds to the number of EVs in each respective county. The top 8 counties in terms of EV stock share are color coded. King County is the leading county in the state both in terms of EV share (3.6%) as well as in the total number of EVs (about 56,000). King County thus represents more than 53% of all EVs in Washington (compared to only 26% of all light-duty vehicles). This highlights the strong propensity for EV adoption in King County, which lies substantially above most of the other counties. In addition, all top 8 counties in terms of EV share are located in the northwest of the state. San Juan County has the second highest EV share (at 3.3%), but only represents a small total number of EVs (as it is a small county with comparatively only few registered vehicles).

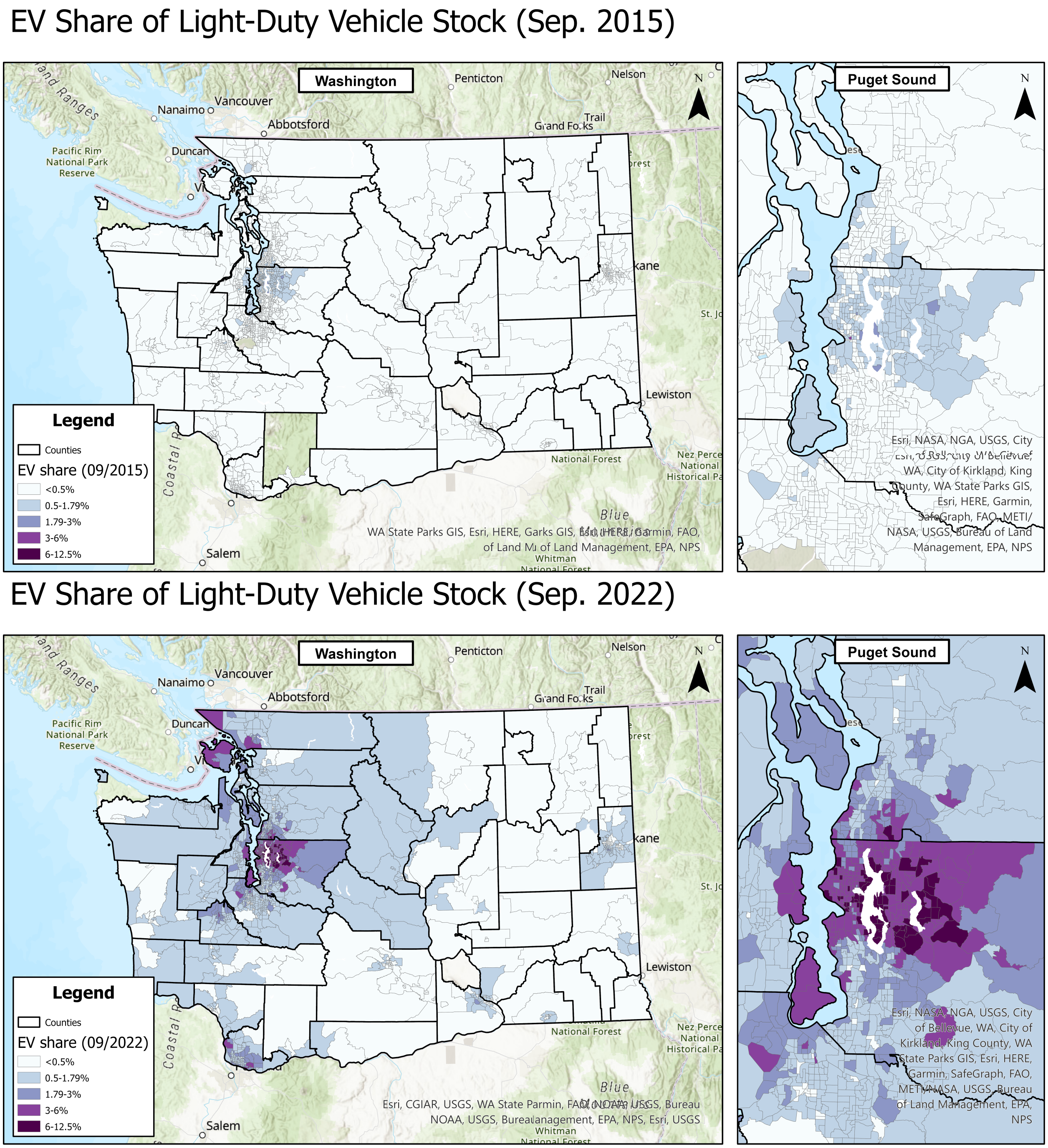


Figure 4.2: Census tract-level map of the EV share in the light-duty vehicle stock in Washington in 2015 and 2022.

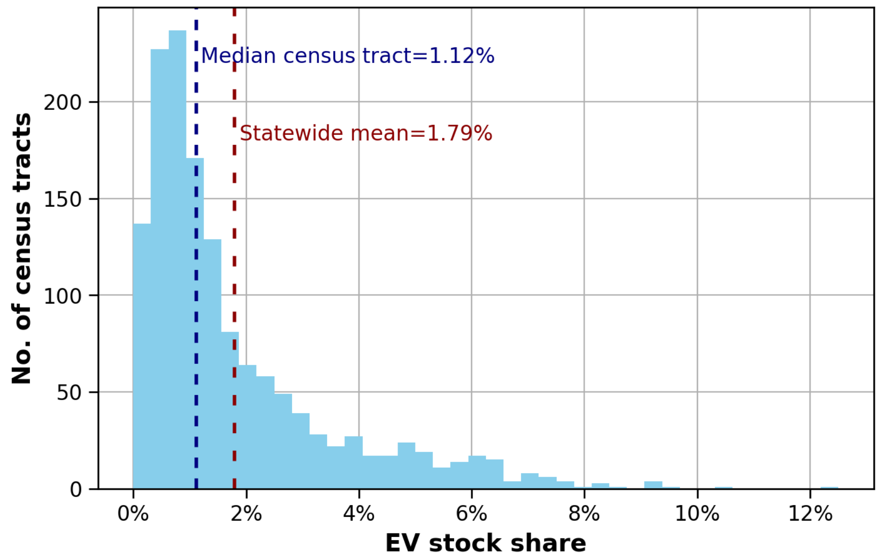


Figure 4.3: Distribution of EV share in the light-duty vehicle stock in Washington by census tract (as of September 2022).

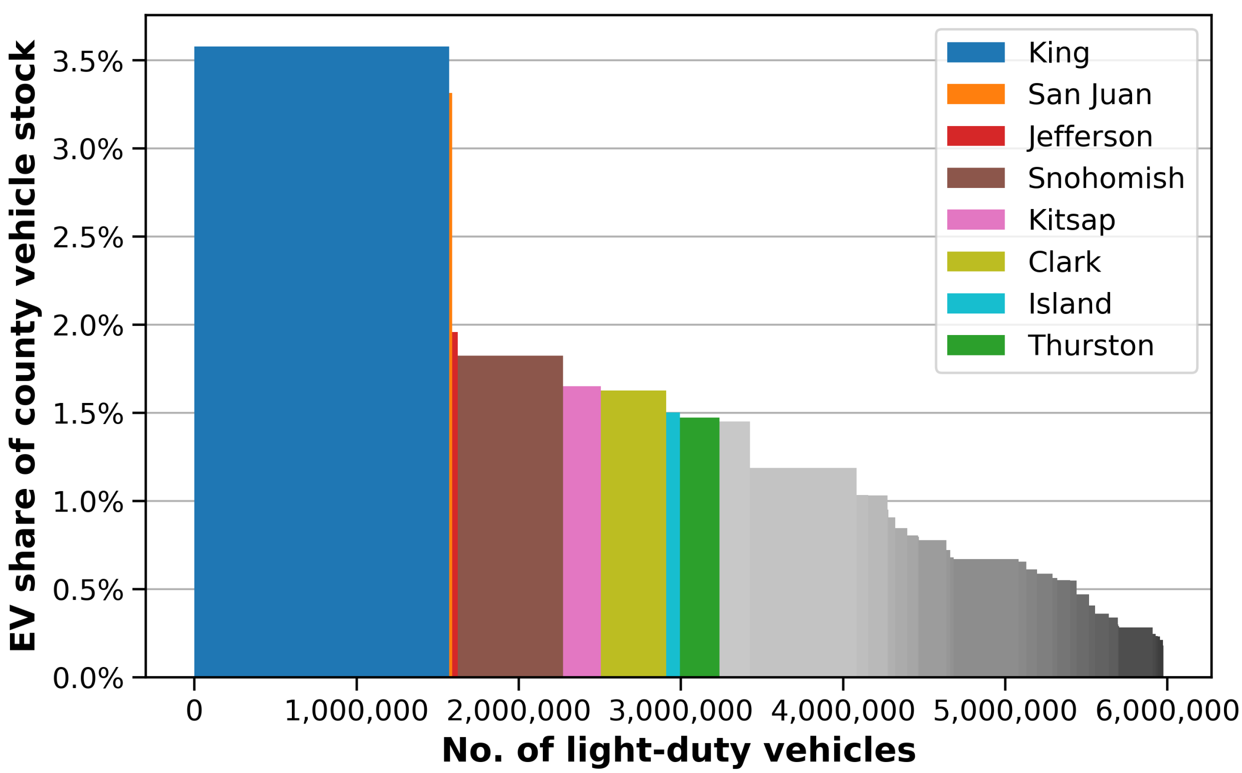


Figure 4.4: EV share and number of light-duty vehicles in Washington counties (as of September 2022).

The above table and figures illustrate the strong geographic heterogeneity in EV adoption across Washington state, as well as an overall increasing time trend in the number of registered EVs. Most of Washington's EVs are registered in a relatively small number of counties or census tracts. These two observations also indicate that using a model with census tract fixed effects (to represent the geographic heterogeneity) and time fixed effects (to represent the statewide trend towards increasing EV adoption) is sensible.

Over time, more and more EV product variety gave consumers more choice between different EV makes and models. This trend is visualized in Figure 4.5. Today, there are more than 120 unique make-model combinations among the EVs registered in Washington, 60 of which are battery-electric models.

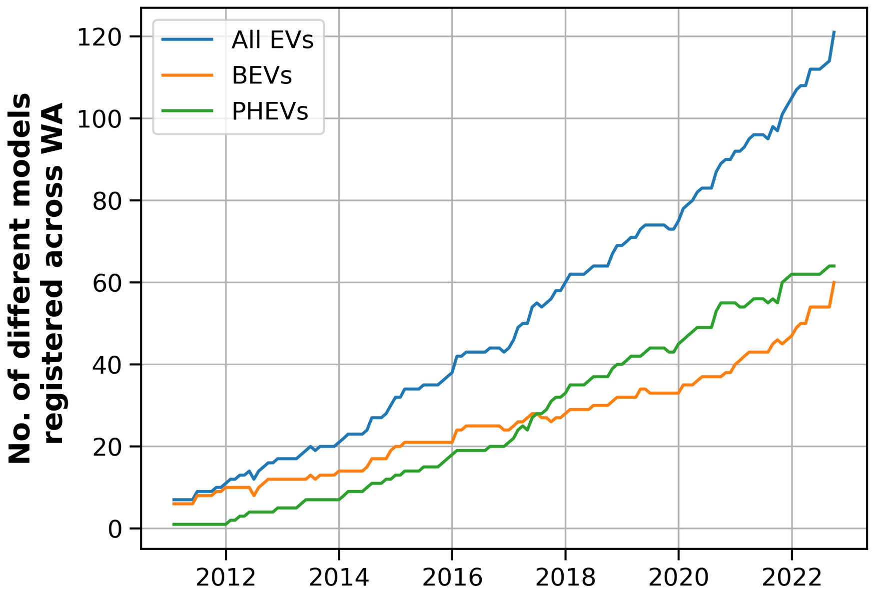
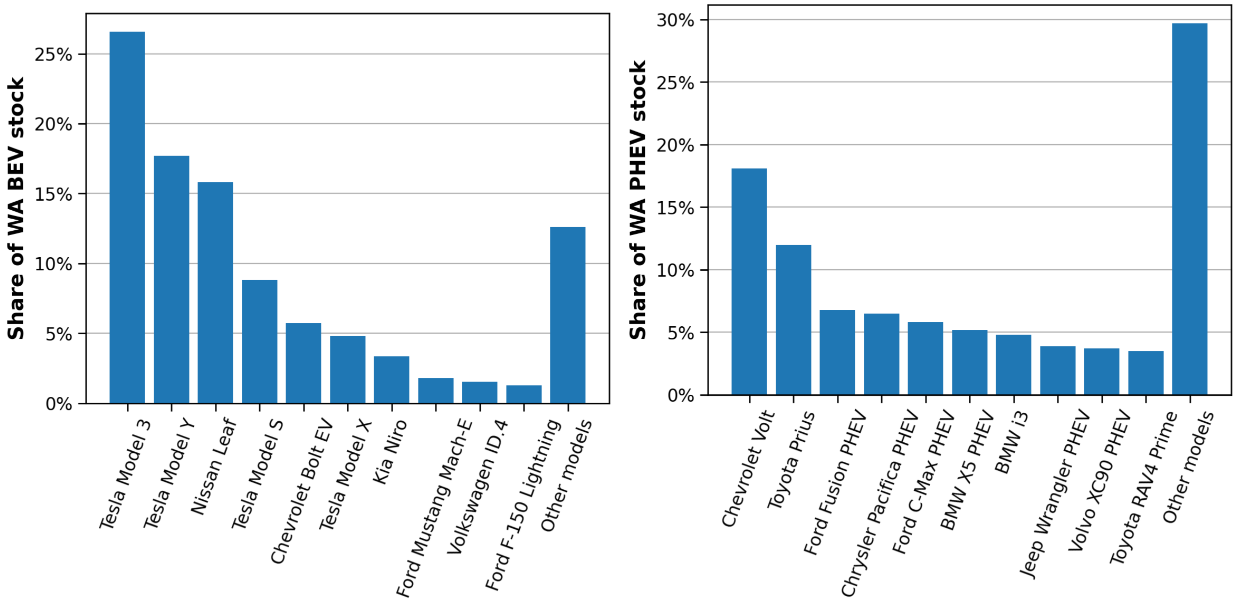


Figure 4.5: Number of different EV models registered across Washington over time.

Among these models, the Tesla Model 3 comprises more than 25% of all registered BEVs in Washington, as can be seen in Figure 4.6(a). The top four BEV models (Tesla Model 3, Tesla Model Y, Nissan Leaf, and Tesla Model S) represent 69% of the BEVs registered in Washington, representing a very high market concentration. The 50 BEV models with the lowest market share represent only 12.5% of Washington's BEV stock. Similarly, in Figure 4.6(b), the different PHEVs' market share in Washington's PHEV stock is shown. With the market concentration being slightly lower than for BEVs, the top two PHEV models (Chevrolet Bolt and Toyota Prius) comprise about 30% of all PHEVs in Washington.

4.3.2 Different model configurations and their predictive power and limitations

As part of this work, different model configurations were tested to understand their respective ability to predict past EV adoption patterns across the state. Table 4.2 shows the results of this process. The table lists different model configurations (that are defined by different sets



(a) BEVs. (b) PHEVs.

Figure 4.6: Distribution of unique EV models among EVs registered in Washington (as of September 2022).

of predictors or independent variables included in the model formulation, see Equation 4.1). The coefficient of determination (or R^2) describes the proportion of the variation present in the data (i.e. EV stock share) that is predictable from the chosen set of predictors. The share of residuals within a certain range shows what share of the data points could be explained by the model with a certain maximum deviation from the input data. Higher shares in either of these indicators mean a greater predictive power by the chosen model. As one can see from Table 4.2, all models achieve comparable results in terms of their ability to predict a large majority of the EV stock share data points across Washington since 2011. In model configurations with more independent variables (in addition to or instead of the time and census tract fixed effects), more than 60% of the EV stock shares across all census tracts in all months since 2011 could be predicted with a deviation of less than 0.1 percentage point, and more than 95% of the data points could be predicted with a deviation of less than 1 percentage point. Different subsets of predictors appear significant in different model configurations to predict EV adoption in Washington. The sign of each predictor (i.e. whether or not a certain variable is positively linked with higher EV adoption or not) varies depending on the chosen subset of the predictors, since many are cross-correlated (such as the percentage of people with a Bachelor's degree and the median household income in a given census tract).

A reasonably high predictive power can be achieved in the model that only includes the time and census tract fixed effects (first row in Table 4.2). This model does not rely on data or forecasts of any of the other independent variables (such as socioeconomics or charging station availability) in order to make predictions on either historic or future EV adoption. This observation, as well as the aforementioned issues on cross-correlation between different variables, confirm that it is a sensible approach to select the model with only the time and census tract fixed effects for the purposes of EV adoption forecasting. In other words, most of the variation that can be explained is explained by the heterogeneity of the state (census tract effects) and an overall time trend of rising EV adoption (time effects). This choice is furthermore supported by the fact that identifying causality between any of the independent variables and the dependent variable (i.e. the EV stock share or sales share) is difficult. This is because there is not a clear directionality between certain quantities, such as EV adoption and charging station availability[12]. Assuming a certain directionality in these correlations might not always hold true. In addition, not all of the independent variables, in particular not the socioeconomic data, represent policy levers that can be manipulated through federal, state, or local policies to increase EV adoption.[13]

[12] I.e. there is literature supporting the point that an increased access to EV charging stations increases the likelihood for adopting EVs (CITE), but there is also an observed trend that public charging infrastructure is typically built in areas with higher EV adoption to begin with, since station operators expect higher utilization and revenue in such areas.

[13] For example, while higher incomes are typically linked with higher EV adoption rates, increasing the median household income in all areas of the state is, while a desirable outcome, not a direct incentive for EV purchases, especially among groups with historically below-average EV adoption.

Table 4.2: Explained variation in the data in different model configurations (different sets of predictors) for the model with the EV stock share as the dependent variable. The asterisks (*) denote significant variables.

Predictors	Coefficient of determination (R^2)	Share of residuals within +/- 0.001=0.1%	Share of residuals within +/- 0.01=1%
Time fixed effects Census tract fixed effects	0.8253	53.5%	88.4%
Time fixed effects Census tract fixed effects No. of charging stations Pct. of white people (*) Pct. with Bachelor degree Pct. in single-family units (*) Median household income (*)	0.8264	61.0%	95.0%
Time fixed effects Census tract fixed effects No. of charging stations (*)	0.8253	60.8%	94.3%
Time fixed effects Census tract fixed effects No. of charging stations Median household income (*)	0.8263	61.0%	94.9%
No. of charging stations Gas price (*) EV product variety (*) Pct. of white people (*) Pct. with Bachelor degree (*) Pct. in single-family units (*) Median household income (*)	0.8263	61.0%	94.9%

4.3.3 EV adoption forecasts

This section presents and discusses some of the results obtained from the EV adoption forecasts produced in this project. Census tract-level forecasts until 2035 were produced in terms of the EV share of new light-duty vehicle sales (sales share) and the EV share of all registered light-duty vehicles (stock share). These forecasts were obtained from using either the EV sales share or the EV stock share as the dependent variable in the forecasting model, and converting the forecast results into the respective other variable using ANL's VISION model, as described in the methodology section.

Figure 4.7 shows the results aggregated to show the statewide EV sales shares (left) and stock shares (right) over time, as compared to the statewide target of 100% EV sales share by 2030 (light blue) and the requirement of 100% ZEV sales share by 2035 (dark blue). The forecasts obtained from using the EV stock share as the dependent variable are shown in red, and from using the EV stock share in orange. Past EV adoption is shown with the black data points to the left of the vertical line that marks today. As one can see, neither of the two forecasts produced in this work project that Washington will hit any of the two goals of 100% EV sales share by 2030 or 2035. The forecast obtained from using the EV sales shares as the dependent variable projects a higher EV adoption than the other one, with the 2035 sales share reaching 34% by the end of 2030 and 67% by the end of 2035. The S-shaped EV adoption pathway in this forecast results in an EV stock share of 25% by the end of 2035.

One additional relevant takeaway from the vehicle stock turnover modeling using ANL's VISION model is that, even in the 100% EV sales share by 2030 scenario, the EV stock share does not exceed 60% by 2035 as it takes time for the whole vehicle fleet to gradually be replaced with electric vehicles.

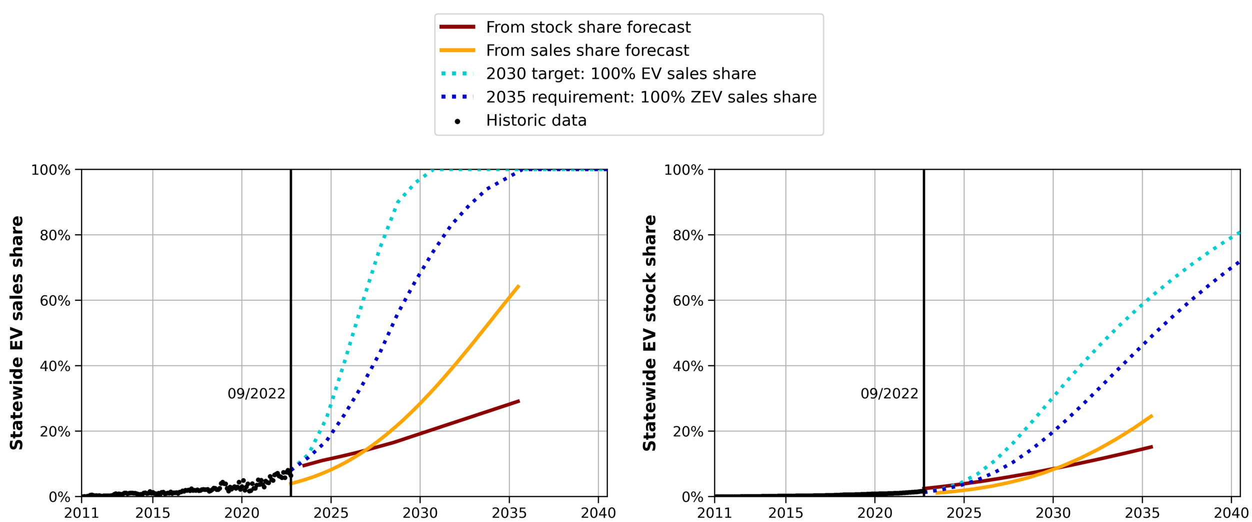


Figure 4.7: EV adoption forecast results in terms of statewide EV sales shares (left) and stock shares (right).

Figure 4.8 shows the results from the forecast using the stock share as the dependent variable (red lines in Figure 4.7) on a map with the census tract-level EV stock share in 2035. Compared to the maps shown in Figure 4.2 for 2015 and 2022, the EV share in the light-duty vehicle stock is forecasted to have increased substantially. The map is now characterized by an overall larger number of areas across the state with EV stock shares exceeding e.g. 6%. Yet, as the figure also reveals, an even stronger geographic heterogeneity results if past trends of EV adoption across Washington are used to project the future: There are some census tracts that are characterized by fast EV adoption pathways, with EV stock shares reaching more than 50% and up to 73% in the fastest-adopting census tract. On the other hand, there are still tracts with EV shares of less than 0.5% in their vehicle stock (white tracts in Figure 4.8), implying an even greater discrepancy between the highest- and lowest-adopting census tracts across Washington. These highly lagging census tracts could be specifically targeted by municipal policies and state grants in order to accelerate local EV adoption.

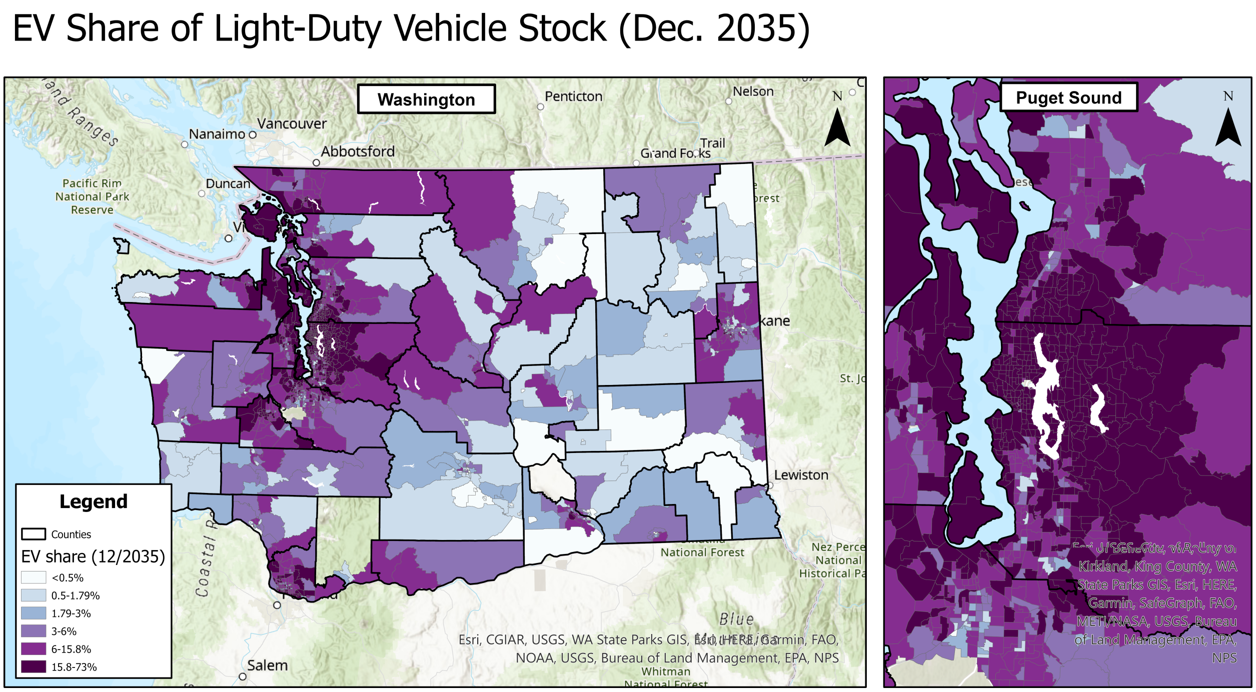


Figure 4.8: Census tract-level map of the EV share in the light-duty vehicle stock in Washington in 2035 based on the forecast using the EV stock share as the dependent variable.

The map also reveals that the west and northwest region of the state is likely to remain leading in Washington's EV adoption pattern if past trends prevail. Especially areas in and around the Puget Sound are among the highest adopting tracts projected in this forecast.

Figure 4.9 shows the results from the forecast using the EV sales share as the dependent variable (in orange) for the 95th percentile census tract[14] (tract number 53033028600, in West Seattle). The 95th percentile represents a tract with a very high EV adoption. As can be seen from this graph, the states' leading census tract might be able to get close to the 2035 EV sales share requirement of 100%, even if past trends of EV adoption prevail. This tract reaches a 90% EV sales share by the end of 2035 in this particular forecast. The

[14] 95th percentile in terms of forecasted EV sales share at the end of 2035.

EV stock share in that census tract closely follows the stock share that would result from reaching the 2035 ZEV sales requirement (in dark blue), with an EV stock share exceeding 40% by 2035.

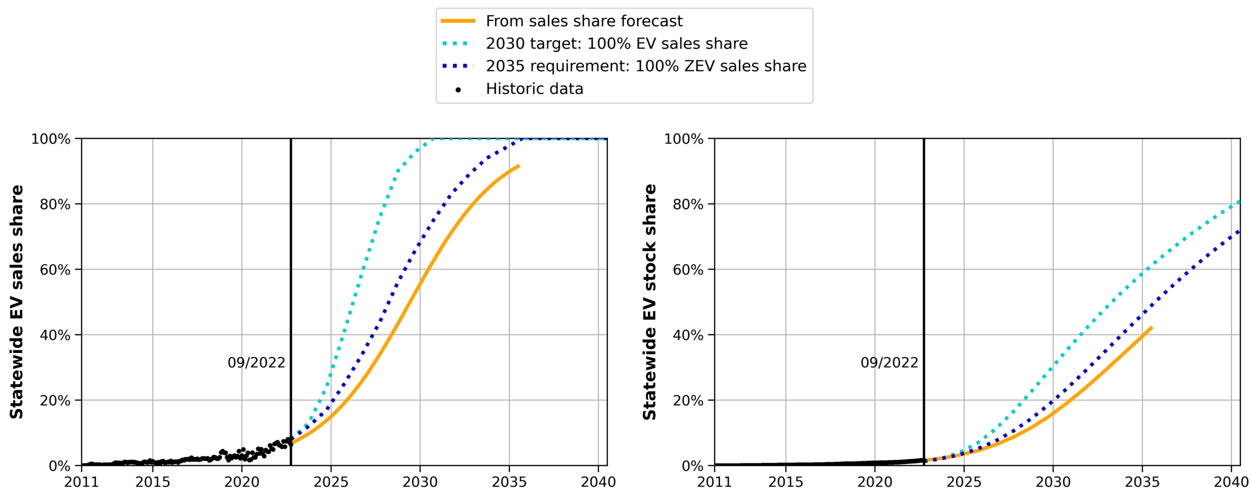


Figure 4.9: EV adoption forecast results in terms of statewide EV sales shares (left) and stock shares (right) in the 95th percentile census tract (i.e. a high-adopting census tract, located in West Seattle).

The results show that, while the state average might not be on track to achieve or get close to either of the two EV adoption targets, Washington's leading census tracts might very well be. That being said, based on historic trends, a considerable geographic heterogeneity in EV adoption could remain across the state. Targeted policies for low-adoption areas, particularly in rural Washington in the east and south, could help mitigate the gap that exists between the leading and lagging census tracts. Especially those tracts and areas projected to remain having a very low EV share in 2035 (e.g. the white tracts in Figure 4.8) could be the focus of such policies, including on the county and municipal level.

4.4 Implications for supporting EV adoption across Washington

For the EV adoption forecasting model presented in this chapter, census tract-level shares of EVs in the vehicle stock and of the new and used vehicle shares were derived from historic Department of Licensing registration data. It is noteworthy that this is the first reconstruction of EV adoption data in Washington with a high spatial resolution (finer than on the level of ZIP codes or counties) and for a multi-year period. The resulting dataset, which was used as an input for the model estimation in this project, provides more research opportunities than present-day snapshots of EV counts, as also provided by the DOL (State of Washington 2022a), due to the additional dimension of time.

Based on the reconstructed EV shares in every Washington census tract for the years since 2011, a model was built that is based on the geographic heterogeneity in terms of EV adoption across the state and the overall time trend of rising EV adoption. This model is able to explain most of the variation in EV adoption that can be explained even when including other related quantities, such as the availability of EV charging infrastructure or socioeconomic variables. Based on the results of the presented work, it could be concluded that the product, price, and policy trends of the last 10 years are unlikely to get us to state goals. However, new models, falling prices, and new federal and state policies may alter the underlying trends but the modeling builds in some of that already by describing the adoption process with an S-shaped adoption curve. Though, no specific future policy measure is considered in the model building. In addition, the EV adoption rate can be impacted by external factors such as gas prices or vehicle supply chain constraints.

Binding ZEV requirements for new vehicles appear to be necessary to achieve 100% by 2030 or 2035, based on the outcomes of this analysis. In order to get the EV market share beyond the early adopters, people who have historically not considered to buy an electric vehicle will need to be convinced. For this, ensuring new EV buyers have a good experience with their vehicles is key to increasing adoption as the market grows beyond early adopters.

Future research projects could use the results obtained in this work to model the electricity demand for charging EVs based on the forecasted adoption levels. Such work could use the information on traffic patterns and vehicle miles traveled from local or regional transportation system models to quantify the charging needs in each census tract. Such work could stratify the charging demand by home, workplace, and public charging (including high-power fast charging). This could inform electric utilities' integrated resource plans as to where to expect what charging loads.

Additionally, the results of this work could be used in the state's zero-emission vehicle mapping and forecasting tool described in the previous chapter. Here, the results could fill in the light-duty EV forecast layer, shown on the right side of Figure 3.1. This work also compiled many of the data layers required for the ZEV-MFT, such as socioeconomic data and information on the location of public EV charging stations.

5 Electric aviation electricity demand modeling

This chapter presents a research contribution aimed at quantifying potential future electricity demand from electric flight operations at regional airports. The methodological framework developed for this project can be applied to airports beyond the two case study airports in Washington discussed in this study. The chapter begins with an introduction, followed by a section that provides context on the topic of electric aviation. Then, Section 5.3 presents the used data and methods developed for this work. Section 5.4 presents and discusses the results found for the two studied airports, and Section 5.5 concludes by describing how the results inform and impact planning for electric aviation.

For this project, I was the leading researcher, having reviewed the market of electric aircraft currently under development, developed the methodology, and assessed and discussed the findings. I also developed an interactive online tool, which is discussed in Section 5.3.3. It can be used to explore different scenarios regarding the growth of aviation operations and the speed of the adoption of electric aircraft.

The work in this chapter was presented in a report submitted to WSDOT's Aviation Planning Division. The report serves as a publicly available resource for airport planners, electric utilities, and the interested public alike to understand the electricity demand impacts of electric aircraft. The report can be accessed on WSDOT's aviation website at https://wsdot.wa.gov/sites/default/files/2023-01/Electric-Airport-Feasibility%20Study-December2022.pdf.

The work in this chapter was also presented at the 2023 Transportation Research Board Annual Meeting and is currently (at the time of writing this thesis) under review for publication in the Transportation Research Record journal.

5.1 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 (Franz, Rottoli, and Bertram 2022), 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 (Gössling and Humpe 2020). Although still comprising a relatively small share of global emissions, flight operations are one of the fastest growing sources of climate-damaging CO2 emissions (Hasan et al. 2021; WWF 2022).

Notwithstanding their climate and air quality effects, fossil-fuel hydrocarbons are hard to beat in terms of the energy density (both per mass and per volume) required for long-haul flights (Schäfer et al. 2009). Nevertheless, in recent years, several companies (newly formed and existing) have pursued the development of electric aircraft, designed to serve certain aviation market segments (Schwab et al. 2021). Given the fact that a significant share of flight operations are short- to mid-haul (Long et al. 2001), 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 (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. For this study, I developed 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 (Boyte-White 2022), the state has evaluated the economic and environmental opportunities of electric aviation (WSP 2020). In Washington, aviation operations are highly concentrated at Seattle-Tacoma International Airport (SeaTac), with about 90% of all annual enplanements in Washington counted there (WSDOT 2022). However, SeaTac is close to 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. Moreover, utilizing electric aircraft for flights with a distance that allows electrification could result in new aircraft operations aligned with climate goals (Puget Sound Regional Council 2021). Thus, I applied a modeling framework to two mid-size case study airports in Washington: Paine Field/Snohomish County Airport (airport code: PAE) and Grant County International Airport (airport code: MWH).

5.2 The context of electric aviation

5.2.1 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 (WSP 2020; Riboldi et al. 2020; TRB ACRP 2022). Electric aircraft have no direct emissions and generally produce less noise compared to comparably-sized conventional aircraft (Riboldi et al. 2020).

In addition, electric aviation has performance advantages relative to conventional aircraft that could expand the aviation market (WSP 2020; Mäenpää, Kalliomäki, and Ampuja 2021). This holds especially true with respect to novel technologies, including electric vertical take-off and landing (eVTOL) aircraft (Goyal et al. 2018; Cohen, Shaheen, and Farrar 2021). Multiple companies founded in the last decade are pursuing the design, construction, and certification of novel eVTOL aircraft allowing for urban air mobility (Schwab et al. 2021). (B. A. Seeley, D. Seeley, and Rakas 2020) 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".

5.2.2 Scope of this work

For this study, the focus was 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 (Federal Aviation Administration 2022a). 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 (Federal Aviation Administration 2022b)).

In addition, operations with eVTOL aircraft were treated separately 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. While many operations with eVTOL aircraft are likely to be considered air taxi operations under the FAA definition, I chose to treat them separately, due to their novelty and unique aircraft design (e.g. vertical take-off and landing), use cases (e.g. replacing ground trips to airports), and power requirements. It should be noted that the Itinerant Air Taxi category as used in this chapter shall not include any operations with eVTOL aircraft.

This study excluded 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 (Hepperle 2012). Table 5.1 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 (Eviation 2023). 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 May 2023, 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 (FLYING Magazine 2021).

Table 5.1: 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)	-	-	Pipistrel 2022
		Bye Aerospace	eFlyer 2	- First flight in 2018 - FAA certification targeted for end of 2022	110	253	83	Bye Aerospace 2022, FutureFlight 2022
eVTOL	**4-seat eVTOL commuter**	Joby Aviation		- 1 pilot, 4 riders - 6 motors - Targeting FAA Part 135 Air Carrier Certificate	-	150	117	Joby Aviation 2021
		Wisk Aero	Wisk Cora	- Designed to (eventually) be autonomous - 12 independent rotors	-	62	100	Wisk 2022, Electric VTOL News 2022
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 2023

References: Pipistrel 2022, Bye Aerospace 2022, FutureFlight 2022, Joby Aviation 2021, Wisk 2022, Electric VTOL News 2022, Eviation 2023

From a technological standpoint, the major bottleneck in the development of electric aircraft are the batteries, which are being improved in terms of per-mass energy density as well as recharging capabilities. Relatedly, the provision of sufficient charging infrastructure is a crucial step towards widespread electric aircraft adoption (Schwab et al. 2021). While there are indications that the large battery capacities required to use mid-size electric aircraft will require Megawatt-level charging, further assessment will be needed as the industry matures to narrow down on individual chargers' required power outputs (Schwab et al. 2021).

This study did not address the engineering design associated with installing adequate charging ports for recharging aircraft batteries. It rather evaluated 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.

5.2.3 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 (Schwab et al. 2021), Utah (*Utah Advanced Air Mobility Infrastructure and Regulatory Study* 2023), as well as 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) 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, I analyzed 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 (Snohomish County PUD 2022b), and Grant County International Airport is served by the Grant County Public Utility District (Grant PUD 2022). 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 (Snohomish County PUD 2022a), 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 (State of Washington 2022a). 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).

5.2.4 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).

This work presents the first effort to quantify potential future electricity needs (energy and power) for electric aviation operations at Washington airports. In early 2023, the National Renewable Energy Laboratory published a report on the impacts of electrified aircraft on airport electricity demand, being the one major other reference discussing this general issue. The report notes the need for "future work to better understand utilities' concerns with electric aircraft" (NREL 2023), which this work is a contribution for.

5.3 Data and methods

5.3.1 Dimensions of analyis

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

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 was conducted for the two different Washington airports PAE and MWH.

Operation category (c): The electricity demand was 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): I used 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) (WSP 2020). 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 was assumed to comprise two processes:

Feasibility rate scenario (f): The technological feasibility to serve aircraft use cases with electric aircraft was 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 was 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 were projected until the year 2039, so scenario estimates end in 2040.

5.3.2 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:

$$\begin{aligned} E_{A,c,o,f,a,t} = \frac{1}{2} &\times (\text{number of operations})_{A,c,o,t} \\ &\times (\text{feasibility rate})_{c,f,t} \times (\text{adoption rate})_{c,a,t} \\ &\times E_c^{\text{flight}} \end{aligned} \tag{5.1}$$

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:

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

The factor $\frac{1}{2}$ in Equation 5.1 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 $P^{\text{average}}_{A,c,o,f,a,t}$ (in kW) can be derived as follows:

$$P^{\text{average}}_{A,c,o,f,a,t} = E_{A,c,o,f,a,t} \,/\, (365 \times 24 \text{ hours}) \tag{5.2}$$

For utility providers and the airports as electricity rate payers, the peak power demand or capacity (in MW) is relevant to prepare for potential increases in demand and to provide sufficient electrical service. To obtain an estimate for the peak power demand $P^{\text{peak}}_{A,c,o,f,a,t}$, 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:

$$\begin{aligned} P^{\text{peak}}_{A,c,o,f,a,t} =& P^{\text{average}}_{A,c,o,f,a,t} \\ & \times \text{(seasonality of operations)} \\ & \times \text{(charging curve factor)} \\ & \times 24 \text{ hours} / \text{(charging window)} \end{aligned} \tag{5.3}$$

No eVTOL operations exist as of today, meaning that I cannot leverage the same methodology for eVTOL as for the existing airport operations. Instead, the number of potential annual eVTOL trips from Paine Field to the SeaTac airport was estimated 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, only residents with an annual household income of $200,000 or more were assumed to 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 (Archsmith, Muehlegger, and Rapson 2022). In the eVTOL case, companies face high development and certification costs which may further increase prices charged to initial users. 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 (Brandon 2013)) was used 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), this 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 5.2. eVTOL flights from Grant County International Airport to SeaTac were not considered under the assumption that such flights (just with fixed-wing aircraft) will be captured in the 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 5.1. All input variables used in the above equations are defined in Table 5.3 and will be further described below. All references to miles (mi) in this chapter imply the use of the statute mile, as opposed to the nautical mile.

Table 5.2: Assumptions behind the different eVTOL scenarios. Using these assumptions, a logistic curve as outlined in Equation 5.4 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 Equation 5.4)	Start year for eVTOL ops.	Share of potential market
Low	10	2040	35%
Medium	8	2035	50%
High	5	2030	85%

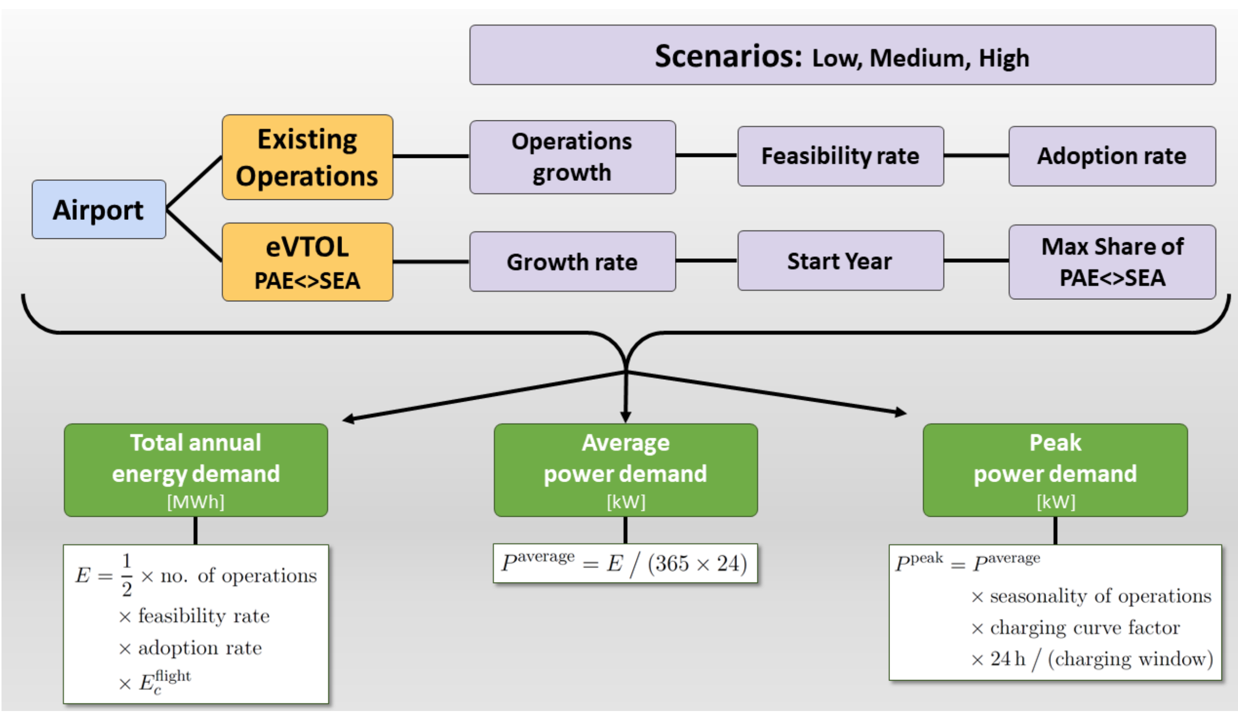


Figure 5.1: Schema of the utilized methodology.

Table 5.3: 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 were taken from the FAA's Operations Network OPSNET (Federal Aviation Administration 2022b). 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. I used 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)$_{c,f,t}$: I estimated 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 (Viswanathan et al. 2022)) 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 (Reuters 2022) to potentially more than 600 Wh/kg that year (Viswanathan et al. 2022). In addition, there is uncertainty among experts as to which battery chemistries have the highest energy density potential (Gao et al. 2021). For the medium scenario, I used 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 5.1) to an estimated 400 mi (810 mi) in 2035[15]. I 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), I leverage a 2001 NASA study to estimate flight lengths (in miles) of single-engine and multi-engine aircraft (Long et al. 2001). 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. I assigned 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 5.2 depicts the estimated feasibility rate in the medium scenario. Here, certification is assumed to occur in 2026, and the majority of flight operations were found to be feasible immediately, due to the Weibull-shape of the distribution of flight distances (skewed towards longer distances). Table 5.4 shows the years in which the feasibility rate reaches a threshold of 95% of all flight operations.

[15]For the slow scenario, electric aircraft range would be expected to increase to 348 and 703 mi, and to 478 and 966 mi in the fast scenario, for single- and multi-engine aircraft, respectively.

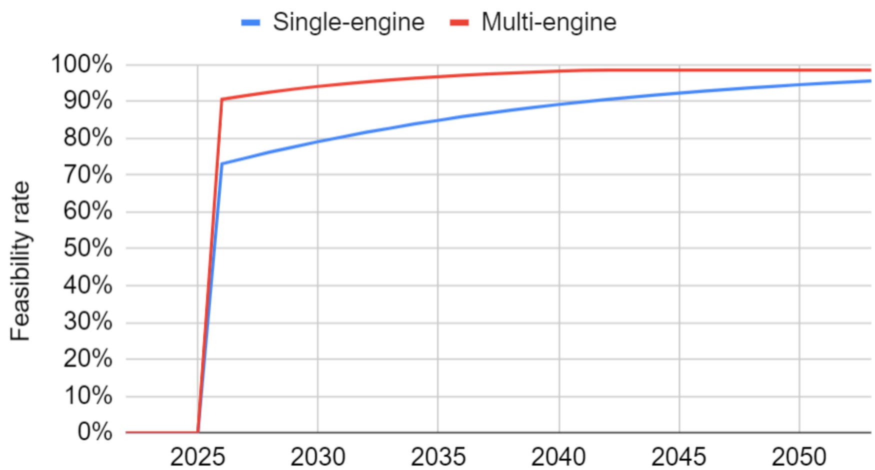


Figure 5.2: The estimated share of single-engine (Local Civil and Itinerant GA) and multi-engine (Air Taxi) flight operations that could feasibly be served using electric aircraft, used as the "feasibility rate" in this study, in the medium scenario.

3. (adoption rate)$_{c,a,t}$: The penetration of electric aircraft on the aviation market 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 thus estimated using the logistic function

$$p(t) = \frac{1}{1 + e^{-g\times(t-2022-t_0)}}\,, \tag{5.4}$$

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 5.4 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 (Schäfer et al. 2009) to e.g. only about 10 years for the almost complete adoption of regional jets around the end of the 20th century (Kar, Bonnefoy, and Hansman 2010). 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 Harrison 2018 and Schäfer et al. 2009), 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

Table 5.4: 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

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. The set of estimated adoption rates thus represents 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 5.4. Figure 5.3 shows the resulting adoption rate curves, by way of example for the General Aviation category.

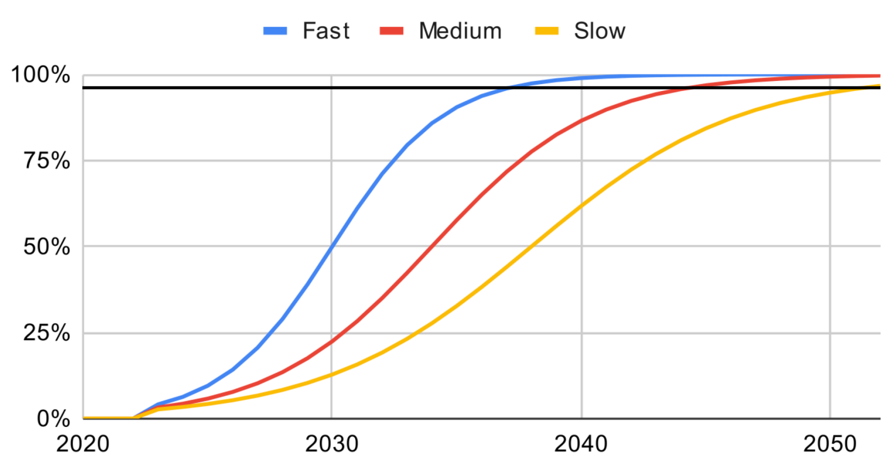


Figure 5.3: The estimated adoption rate curves for the General Aviation operation category, as an example. A 95% threshold is shown with the black horizontal line. The intersections of the curve correspond with the years shown in Table 5.4.

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 were 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 5.1). 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 were revised and confirmed using findings from the aforementioned NASA 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, see Lincoln 2022) as well as the Eviation Alice's planned battery capacity (820 kWh). All three quantities used to derive the energy demand for a typical flight in each category are averages over all operations in that category. It is worth emphasizing that these quantities typically have wide distributions around these averages, depending on the exact flight use case. The resulting values used for the subsequent electricity demand estimates are shown in Table 5.4, too. The values were vetted against information in ACRP Research Report 236 (TRB ACRP 2022). While each quantity assumes values varying greatly from one flight and aircraft model to the next, it should be noted 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 (Trivedi et al. 2018). Based on the available literature (University 2021) as well as data found by automotive battery testers (InsideEVs 2021b), 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) (InsideEVs 2021a). 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. I 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, it is reasonable to assume that charging strategies will be similar to those of electric cars, given this study's findings on the reported plans of electric aircraft companies to use lithium-ion-based batteries and prior research that drew comparisons to the battery technology in electric cars (Rajashekara 2014; Alexander, Meyer, and Wang 2018).

- (charging window): The charging pattern of electric aircraft has the potential to significantly impact 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. I 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.

5.3.3 Interactive tool

As part of this work, I developed an interactive tool that was made available under 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. There, further documentation on the tool, its usage, and the underlying software code can be found.

The tool utilizes the Python Streamlit package (Streamlit Inc. 2022), allowing users to dynamically update the projections based on the chosen scenarios. Figure 5.4 shows a screenshot of the tool. The user can select which output variable they would like to explore (annual energy, average power, peak power), which airport the electricity demand should be modeled for, and which operation categories to include. The user can then define a custom combination of the three uncertain analysis dimensions (three scenarios each on operations growth, feasibility rate, adoption rate). In doing so, $3 \times 3 \times 3 = 27$ scenarios can be explored, based on which combination is considered the most likely one[16]. By changing the number of hours in a day during which all charging sessions are assumed to occur (charging window), the user can furthermore test the effects of different charging strategies and patters (such as shorter times in between flights).

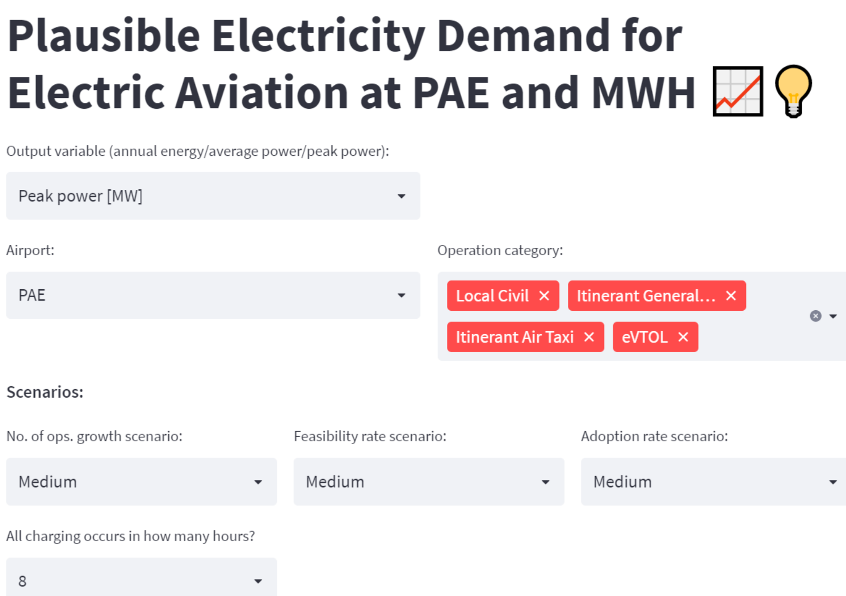


Figure 5.4: Screenshot of the interactive tool published along with this work. The screenshot shows the drop-down menus that can be used by the viewer to determine the specific scenario. Here, the medium-medium-medium scenario of operations growth, feasibility rate, and adoption rate is selected.

[16] Or the most relevant one: An electric utility might choose to prepare for the highest possible power demand by selecting a high-fast-fast combination of the three dimensions. An airport expecting little operations growth but a quick adoption of electric aircraft could, for instance, explore the low-fast-fast scenario.

5.4 Results and discussion

5.4.1 Airport operations

Figure 5.5 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: At Paine Field, general aviation operations (local and itinerant) make up for more than 94% of all airport operations, with Air Carrier being the third most frequent category. There is negligible military operation activity at Paine Field. At Grant County International Airport, however, general aviation comprises about 58% of all operations. Compared to Paine Field, a substantially higher portion of air taxi operations was found, and military activity accounts for nearly 16%. Consistent with descriptions on its own website (Port of Moses Lake 2022), the airport is frequently used for military and commercial test flights. Air carrier and military operations were not considered in this study for the estimation of future electricity demand for electric aviation, since these categories typically feature larger and heavier aircraft, coming with much bigger physical and technological difficulties for electrification.

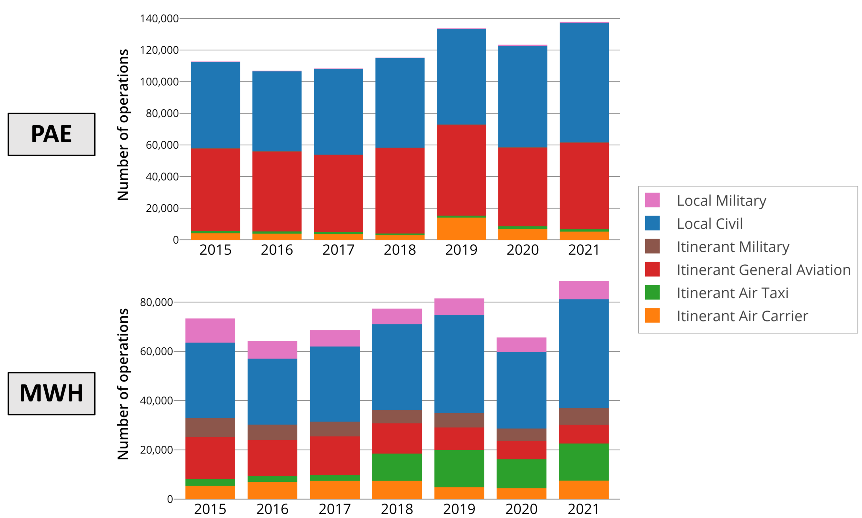


Figure 5.5: The numbers of operations at PAE and MWH in the years 2015-2021, by operation category. Note the different vertical axes for the two airports.

To estimate 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 5.2). 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. Based on the method deployed in this study, eVTOL aircraft has the potential to account for up to about 180,000 flights between PAE and SeaTac by 2040, though this is 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.

5.4.2 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 were 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 Table 5.1 and 5.4).

Figure 5.6 shows the annual electricity demands converted into estimates for the peak power demand (in MW), following Equations 5.2 and 5.3, 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 (Port of Moses Lake 2022). 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, I 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

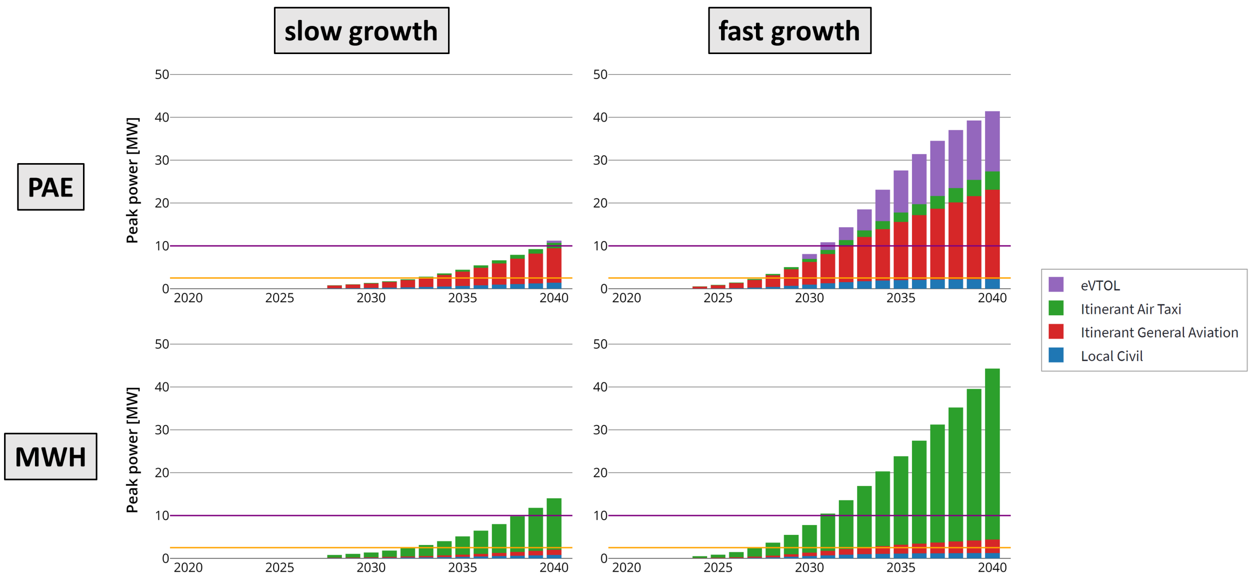


Figure 5.6: The estimated peak power demands (in MW) for electric aircraft operations at Paine Field (PAE) and Grant County International Airport (MWH), by operation category. Shown are a low (left) and a high (right) scenario for electric aviation, with all three scenarios (number of operations growth, 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.

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 the 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. This conclusion could possibly be different at other airports not considered in this work. The framework developed in this work can, however, help determine if projected power needs can be met with available capacity at such other airports.

5.5 Implications for supporting electric aviation

The framework model presented in this thesis chapter 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.

The developed framework and the interactive online tool can be adopted for use with other airports in the state and outside of it. By doing so, airport managers at other airports can do initial assessments of potential electricity loads from electric aircraft at their airports. The framework is constrained by the availability of historic counts of operations by operation category, which for all FAA OPSNET-registered airports should not present an issue.

The exact power requirements at a given airport will strongly depend on the exact charging patterns for the electric aircraft in use. Private general aviation use cases, such as flying small airplanes for leisure, can be met with relatively slow overnight charging cycles. On the other hand, scheduled flight operations, such as commercial air taxi service or flight schools, are dependent on the availability and capabilities of fast-charging facilities or efficient battery swapping processes. Appropriately-sized chargers for each use case as well as common charging plug standards will have to be planned and designed with diligence, in order to ensure seamless integration of charging processes into the airports' regular operations. While the Combined Charging Standard ("CCS", see CharIN 2023) plug standard known from the electric vehicle space could become a quasi-standard for charging with up to 350 kW of peak power for electric aircraft too, the future remains uncertain as to how many of these chargers should ideally be co-located at a given airport. Additionally, higher power outputs reaching into the Megawatt-level (1000 kW) for each charger appear likely to be needed to meet the charging needs for electric aircraft Schwab et al. 2021. Electrical design as well as operational constraints (airside and landside) will determine these questions to a large extent. The time between consecutive flights of the same aircraft and the charging needs resulting from that can vary greatly between commercial air taxi applications and, for instance, private leisure flights.

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 inform future estimates on peak power demand and reduce uncertainty in the model.

6 Conclusion and future work

This thesis presented three research contributions to assist the ongoing transportation electrification in Washington state. To support and inform the procurement of the ZEV mapping and forecasting tool, Chapter 3 reviewed and scored existing tools' capability to meet the requirements set forth by HB 1287. The process revealed that none of the tools can do so alone or in combination. This was largely due to a lack of coverage of harder-to-decarbonize sectors, such as rail, aviation, and maritime shipping, but also other missing features. The state used the recommendations made by our research team to allocate sufficient funding for setting up the tool on internal systems and contracting out for the procurement of specific analysis and forecast layers.

Chapter 4 presented the development of a logistic regression model that was used to produce high-resolution EV adoption forecasts. The results showed that the past product, price, and policy trends will not get us to state goals. However, policy interventions, a greater EV product variety, and falling prices may alter this projection. External factors, such as fluctuating gas prices and supply chain constraints in the automotive, battery, and semiconductor industries have the potential to disrupt and change the current trend – in either direction. Additionally, the analysis was useful for the state to better understand the strong geographic heterogeneity in EV adoption across its different areas. These insights can guide future policy measures targeting especially low-adopting cities and counties with targeted incentives.

Lastly, Chapter 5 presented a modeling framework to quantify plausible future electricity demand from electric flight operations. The framework was applied to Paine Field/Snohomish County Airport and Grant County International Airport. The findings implied that utility companies are expected to be able to serve the power needs for charging electric aircraft, at least in the early adoption phases over the next 10-15 years. As a useful outcome of this research effort, the publicly accessible interactive online tool can be used by state agencies, airports, and utility planners to understand the magnitude of the power demand imposed by charging electric aircraft.

Woven into each of these research contributions is the existence of uncertainty in technology transitions and the need for updating projections: The mapping and forecasting tool procurement is informed by the availability and capabilities of existing ZEV infrastructure planning tools. The set of available tools and their respective features changes over time, especially in this nascent stage of the market. The tools and their features have likely changed, to different extents, since the evaluation was done initially. The EV adoption forecasting work greatly highlights the need for updating. The outlook for low-adopting census tracts can change substantially once a few more EVs were added through recent vehicle purchases. These effects cascade through the forecasting model and can have drastic impacts on the EV adoption level projected 12 years from now. Regarding electric aviation, the market is even more nascent. There is hardly any experience with charging electric aircraft, and no commercial operations with fixed-wing or eVTOL aircraft have commenced yet, due to pending FAA certification processes. Our electricity demand estimation can and should be updated once initial charging session data was obtained from early-adopter electric flight operations.

Academic research beyond foundational science is needed, especially in real-world transitions such as the ongoing transportation electrification. Practical research results can tangibly increase industry and public agency preparedness and close policy-related knowledge gaps. Independent academic research has the unique ability to contribute to the public good in these ways, facilitated by analytic rigor and the self-correcting dynamics of peer review. These features set it apart from private-sector research.

Future research opportunities are motivated by the ongoing speed and scale of the mobility transition. Understanding future charging demand for electric vehicles at high spatial resolutions remains desirable to ensure sufficient coverage of all subareas of the state or of a given region as well as to allow electric utilities to further prepare for the expected loads they will be required to serve, especially once more substantial parts of the vehicle fleet get replaced with EVs. Adding predictors to the EV adoption forecasting model that could feasibly serve as policy levers would help understand policymakers what kinds of EV incentives and aspects of the public charging station system to focus resources on.

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