Electric vehicle (EV) / solar PV forecasts

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Introduction

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Distributed energy resource

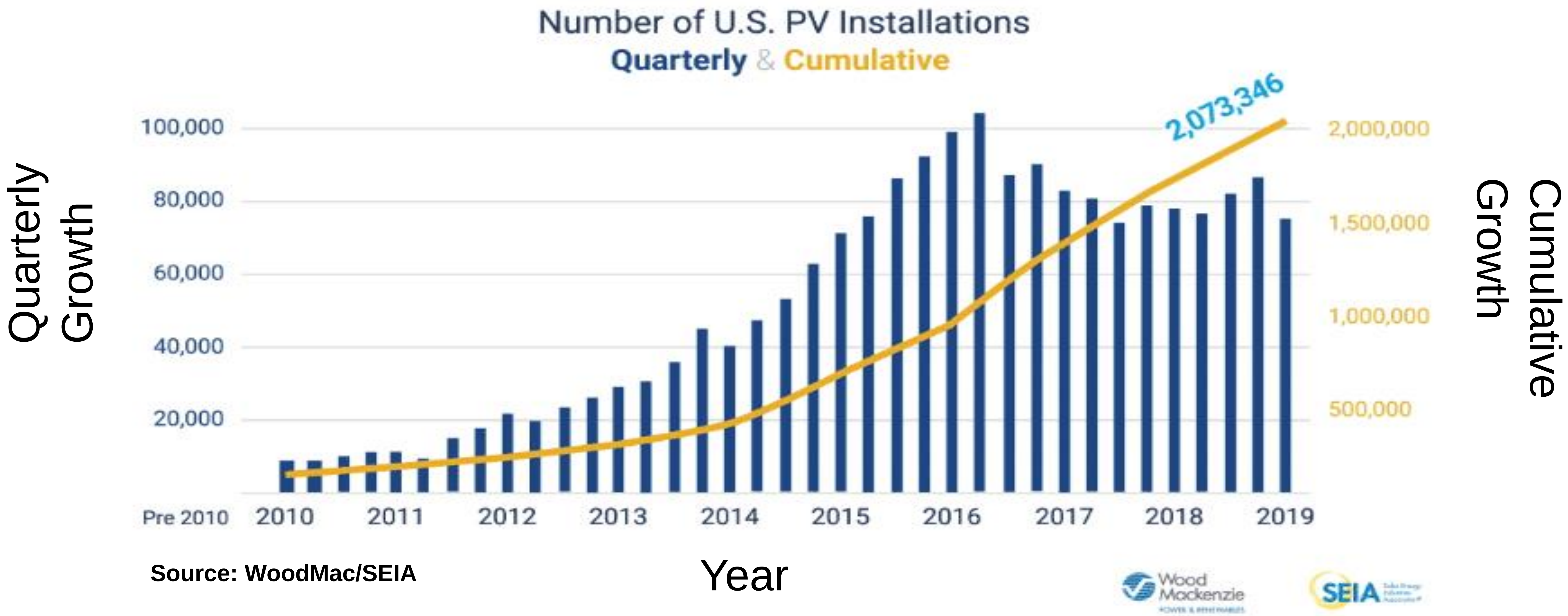
Distributed energy resources (DERs) are small-scale energy generation and storage technologies that are connected to the electricity distribution system.

Electric Vehicles (EV)

Customer Solar

Objective

Number of solar installations in the United States



Source: WoodMac/SEIA

- → Provide a long-term substation-level and territory-level forecast for the growth of EV and customer solar on AES Indiana's system.
- → Provide base, high, and low forecasts for inclusion in AES Indiana IRP Scenario Analysis.
- → Reveal insights that inform strategic decision-making.

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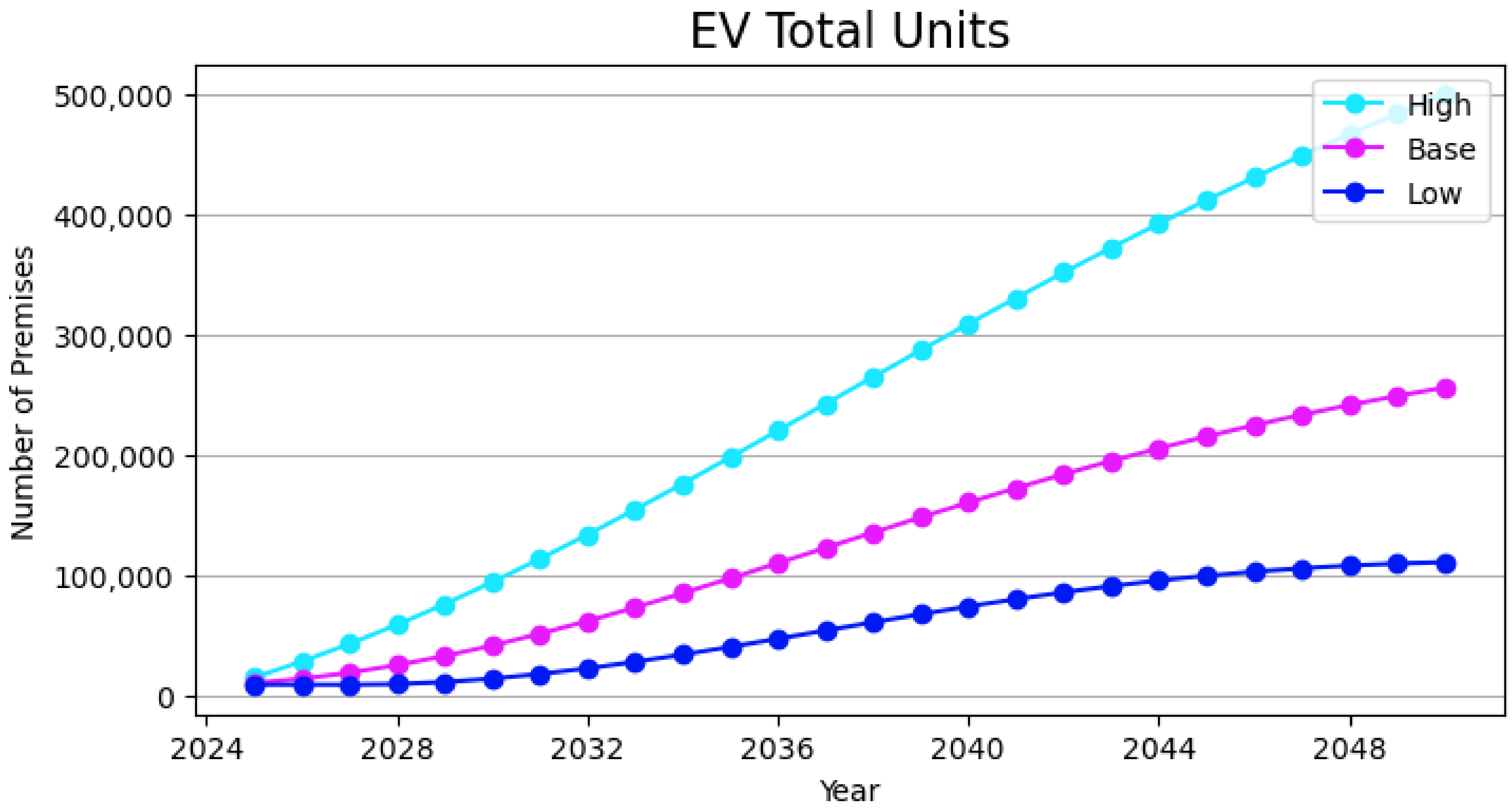
Result: EV unit prediction

110k~500k



A steadily accelerating market and increasing uncertainty over the coming decades, underscoring the need for:

→ proactive infrastructure investments,

→ resource planning, and

→ strategic readiness to capitalize on rising demand.

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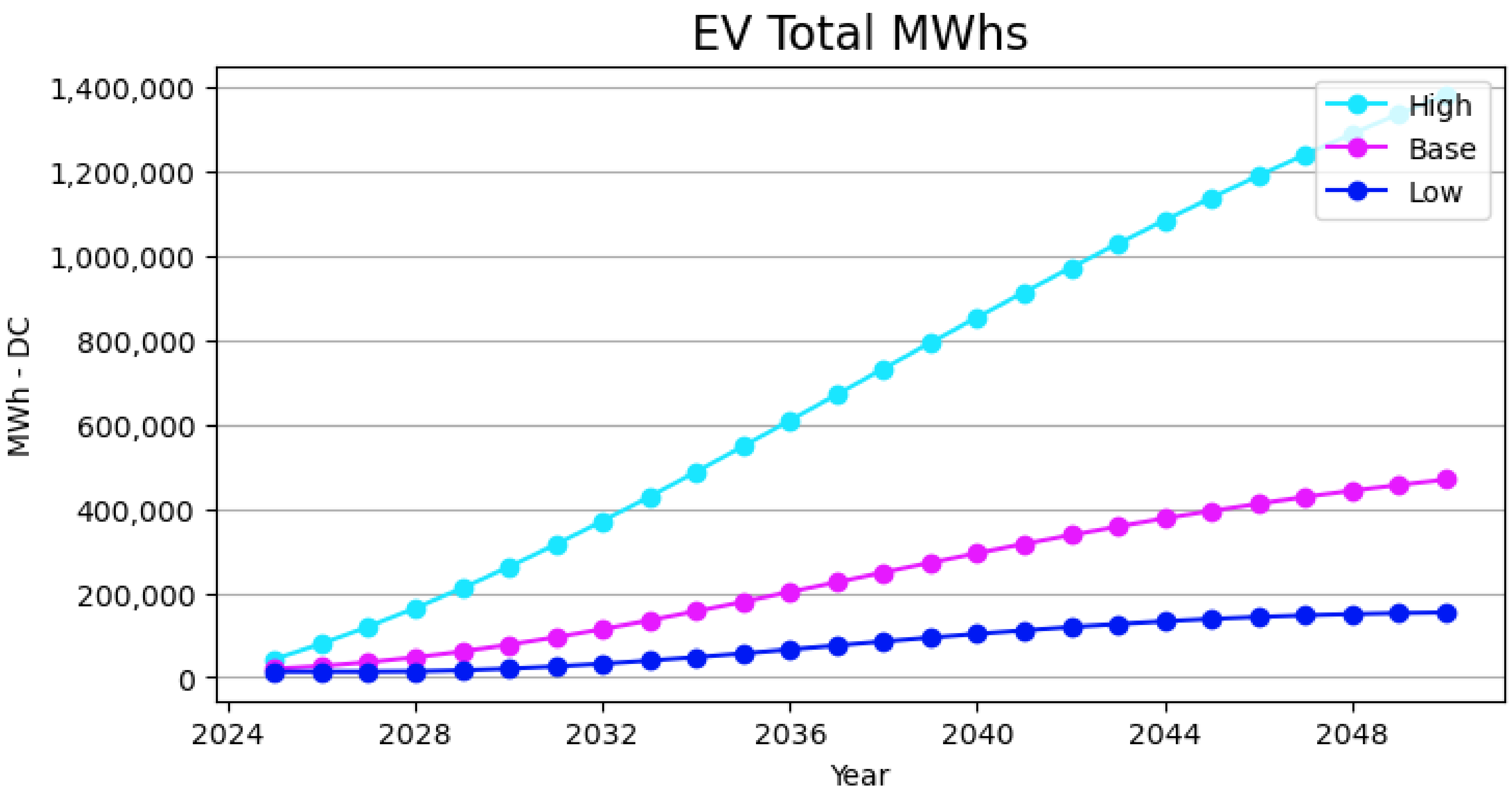
Result: EV Energy (MWh) Prediction

0.2M~1.4M



A steadily accelerating market and increasing uncertainty over the coming decades, underscoring the need for:

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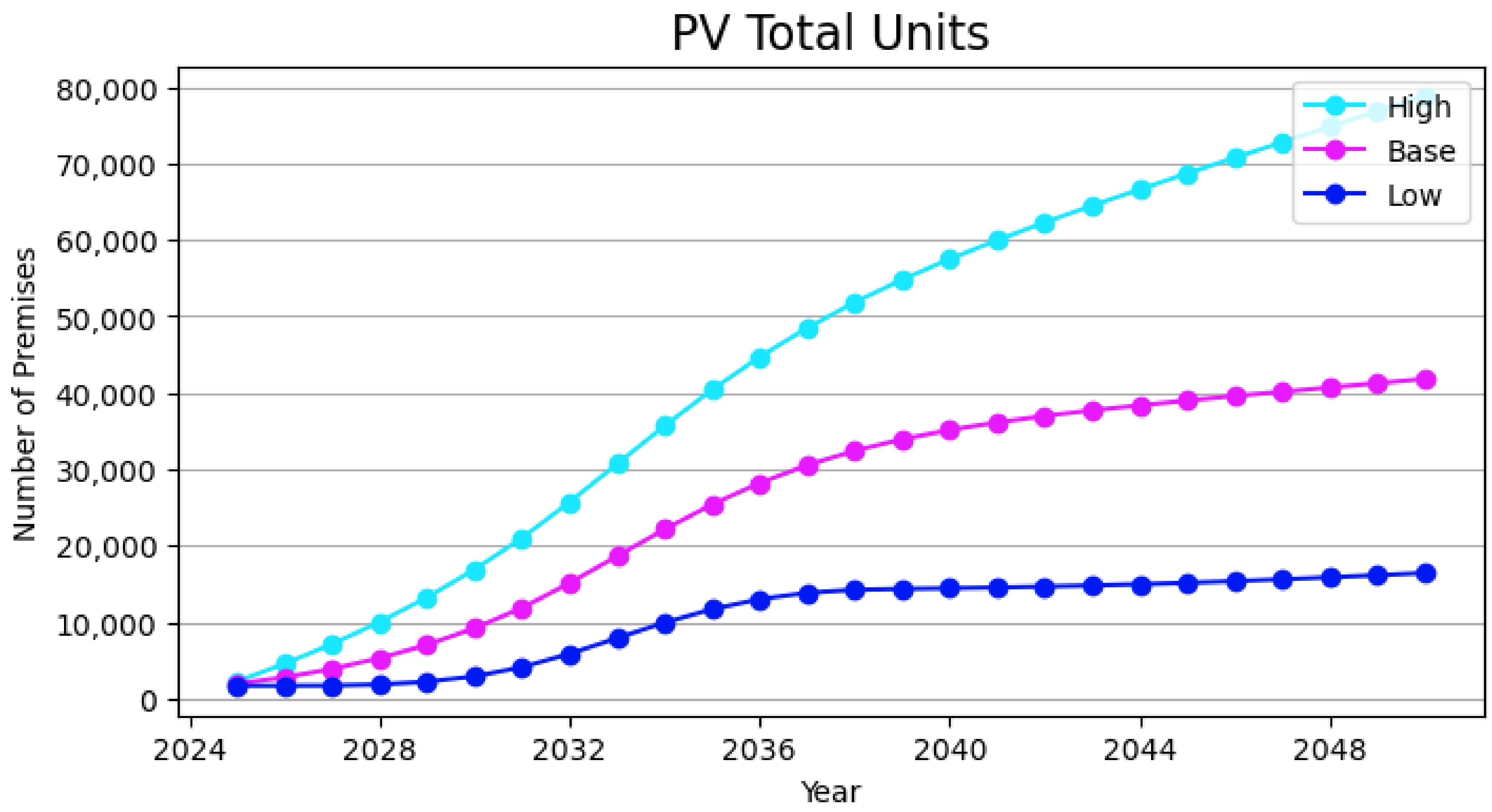
Result: Customer solar unit prediction

18k~80k



A steadily accelerating market and increasing uncertainty over the coming decades, underscoring the need for:

→ proactive infrastructure investments,

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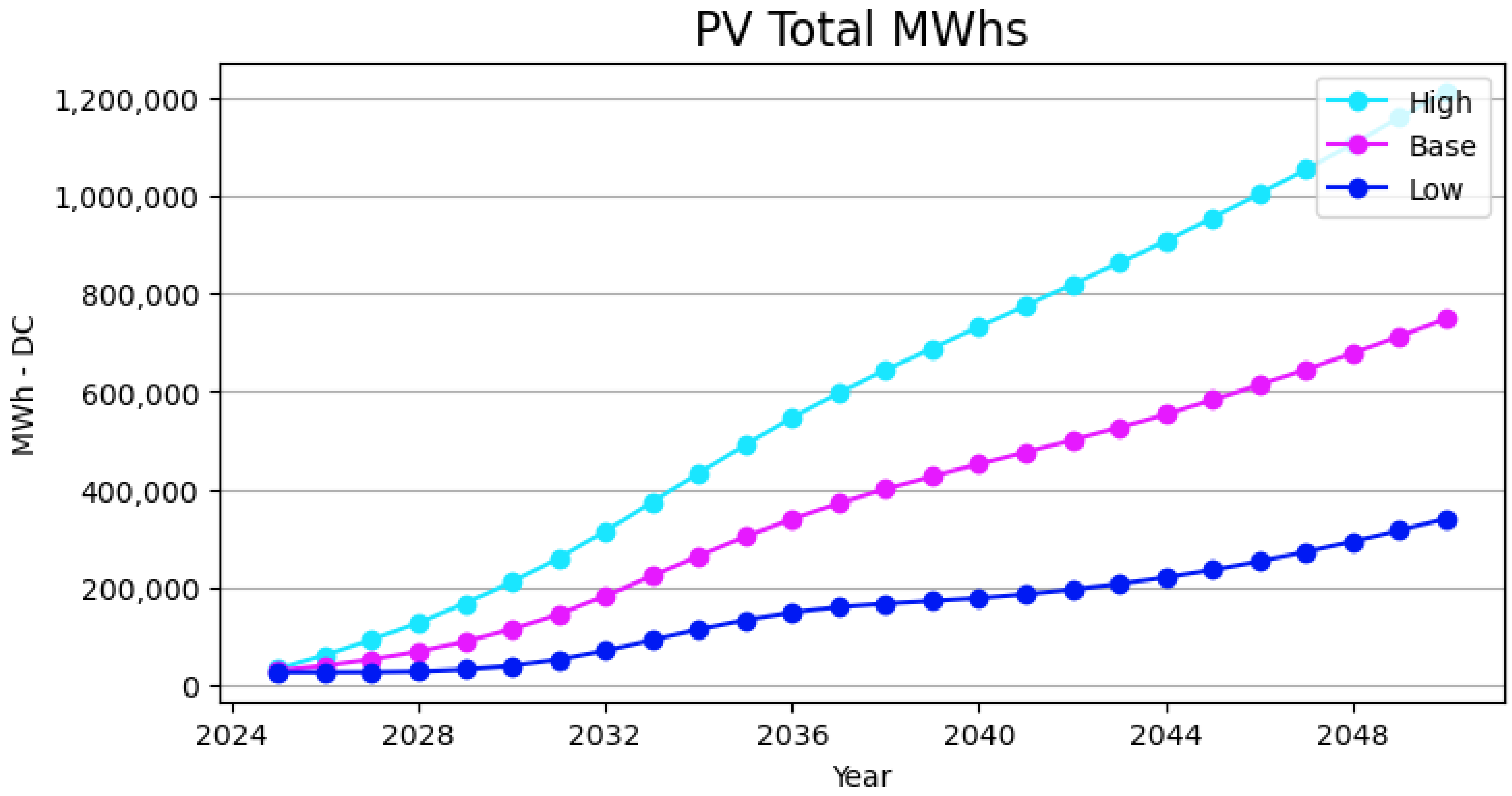
→ strategic readiness to capitalize on rising demand.

Result: Customer solar energy (MWh) prediction

0.3M~1.2M



A steadily accelerating market and increasing uncertainty over the coming decades, underscoring the need for:

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Key takeaways

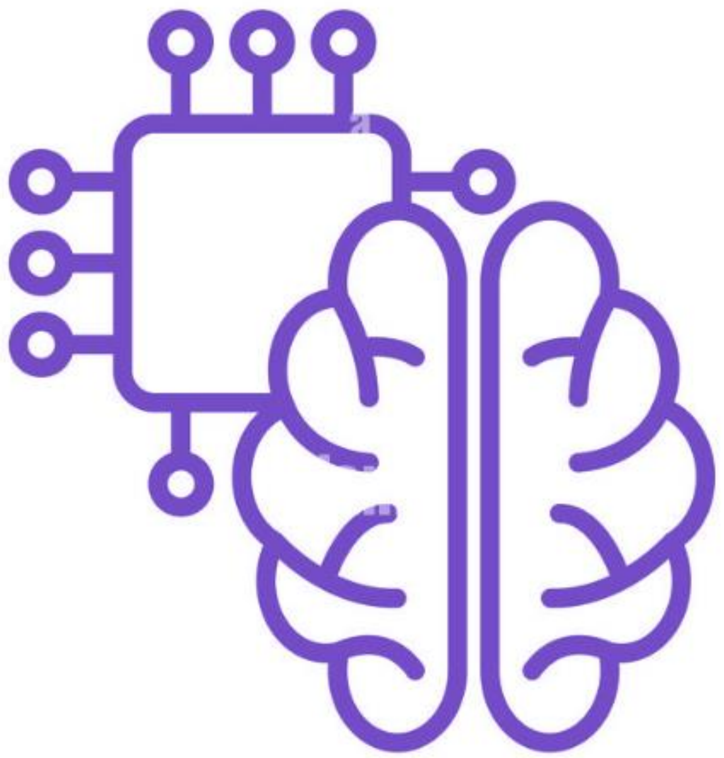
→A **rapid initial growth** phase for EV/solar adoption, which gradually slows, with **a plateau projected around 2036**.

→At the substation level, our analysis identifies **significant spatial disparity** in growth magnitude and uncertainty.

→This pattern suggests that high-adoption substations are also areas of high forecast uncertainty.

Methodology

Real-world data



Machine learning model

Forecast & insight

Data overview

→**PV data** (Customer solar records from AES)

→**EV data** (Vehicle registration records from Indiana BMV)

→Power grid data (from AES)

- →Outage records
- →Load records

→Census data (from US Census Bureau)

- →Demographic survey collected by ACS

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Electric vehicle energy (MWh) forecast

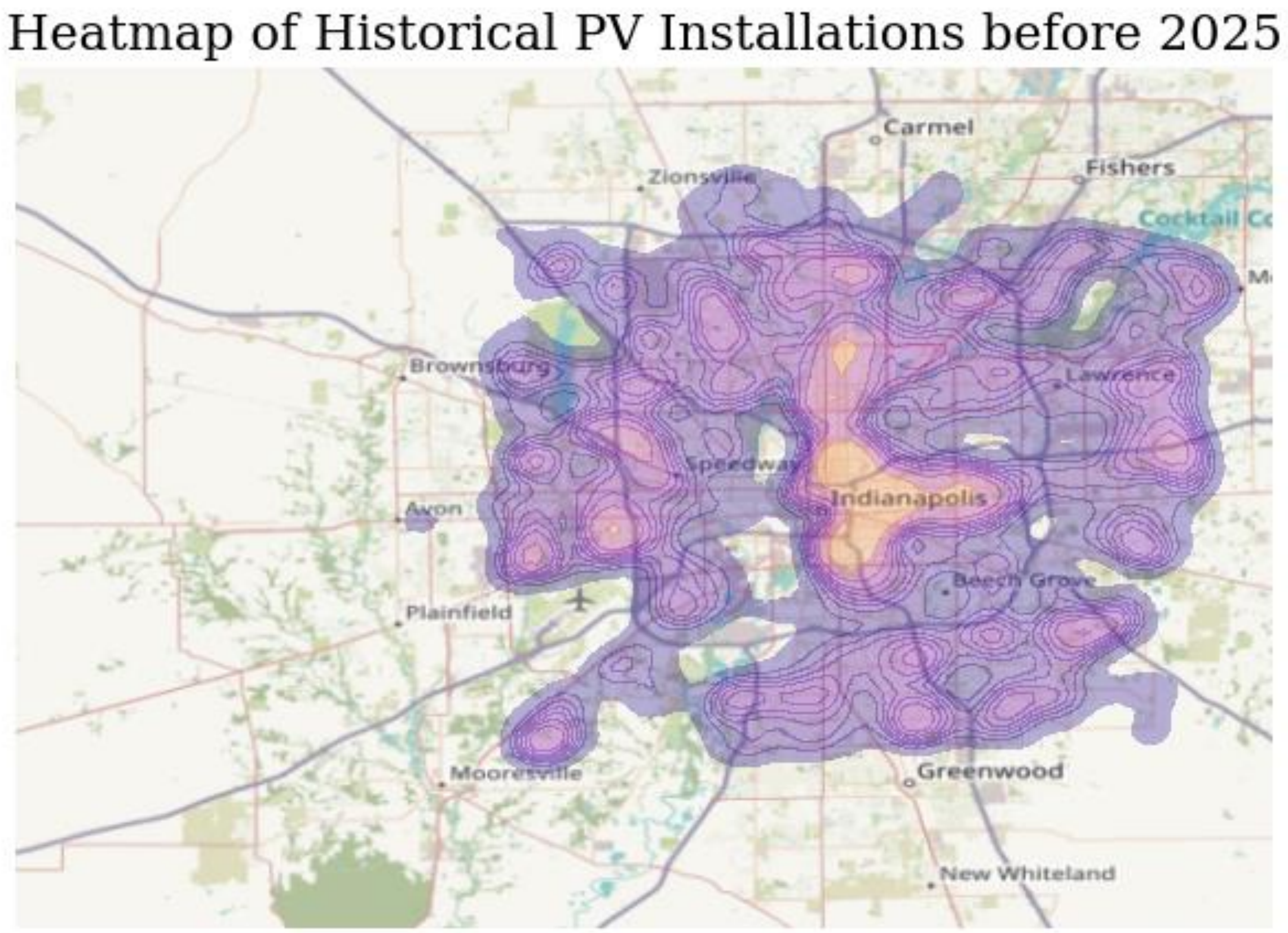
- →Energy is a function of total EV units, average kWh/mile, and total number of miles/year/EV.
- →Three trend scenarios were modeled:
  - →Low, Base, High

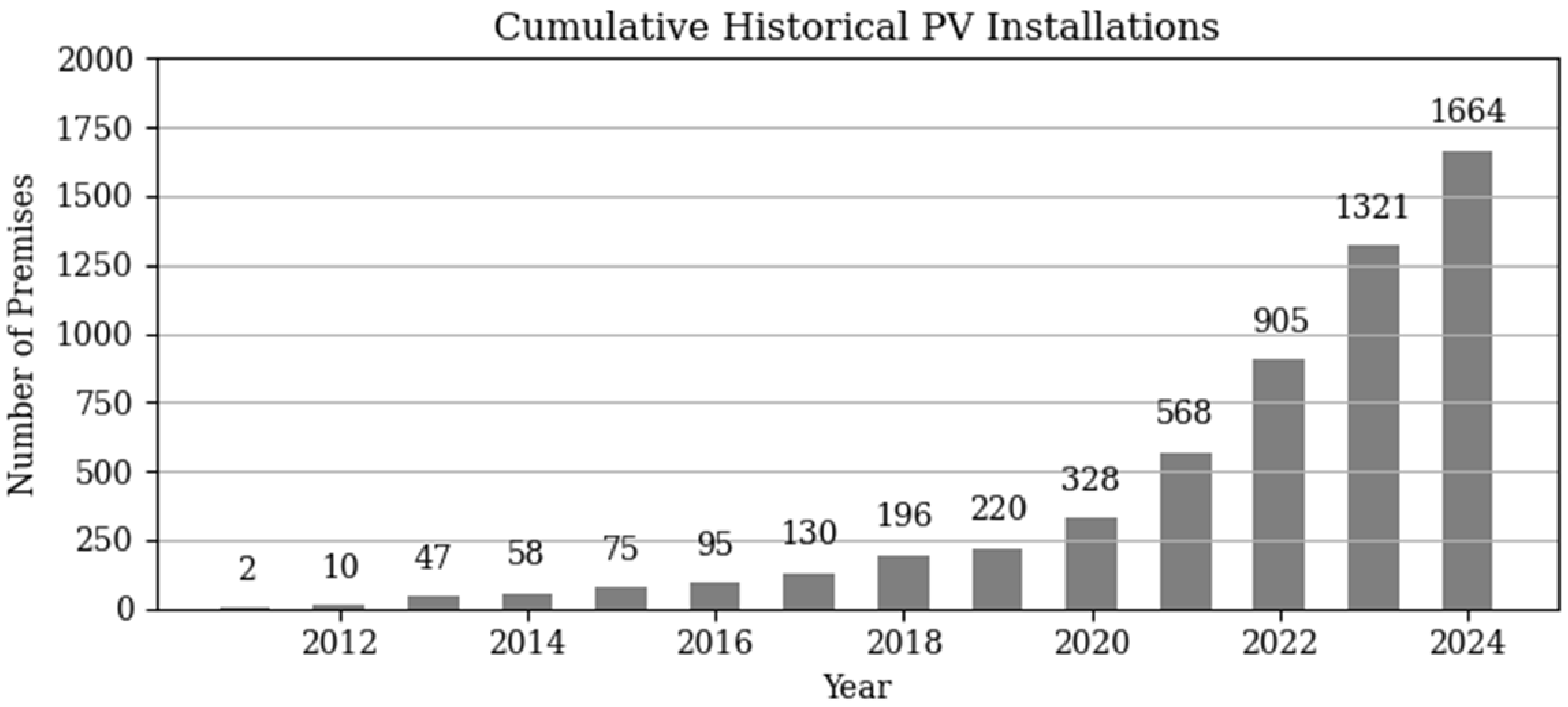
Assumption Chart

Input	Base	High	Low	Source
Average kWh/mile		0.345		Department of Energy & Energy Information Administration
Miles/year/vehicle	5,300	8,000	4,000	Car & Driver

Follow the same rule from IRP 2022

Data overview: PV data





→Rapid growth

→High PV demand in downtown Indianapolis

→Strong spatial heterogeneity

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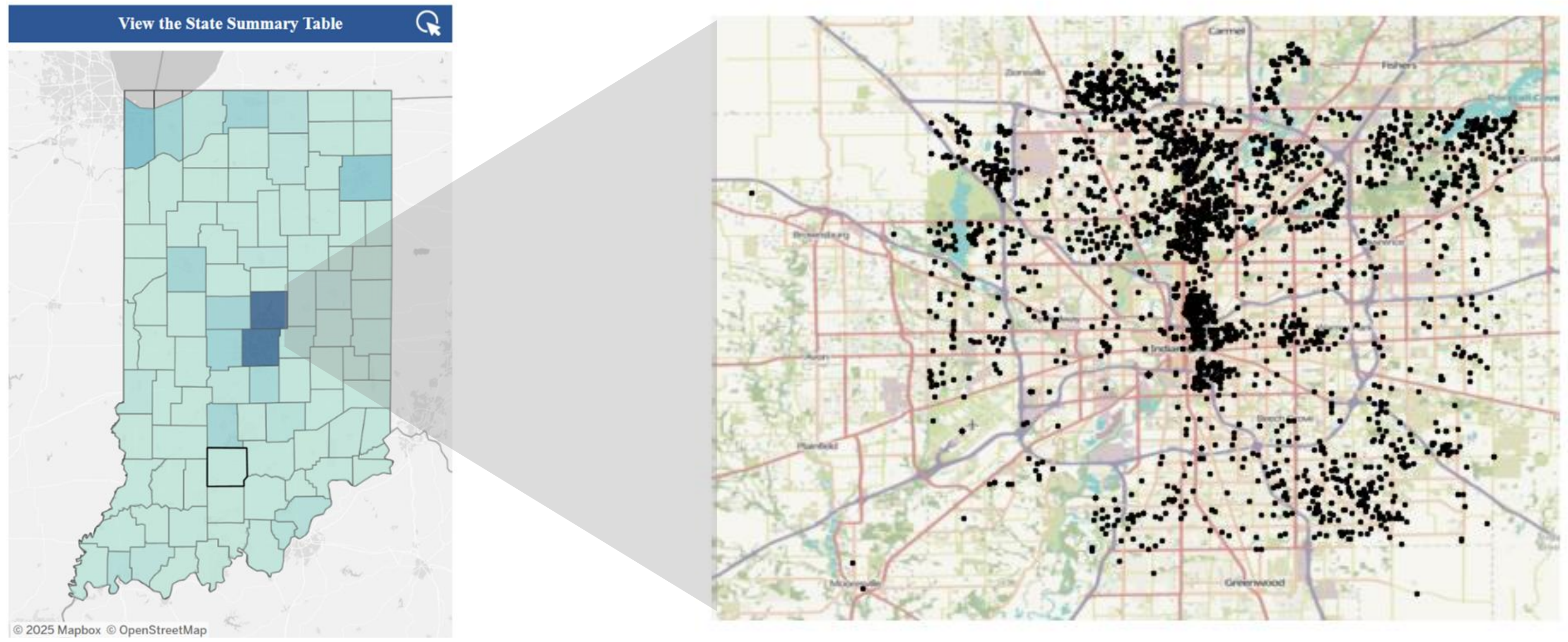
Data overview: EV data

- →**Concentration in AES Service Region**
- →**Fast-growing trend** compared to other vehicle types (e.g. gas)
- →**Strong spatial heterogeneity**

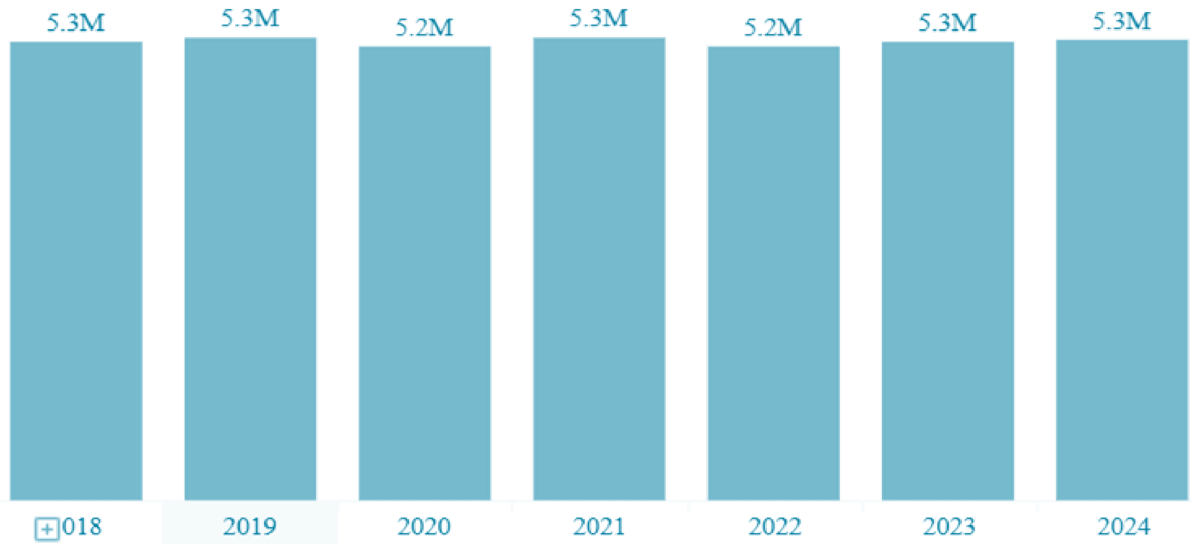
EV in Indiana

AESIndiana service region



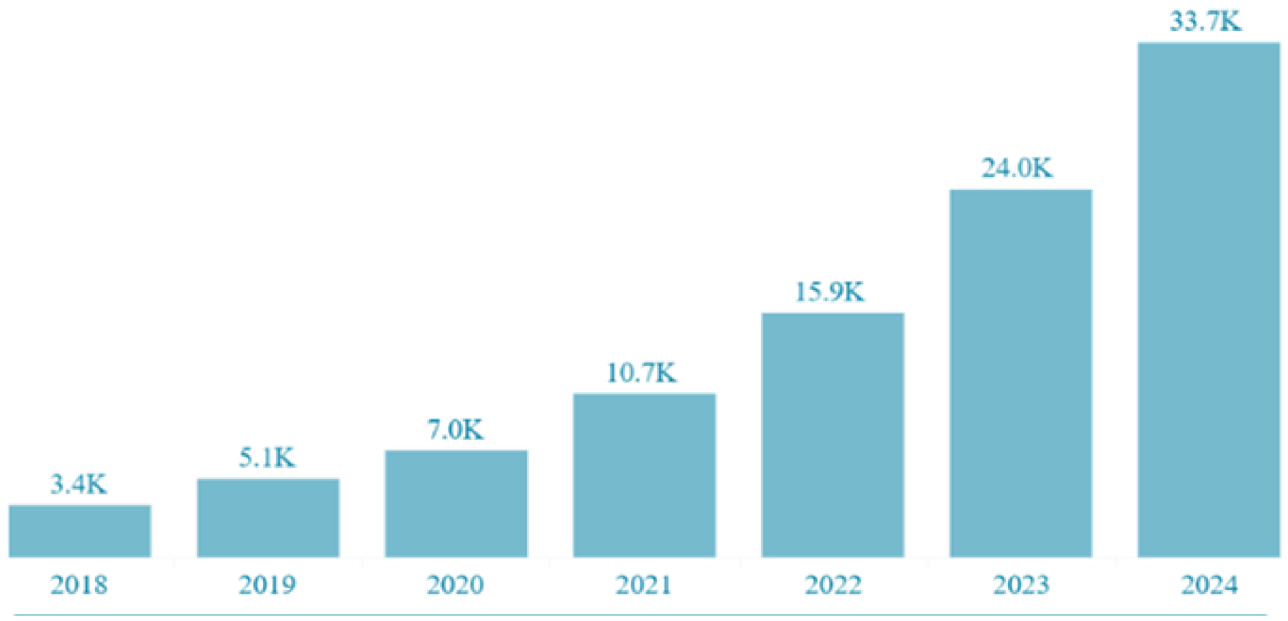
Gas Vehicles

Registration per year in Indiana



Indiana Office of Energy Development

EV Registration per year in Indiana



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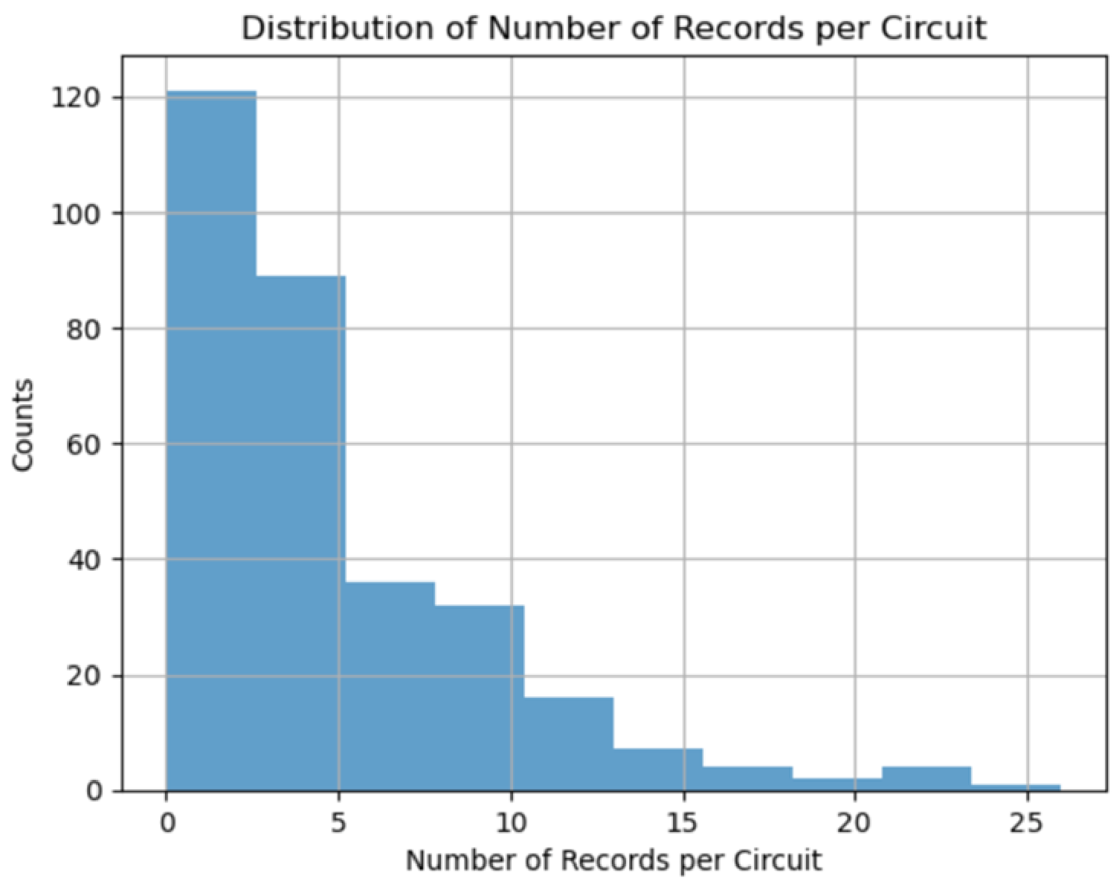
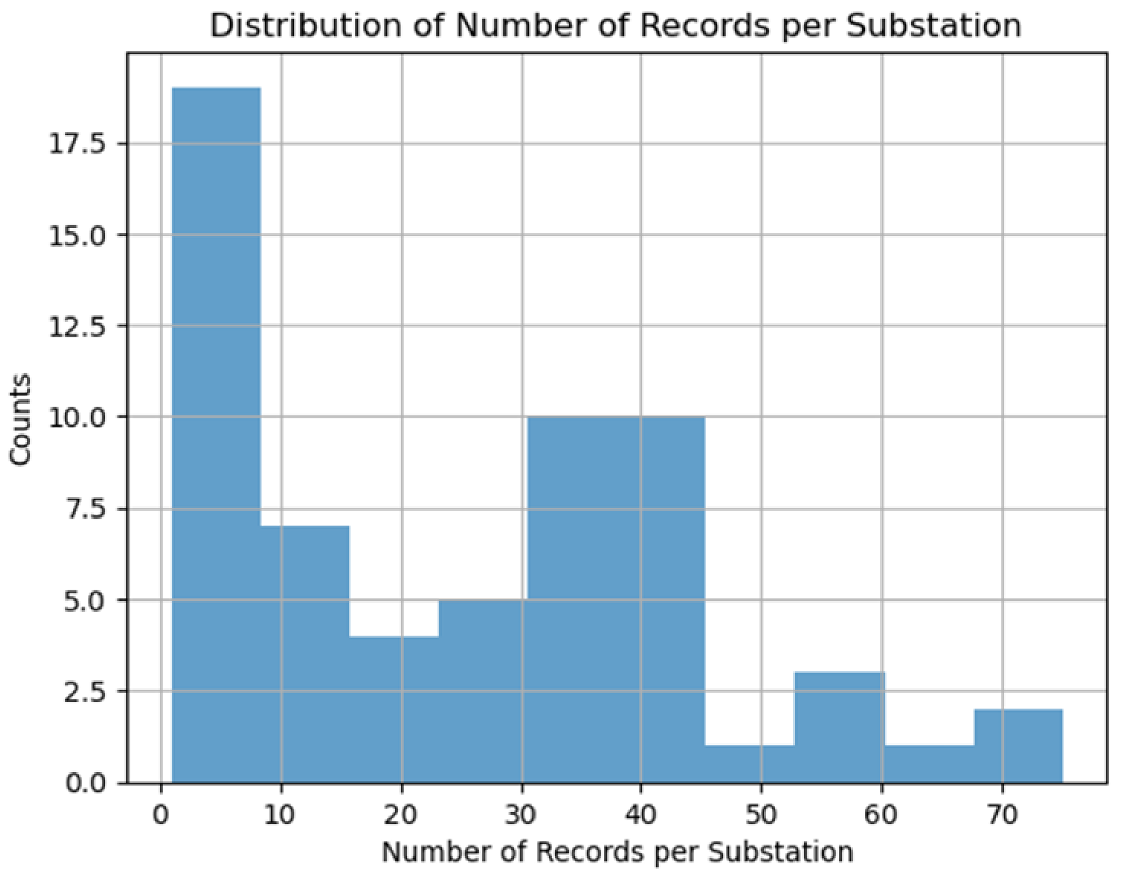
Distribution system analysis



~5 installations per circuit



~24 installations per substation

→**Data sparsity** at substation and circuit level.

→**Need action** to meet growing demand.

→e.g. substation average ~24 installations (2025) to ~786 installations (2050 prediction)

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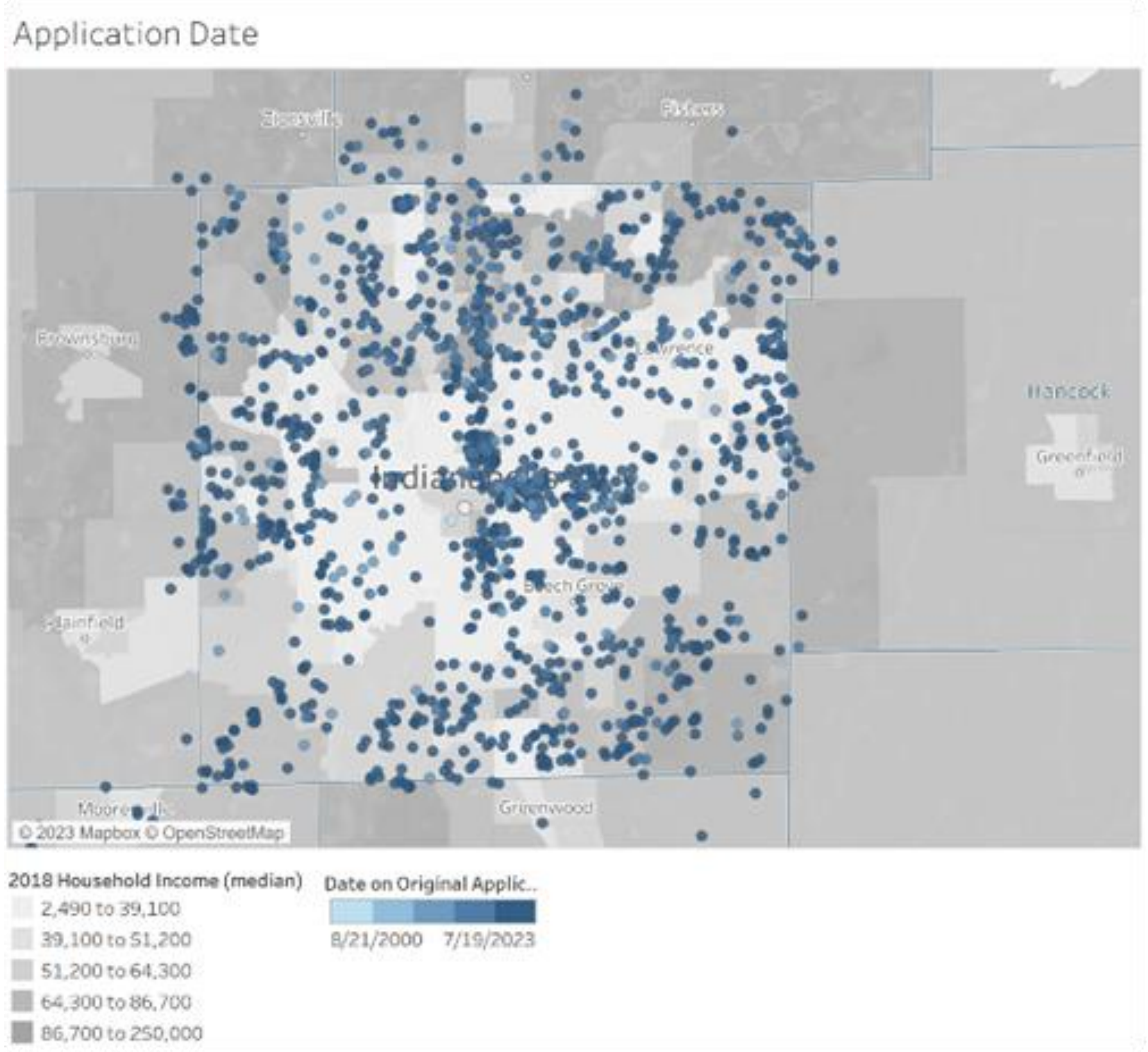
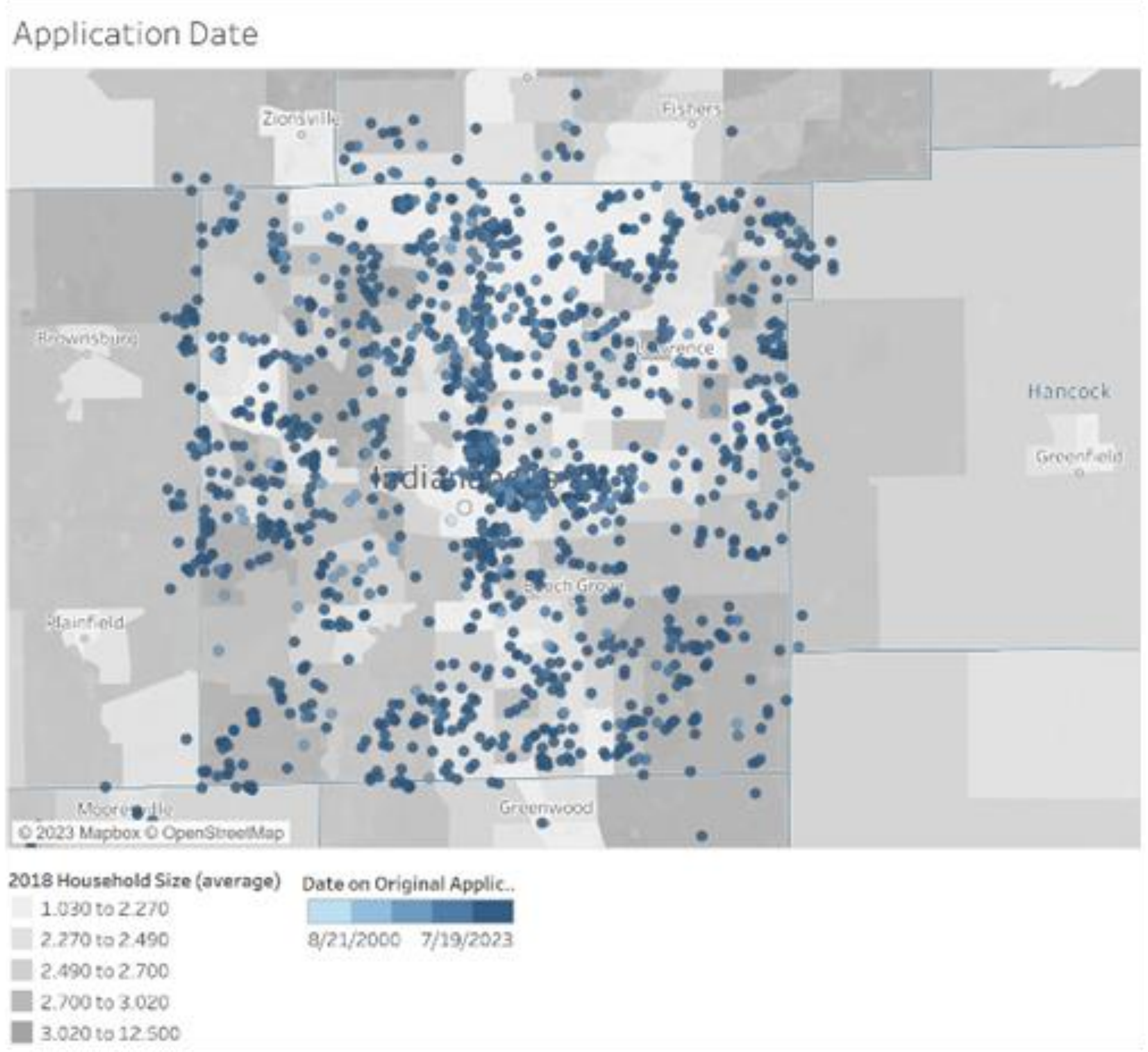
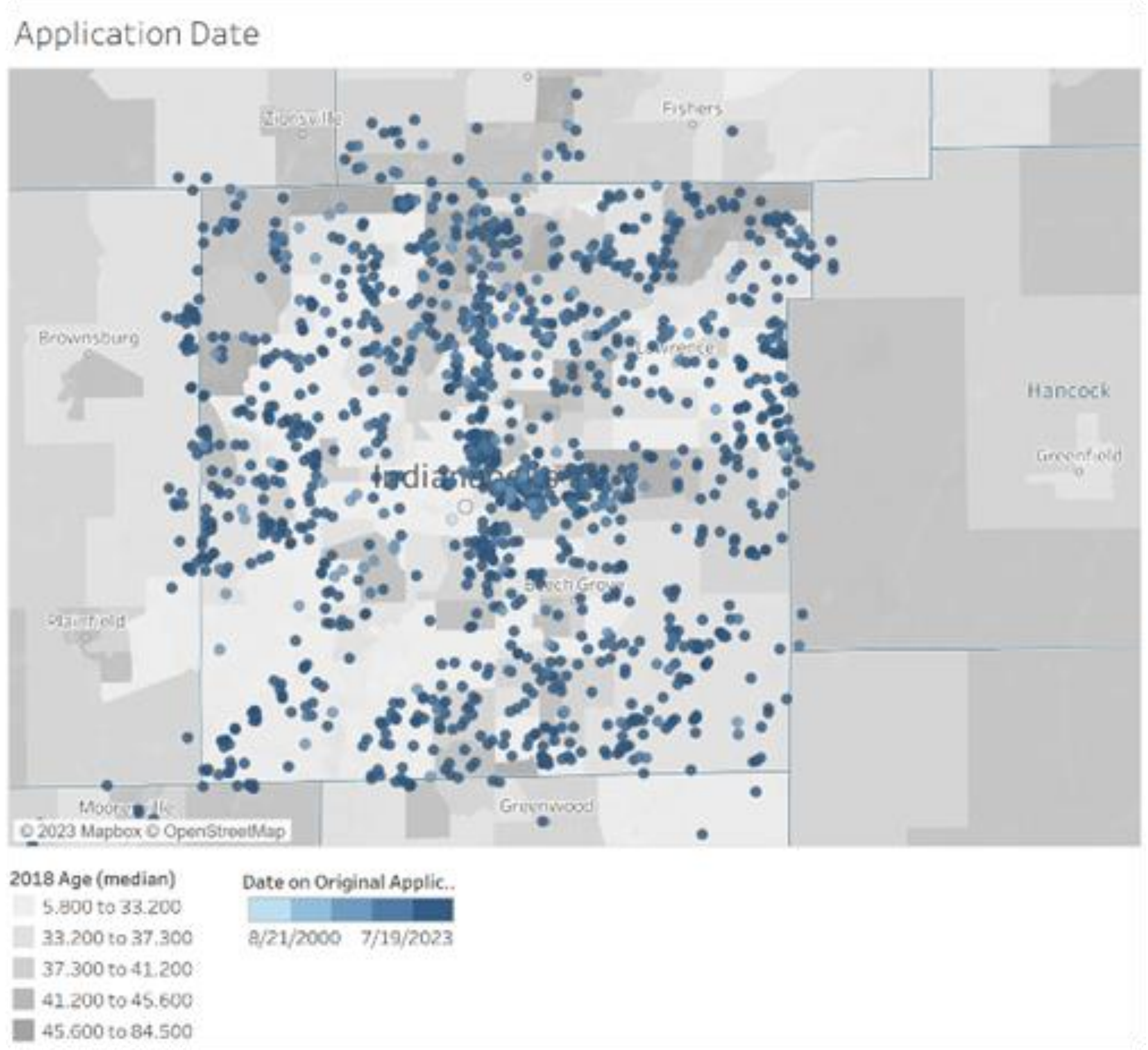
Correlation analysis



Household income



Household size



Median age

→EV / PV growth **depends on other covariates**

→Need to **include these covariates into the prediction**

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Takeaways from data analysis

→DER Data shows considerable **sparsity** both temporally and spatially.

→Individual unit records are highly **random** and **unpredictable**.

→The growth of DER may **depend on some key exogenous factors**.

Method

→Machine Learning Model for EV/PV Adoption

 →Base Forecast

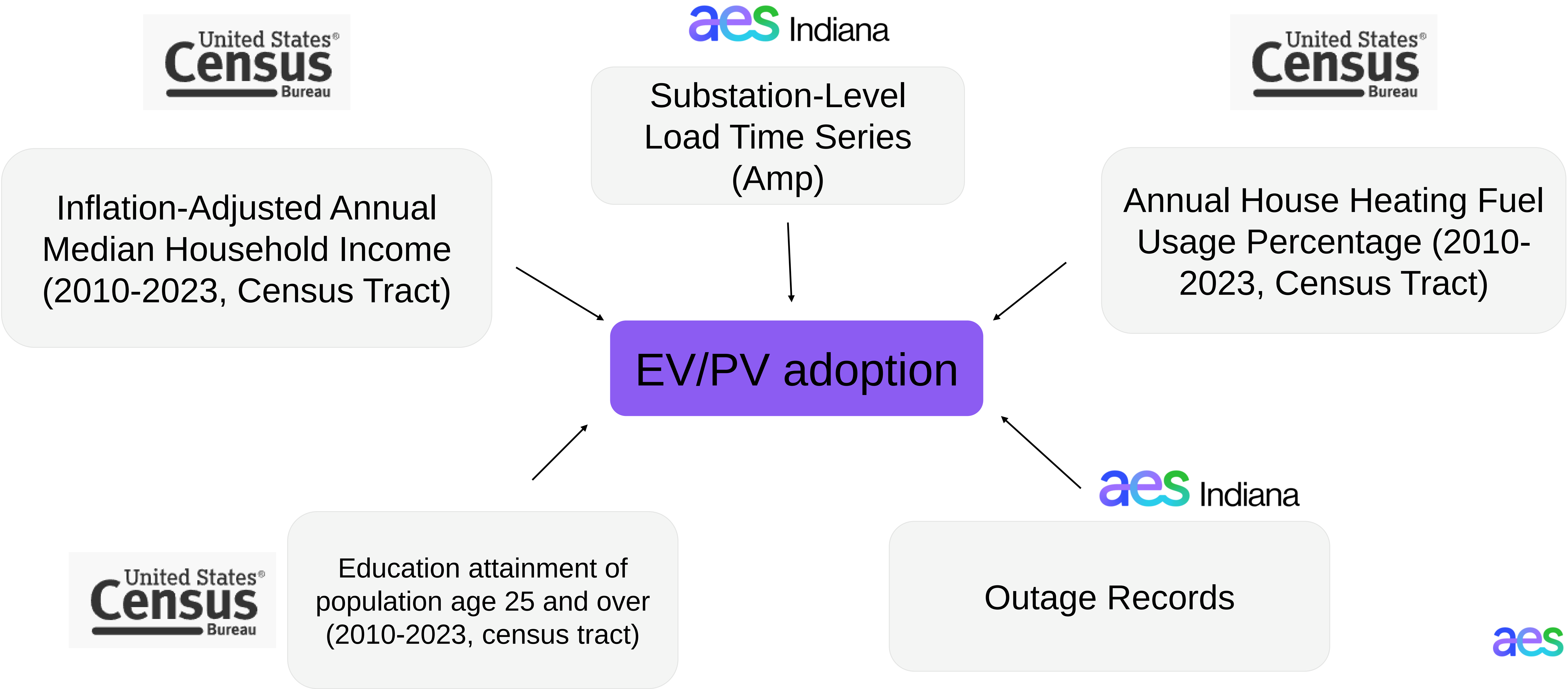
→Statistical Framework for Uncertainty Quantification

 →High and Low Forecast

→Model Evaluation

EV/PV prediction model

Adoption in the next month in a region = **Exogenous Influence** + Endogenous Effect



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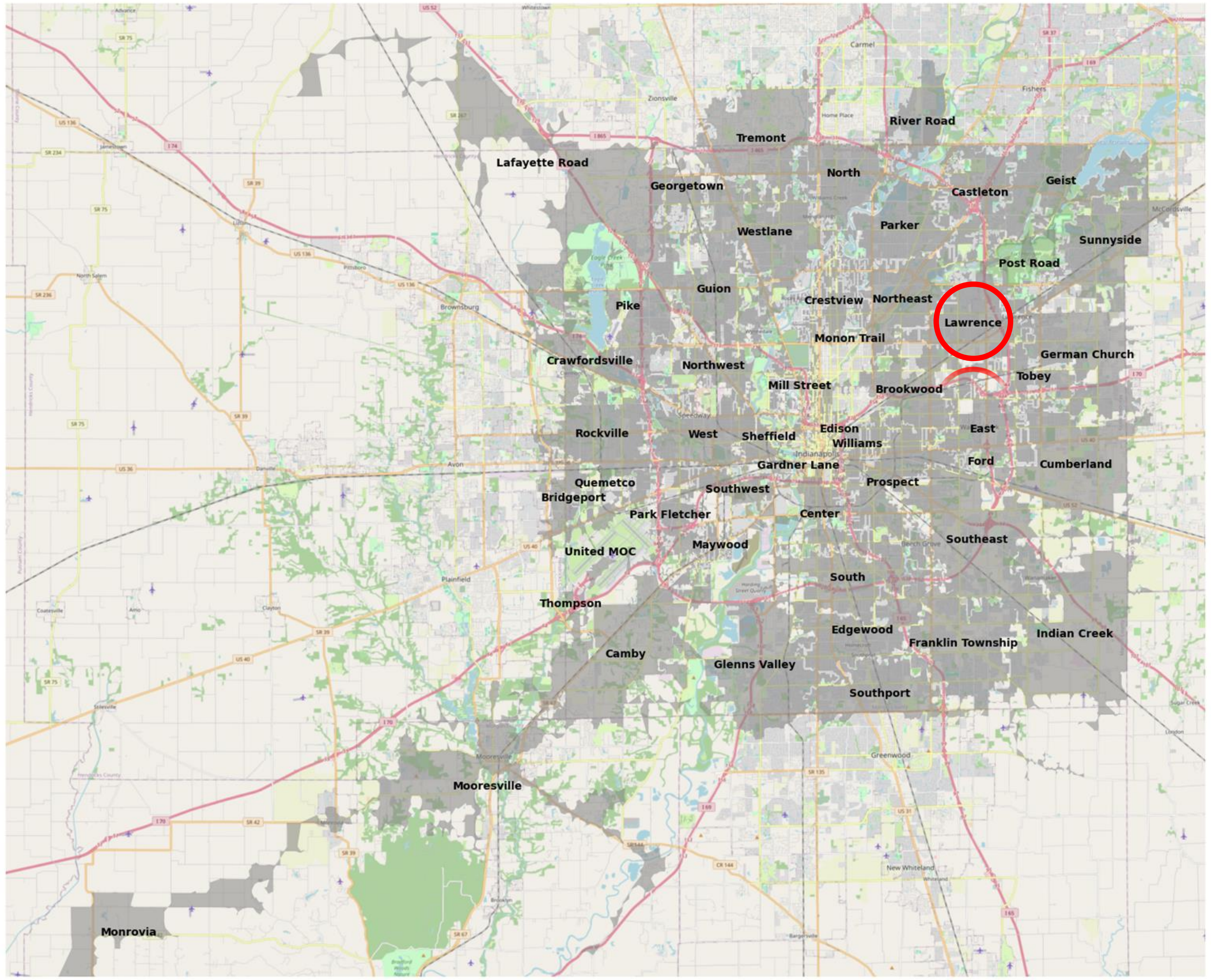
EV/PV Prediction Model

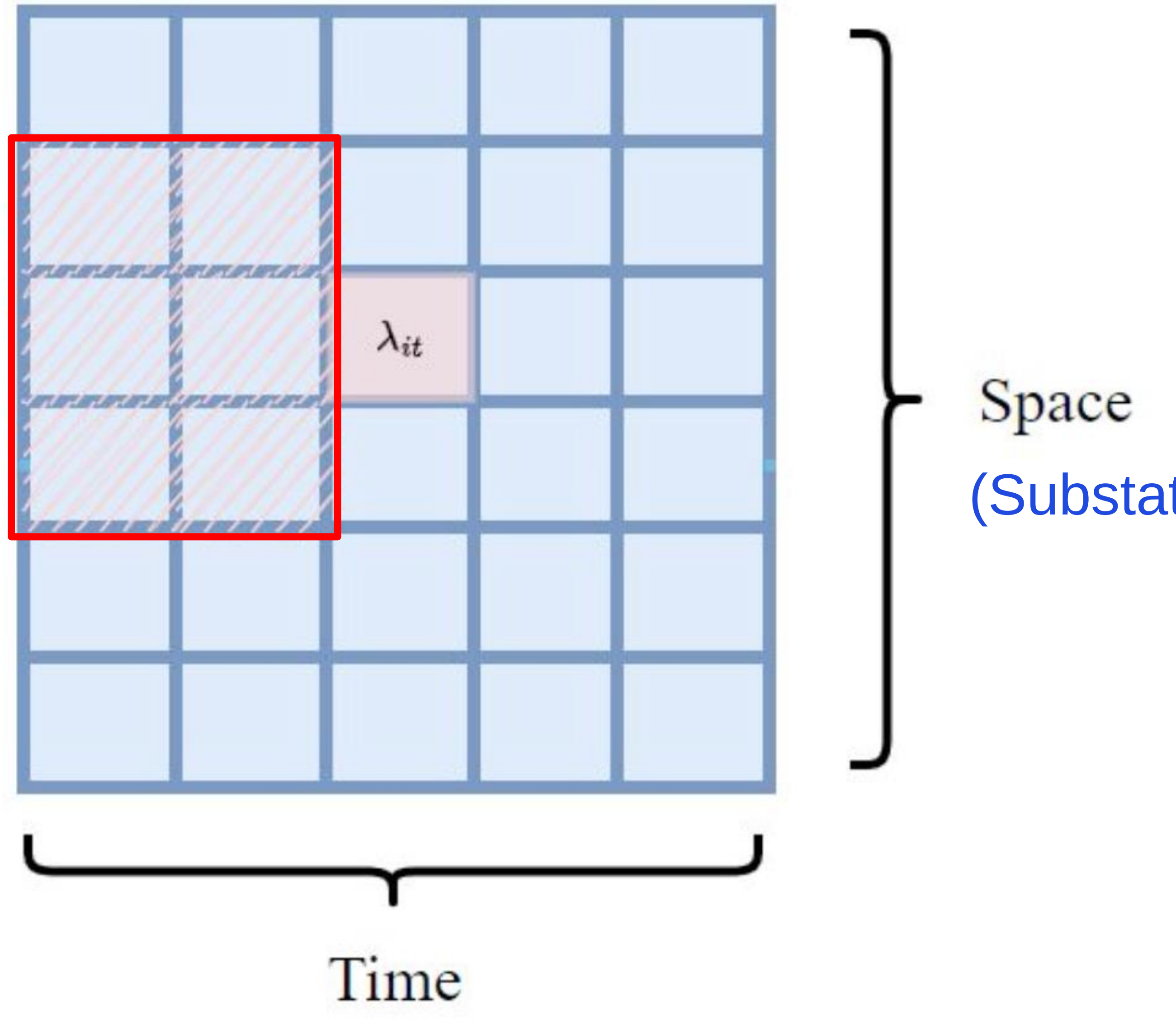
\# Adoption in the next month in a region = Exogenous Influence + **Endogenous Effect**

"The adoption in a substation may depend on the adoption level of its history and neighbors."



Neighbors and their history

\# installations for each grid



(Substation)

(Month)

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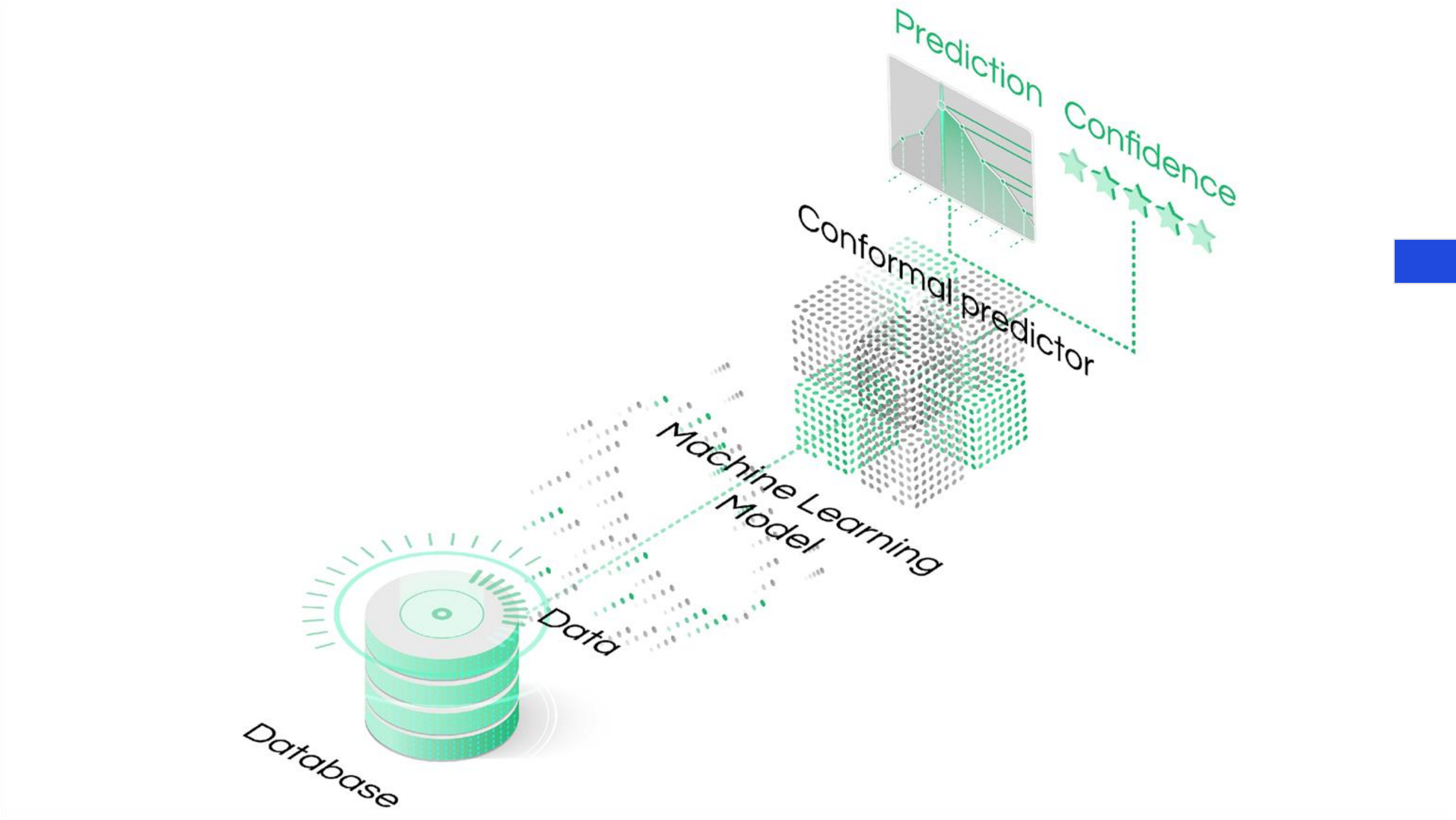
Uncertainty quantification

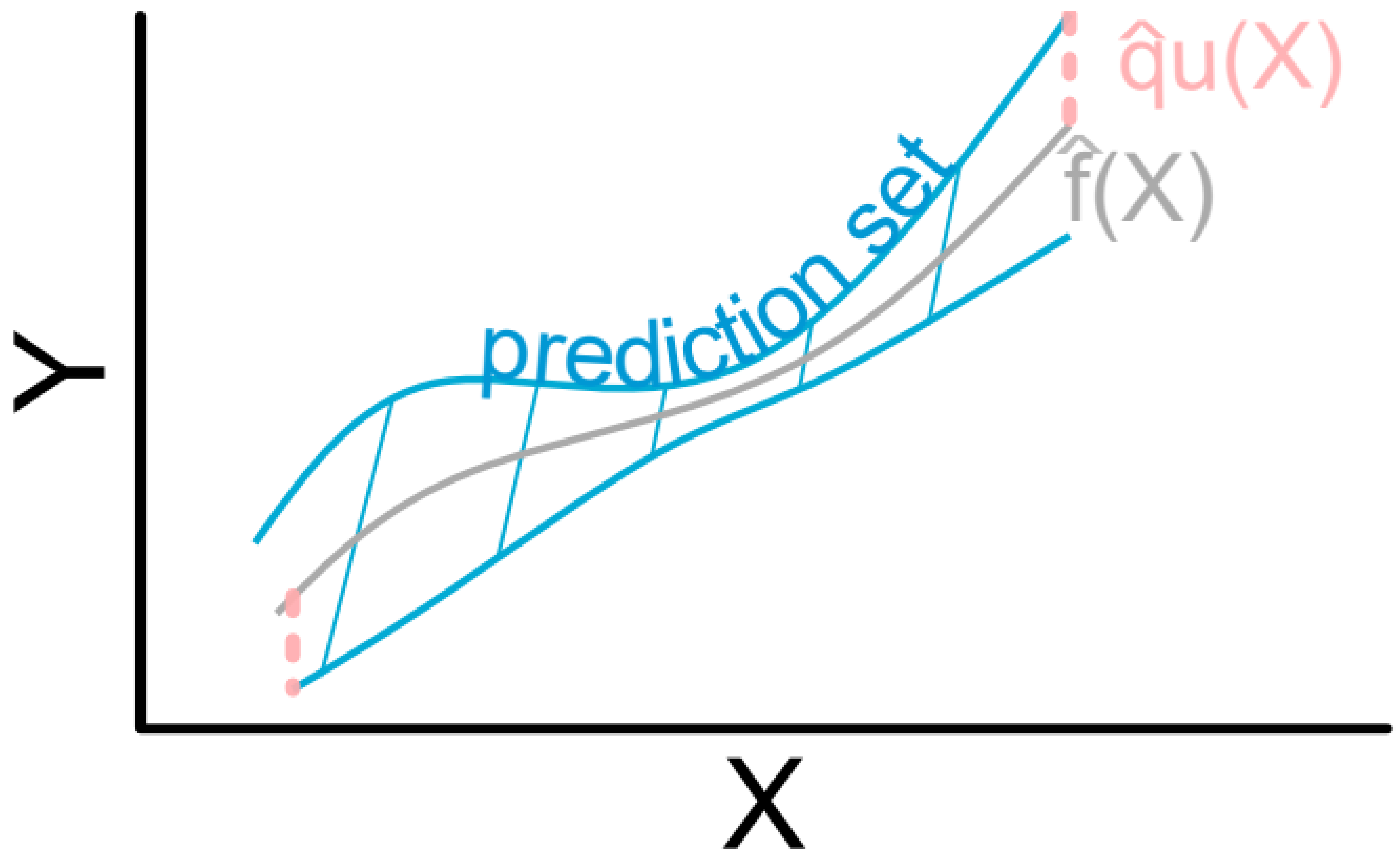
Conformal Prediction

A model-agnostic

uncertainty quantification framework



Construct the high and low base prediction



Hyper-parameters selection (EV)

Supporting evidence to our key assumptions on the hyperparameters:

→ **Confidence level:** Confidence with the low and high predictions

→ Quality and quantity of data + model evaluation

→ **Our choice: 70%**

→ **Tipping point:** The timing when fastest growth rate hits

→ Expert opinions: US tipping point arrives 2021~2031.

- Camus Energy: Indianapolis region arrives at 2029

→ **Our choice: 2029**

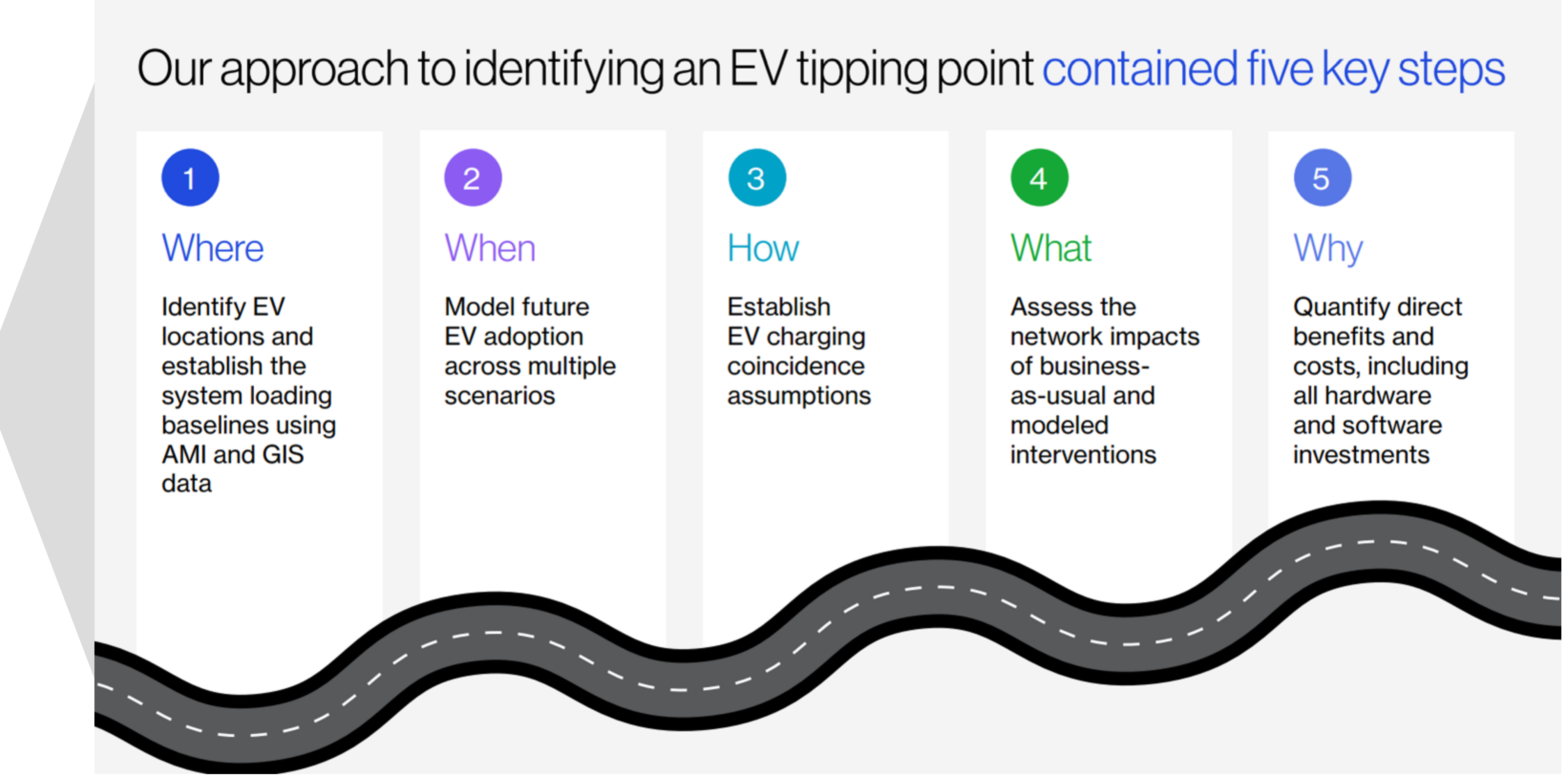
→ **Penetration rate:** Saturated market size theoretical limit

→ Multiple public surveys: >50% of American people will consider purchasing EV

- e.g. 54%, 57%, 38+40=78%

→ **Our choice: 56%**

aes, CAMUS



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Hyper-parameters selection (PV)

Supporting evidence to our key assumptions on the hyperparameters

Confidence level: Confidence with the low and high predictions

→Quality and quantity of data + model evaluation

→**Our choice:** 90% (Res) and 10% (Com)

Tipping point: The timing when fastest growth rate hits

→*SEIA:* solar panel growth trend continue rising until 2029

→Indiana ranks high (12th) in solar generation.

→Policy incentives (e.g. ITC CEIC) effective until 2032

→**Our choice:** 2032

Penetration rate: i.e. saturated market size theoretical limit

→Current highest state: California = 8%

→**Our choice:** 7% (Res) and 4% (Com)

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14	**Los Angeles**	CA	Pacific	166.7	649.9	1
15	**Sacramento**	CA	Pacific	159.8	83.9	14
16	**Indianapolis**	IN	North Central	142.1	126.1	12
17	**Newark**	NJ	Northeast	112.0	34.9	27
18	**Hartford**	CT	Northeast	102.1	12.4	41
19	**Charleston***	SC	South Atlantic	101.5	15.2	38

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User portal

Global Hyperparameter

Confidence level: 70%

Meaning: Model's statistical confidence in the low and high forecast.

Penetration rate: 56.25%

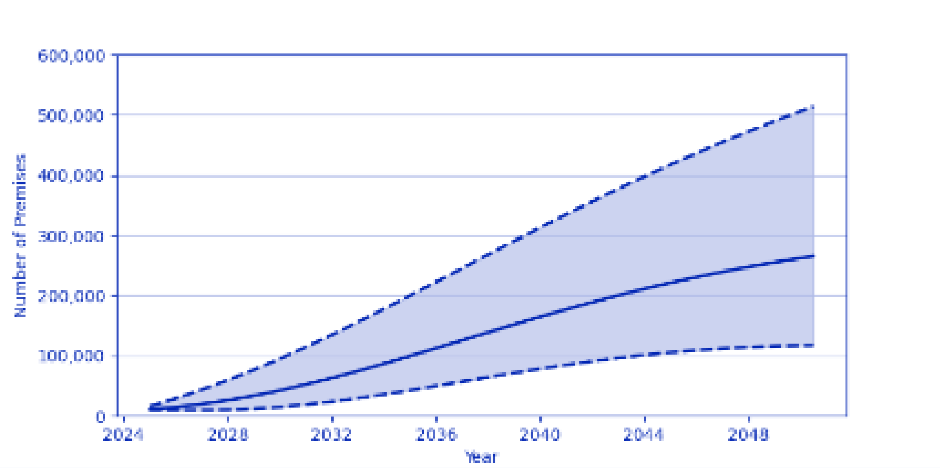
Meaning: Theoretical limit of penetration rate (number of adoptions per capita within the network).

Tipping point: 2029-01

Meaning: The date when the *decaying effect* kicks in.

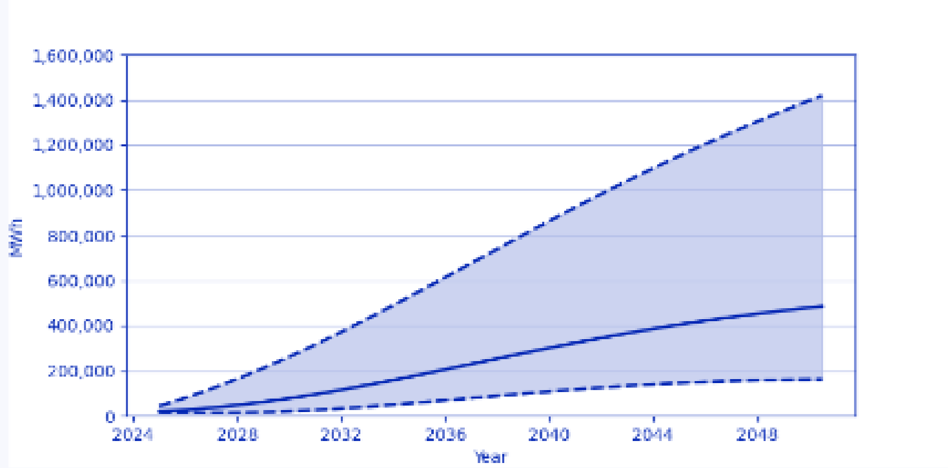
Total

Number of Vehicles



Download data

Energy Sales



Download data

Dashboard demo link:

EV:
https://wbzhou2001.github.io/EVPV-Dashboard/ev_dashboard.html

PV:
https://wbzhou2001.github.io/EVPV-Dashboard/pv_dashboard.html

References and more detail of hyperparameter selection are included.

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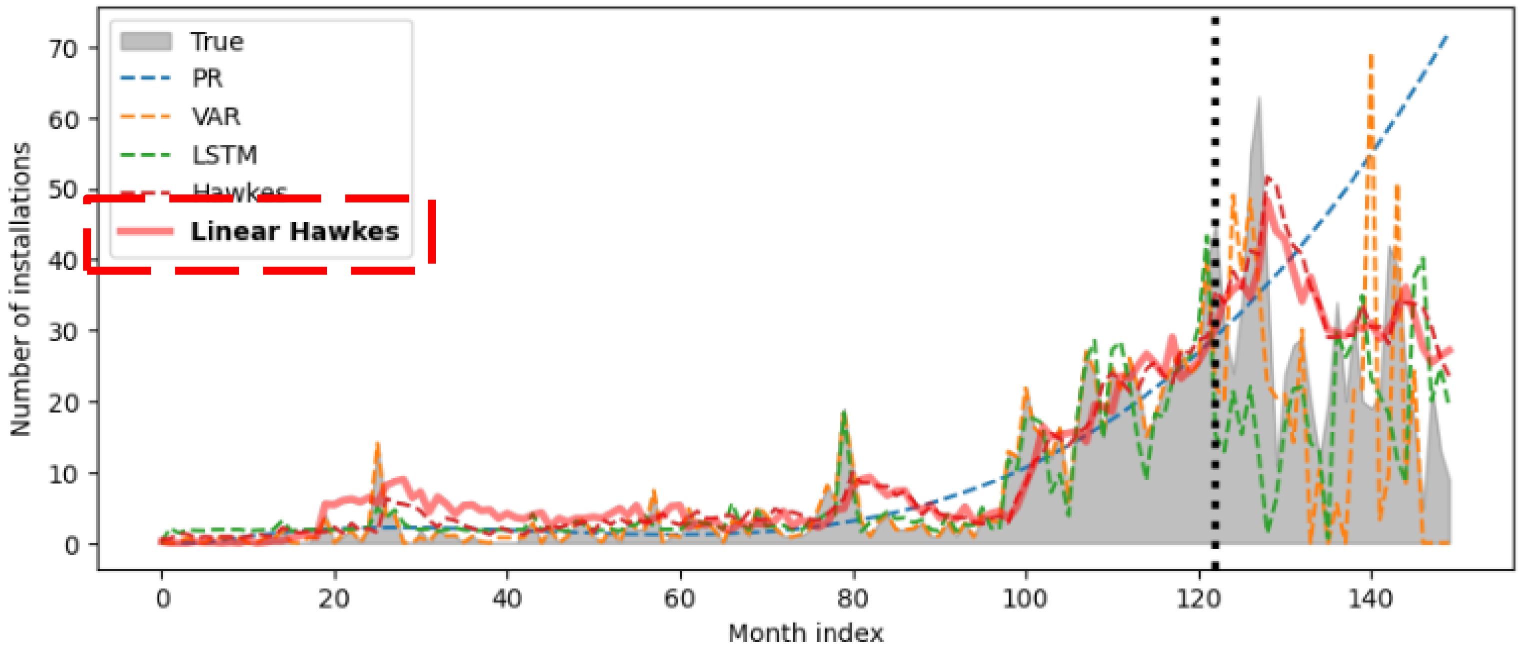
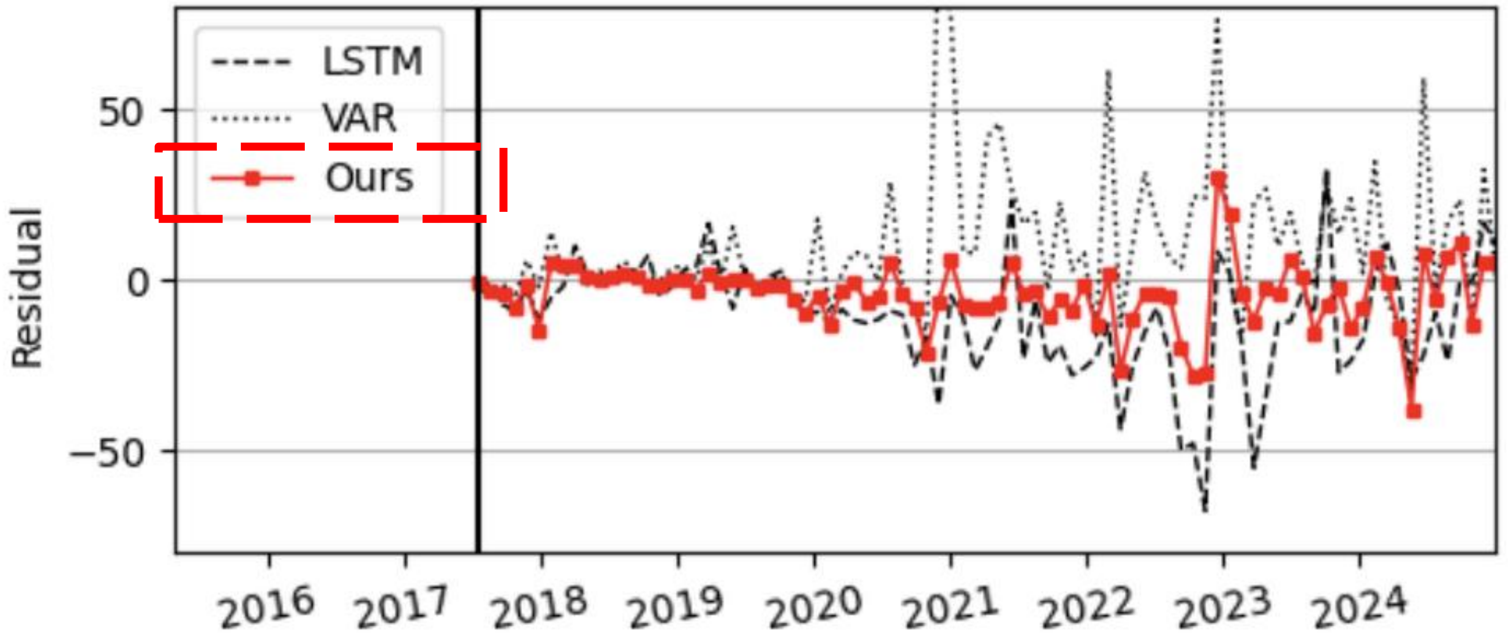
Evaluation

Our method (in red) outperforms other methods significantly regarding predictive error



PV Adoption Prediction Over Time



Prediction Error Over Time

Method	Aggregated MAE	Regional MAE	Regional STD
PR	26.51	0.23	0.34
VAR	15.17	0.40	1.19
LSTM	14.96	0.21	0.37
Vanilla Hawkes	13.35	0.19	**0.31**
Covariate enhanced Hawkes	**12.59**	**0.18**	**0.31**

Prediction Error Comparison

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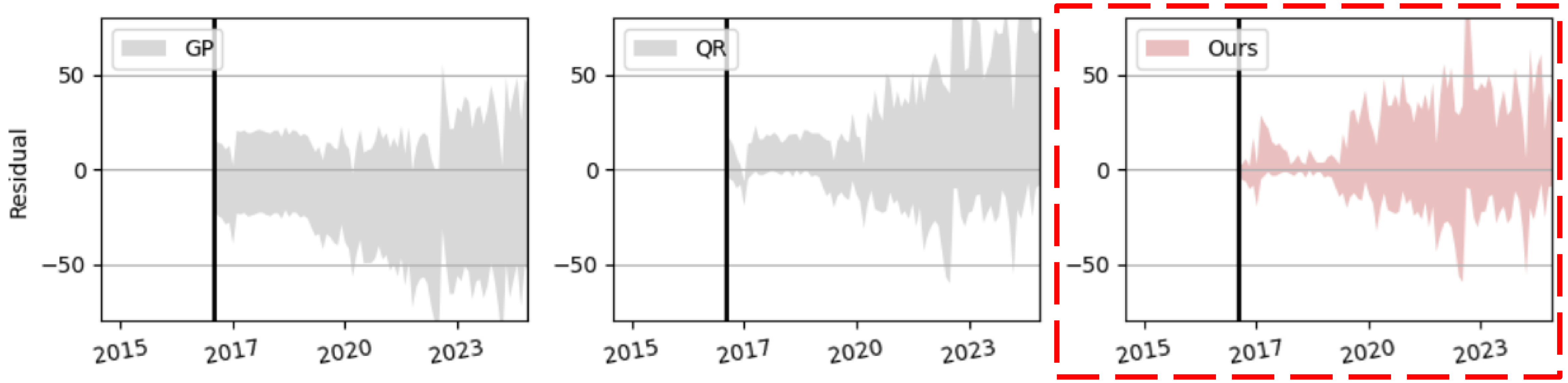
Evaluation

Our method (in red) achieves better uncertainty quantification (narrower prediction band)



Estimated Uncertainty Band Error Over Time Evaluation

Method	Full			Half		
	Val ↑	AggVal ↑	Size ↓	Val	AggVal ↑	Size ↓
LSTM	No (-)	No (-)	-	No (-)	No (-)	-
VAR	No (56%)	No (45%)	0.37	No (68%)	No (79%)	0.37
GPR	No (83%)	Yes (96%)	1.24	No (83%)	Yes (98%)	1.24
QFR	Yes (93%)	Yes (99%)	1.09	Yes (93%)	Yes (100%)	1.09
HST-Conformal	**Yes 99%**	**Yes 100%**	**1.06**	**Yes 99%**	**Yes 95%**	**0.77**

Uncertainty Band Validity (Probabilistic Coverage) and Efficiency (Size) Evaluation

Final Q&A and next steps

Next Steps

- AES Indiana Public Stakeholder Meeting #1 – 1/29/2025, 10am – 3pm

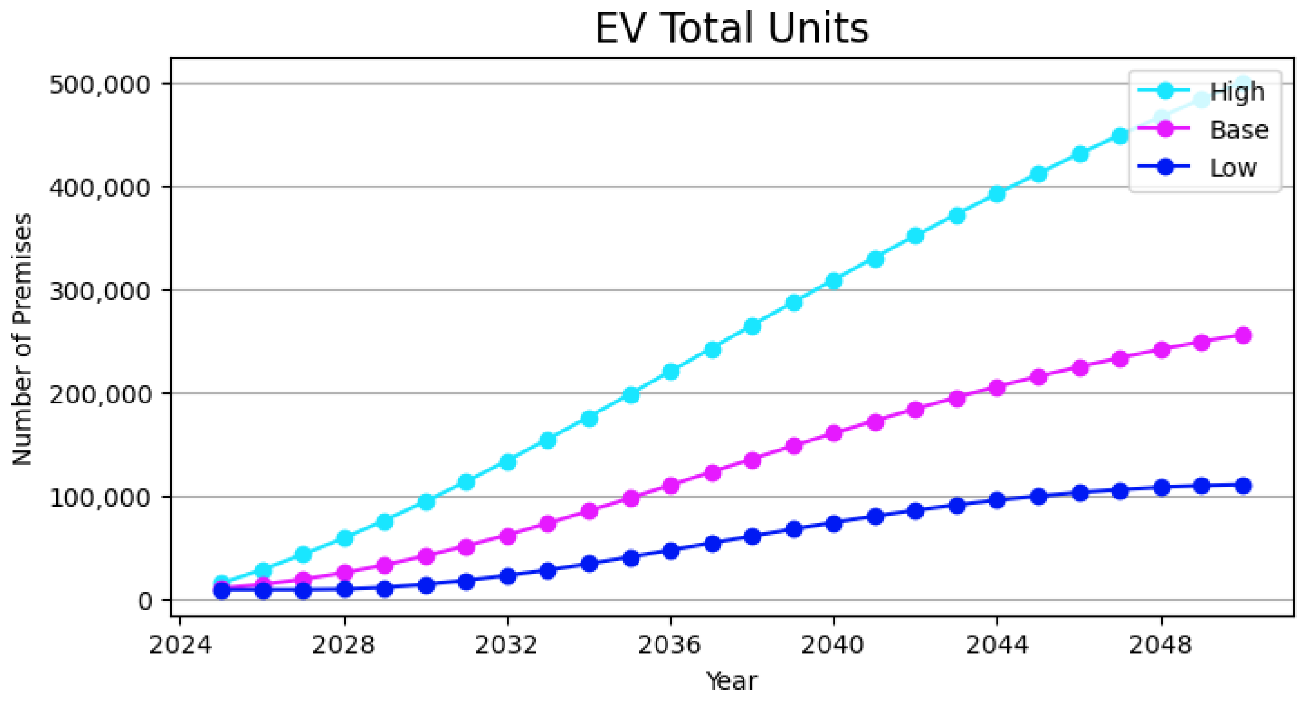
- AES Indiana will share data with stakeholders with NDAs within 10 days after each Public Stakeholder Meeting
  - First Data Share will be provided at the beginning of February and include the documents associated with the Load Forecast and EV and Solar PV forecasts

Thank You

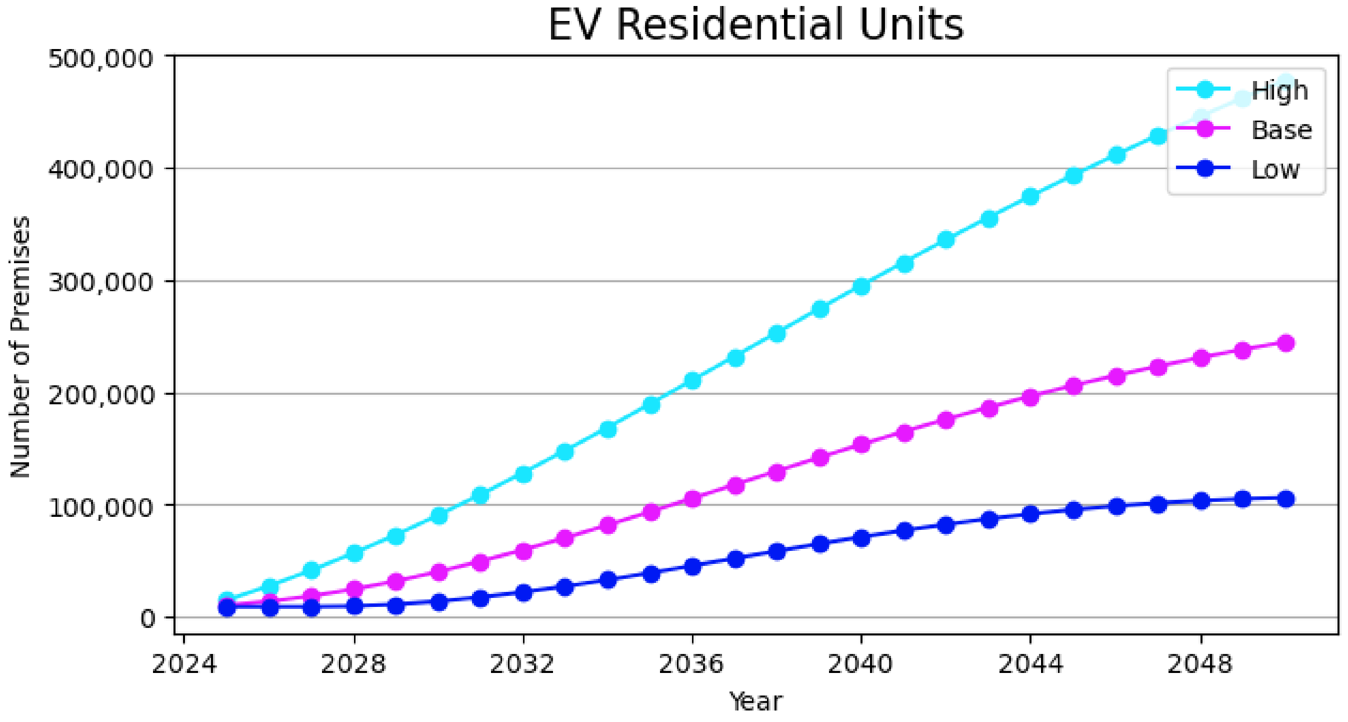
Appendix

Appendix: EV Prediction

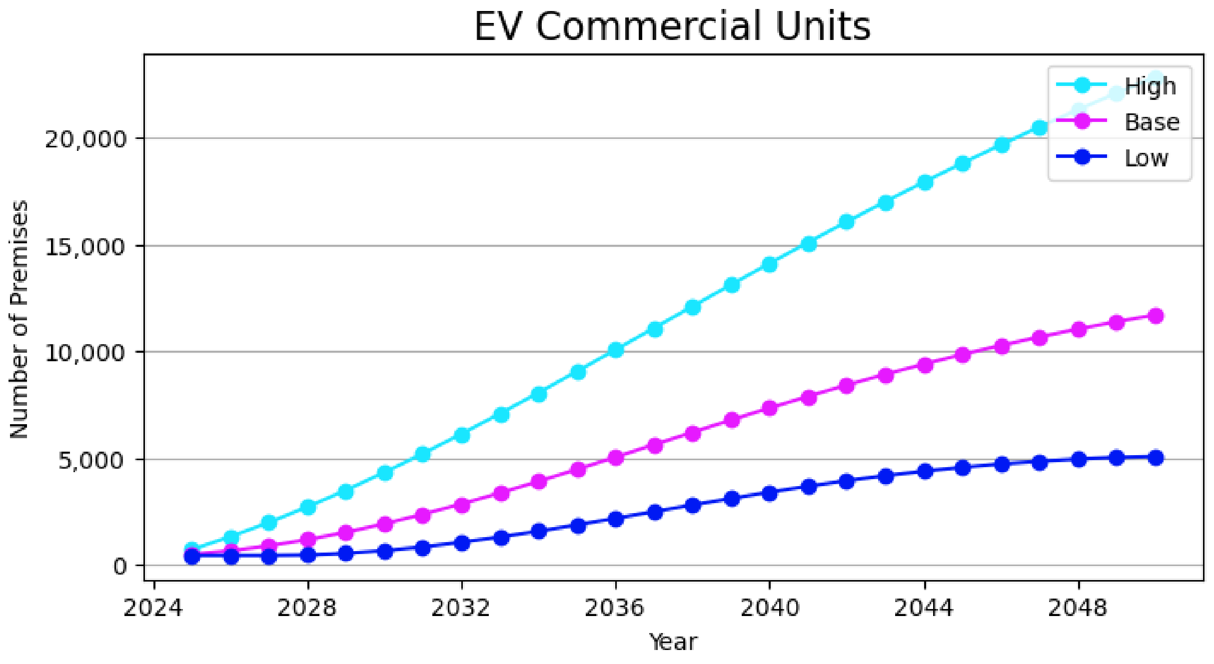
110k~500k



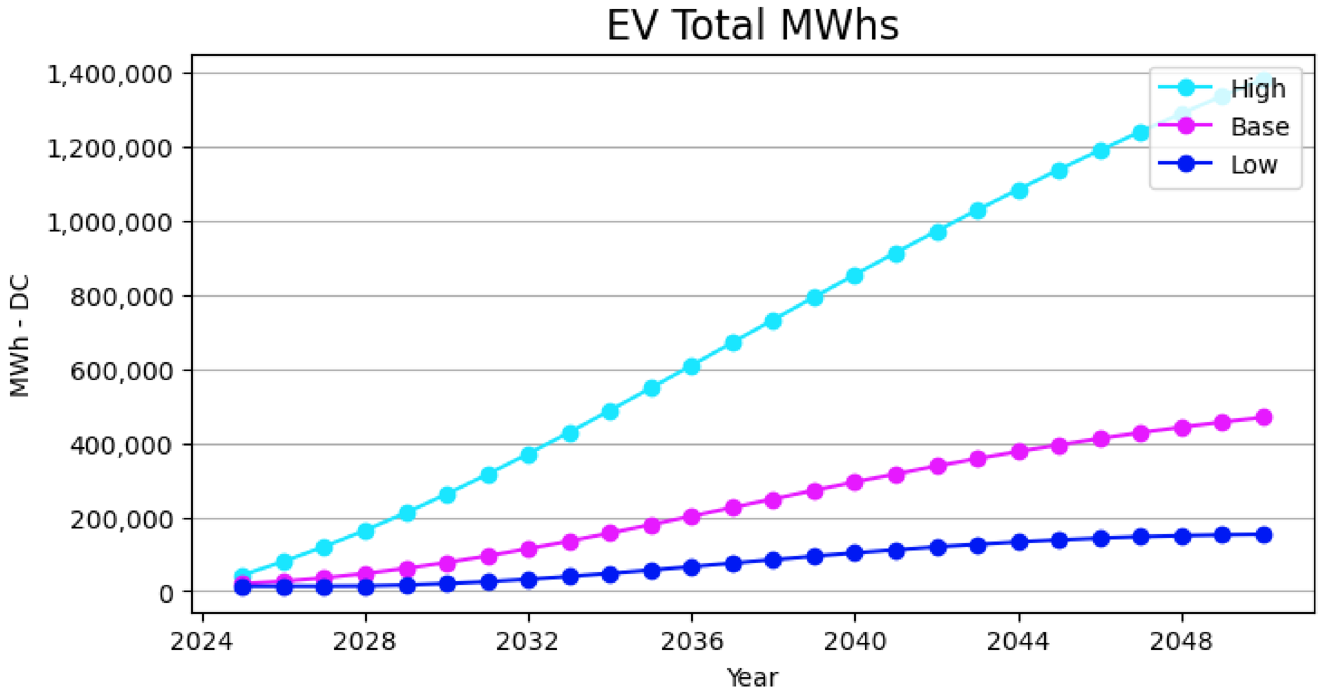
100k~480k



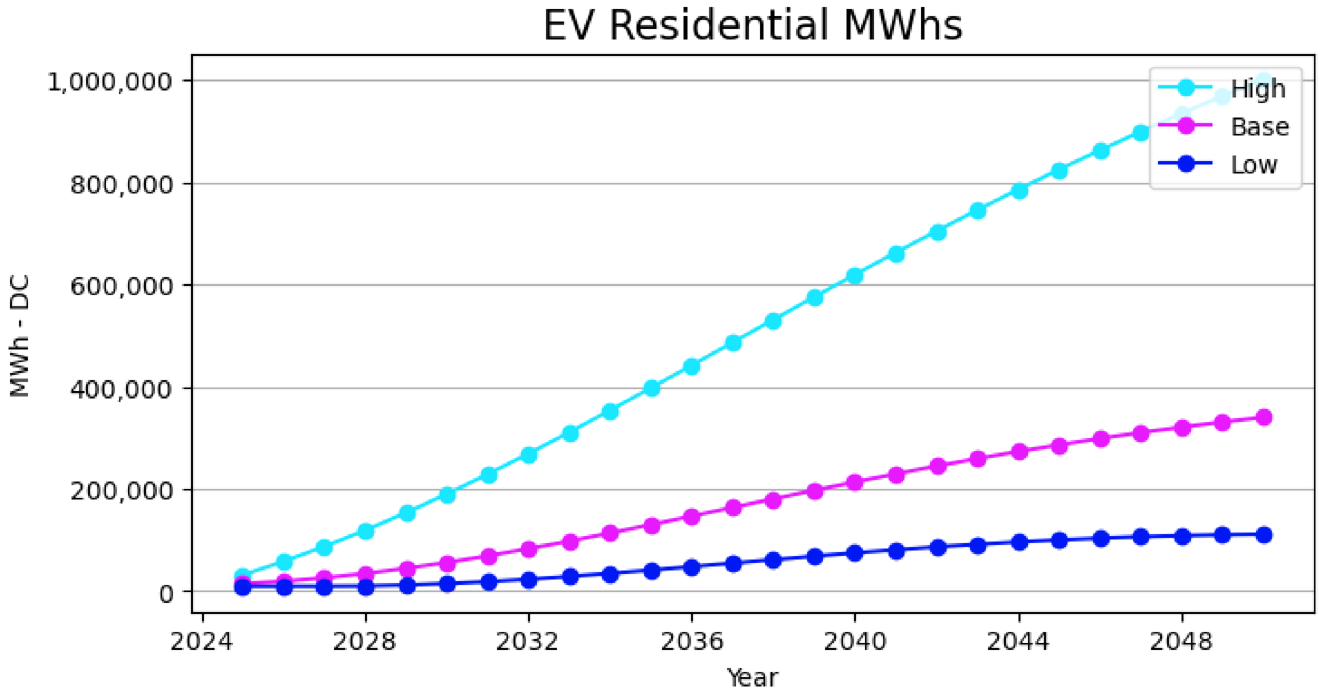
5k~22k



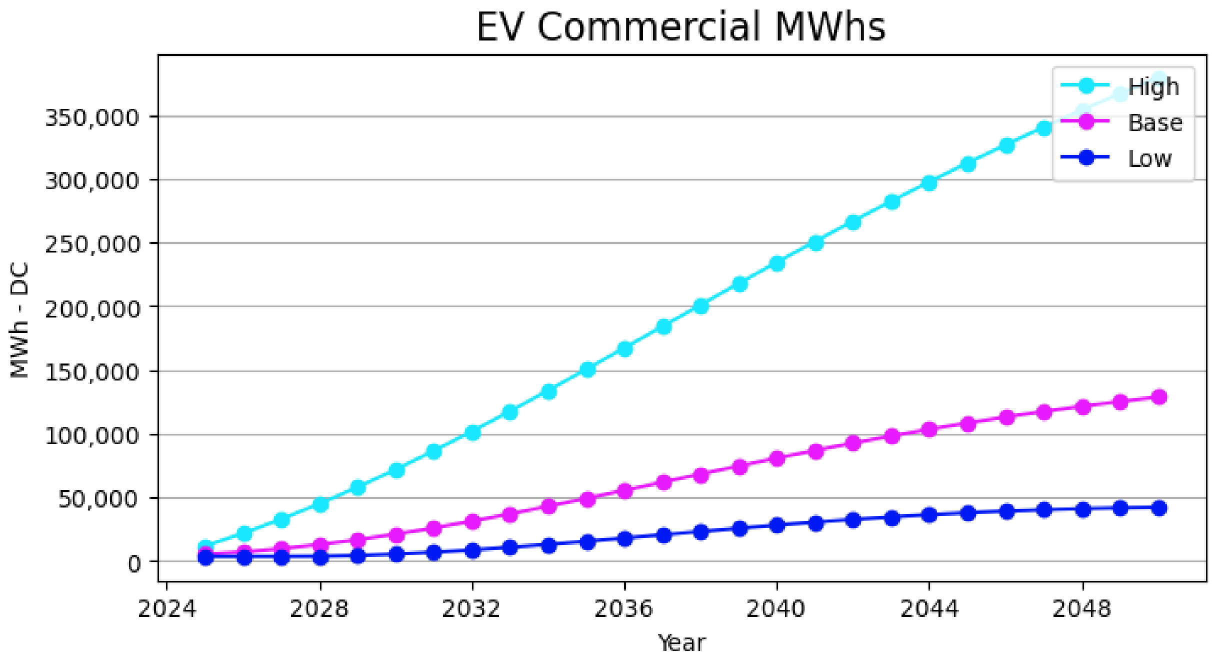
0.2M~1.4M



0.1M~1M



0.05M~0.4M



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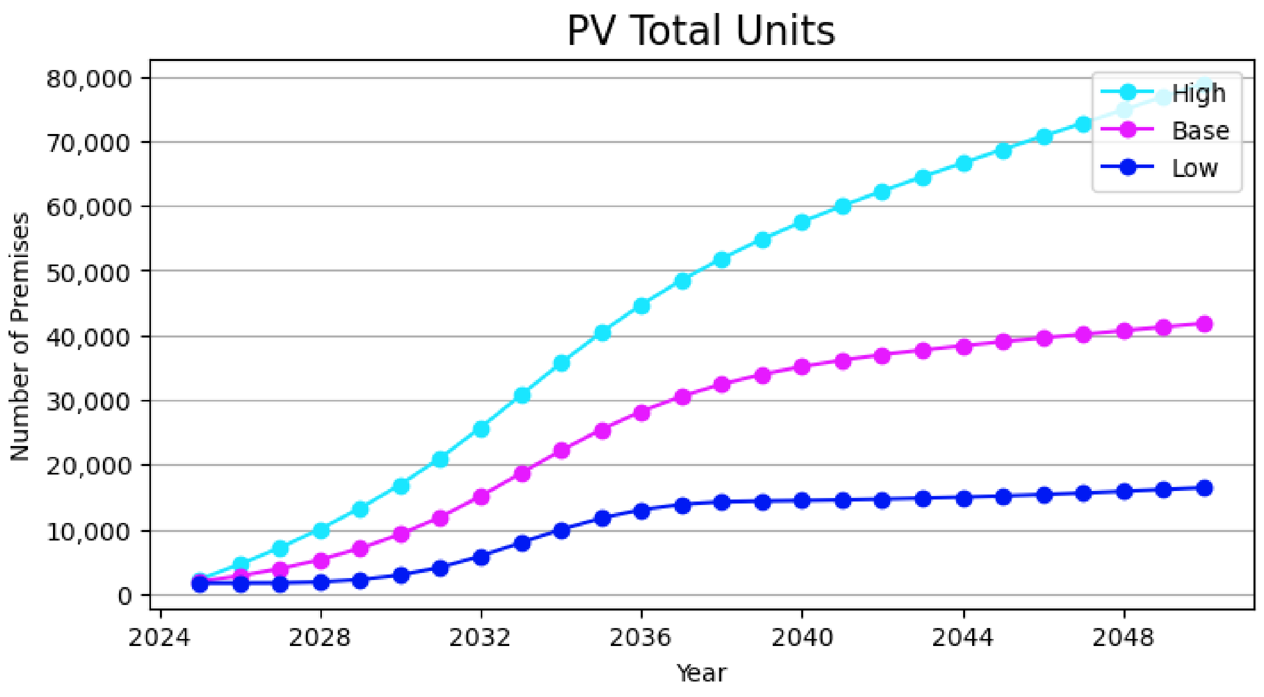
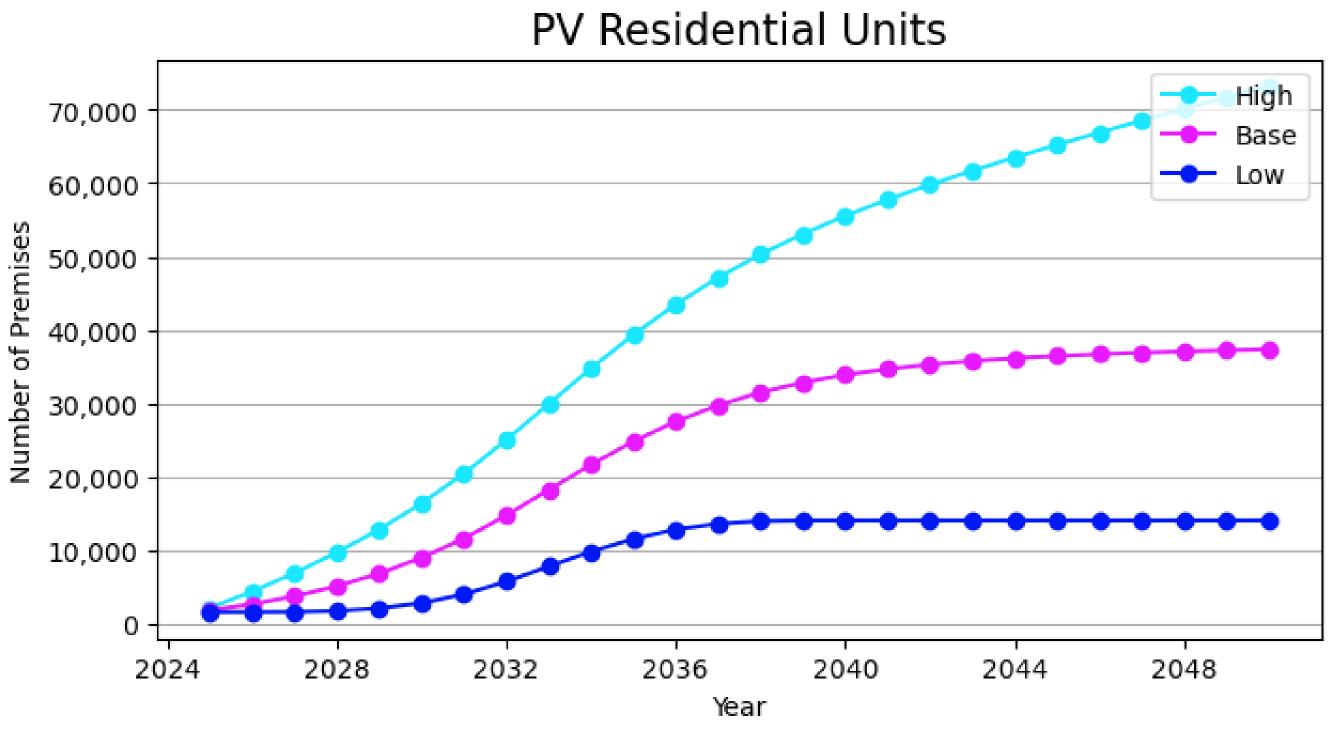
Appendix: Customer solar prediction

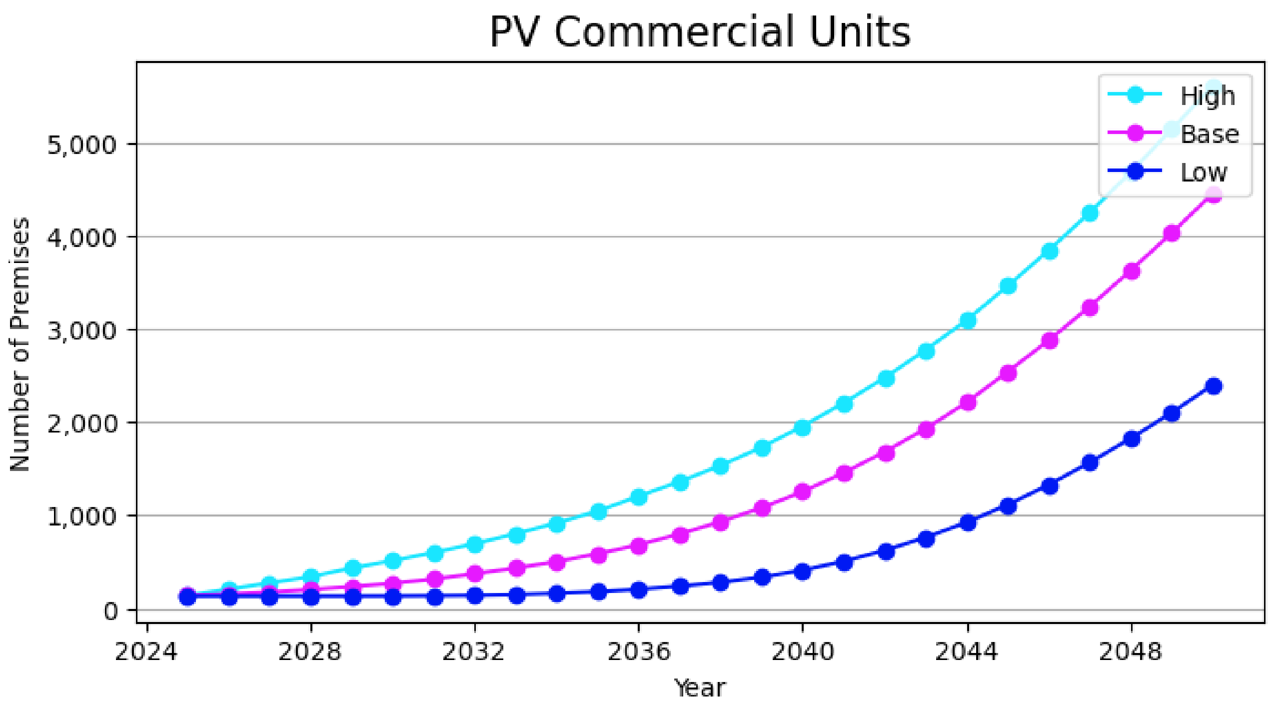
18k~80k



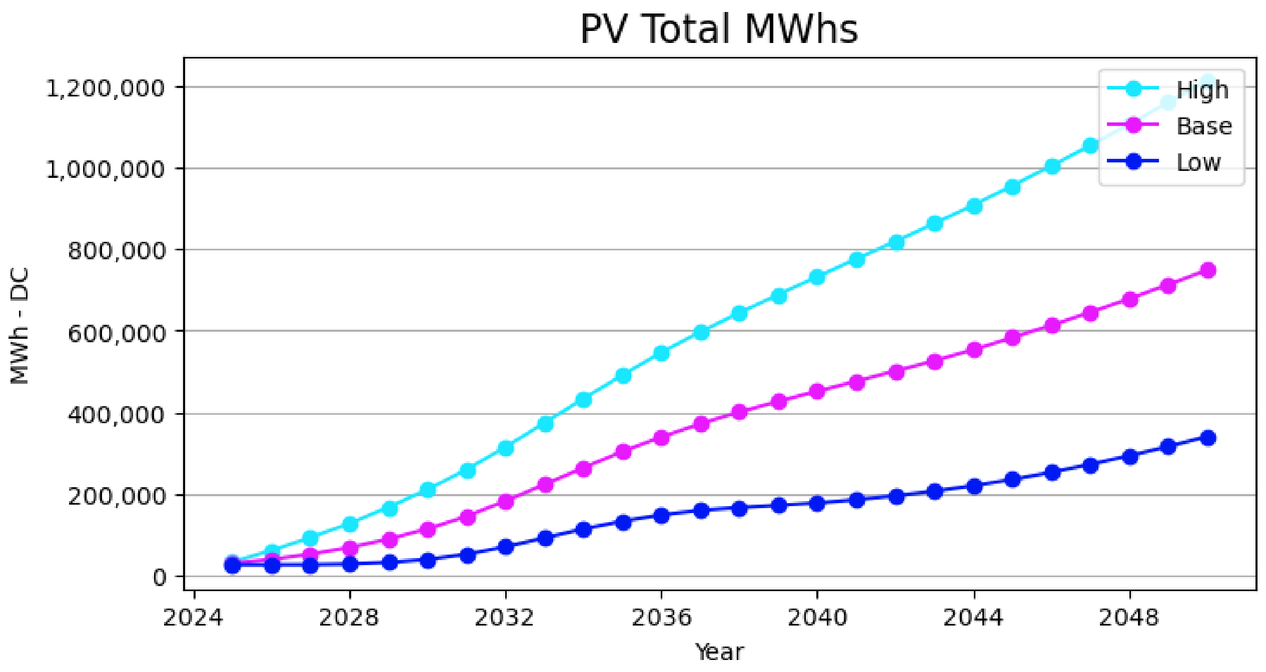
15k~75k



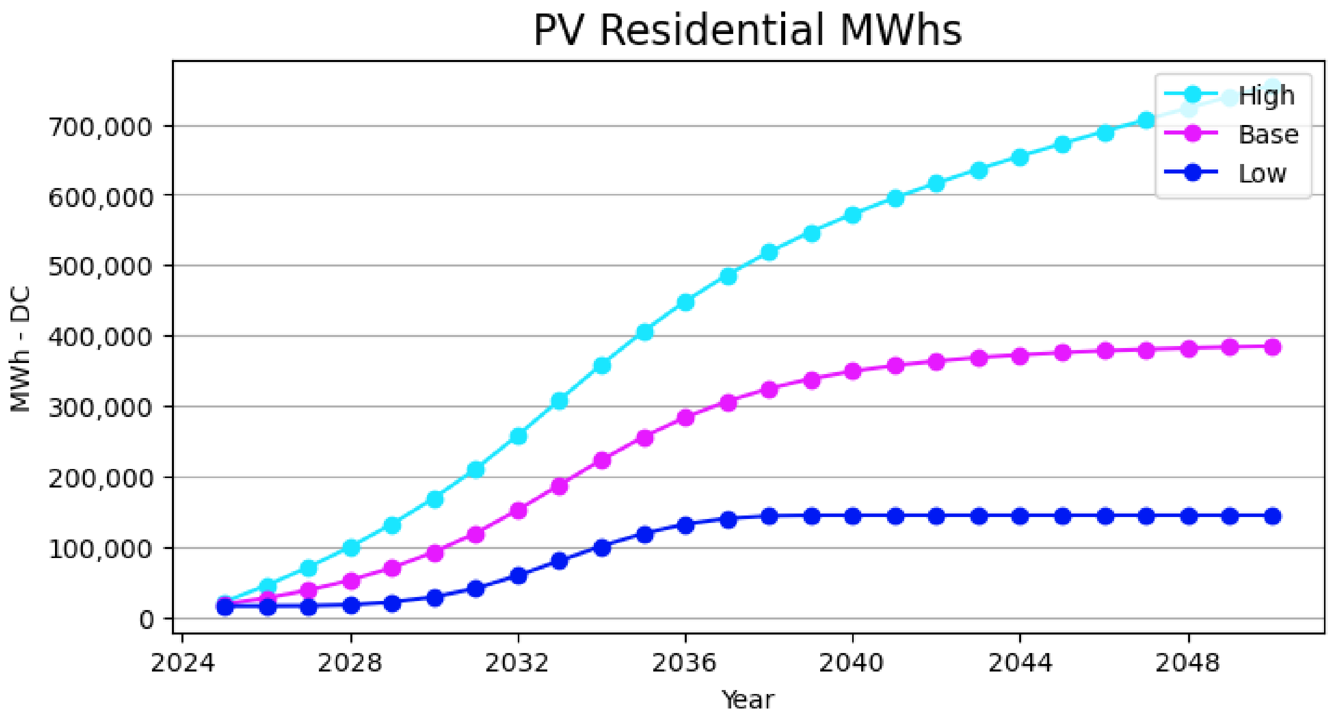
2k~5k



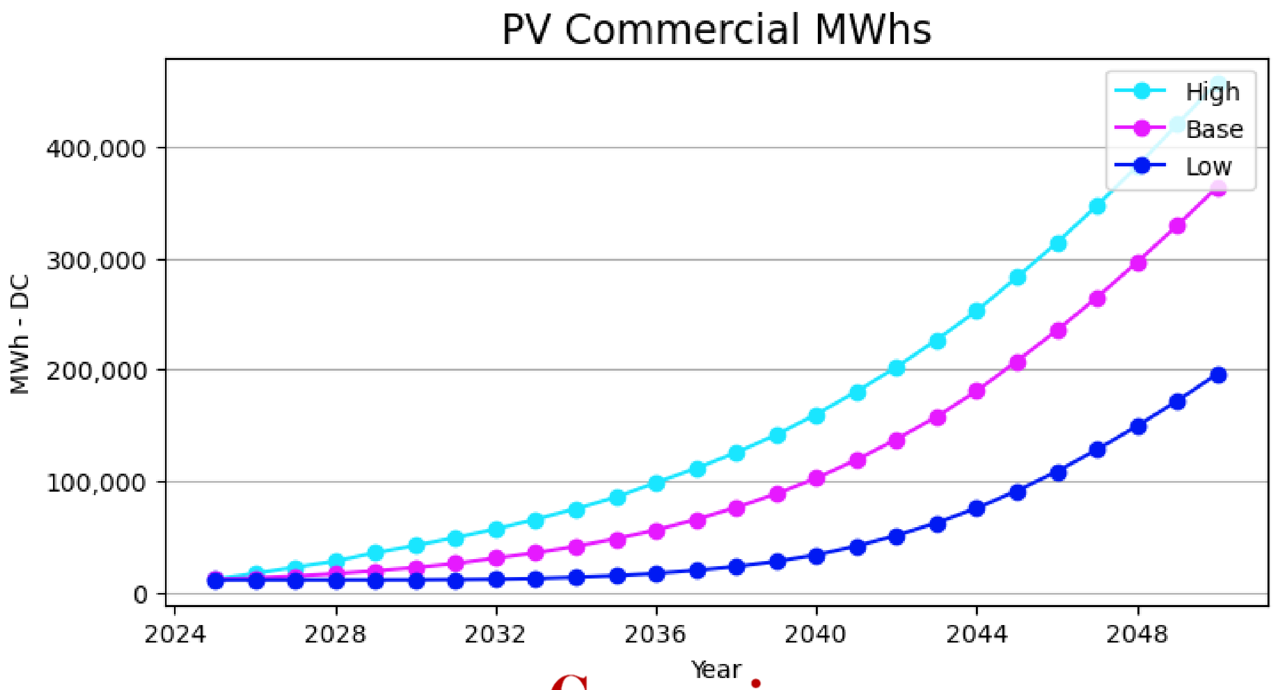
0.3M~1.2M



0.15M~0.75M



0.2M~0.45M



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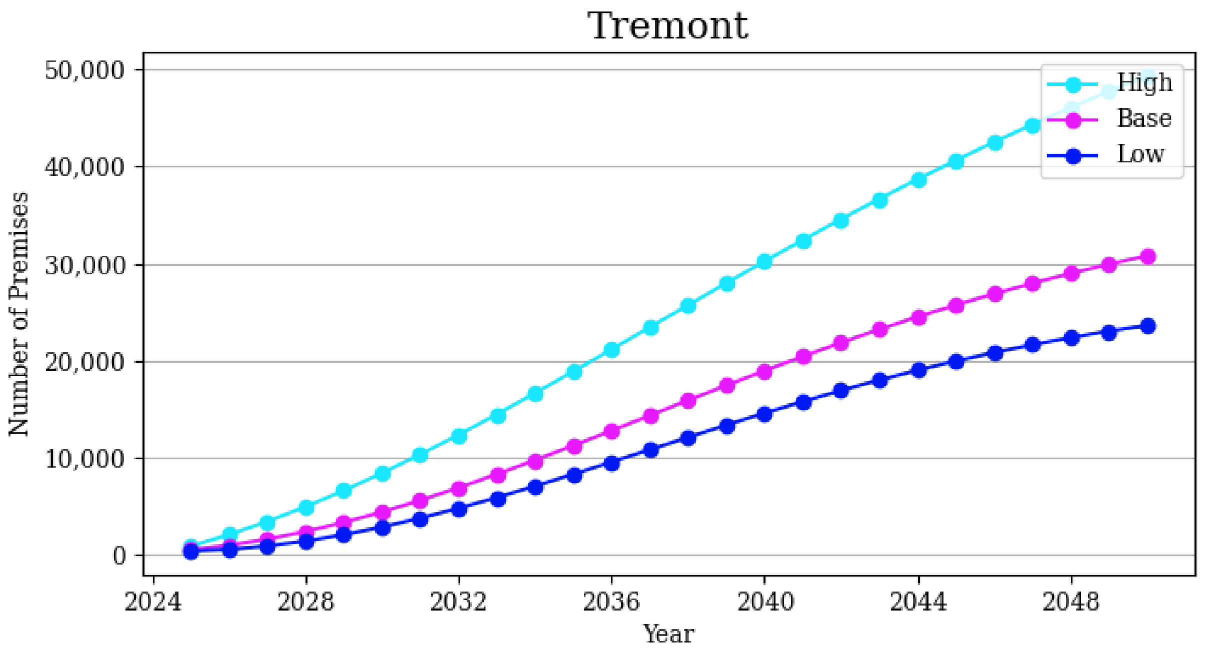
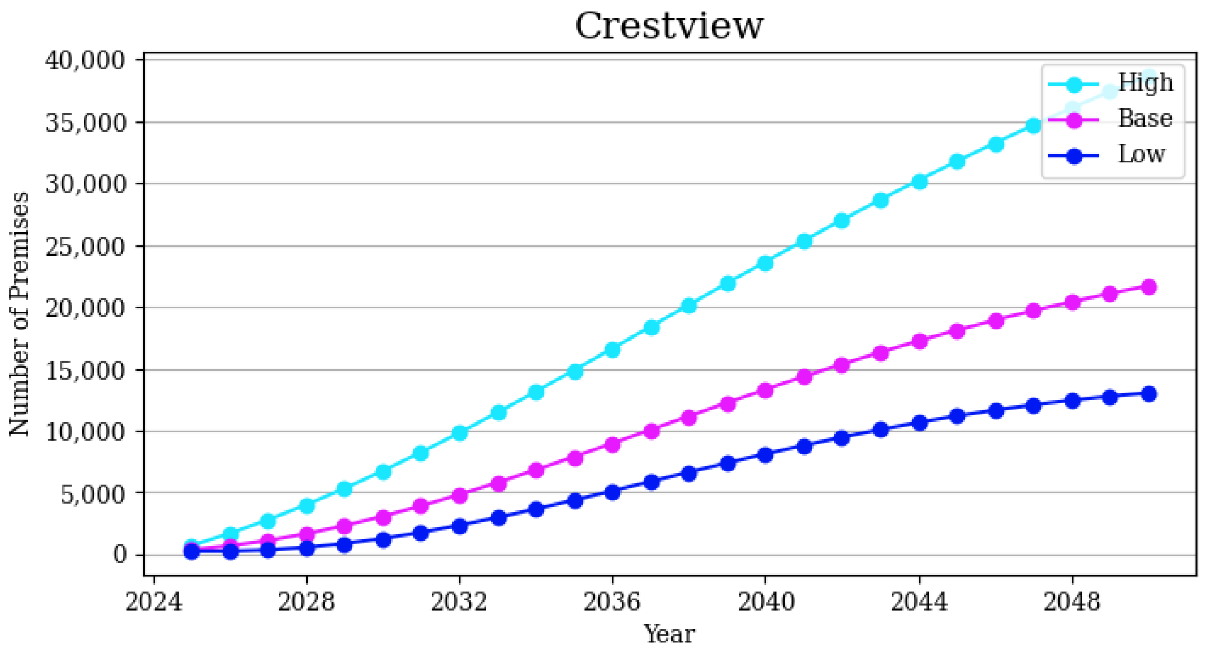
Result: Sub-station EV Prediction

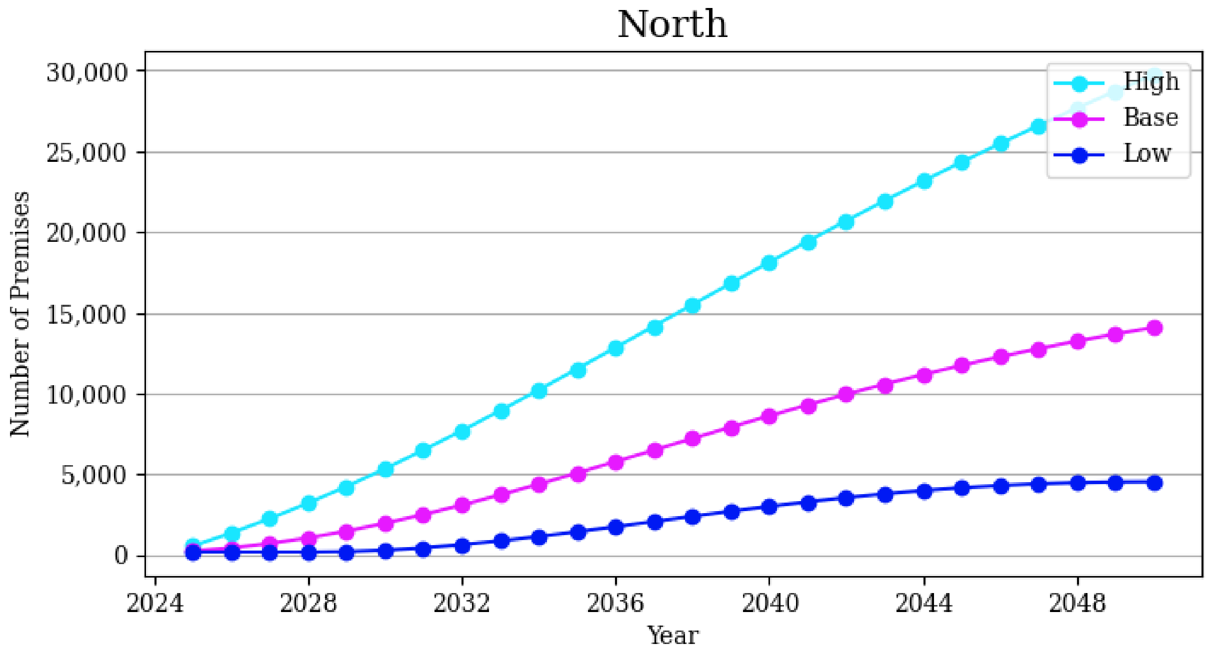
Final predictions and their uncertainty vary significantly across substations



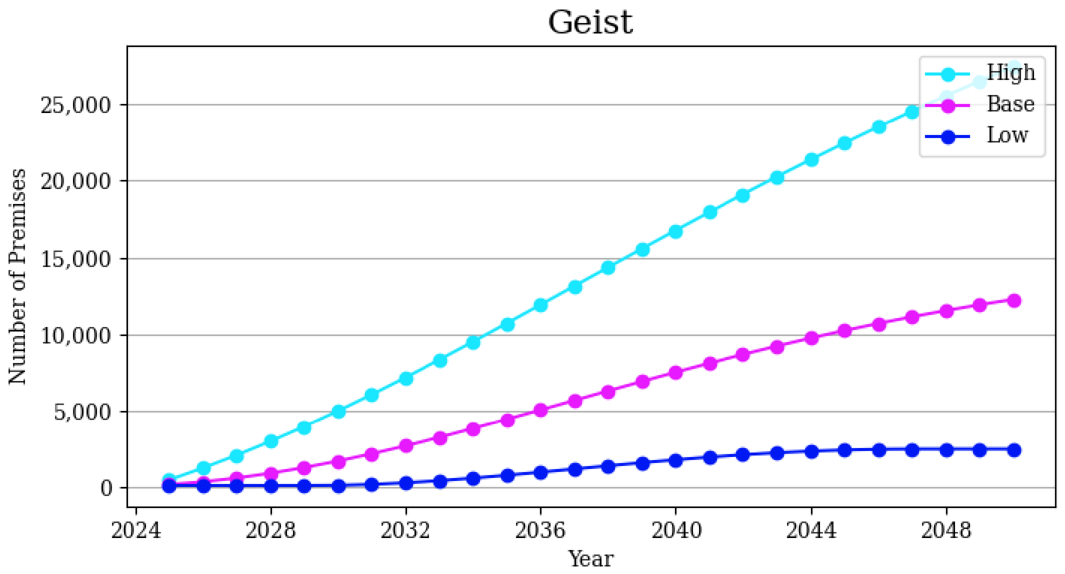
Top 1



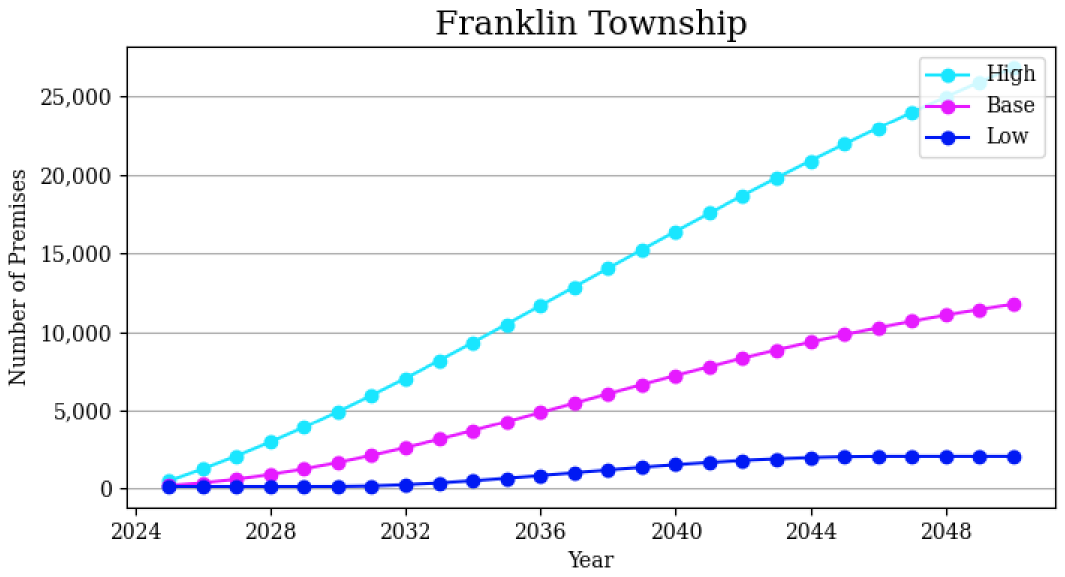
Top 2



Top 3



Top 4



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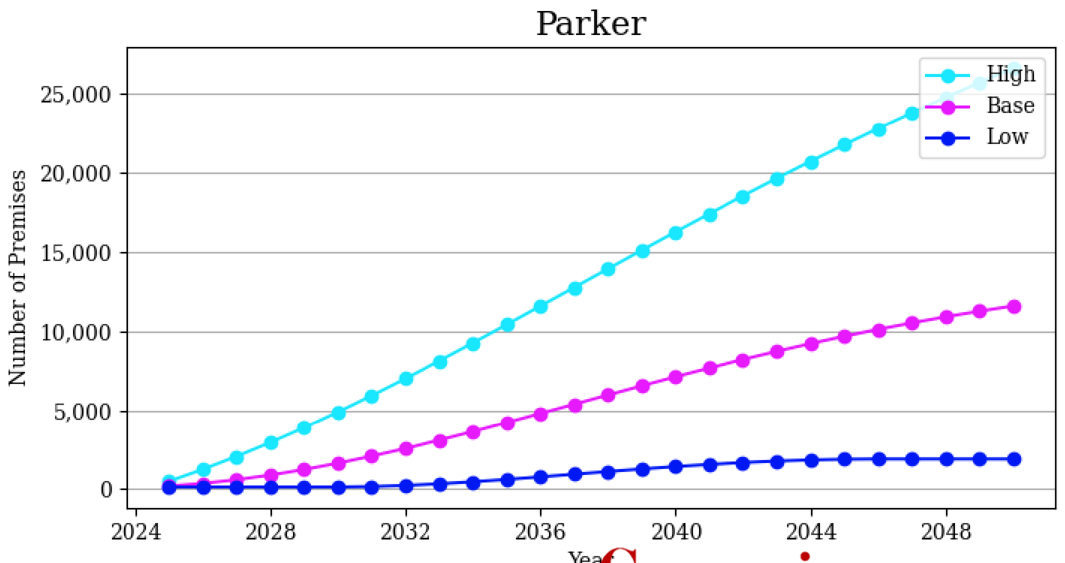

Top 6

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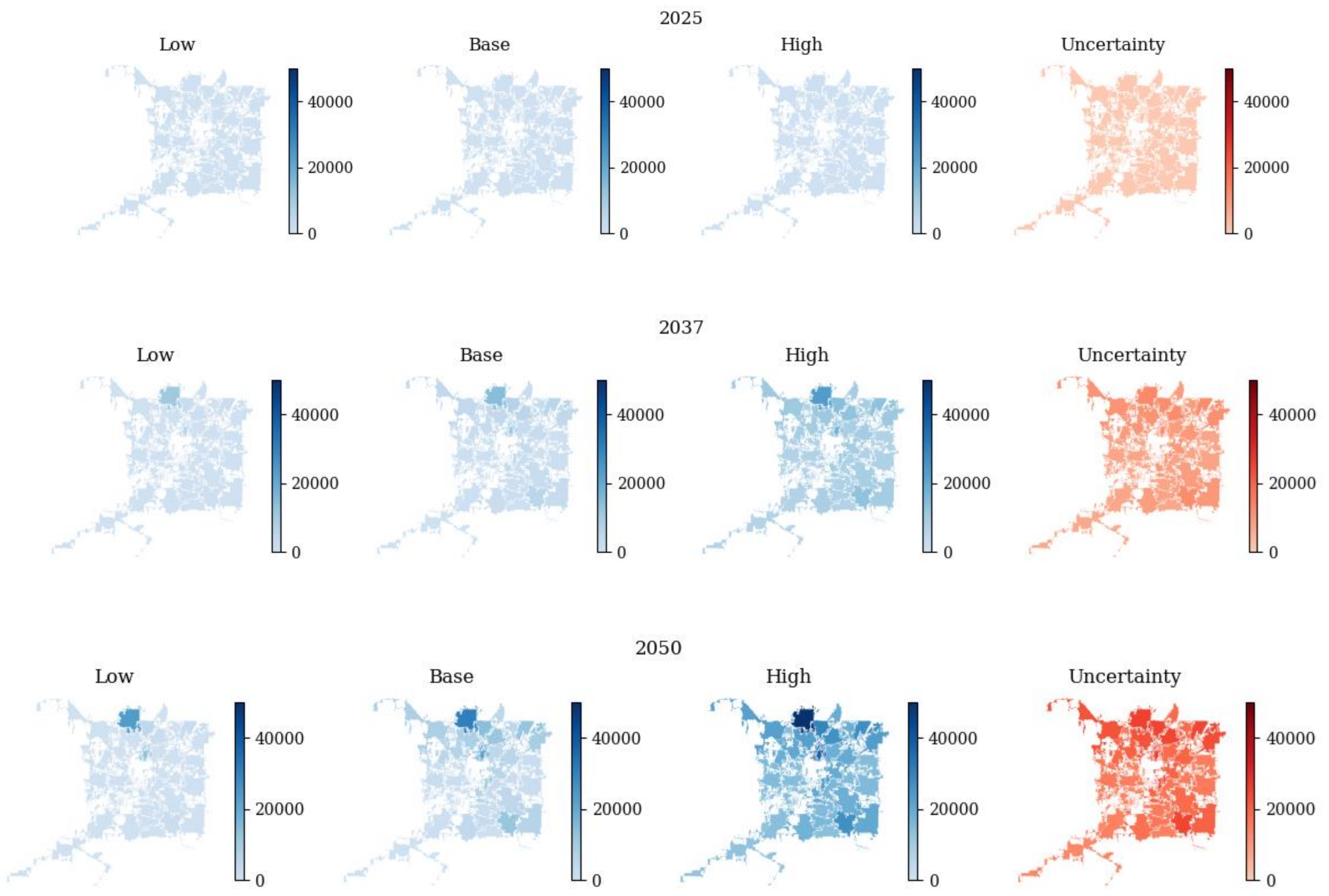
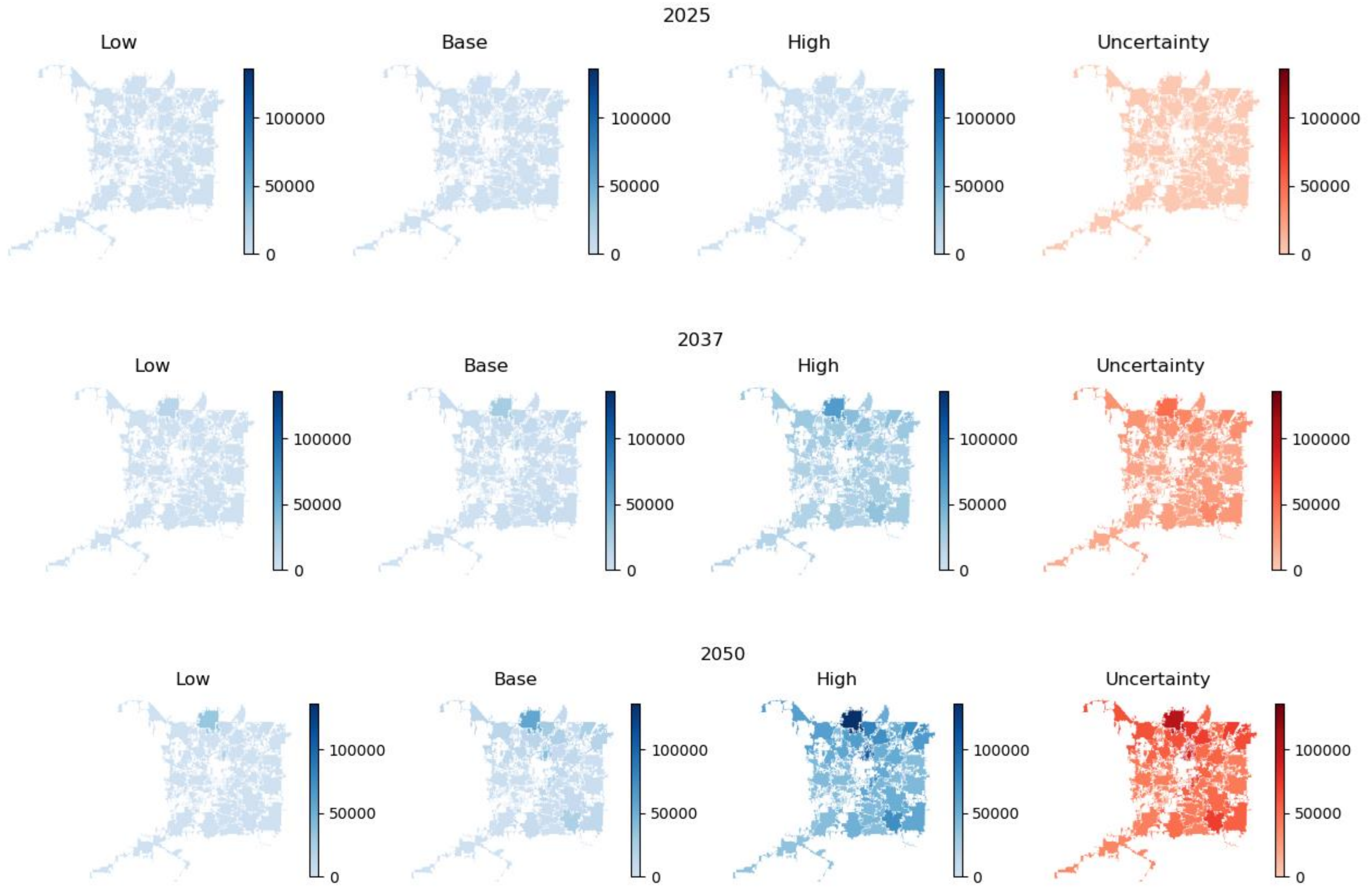
Result: Sub-station EV Prediction

EV Total Units



EV Total Load



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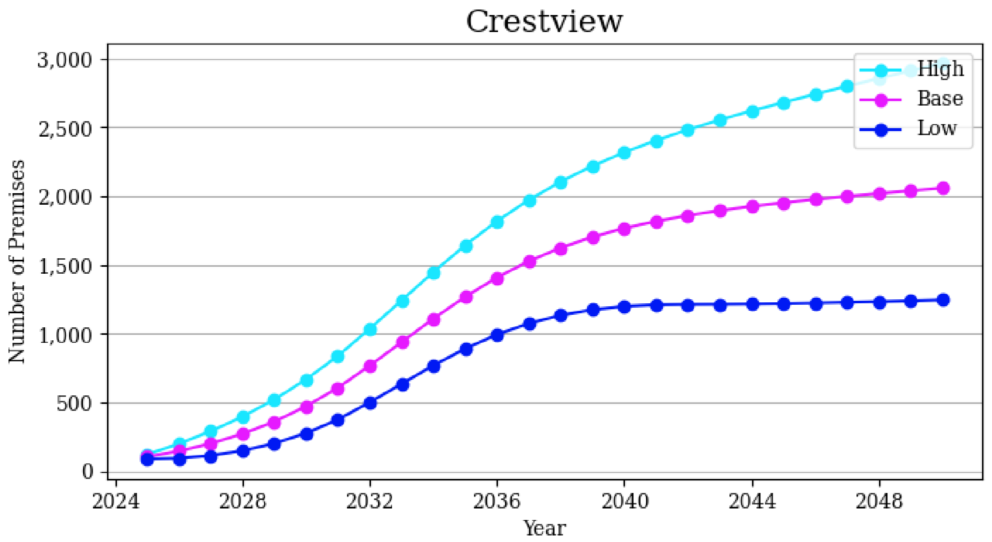
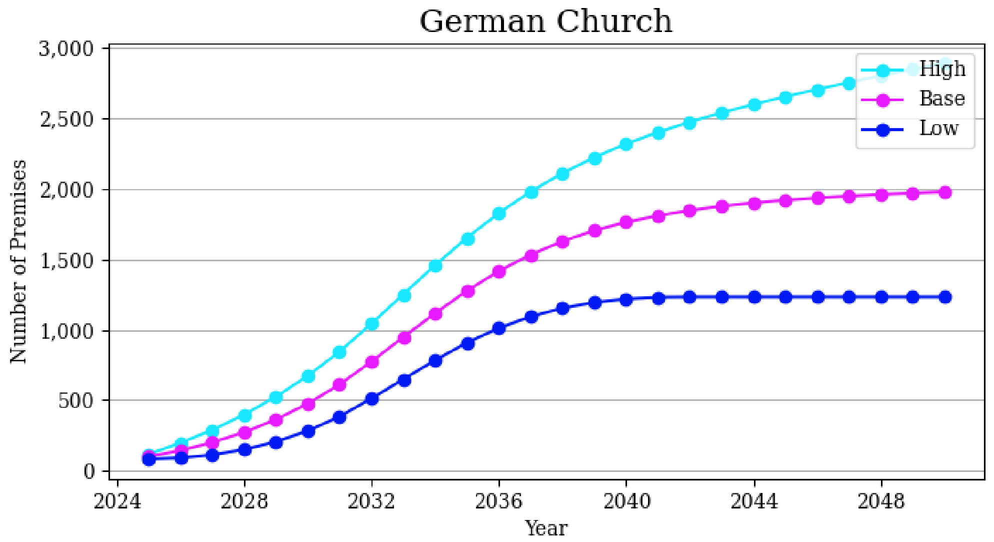
Result: Sub-station PV Prediction

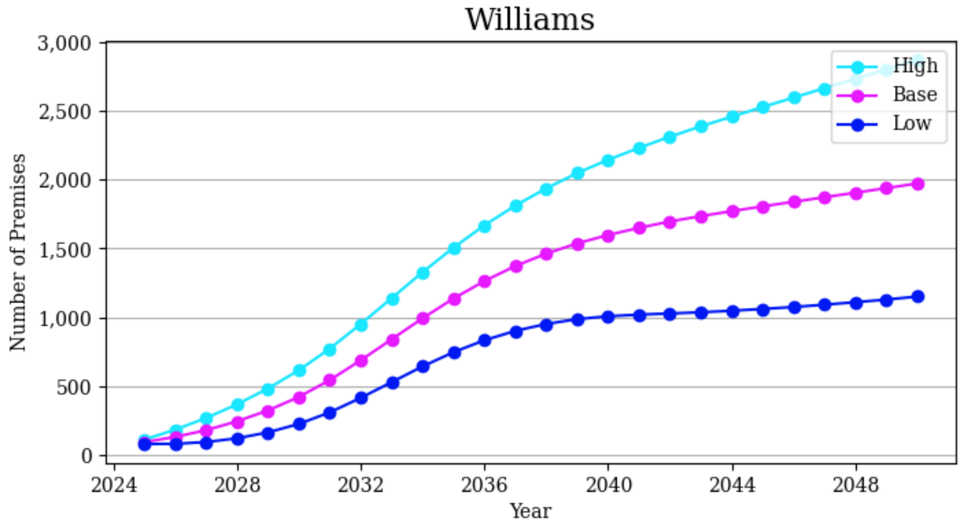
Final predictions and their uncertainty vary significantly across substations



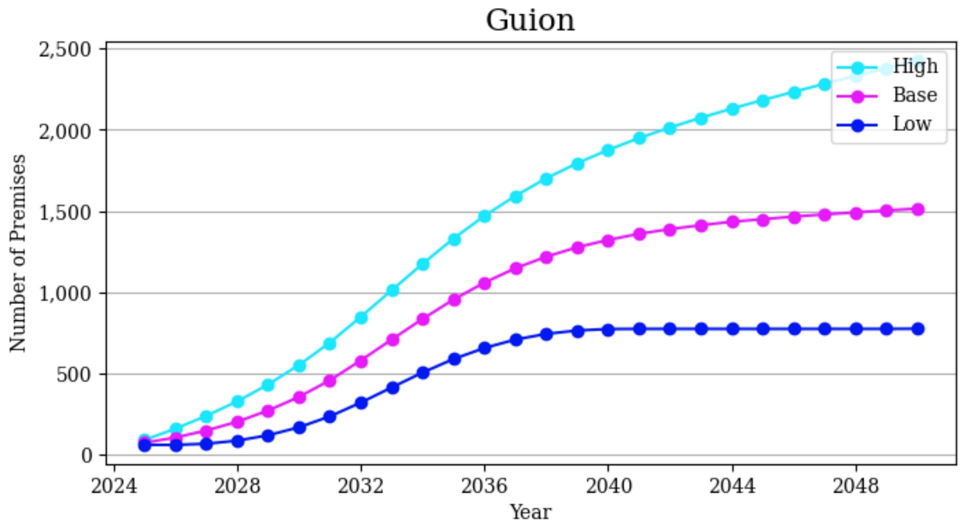
Top 1



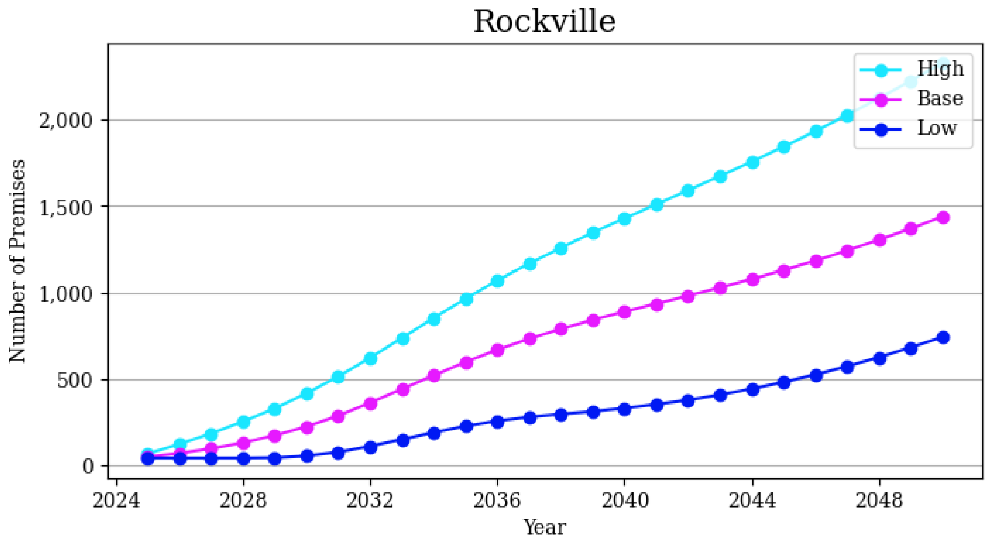
Top 2



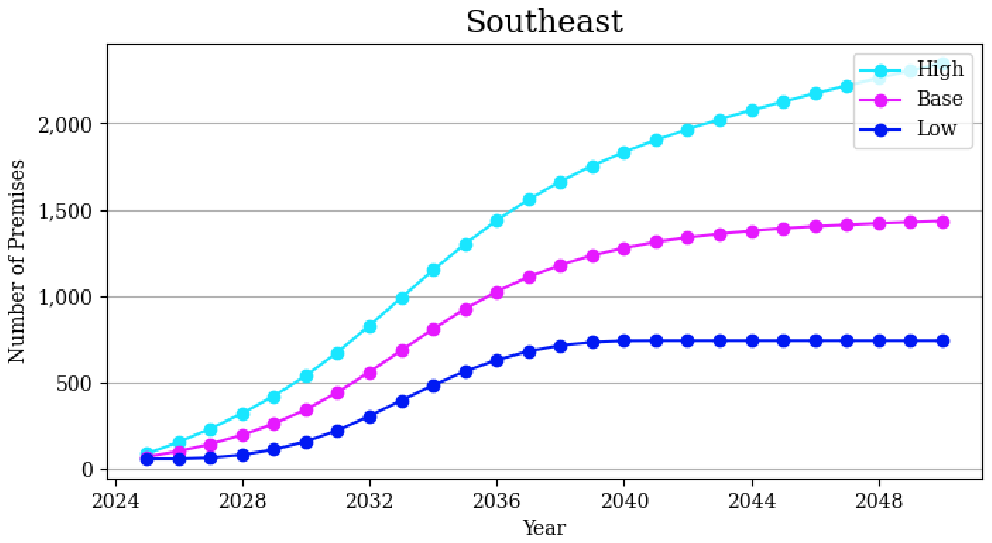
Top 3



Top 4



Top 5



Top 6

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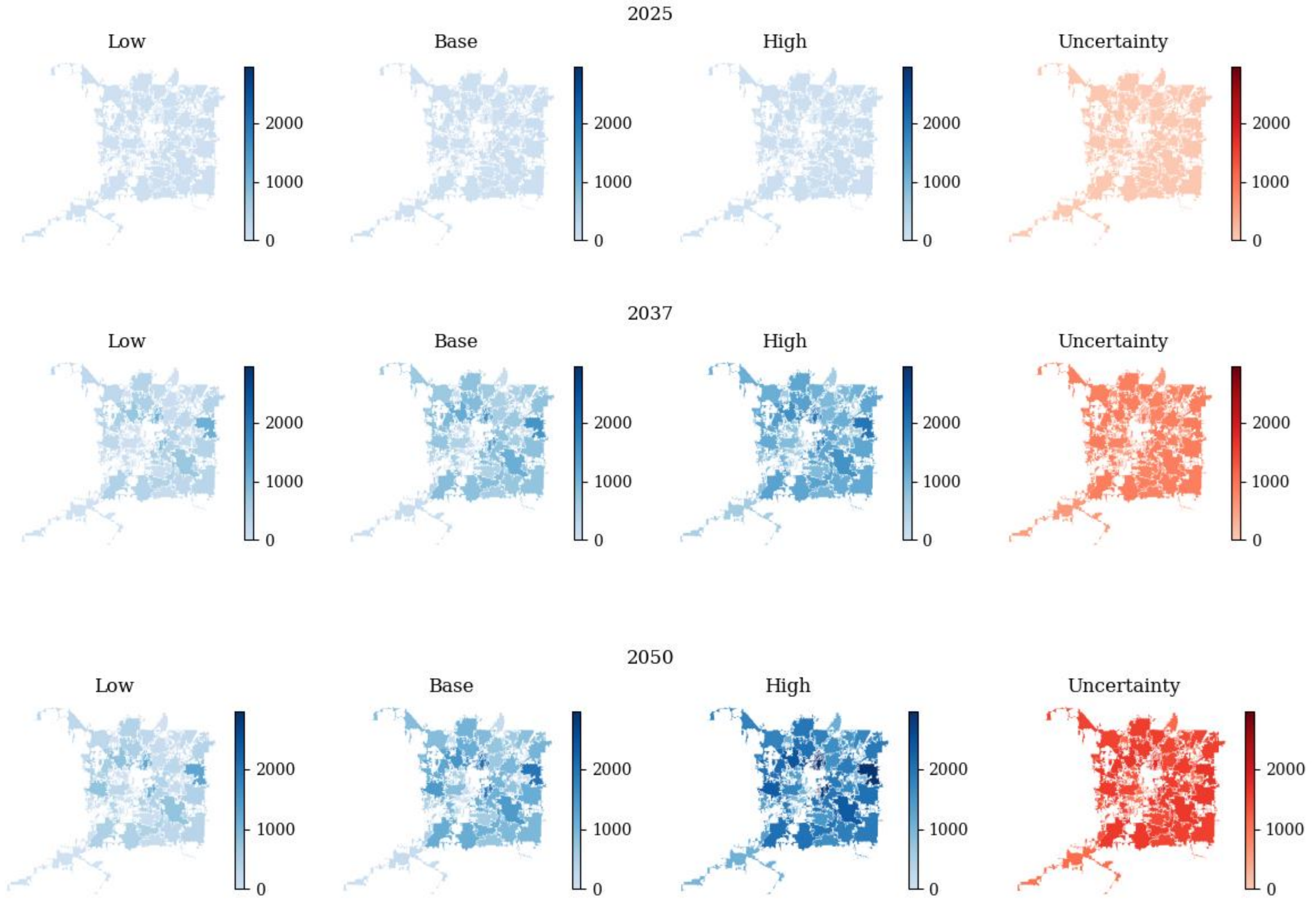
Result: Sub-station PV Prediction

PV Total Units



PV Total Generation

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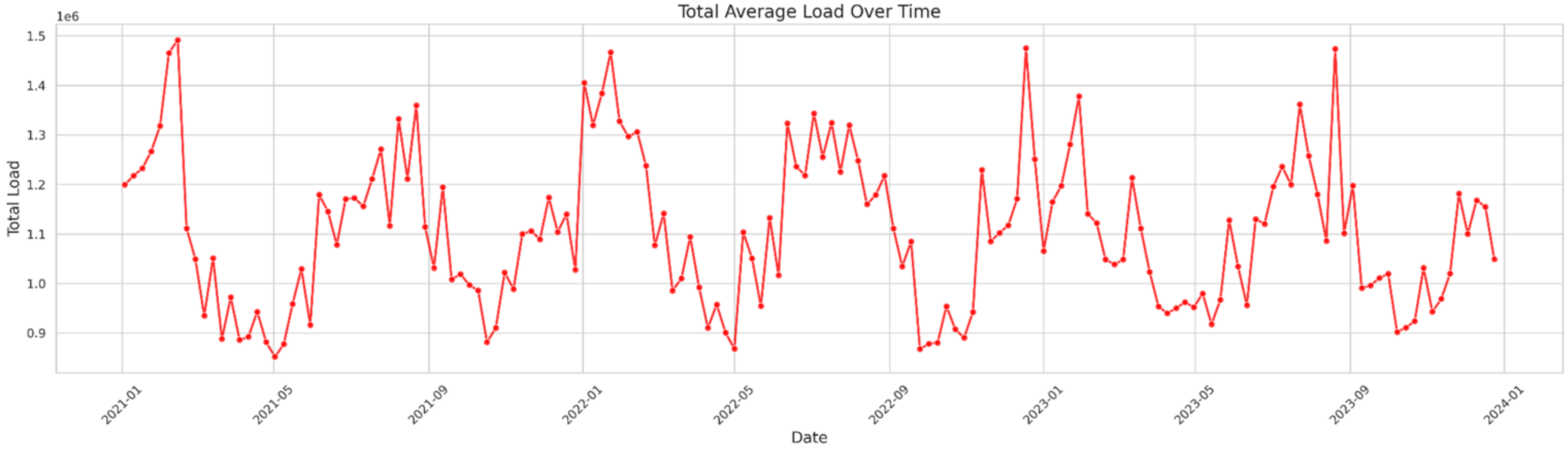
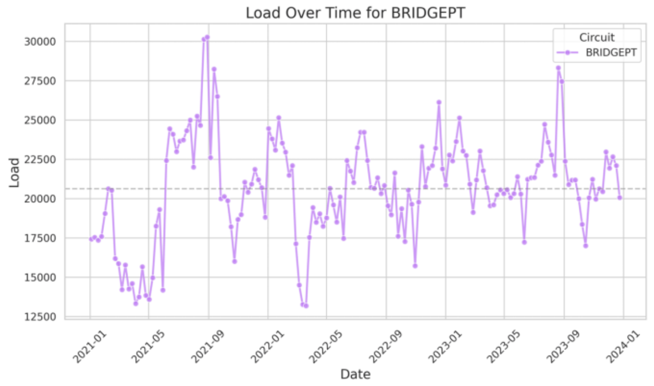
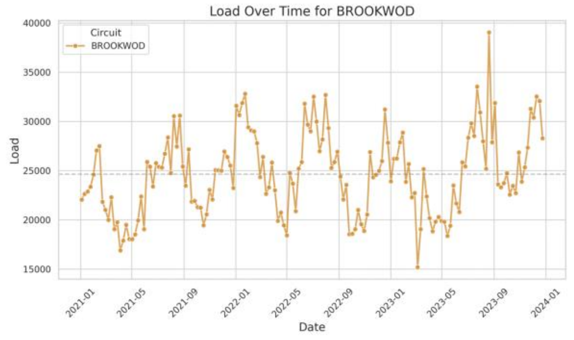
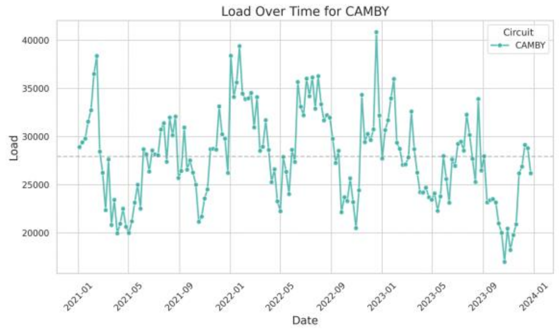
Appendix: Load Data

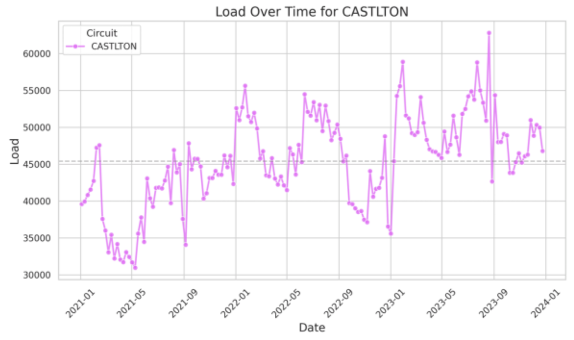
Avg



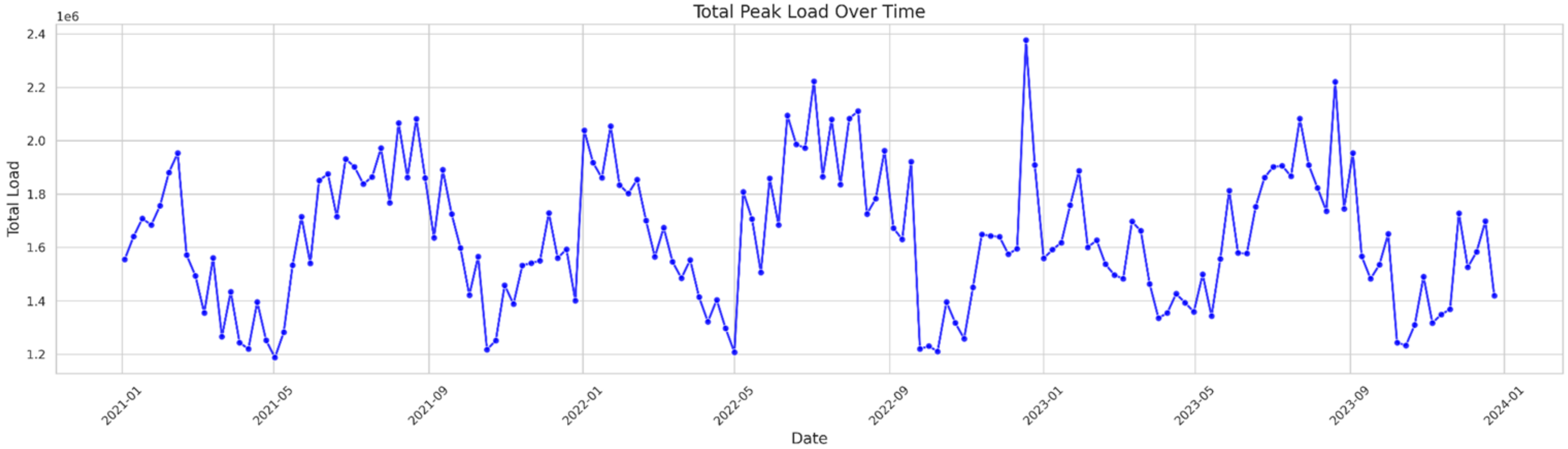


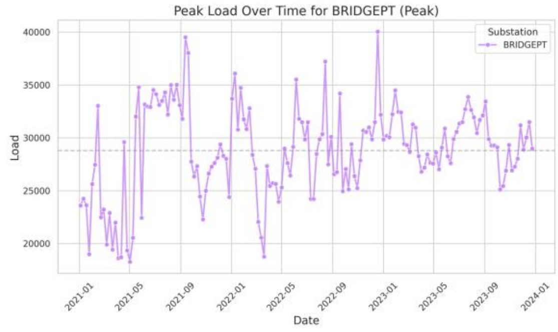


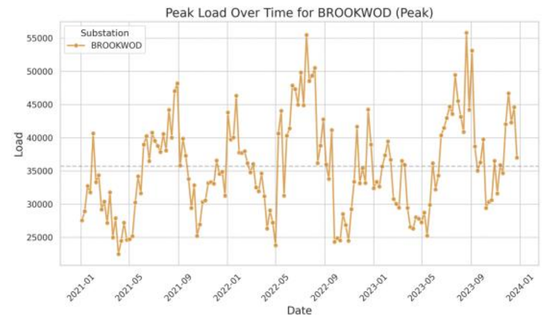


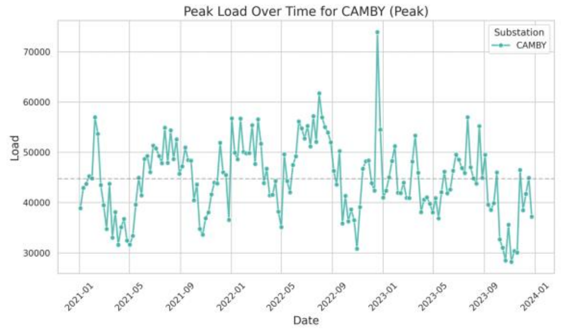


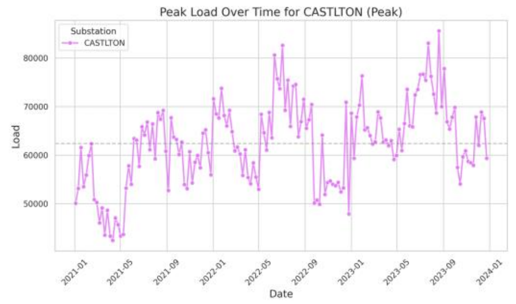
Peak











Total

Substation-Level

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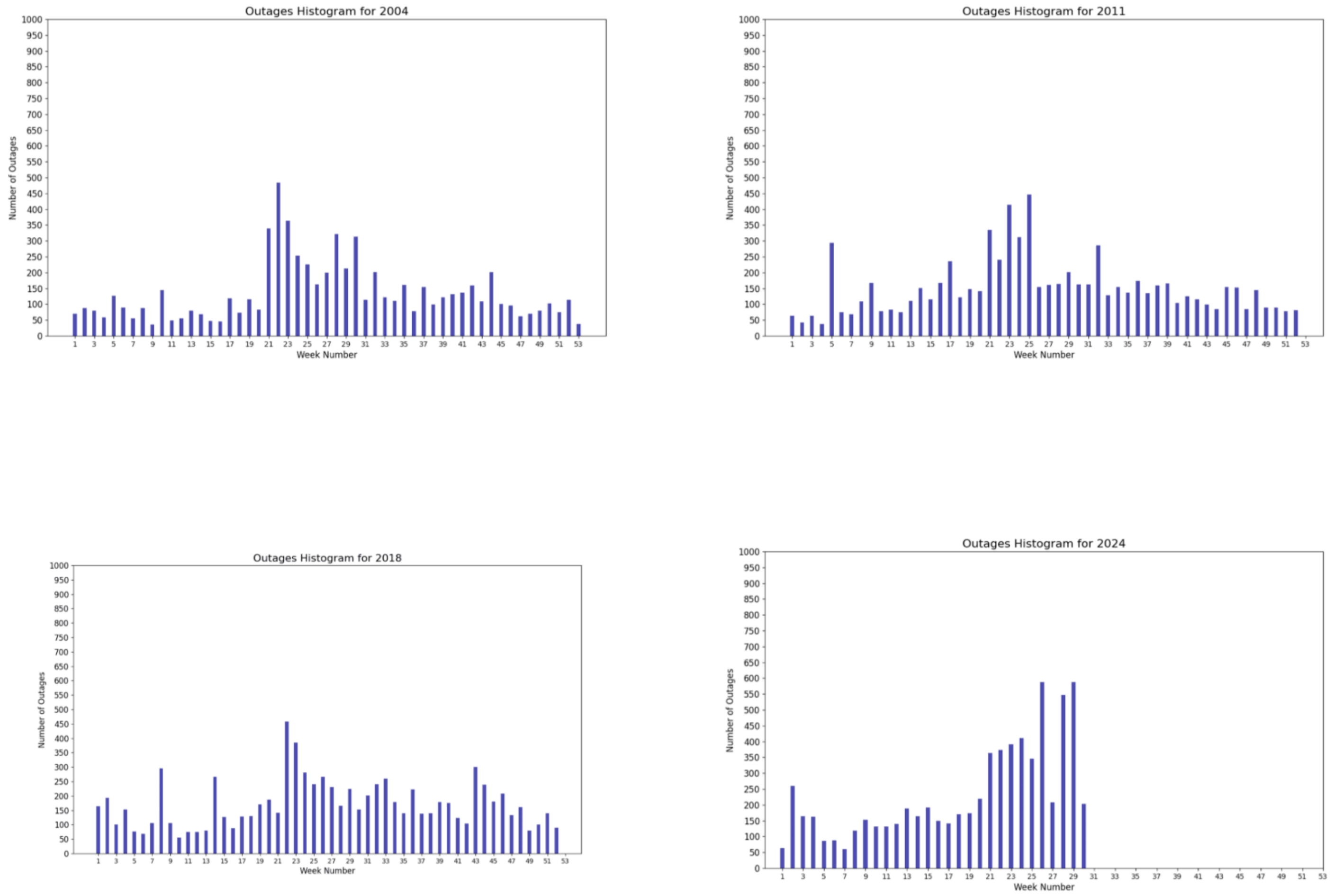
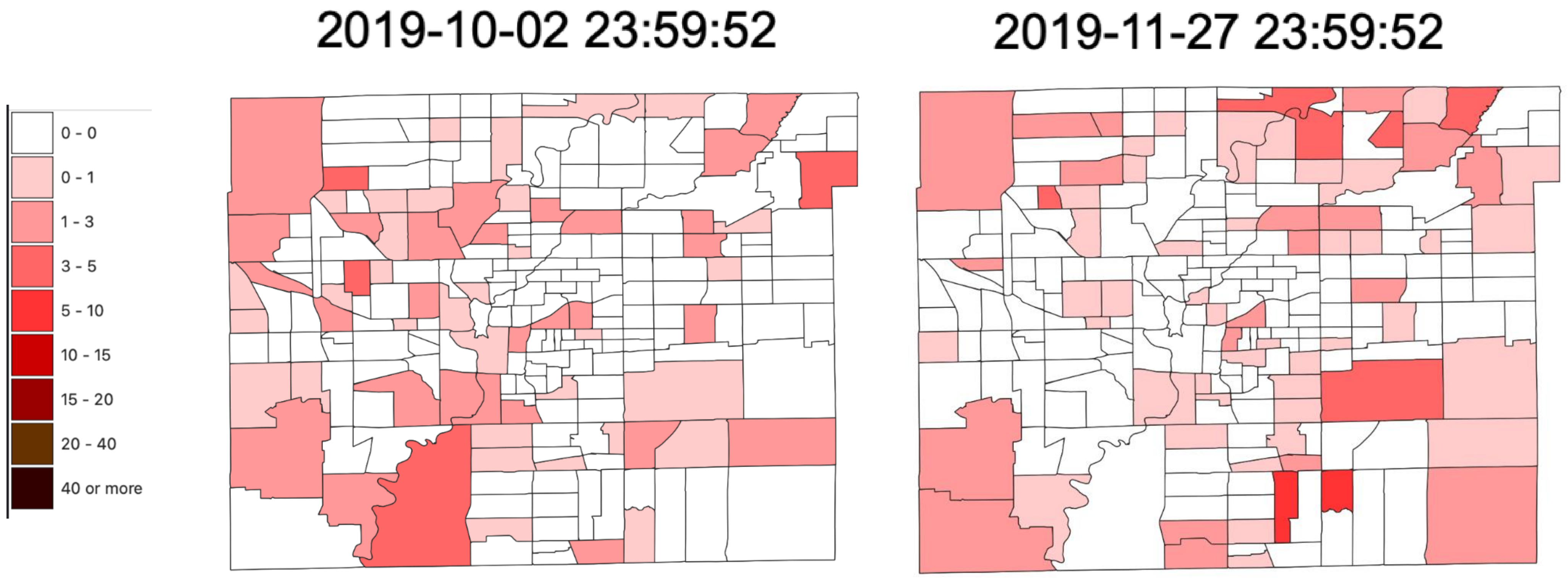
Appendix: Outage Data



Temporal View



Spatial View

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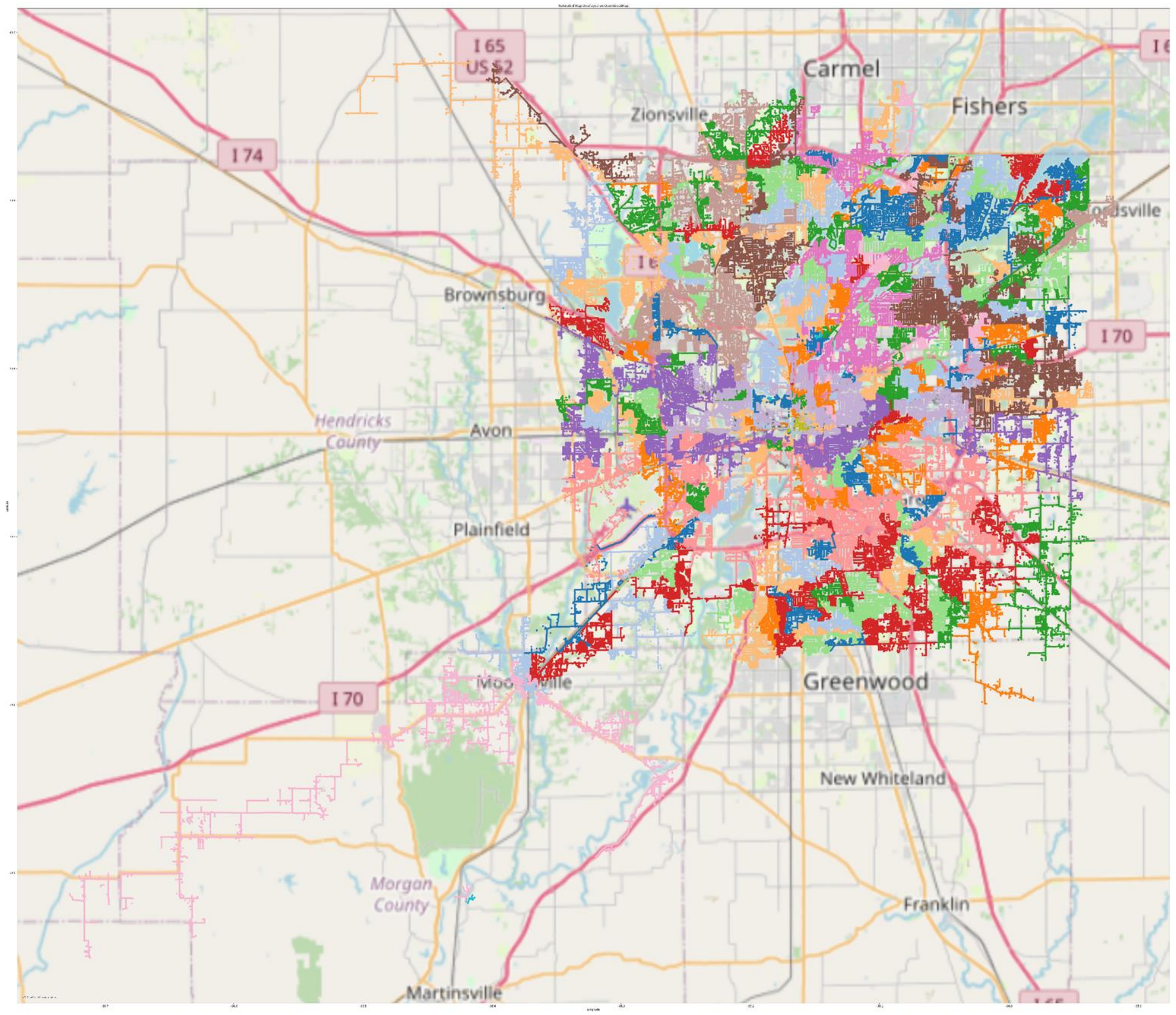
Appendix: Transmission Topology



Match data from multiple sources to each household

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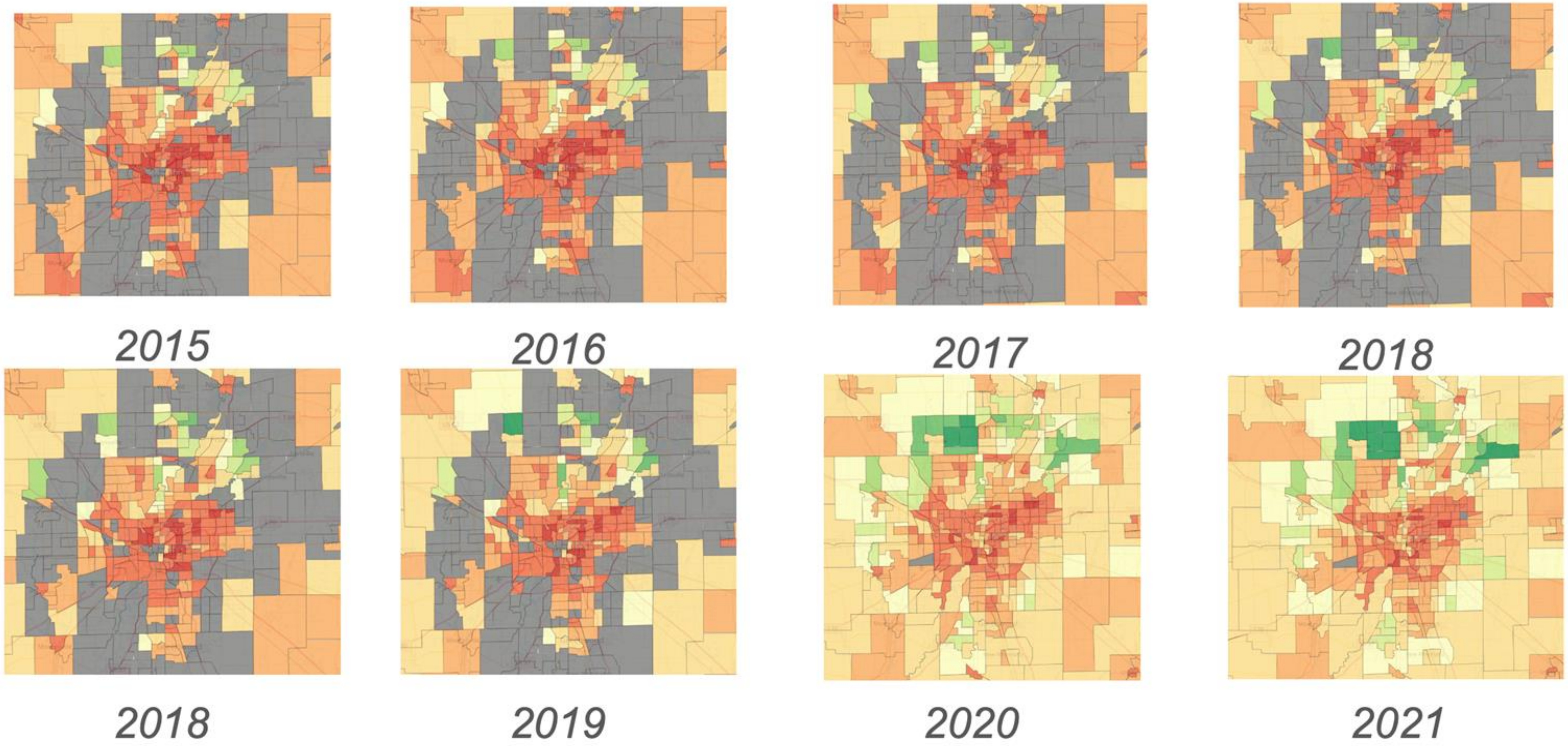
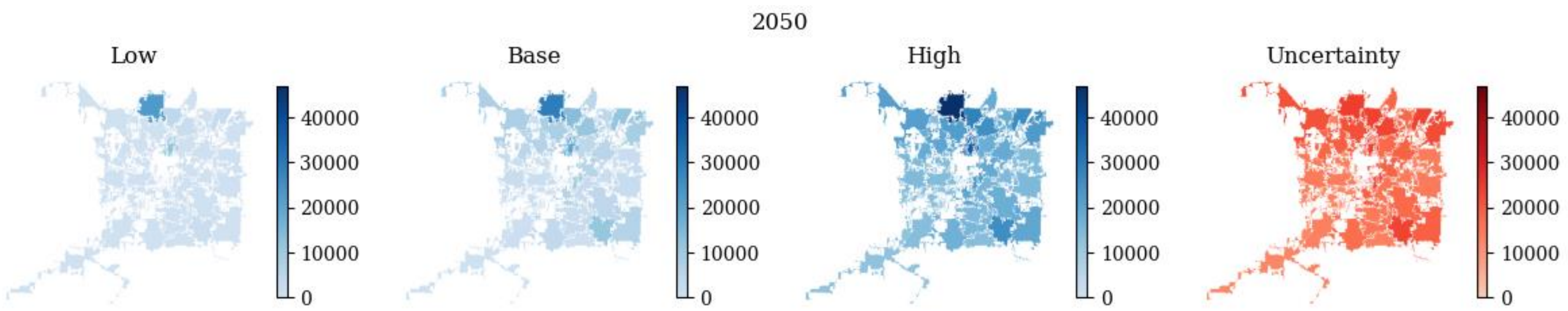
Appendix: Demographic Factors

e.g., Household Income

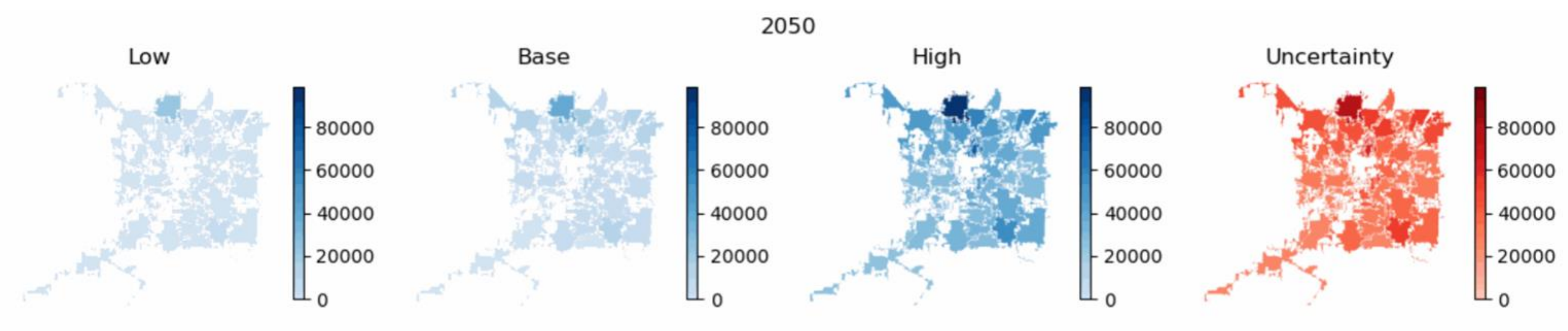


Appendix: More Results

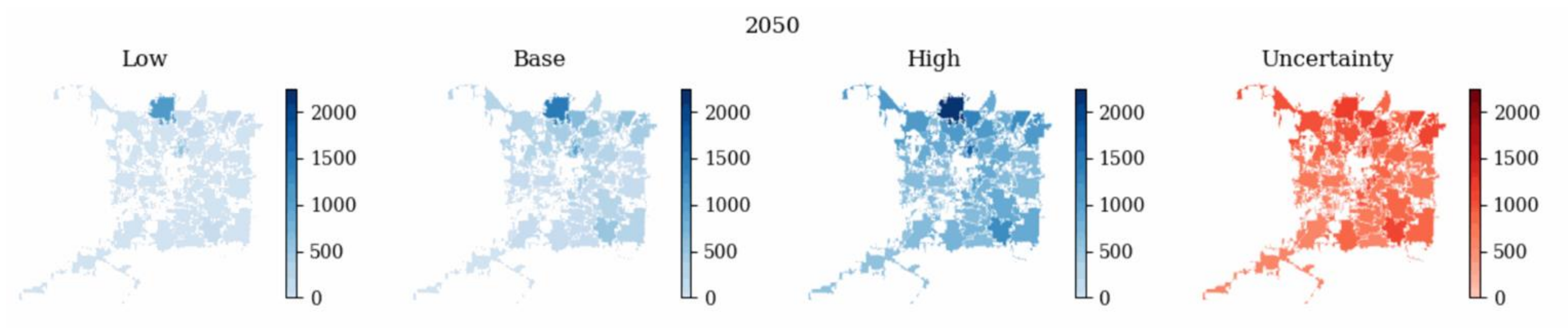
EV Residential Units



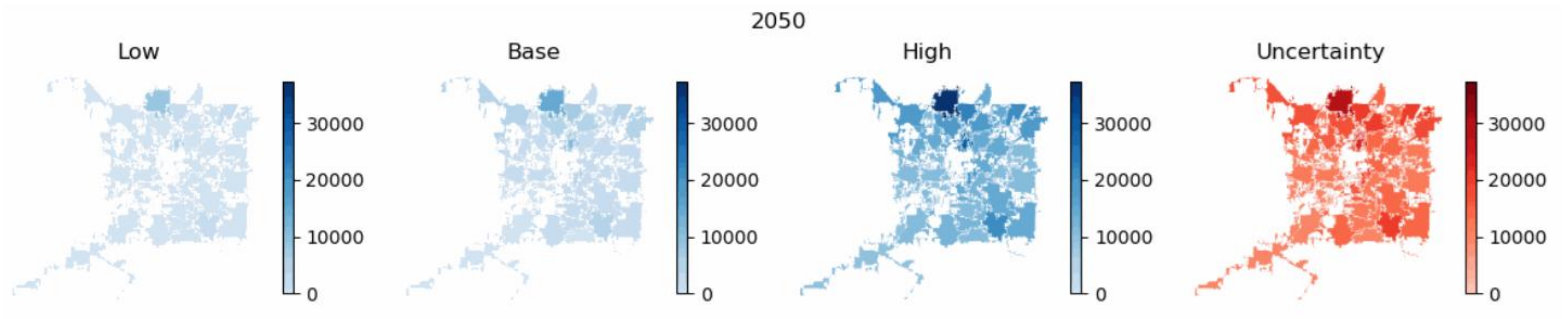
EV Residential Load



EV Commercial Units

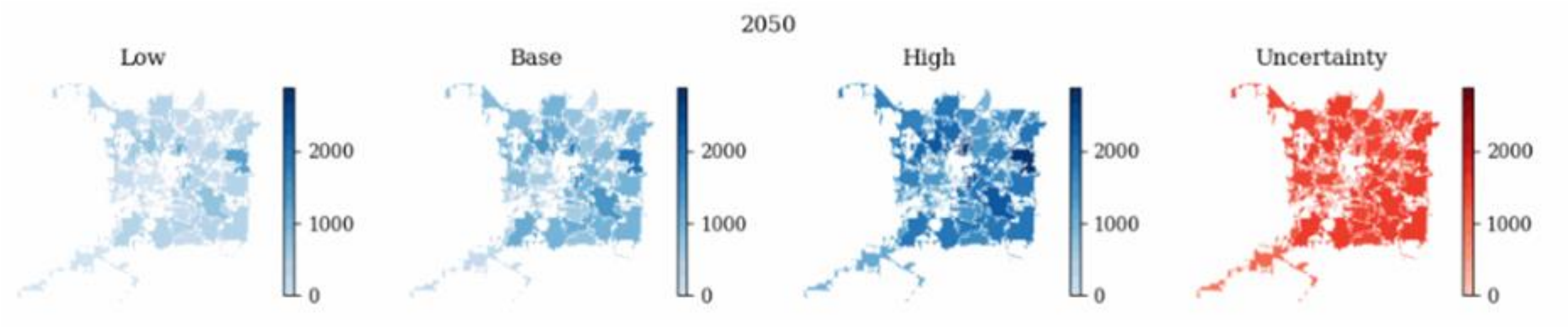


EV Commercial Load

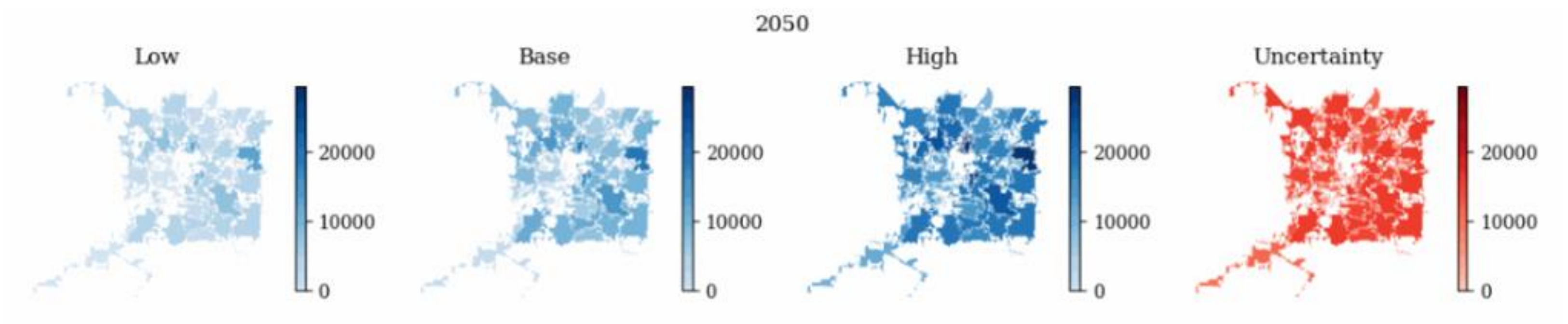


Appendix: More Results

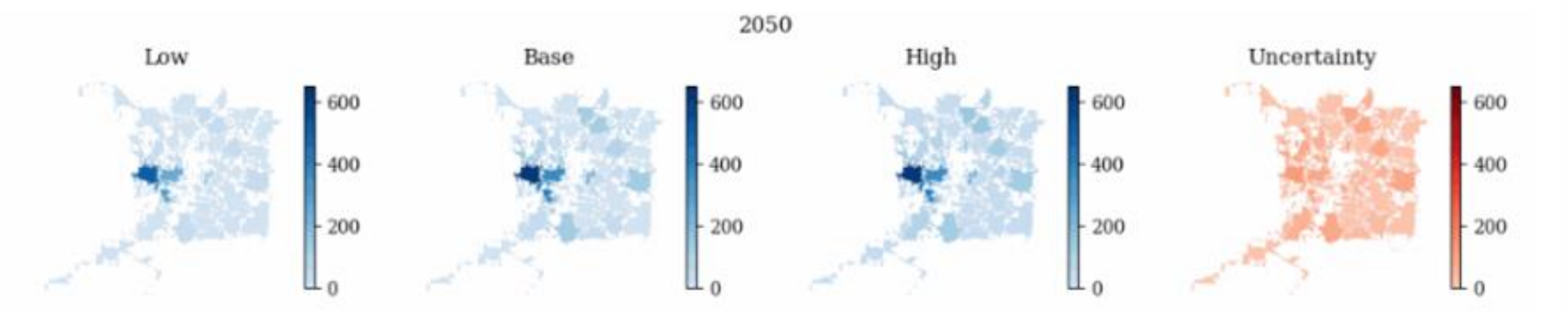
PV Residential Units



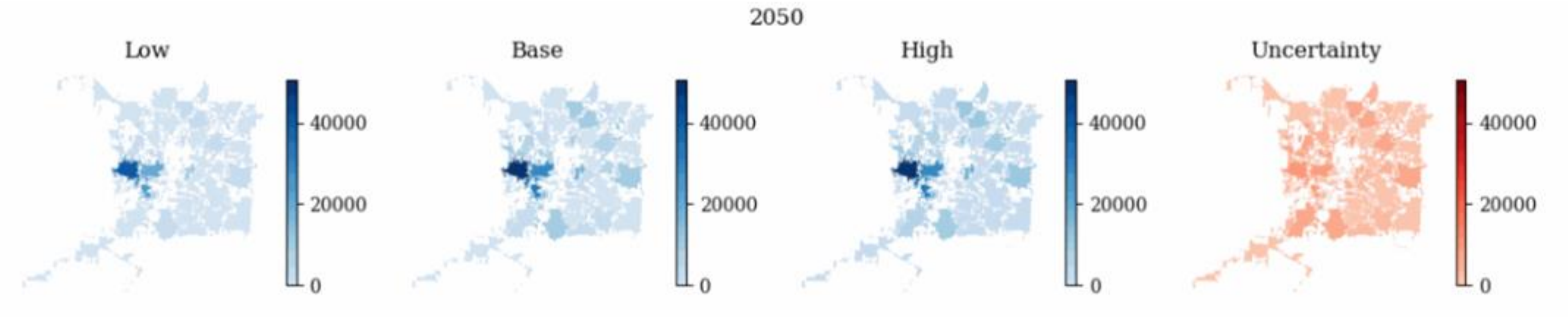
PV Residential Generation



PV Commercial Units



PV Commercial Generation



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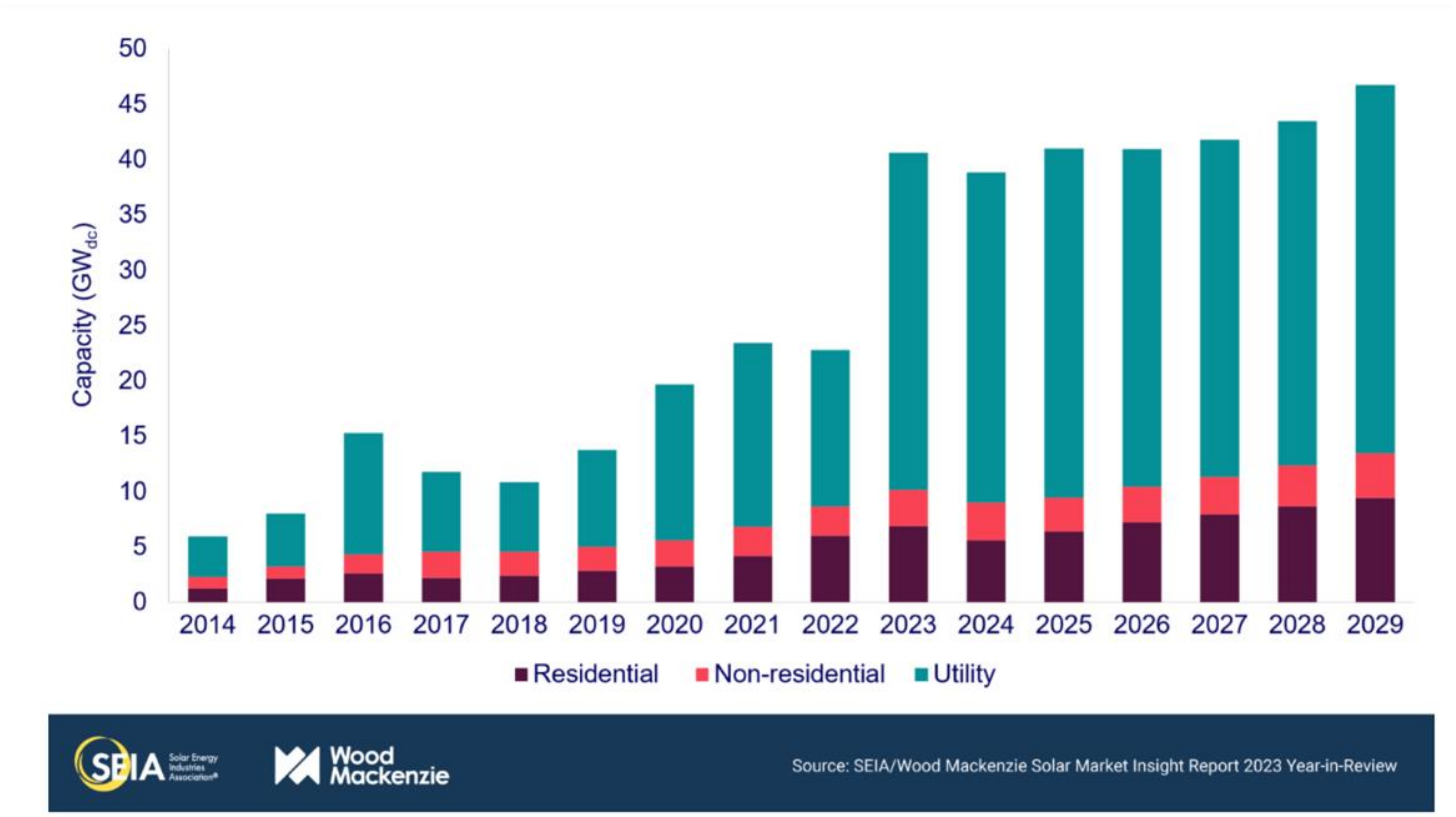
Appendix: Facts about PV installations



U.S. Adoption Rate Table

State	Total # of Houses[A]	Total # of Solar Installed	Total % of Solar Installed
California	14,392,140	1,183,653	8.2%
Florida	9,865,350	~ 99,530	1.0%
Hawaii	561,066	86,866[x]	15.5%
Massachusetts	2,998,537	~ 118,273	3.9%
New York	8,488,066	112,424[x]	1.3%
Texas	11,589,324	~ 125,003	1.1%

Sources: U.S. Census Bureau; California Distributed Generation Statistics ; Solar Energy Industries Association, Hawaiian Electric, New York State Projects

US PV Installation and forecasts by sectors, 2014 - 2029 (by Solar Energy Industries Association)

US PV adoption rate, where California has approximately 8.2% penetration rate.

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Appendix: Details on Tipping Point

- **Definition**: Date when the **5% EV adoption mark** is hit.
  - This is equivalent to the time when EV demand reach fastest growth, as defined in our model.

- Camus Energy gave an estimation based on their feeder-level EV projection trajectory as part of their study analyzing investment optimization for AES.

- **Source**: National Renewable Energy Laboratory's (NREL) Demand-Side Grid (dsgrid) TEMPO Light-Duty Vehicle Charging Profiles, U.S Energy Information Administration's Annual Energy Outlook.

- **Result**: the mark occurs in 2029.

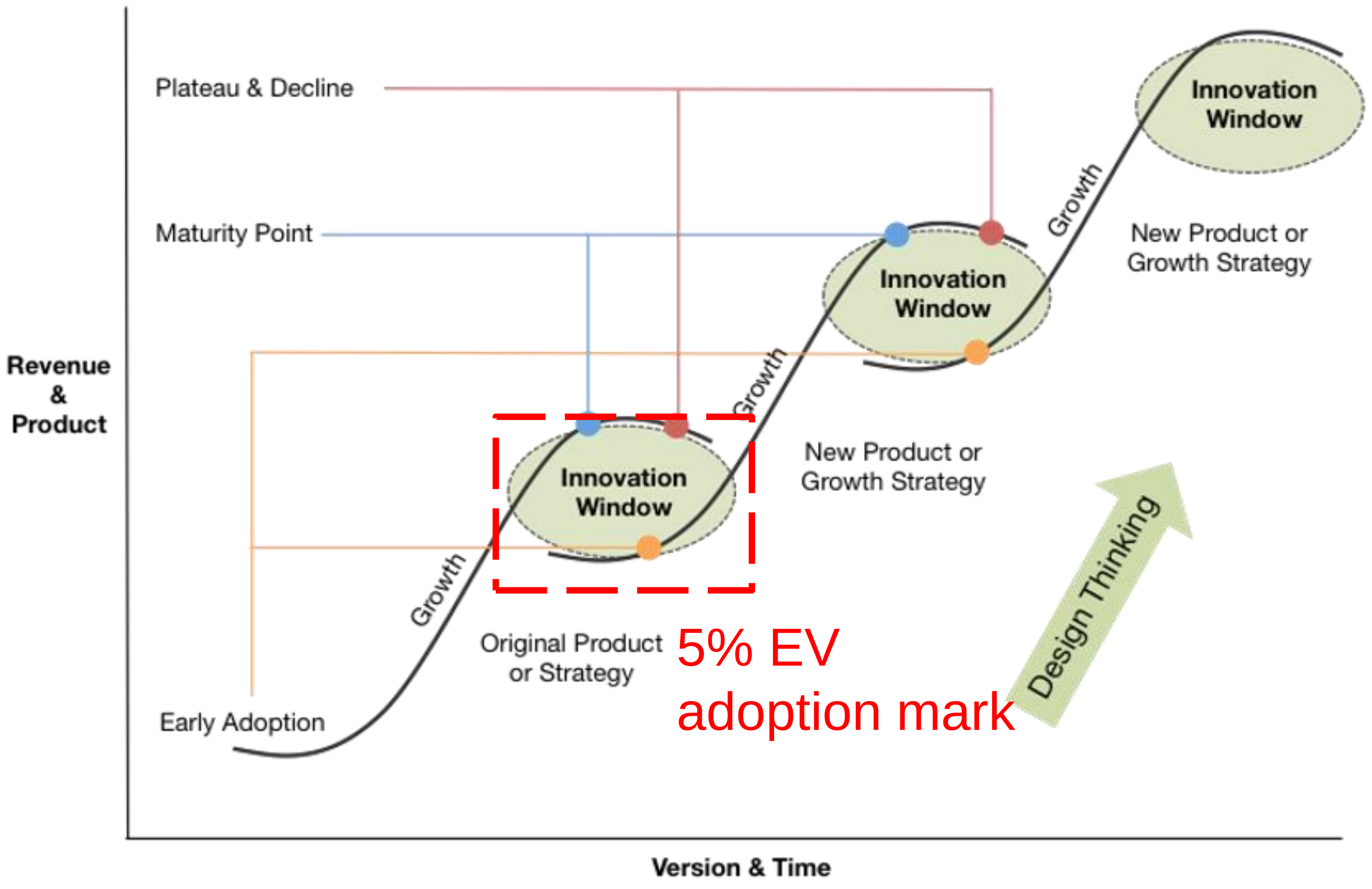

Figure: Diagram showing the theoretical evolution growth trend of EV adoption.

Appendix: Details on Tipping Point (Cont.)

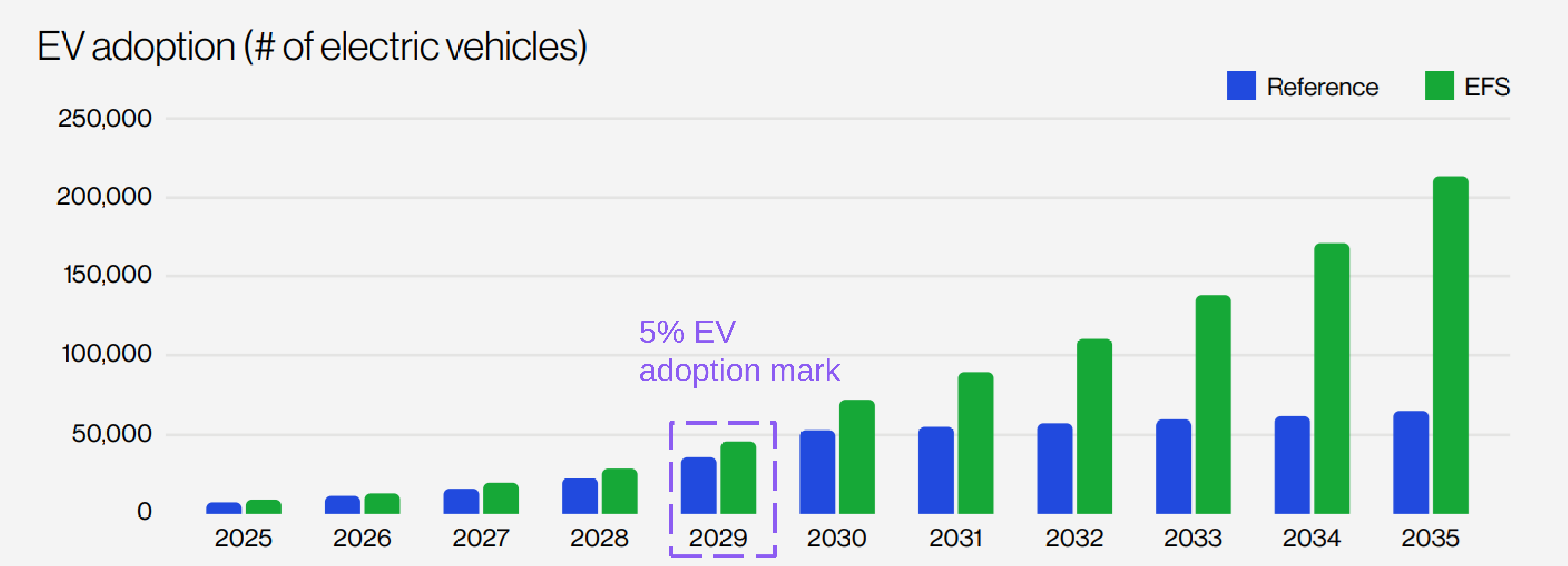

Fig 4. Residential EV adoption for AES Indiana service territory by case. Reference (blue) refers to the Energy Information Administration's Annual Energy Outlook. EFS (green) refers to NREL's Electrification Futures Study.