# Charging for electricity distribution networks in scenarios of increased residential end-user electrification

Graham Turk
Jointly with Tim Schittekatte and Pablo Dueñas Martínez

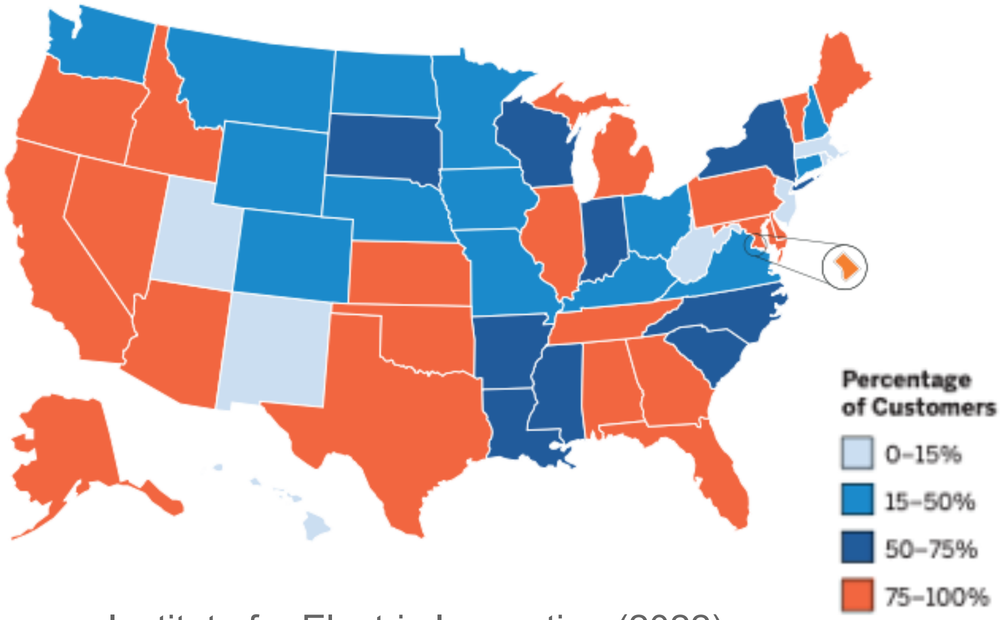
MIT Energy Initiative

# Presentation outline

- Motivation
- Methodology
- Results
- Conclusions & next steps

# What do residential consumers pay in the US?

## Smart Meter Deployment in the US (2022)

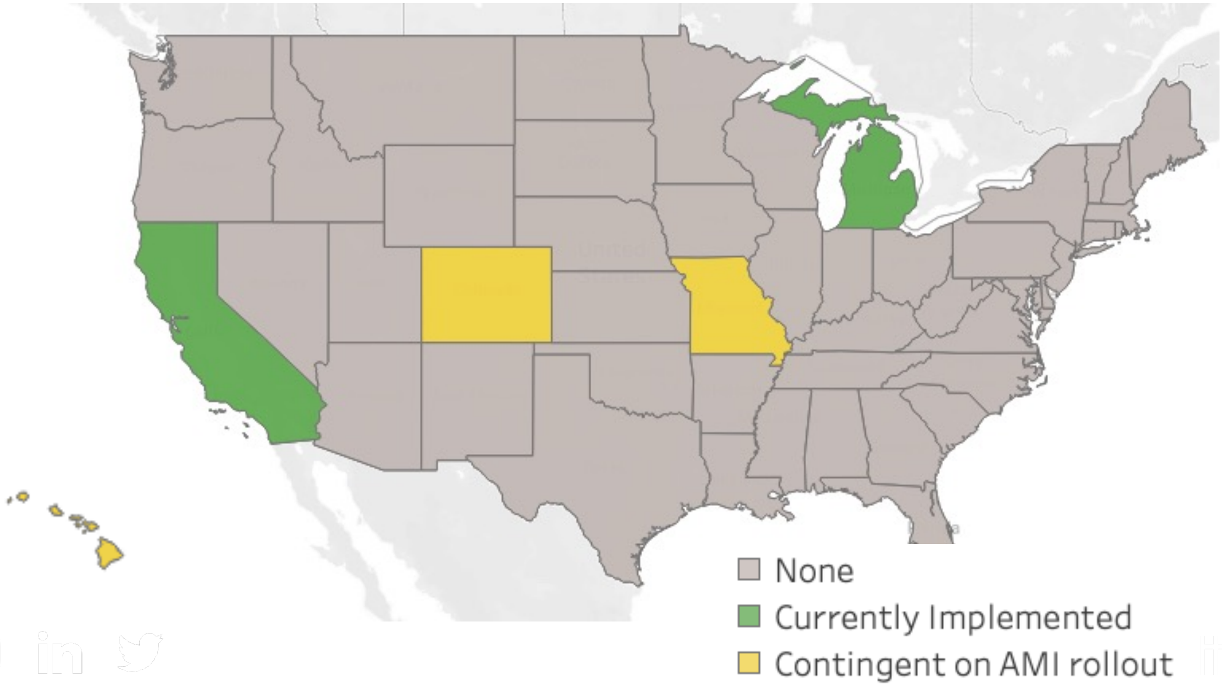



Source: Institute for Electric Innovation (2022)

Many utilities offer opt-in volumetric time-of-use (TOU) rates

The Brattle Group estimated in 2019 that only **1.7% of all residential customers** were on TOU

## Default TOU Rates in the US (2023)



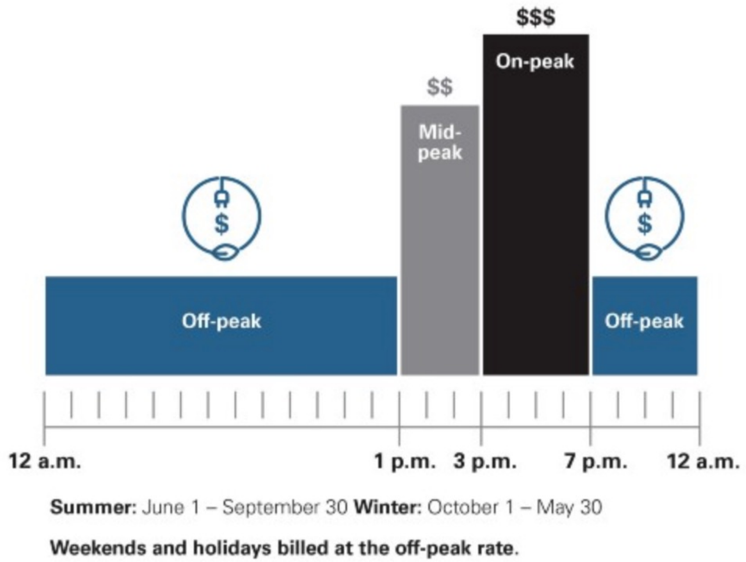
# What are the leading US states doing?


Source: Pacific Gas & Electric

| | Oahu |
|---|---|
| Off-Peak (10 p.m. to 9 a.m.) | 37.8 |
| Mid-Day (9 a.m. to 5 p.m.) | 28.0 |
| On-Peak (5 p.m. to 10 p.m.) | 45.1 |

Source: Hawaiian Electric

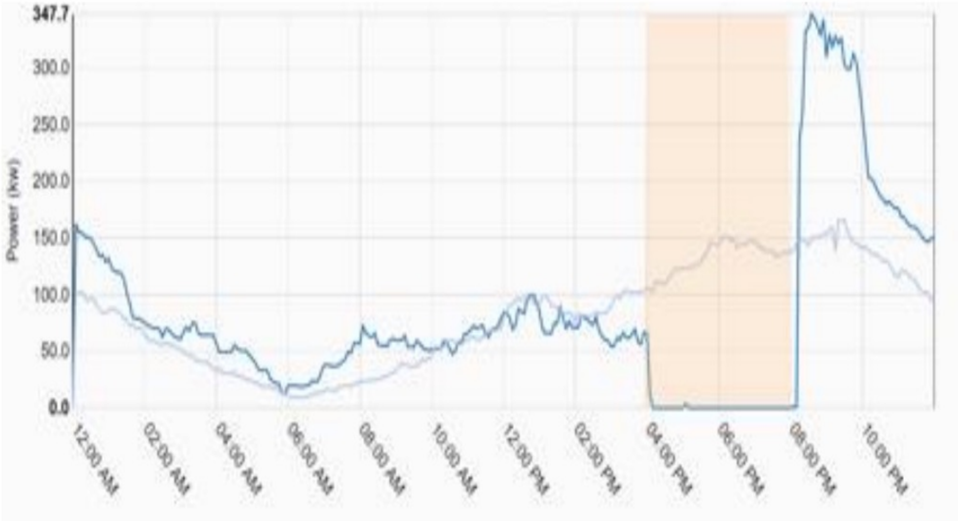
**Emerging preference for simple volumetric TOU, often with network and energy bundled into one charge (in states with no retail choice)**

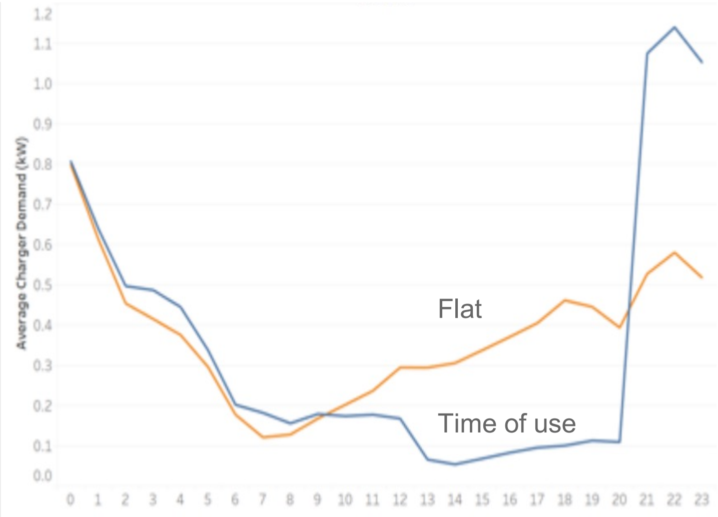



Source: Xcel Energy

# What programs exist specifically for EV charging?

| Utility | State | Details |
|---|---|---|
| Xcel Energy | Minnesota | Unlimited charging between 9pm and 9am for $42.50/month |
| MMWEC | Massachusetts | $6/month credit to limit charging to 1.25 kW between 5-9pm on weekdays |
| PSEG | New Jersey | $0.105/kWh credit for off-peak charging (between 9pm – 7am M-F) |
| Sonoma Clean Power | California | $250 rebate + $5/month to allow curtailment up to 120 hours/year |

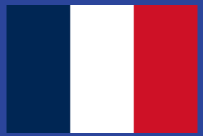



**Programs lead to ”snapback” demand from programmable devices responding to price**

Source: Green Mountain Power 2021 Integrated Research Plan

# What can we learn from our friends across the pond?

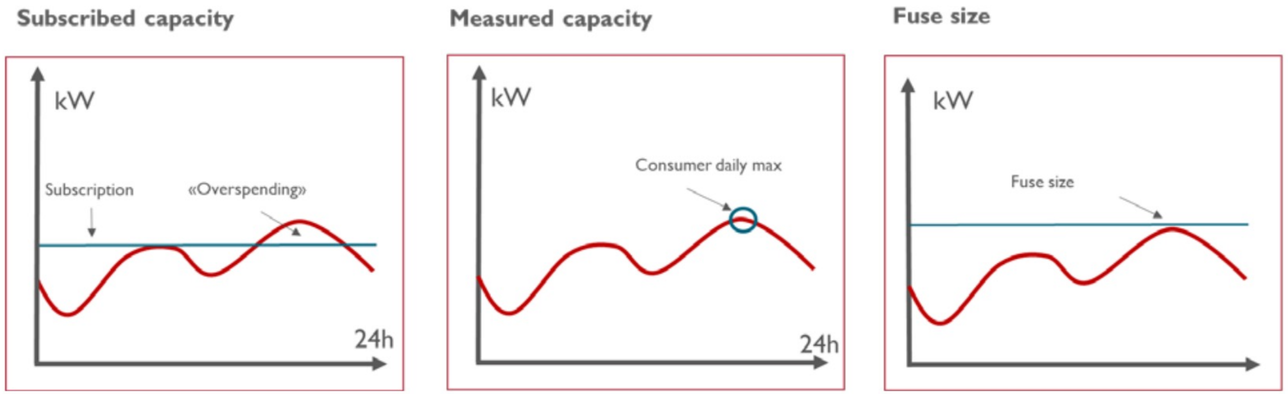
| |  |  |  |
|---|---|---|---|
| **Measured or subscribed** | Subscribed | Subscribed | Measured |
| **Time differentiation** | No | Two periods with different prices | No |
| **Absolute magnitude** | About 20 euro/kW per year | About 25 euro/kW per year (total) | About 40 euro/kW per year |


Joule

Commentary
Reforming retail electricity rates to facilitate economy-wide decarbonization

Tim Schittekatte,[1,4,*] Dharik Mallapragada,[1] Paul L. Joskow,[2] and Richard Schmalensee[2,3]

Source: NVE (2020)

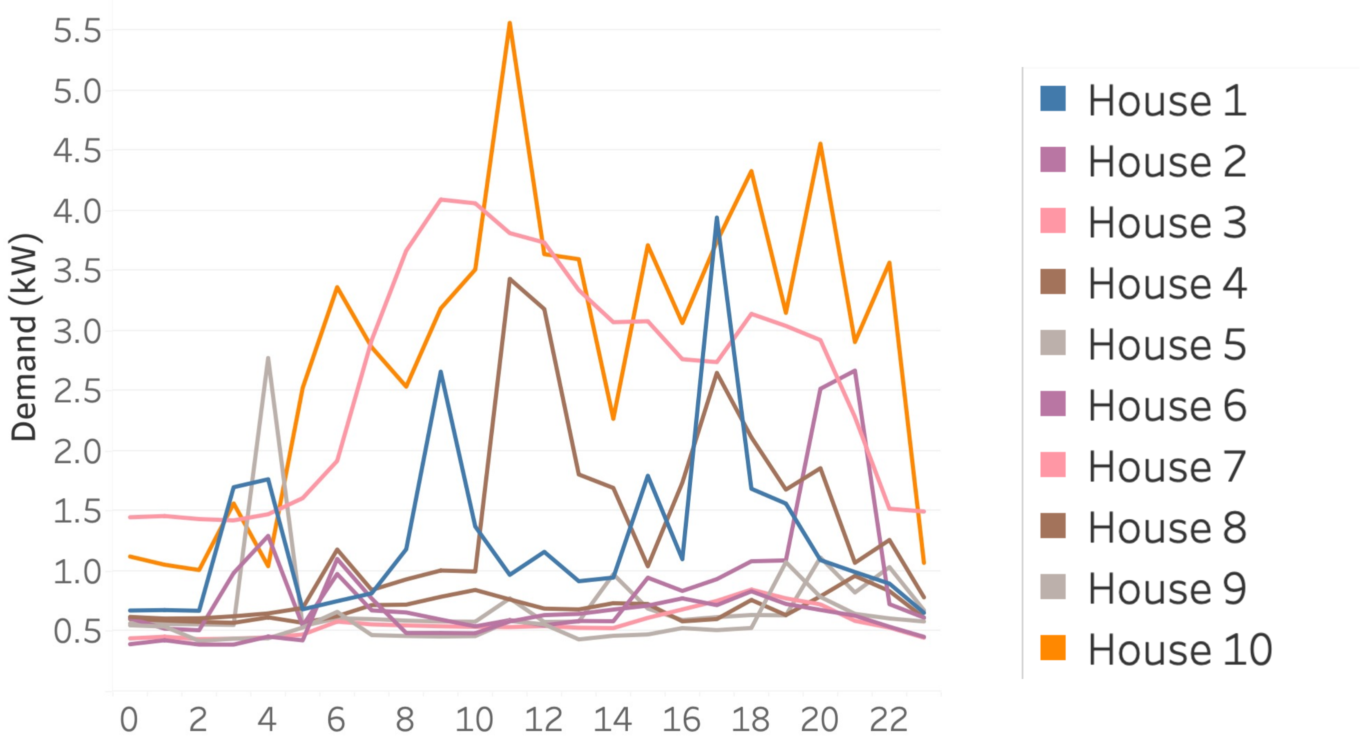


# Our scope

- **Objective of the network tariff:**
  - Efficiency (cost-reflectiveness) ≈ not distorting the short-term marginal cost of electricity to end-users while limiting overinvestment in networks
- **Real-world constraints:**
  - Redistributional impacts between end users
  - Simplicity and predictability
  - Non-discriminatory
  - Cost recovery of distribution network investment
- **We assume a world with (simple) price coordination only**
  - Alternative: control by utility over electric appliances or more advanced schemes
- **Special focus on the interaction between time-varying energy prices and the network tariff design (consumers react on the aggregate!)**

# High-level overview methodology (1/7)

- We model 400 households with unique hourly load profiles for one year



# High-level overview methodology (2/7)

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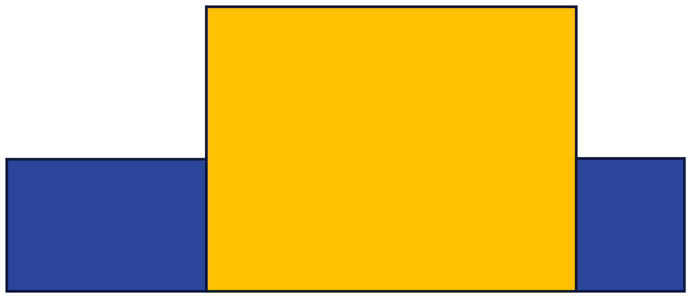

# High-level overview methodology (3/7)

- We model 400 households with unique hourly load profiles for one year
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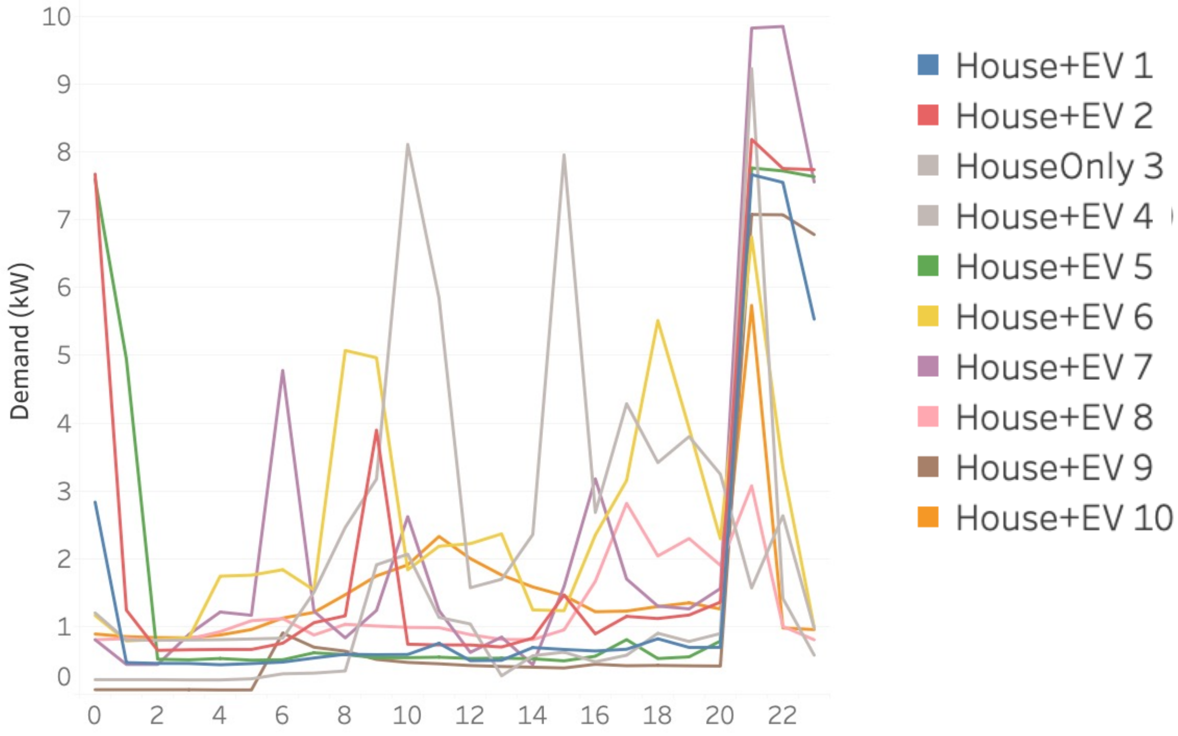
- We vary the rate of electrification over the households; each EV has a unique driving schedule:
  - EV load responds rationally to price signals when plugged-in (perfect foresight) – MILP



# High-level overview methodology (4/7)

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- We vary the rate of electrification over the households; each EV has a unique driving schedule:
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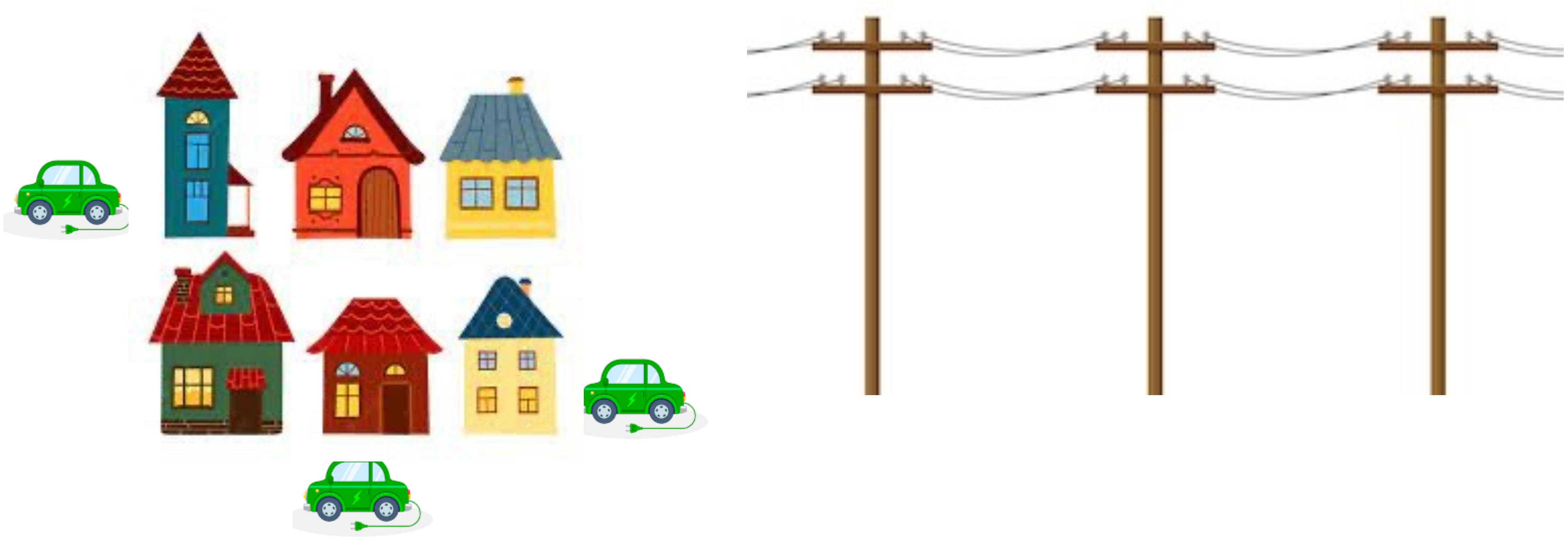
- We test **four standard formats network tariff designs**: fixed, volumetric, capacity with and without time differentiation, and subscription

## Magnitudes under 0% of EV adoption

| Tariff Type | Cost |
|---|---|
| Fixed charge | $1000 per year |
| Flat volumetric (baseline) | $0.11/kWh all hours |
| TOU volumetric 2-period | $0.07/kWh off-peak<br>$0.18/kWh peak |
| Flat capacity | $158/kW-year |
| TOU capacity 3-period | $30/kW-year off-peak<br>$70 /kW-year mid-peak<br>$87/kW-year on-peak |

# High-level overview methodology (5/7)

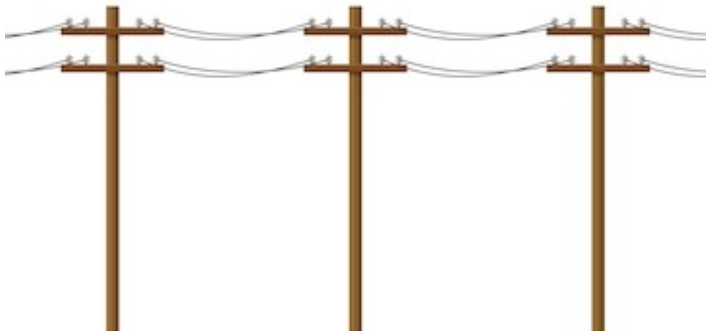
- We assume those 400 households are connected to one feeder and increases in the annual aggregated coincident peak demand lead to linearly increasing network costs

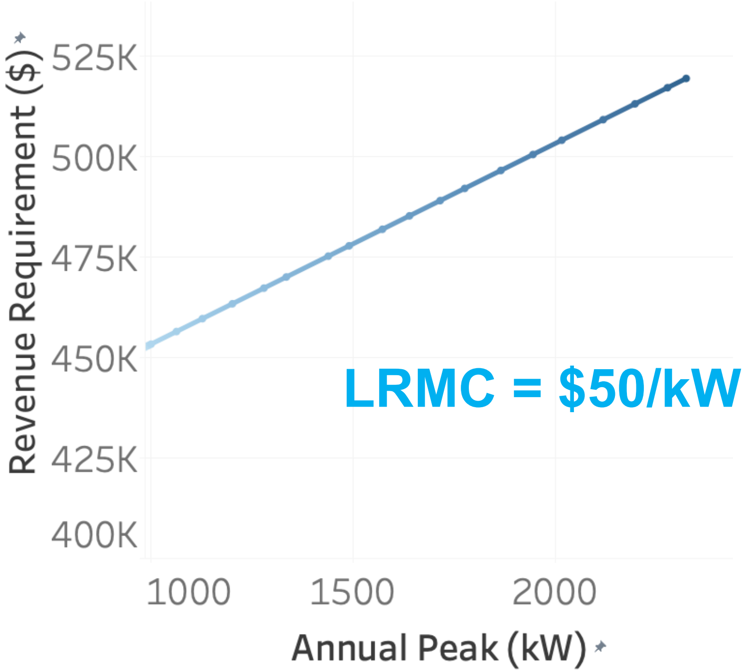


# High-level overview methodology (6/7)

- We assume those 400 households are connected to one feeder and increases in the annual aggregated coincident peak demand lead to linearly increasing network costs

- The revenue requirement equals the base case network costs (no electrification) plus a constant (≈ LRMC) multiplied by the delta in coincident peak demand relative to the base case (iteration until equilibrium = cost recovery)





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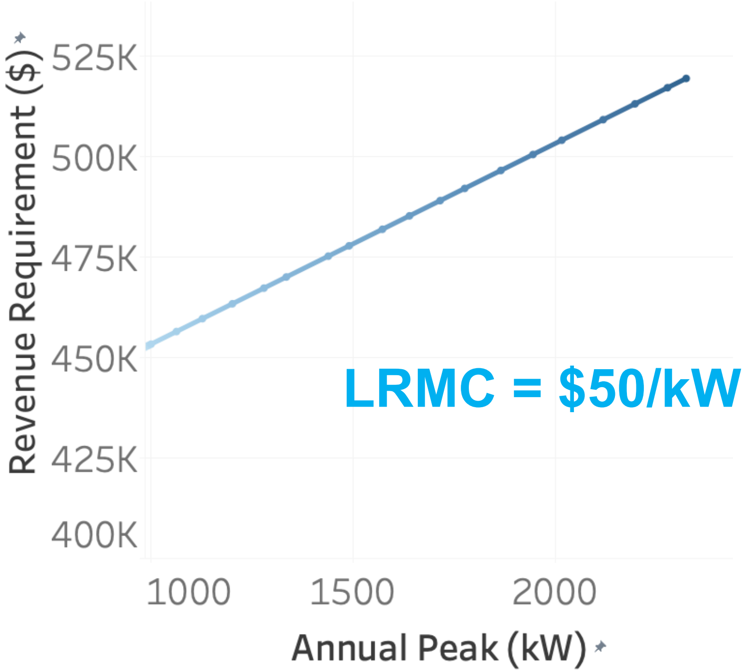
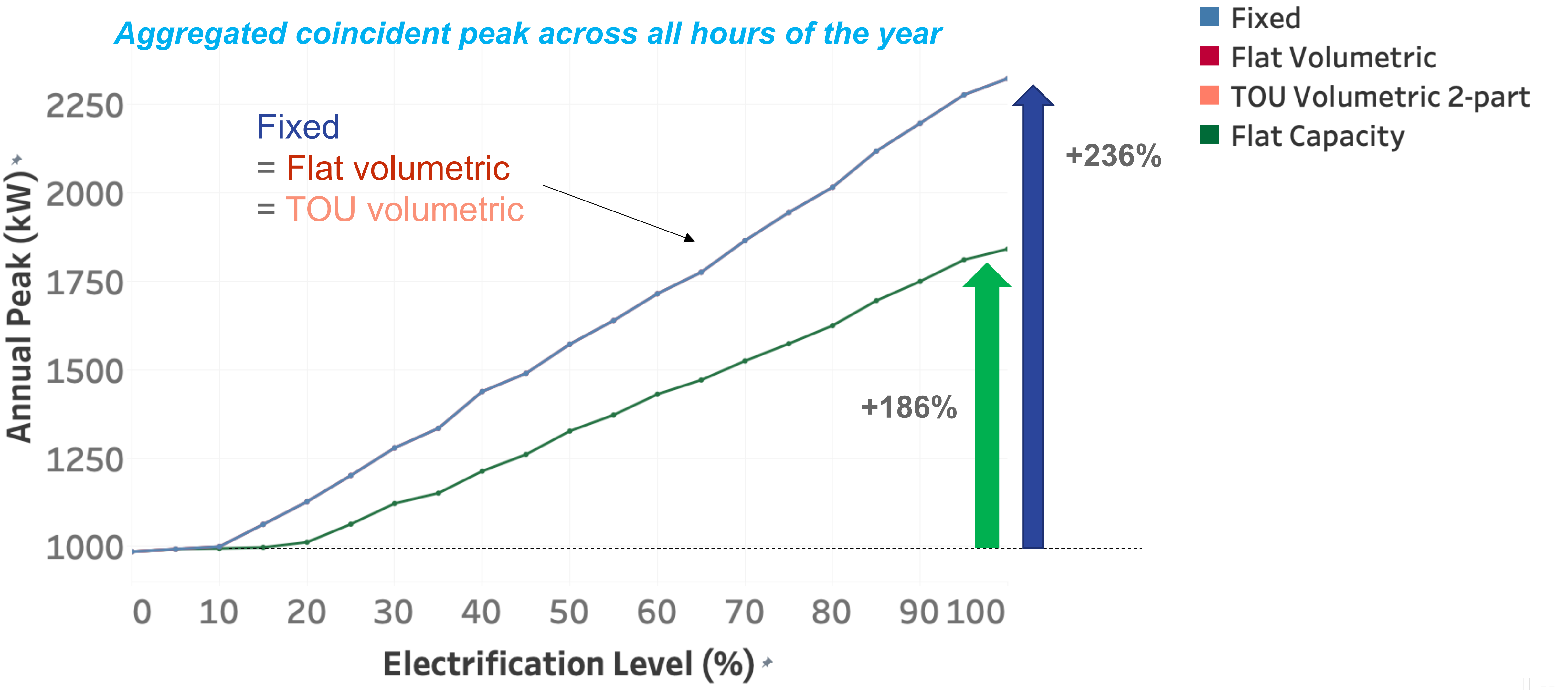


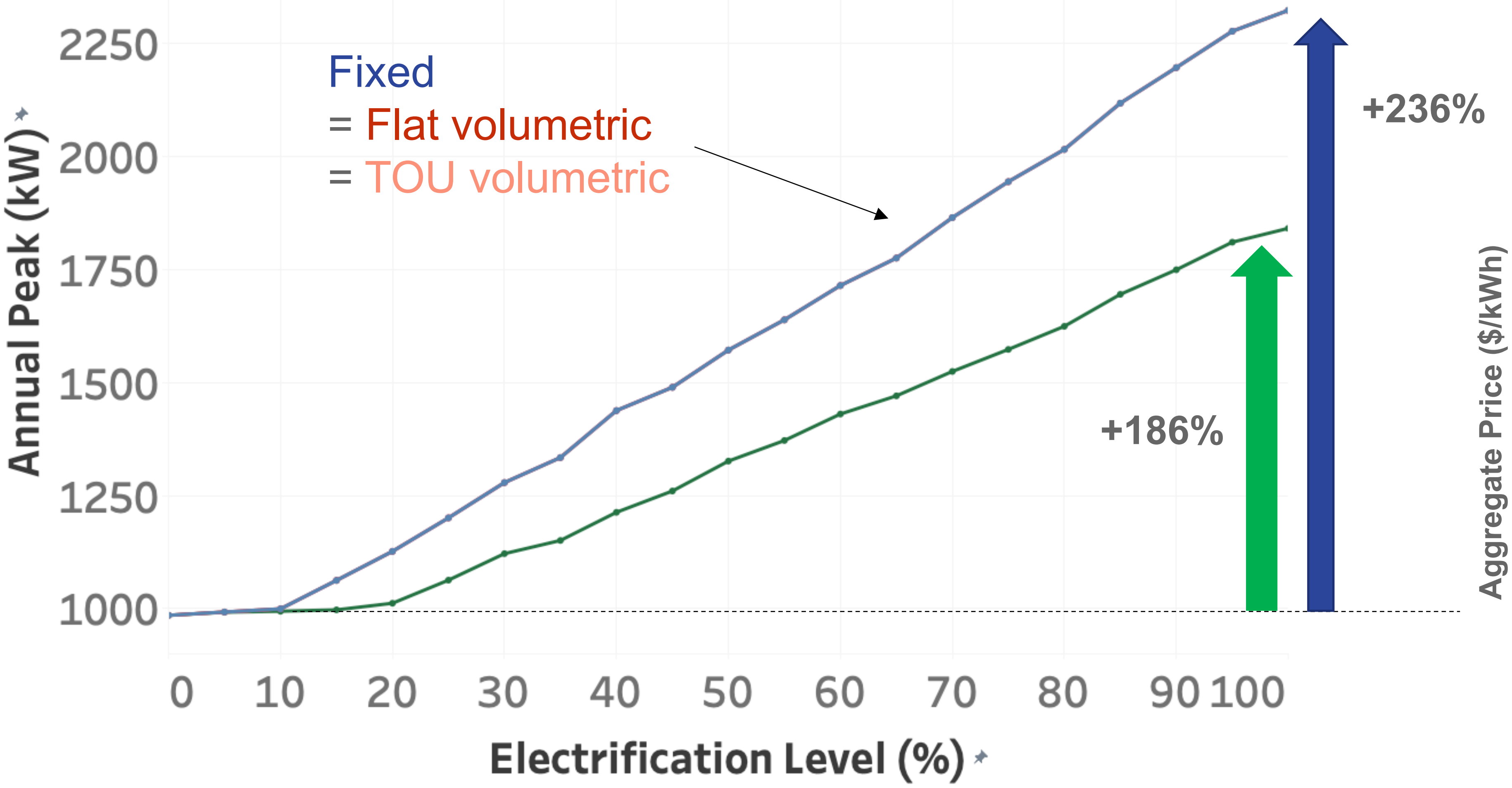

- We asses the results based on **three metrics**: annual aggregated coincident peak, levelized cost of charging, and change in the network costs for non-EV households

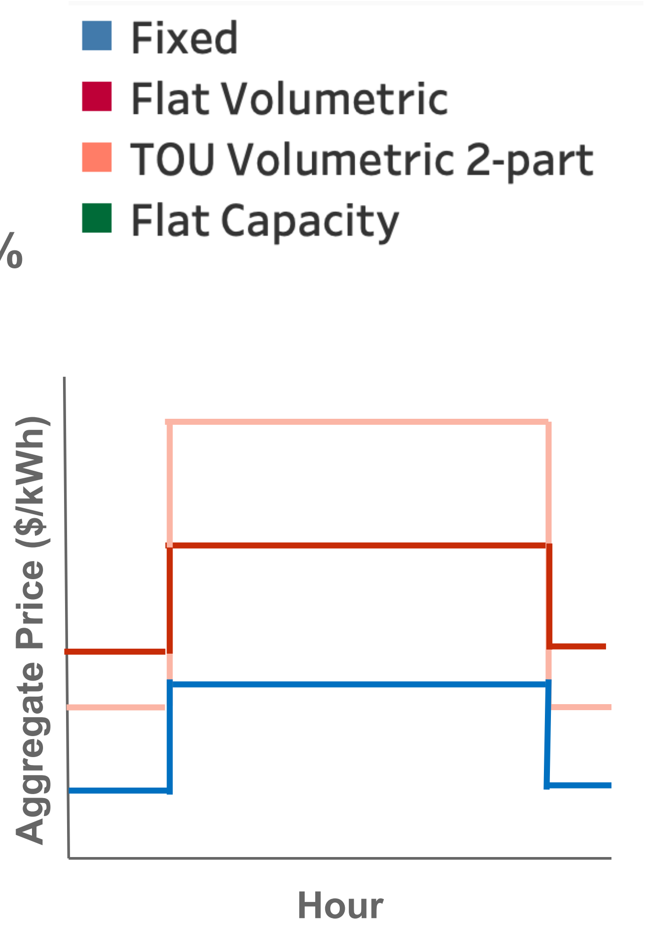
# What is the aggregated peak under each tariff at different electrification levels?



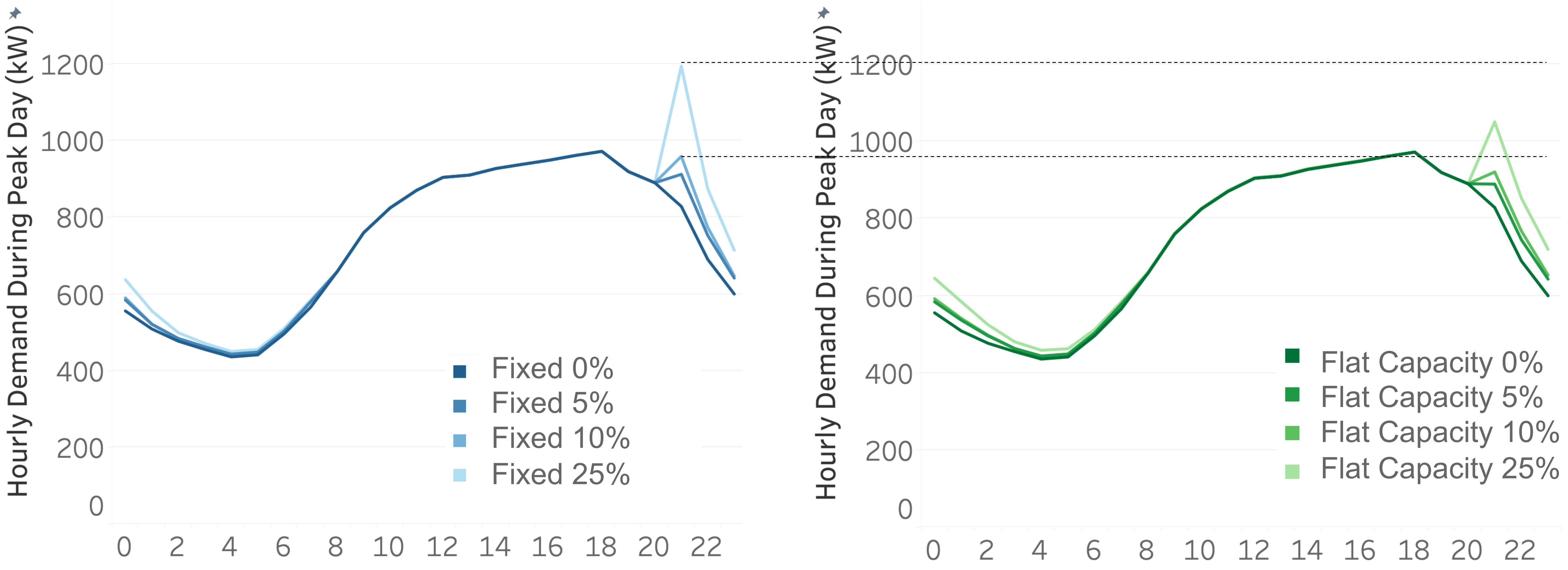
# What is the aggregated peak under each tariff at different electrification levels?

*Aggregated coincident peak across all hours of the year*



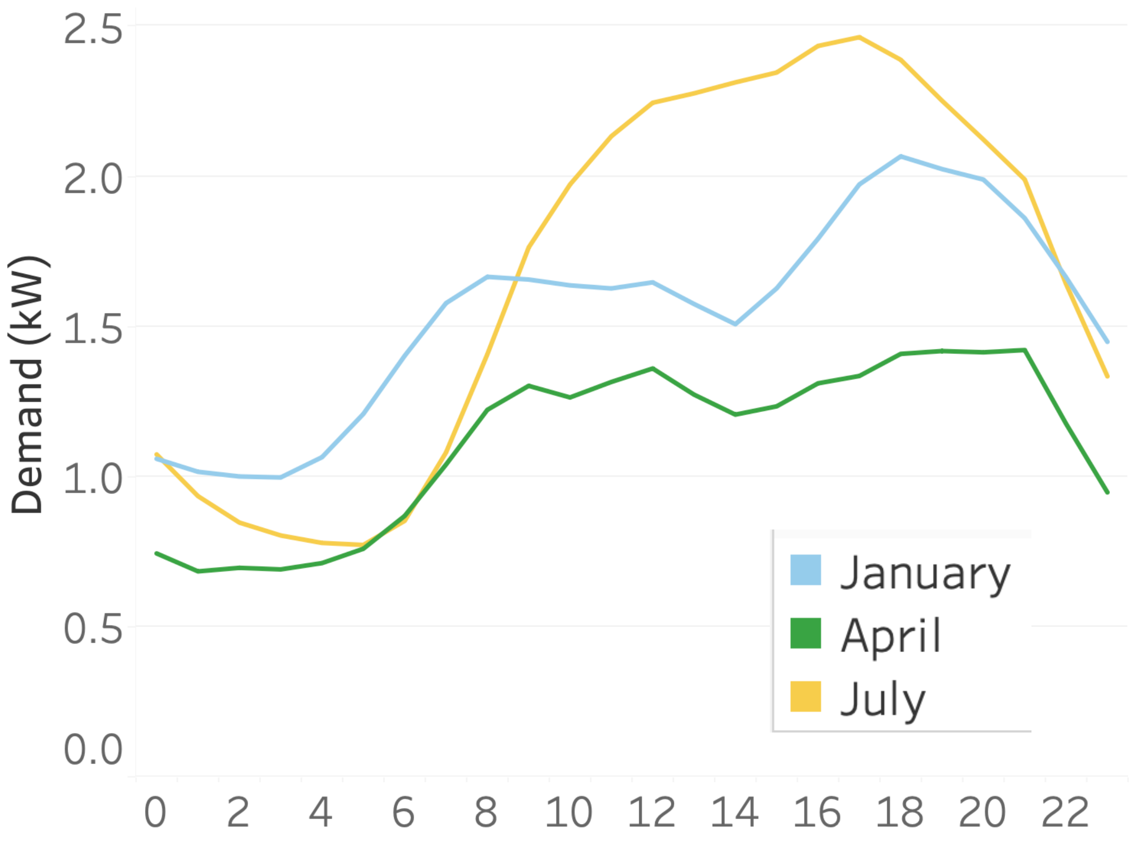



# What is driving the peak up?

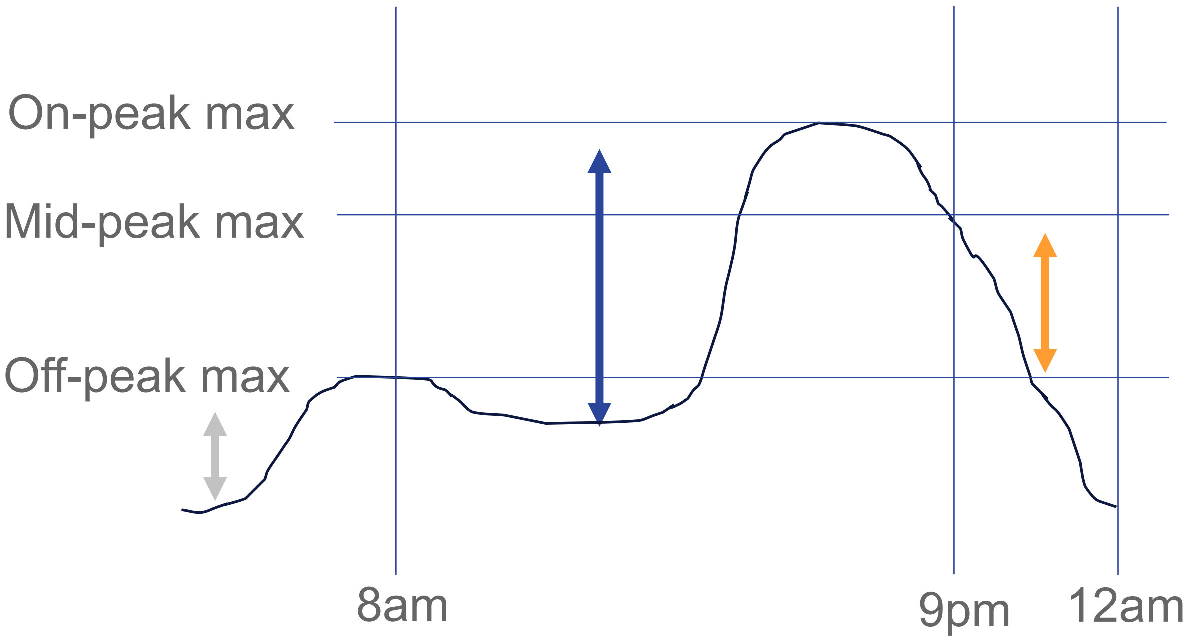



***EVs react to start of off-peak energy in both cases, but under a capacity charge they limit charging to avoid increasing individual peak demand***

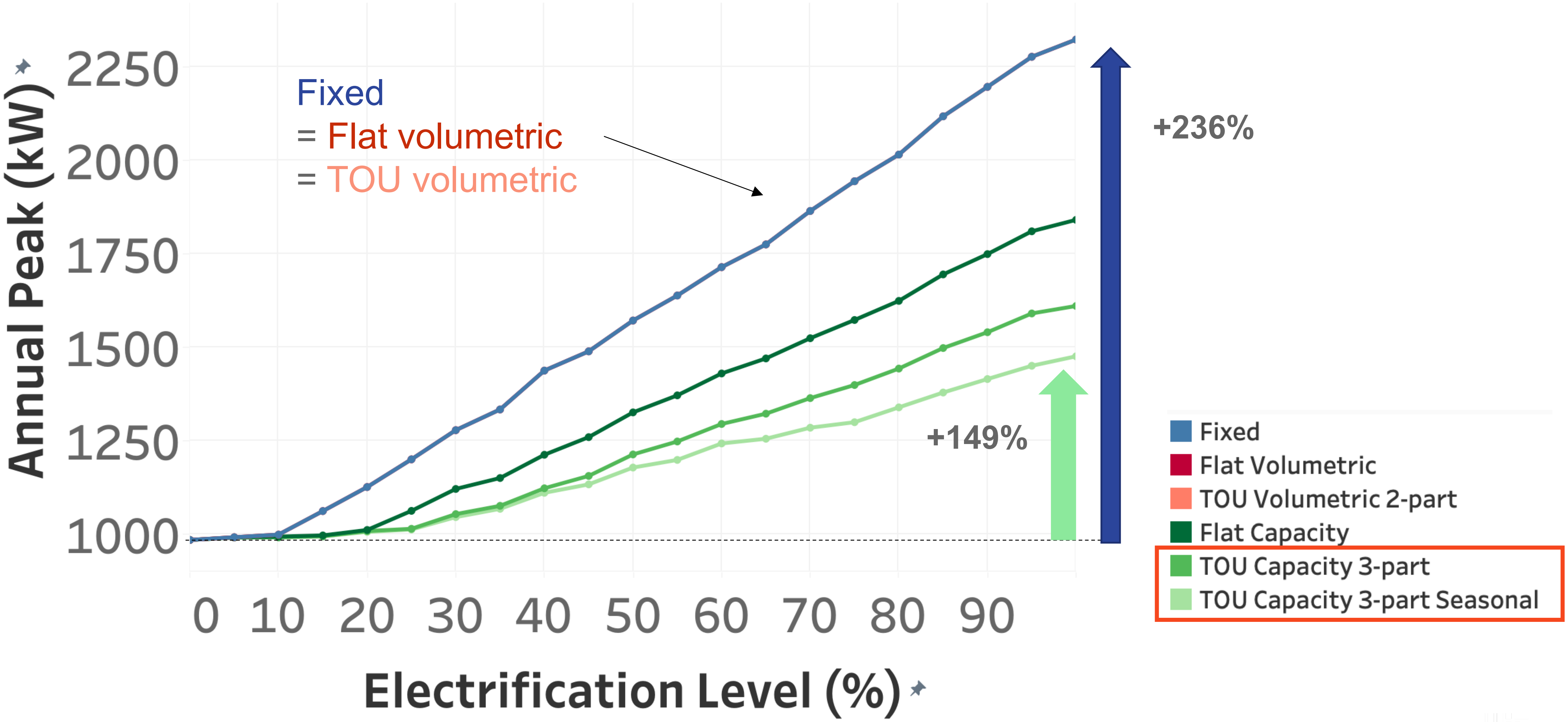
# Can we do better with time/seasonal differentiation?



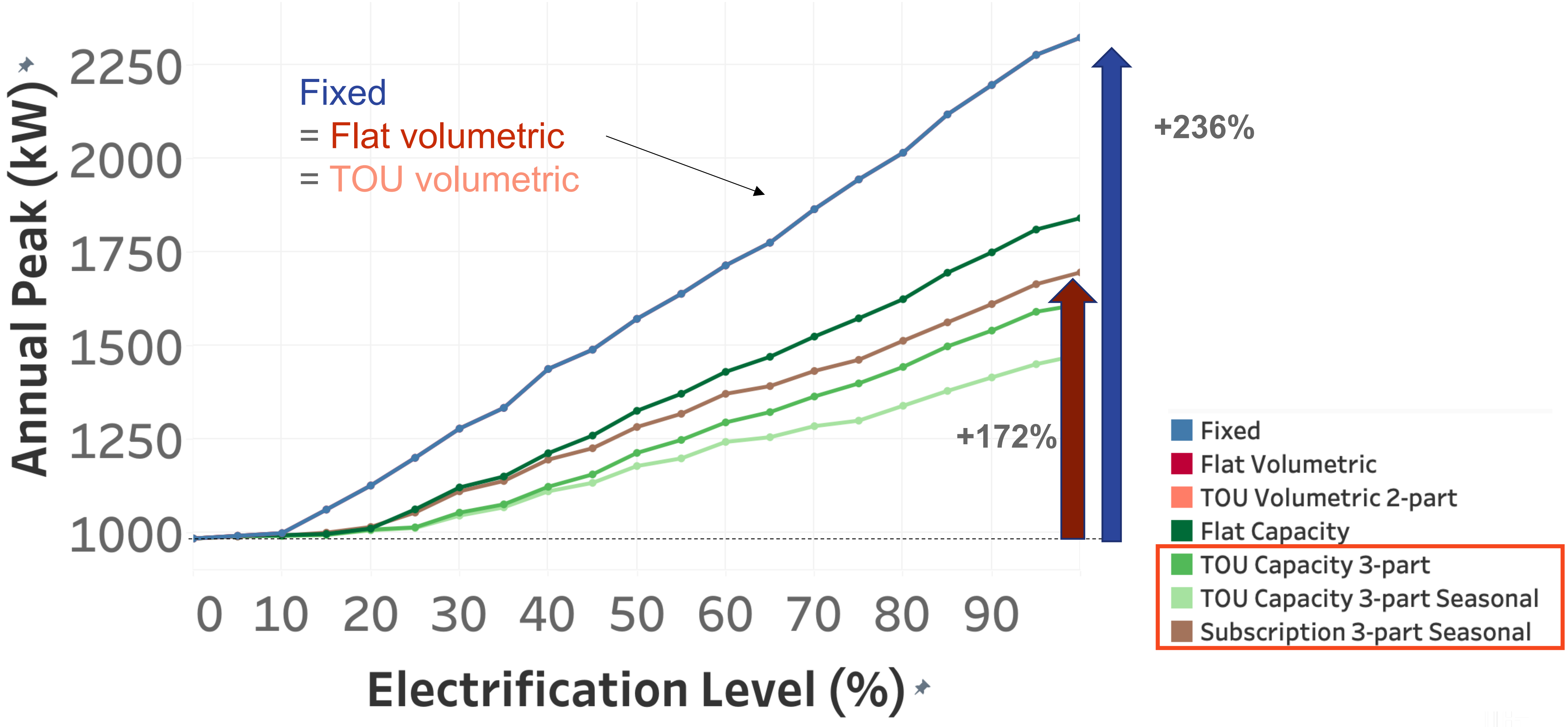

*Demand of average house on peak day in each month at 0% adoption*



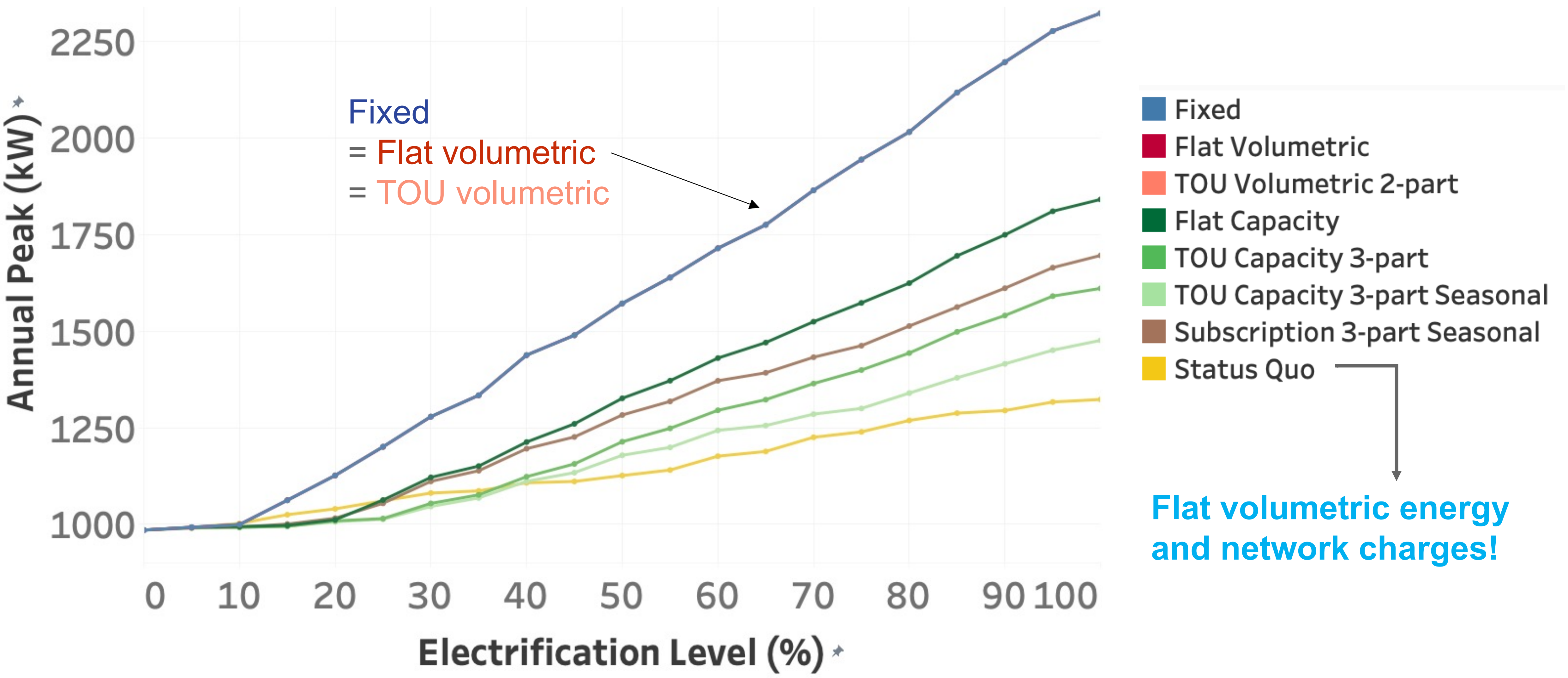
# How can we improve by considering daily & seasonal variation?



# How does a subscription tariff perform?

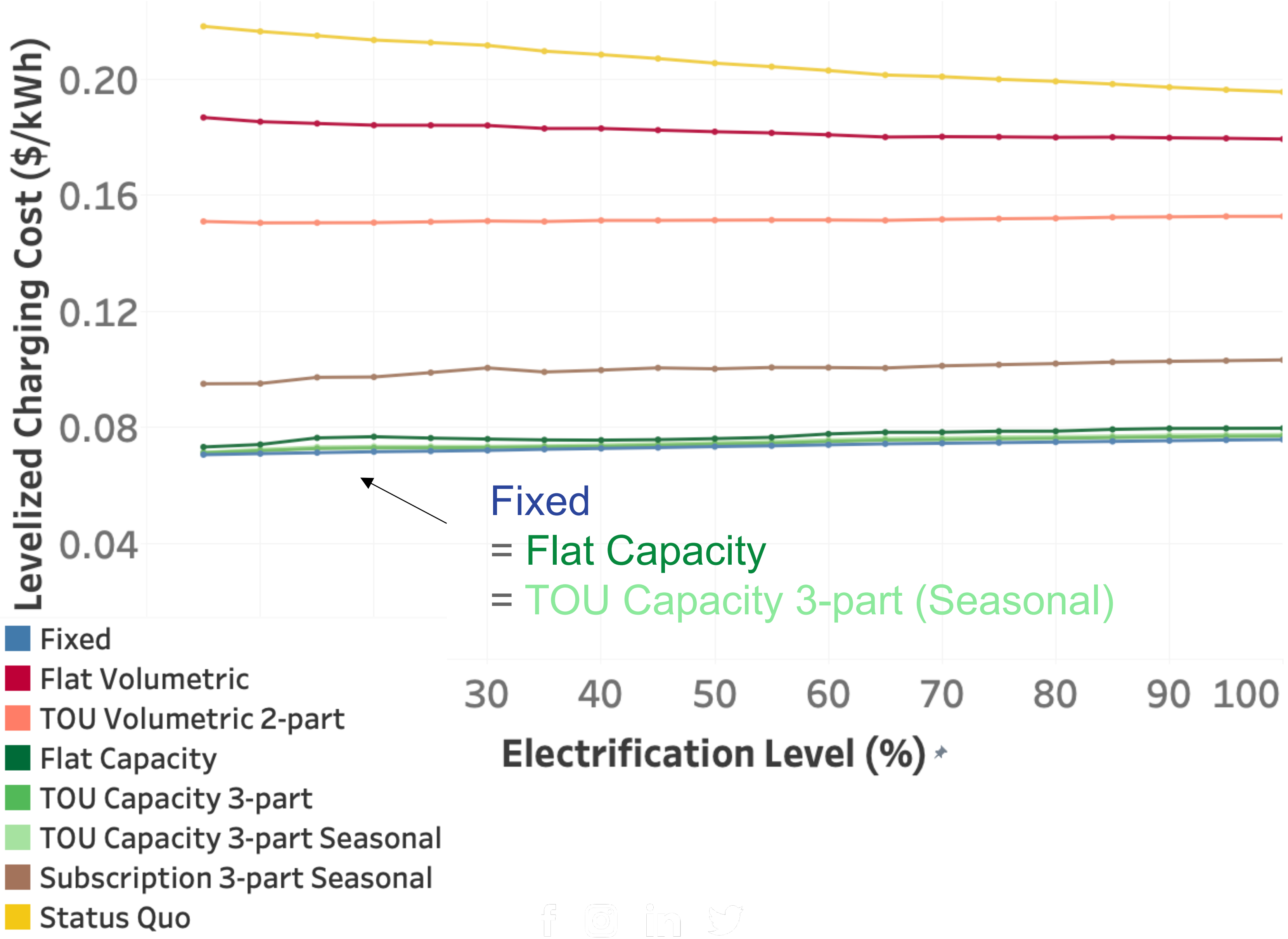


# The paradox: the status quo (leveraging heterogeneity)

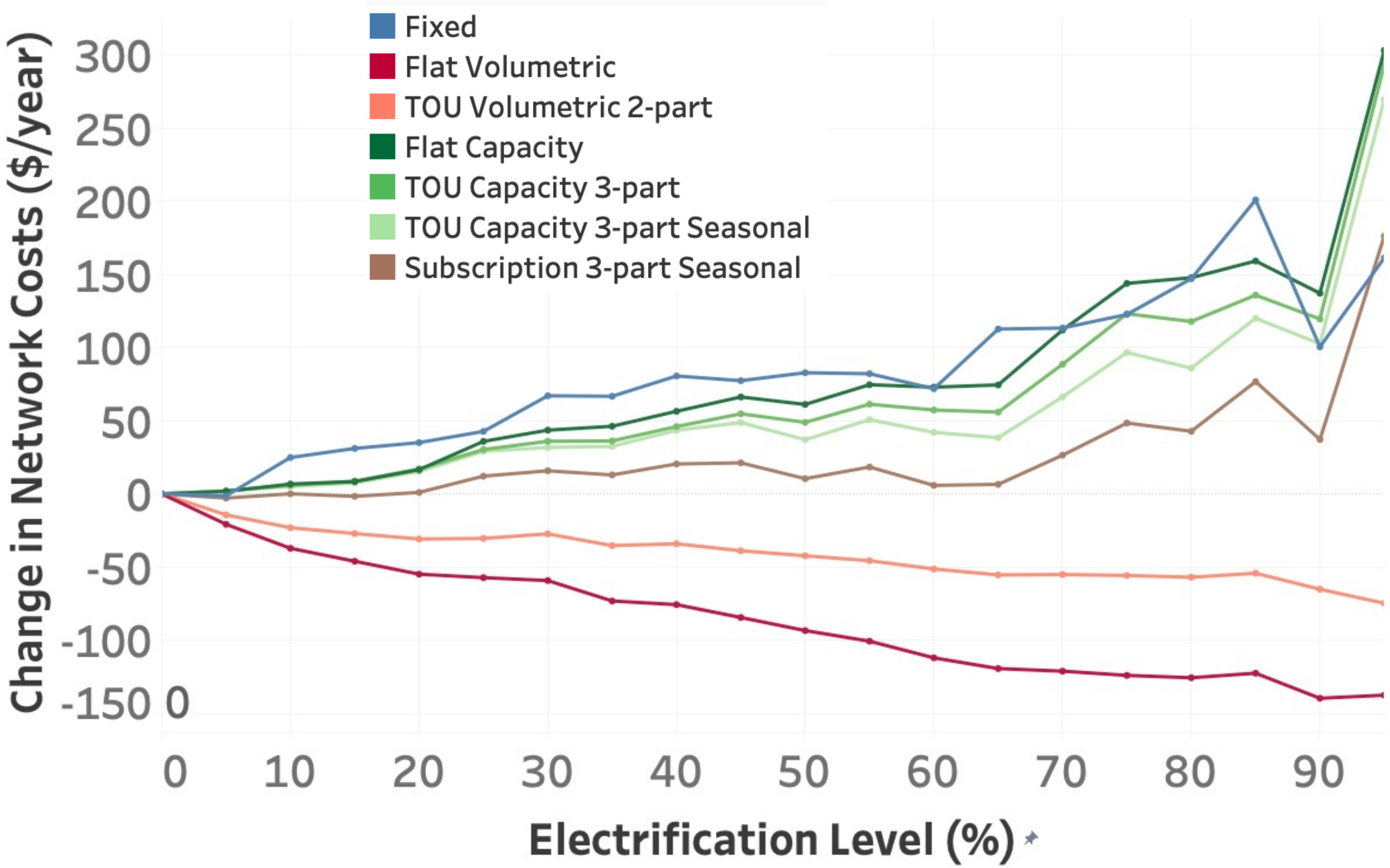



**Flat volumetric energy and network charges!**

# But status quo is an unstable equilibrium

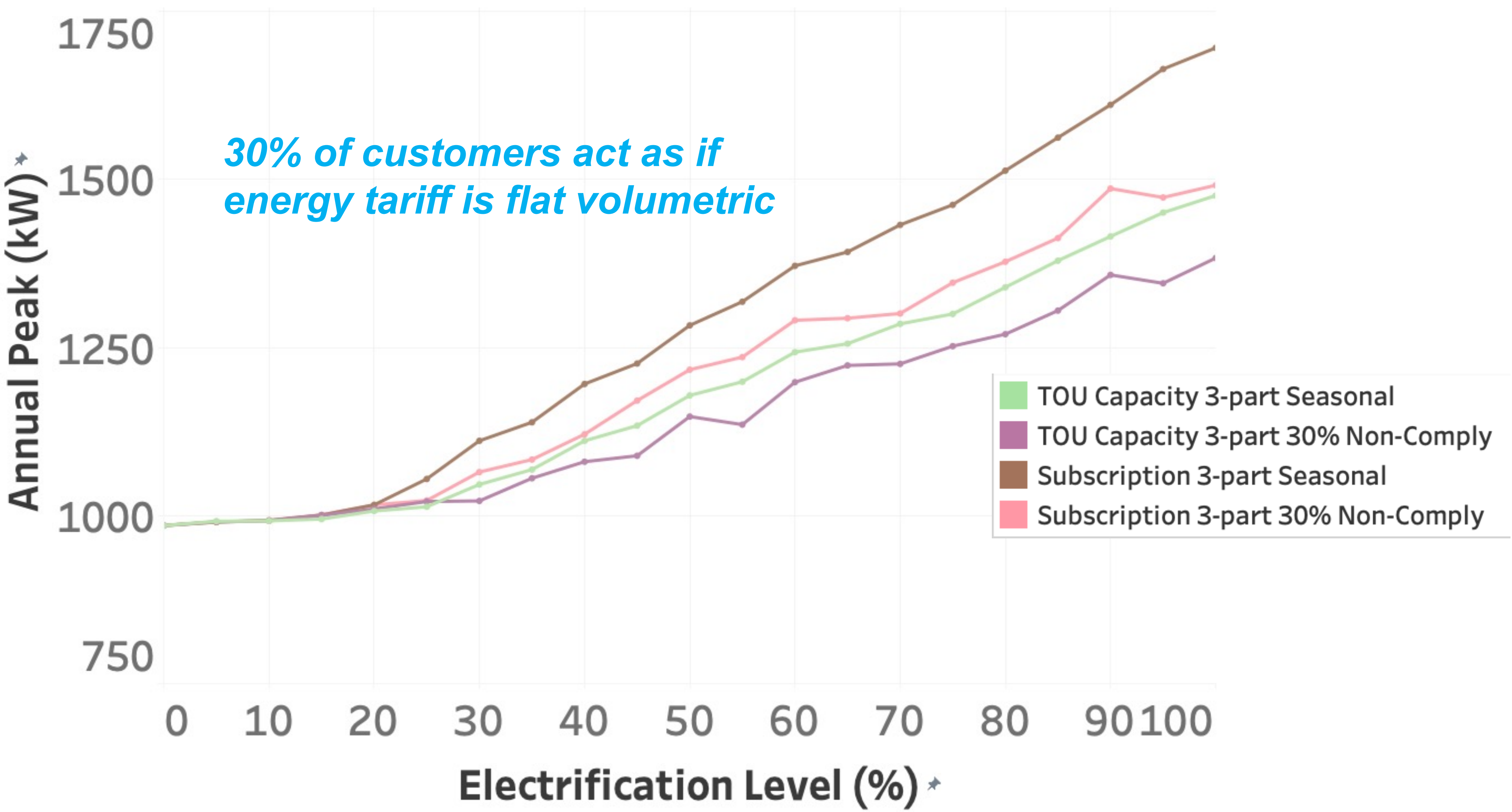


# What are the distributional impacts on non-EV households under each tariff?

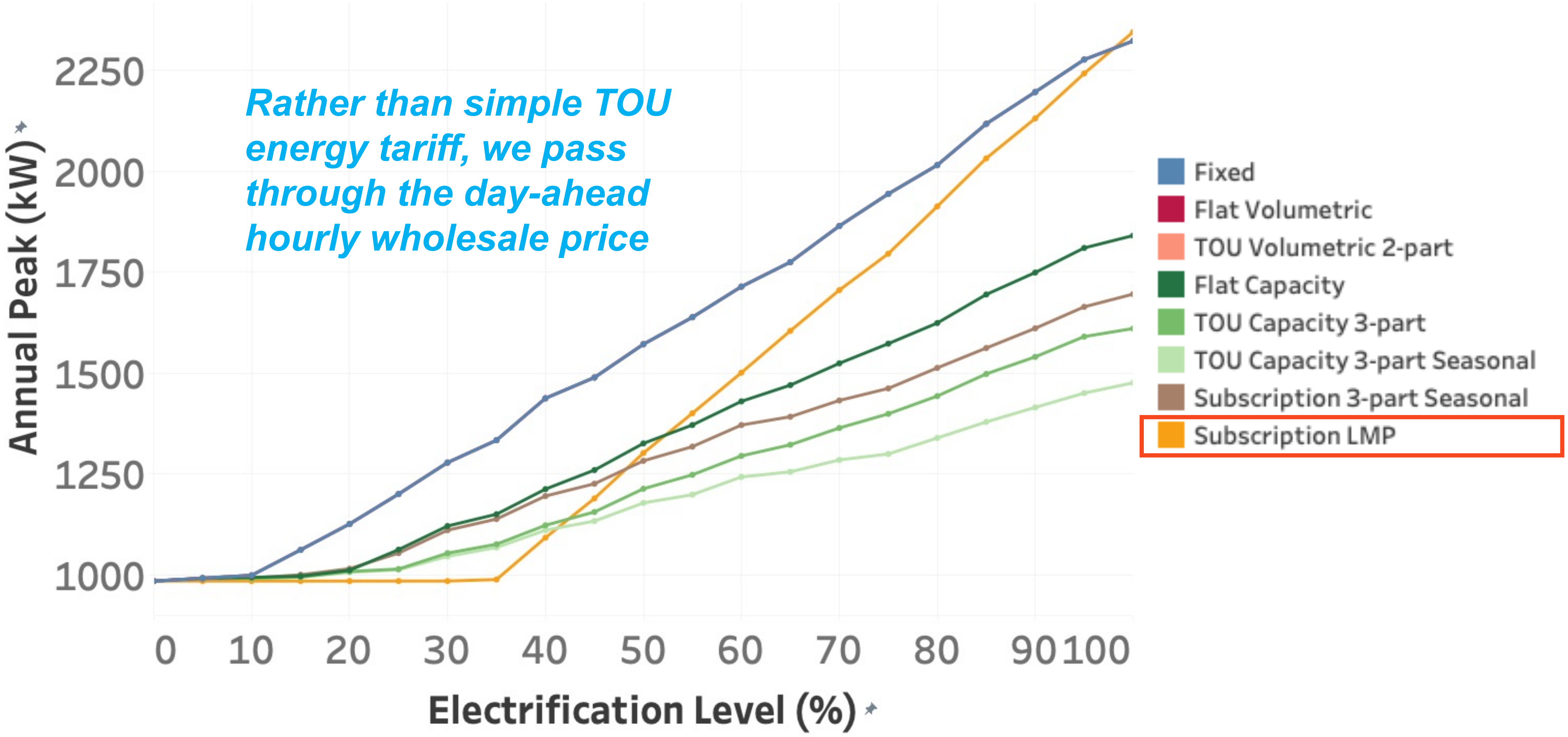



***Strongly impact by assumed LRMC!***

# The good (antifragile) news: some consumers ignoring the rate design makes its performance better!



# The bad news: if EV owners adopt dynamic energy prices the whole story becomes (even) more complicated



# What are the key findings? (1/2)

- Uncontrolled EV charging becomes very quickly an issue (newly created peaks from **15% of adoption levels** and adoption will be concentrated!)

- **Purely volumetric network charges (with or without time-differentiation)** are not a good idea:
  - No signal to limit aggregated peaks & makes electrification expensive

- **Fixed network charges** also do not seem a good idea as they send no signal to limit aggregated peaks. They do foster electrification but can lead to distributional impacts when not differentiated.

- **Capacity-based tariffs** perform well but might not be easy to implement. A **three part-subscription based tariff** seems like a pragmatic solution. The exact design needs tailoring to be effective.
  - Increase in aggregated peak limited & even better if some consumer ignore price signals
  - Fosters electrification & no exaggerated distributional effects

# What are the key findings? (2/2)

- **The inclusion of heat pumps** reduces the effectiveness of subscription-based tariffs; opportunities for pre-heating/pre-cooling to limit temperature-driven peaks

- The whole analysis become more complex when **dynamic energy prices** are adopted
  - Solutions: **need for load control**, discriminate rates to create randomness, daily capacity charges, auctions for network capacity, price setting based on equilibria estimations, etc.

# Thank you

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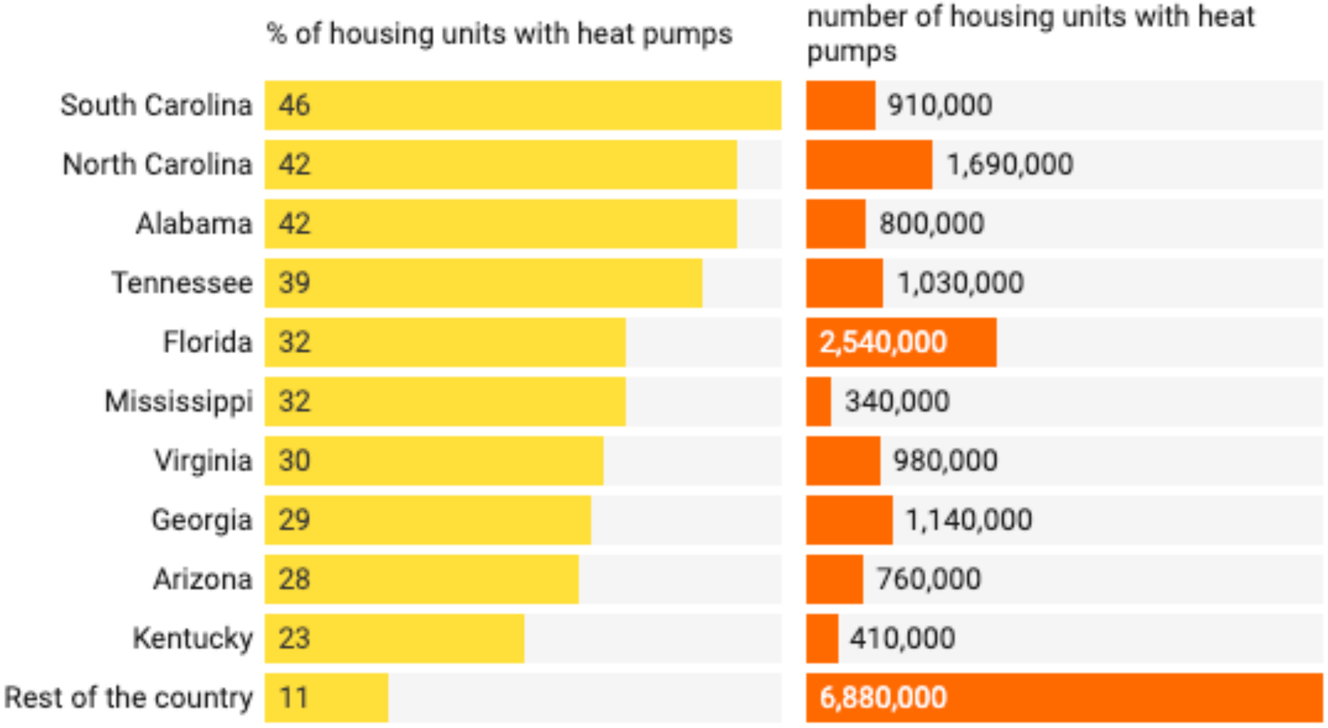
# Appendix Slides

# How do the results change in different geographies?

"[E]lectrification of end uses, **particularly space heating through the use of electric heat pumps, was found to be the most economically advantageous and cost-effective** decarbonization strategy for widespread deployment across the Commonwealth's building sector, especially for residences and homes, which account for about 60% of all buildings sector emissions"

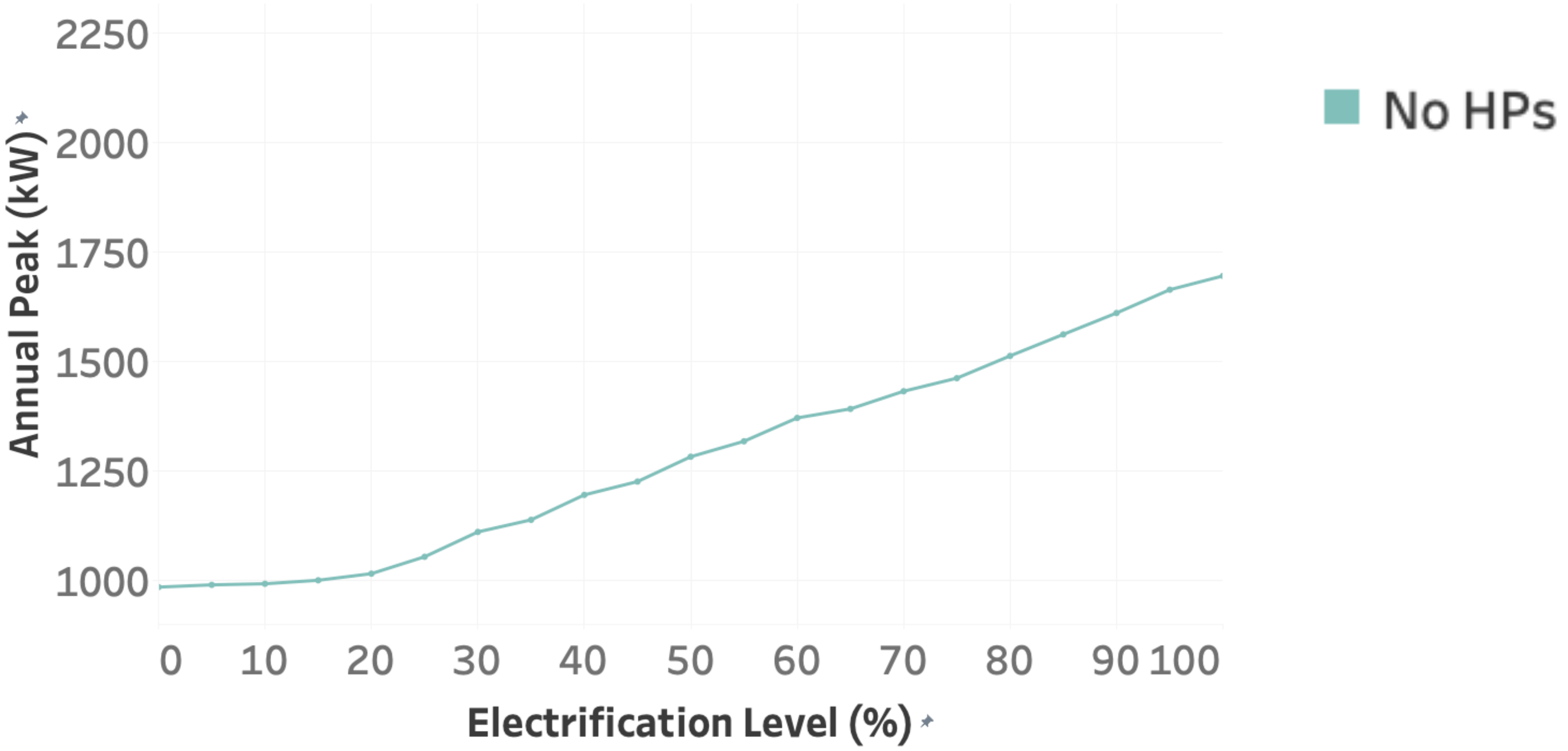
**Massachusetts 2050 Decarbonization Roadmap**




Source: Canary Media

# How do the results change in different geographies?

*3-part seasonal subscription tariff w/ TOU energy*



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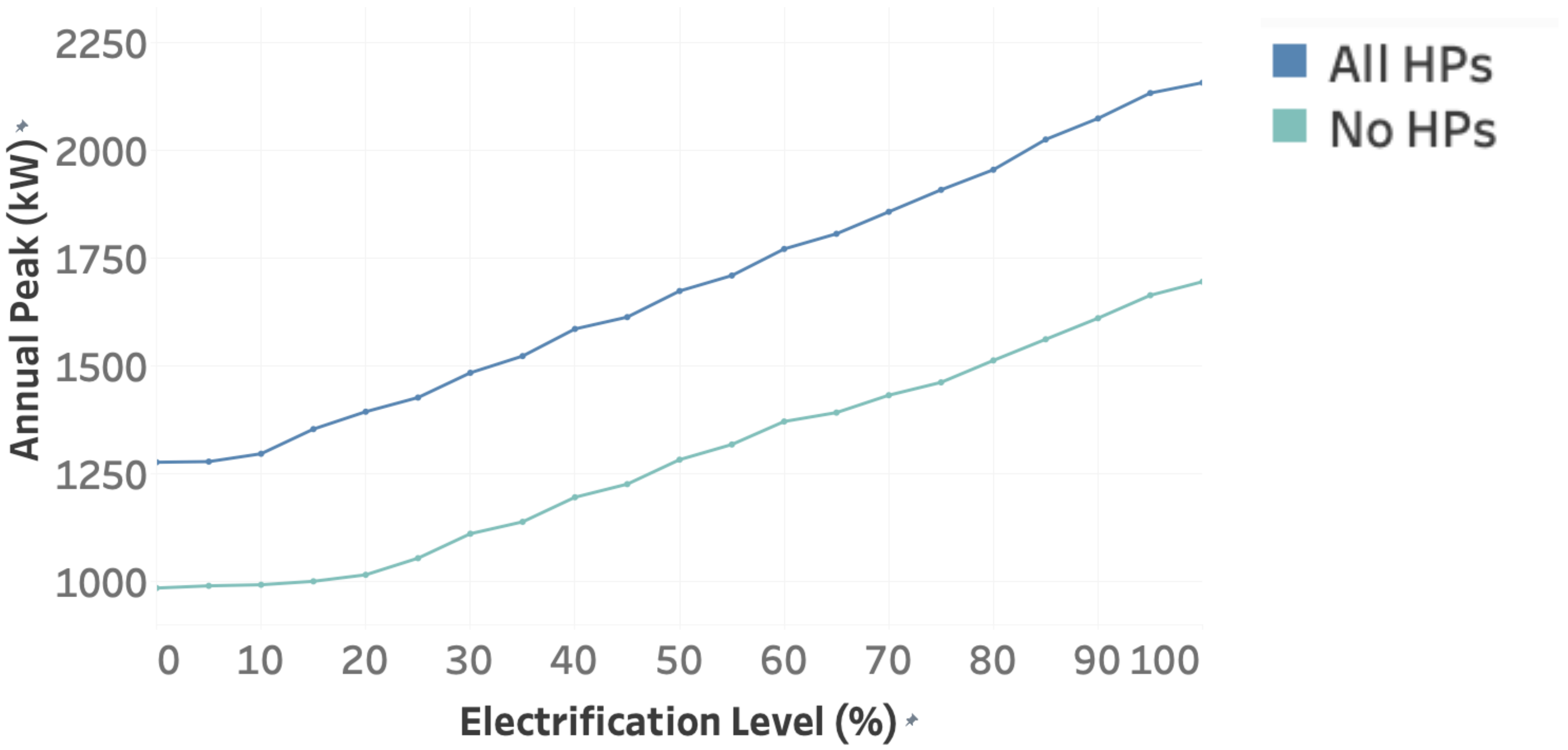

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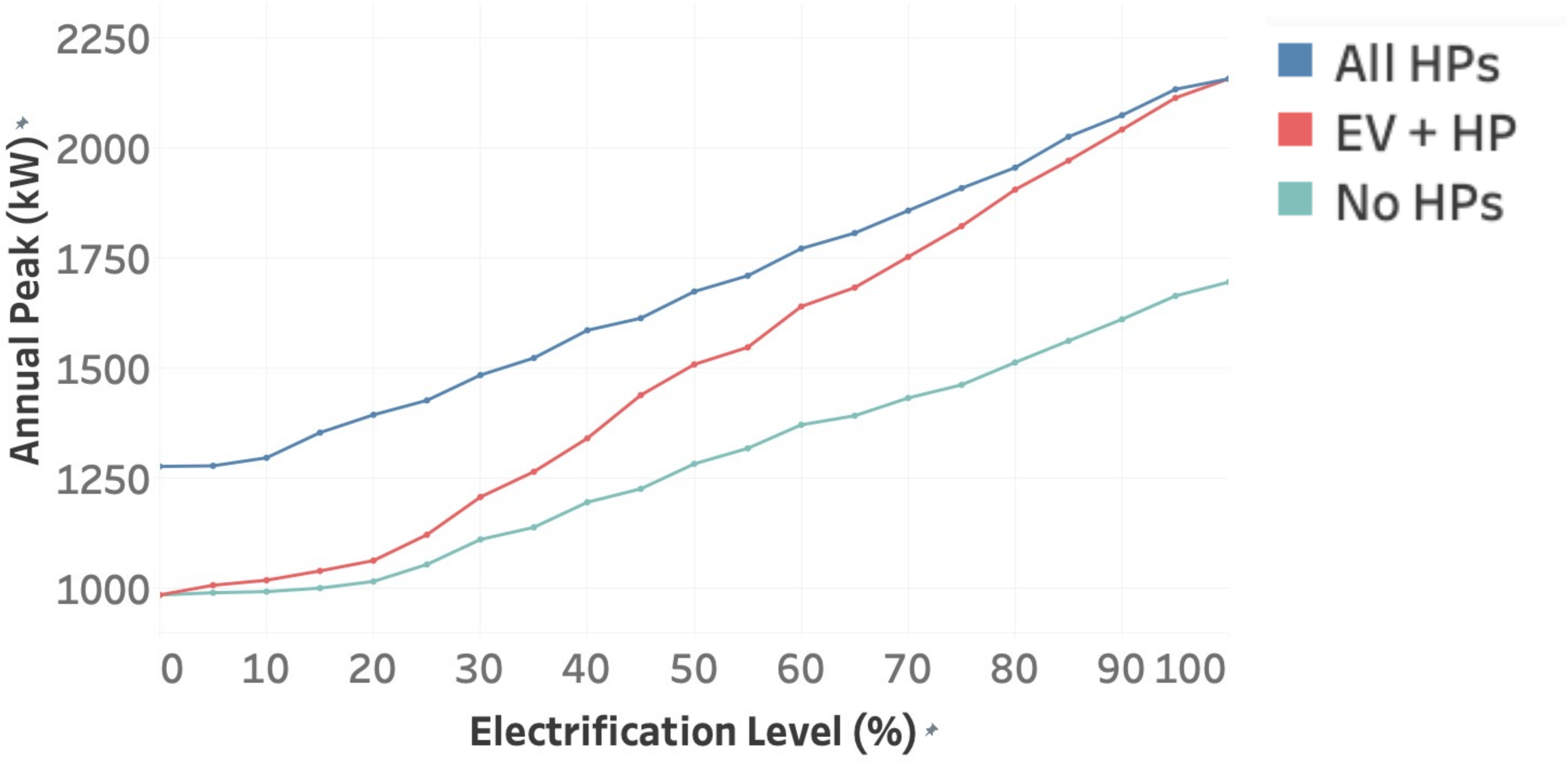

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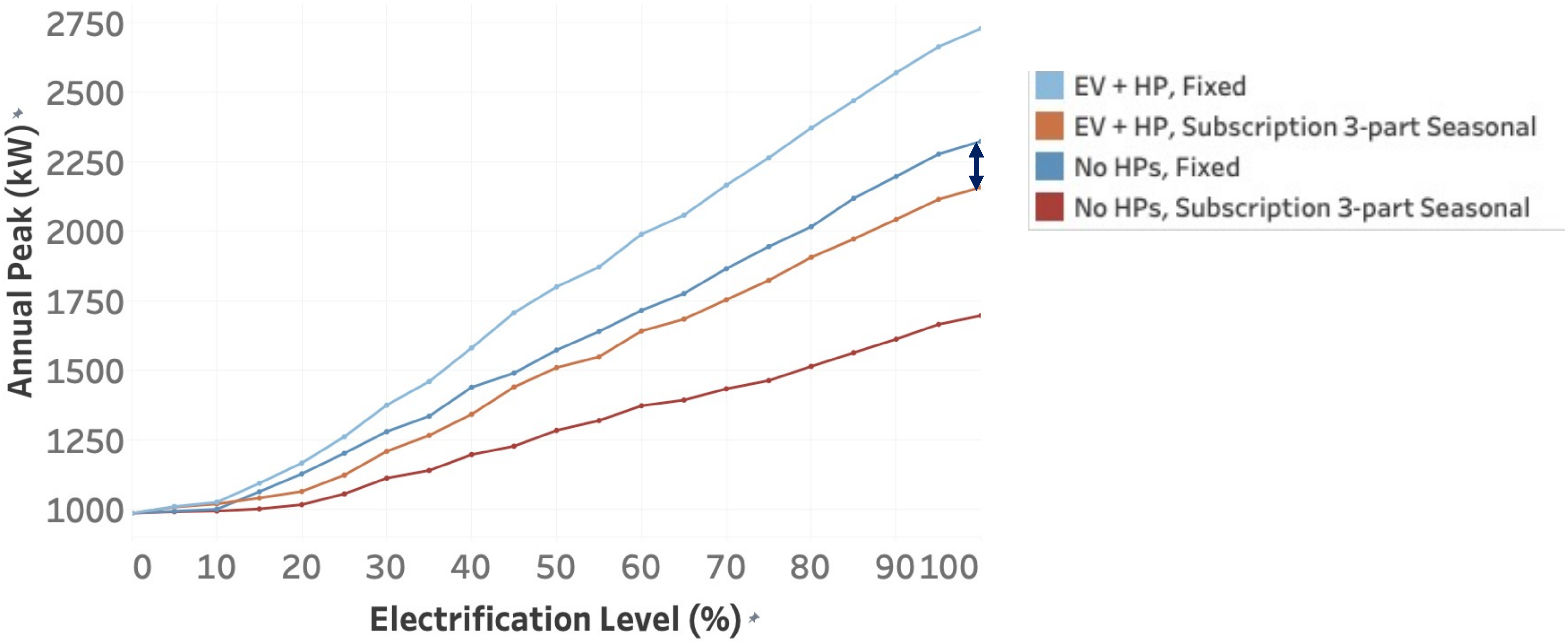


# Which standard tariff designs do we test and how are they structured?

## Magnitudes under 0% of EV adoption

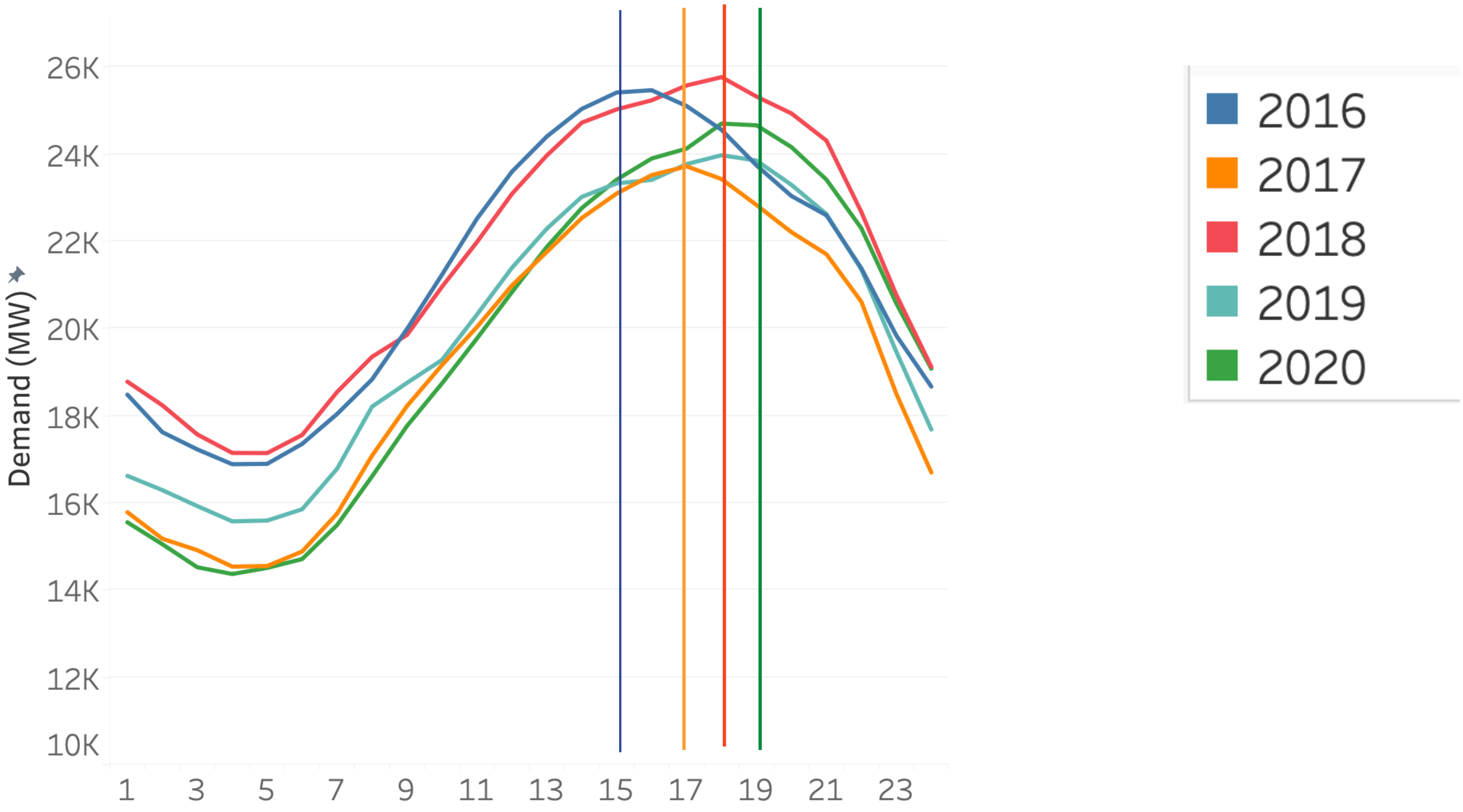
| Tariff Type | Cost |
|---|---|
| Fixed charge | $1000 per year |
| Flat volumetric (baseline) | $0.11/kWh all hours[a] |
| TOU volumetric 2-period | $0.07/kWh off-peak[b]<br>$0.18/kWh peak[b] |
| Flat capacity | $158/kW-year |
| TOU capacity 3-period | $30/kW-year off-peak[c]<br>$70 /kW-year mid-peak[c]<br>$87/kW-year on-peak[c] |

***All tariffs tested with 2-part volumetric energy prices***

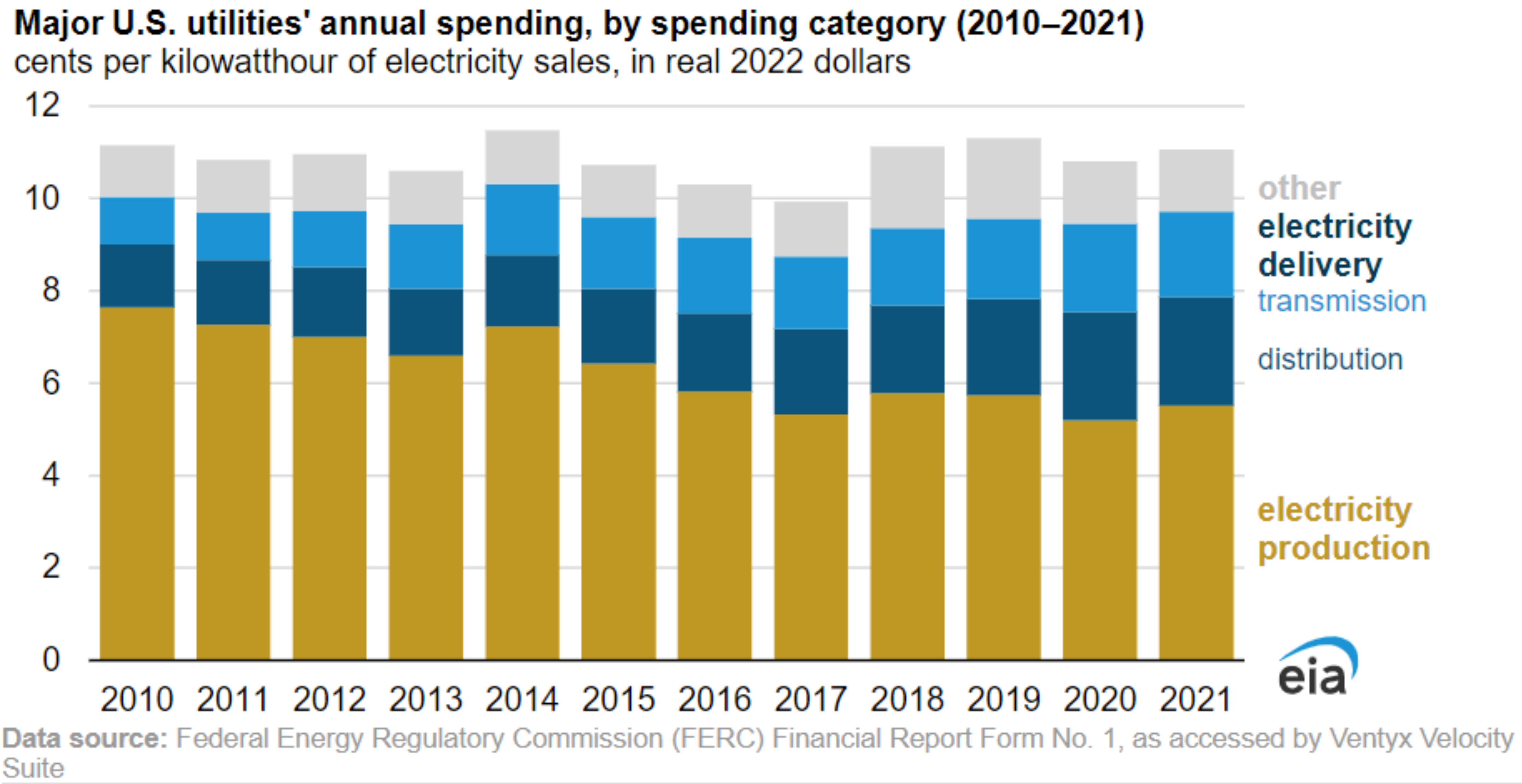
[a] Eversource network charge as of March 2023
[b] Peak hours are M-F 8am-9pm, on-peak set at 2x peak based on National Grid rate G3
[c] Peak hours are M-F 8am-9pm, mid-peak hours are M-F 9pm-12am, off-peak all other hours

# Where have we seen this problem before?

## New England regional peak shifted from hour ending 15 to hour ending 19 in just 4 years due to solar



# Network costs on the rise & continue to do so



# Redesigning network tariffs: what (polar) alternatives?

ENERGY INSTITUTE AT HAAS

Energy Institute WP 314

**Designing Electricity Rates for An Equitable Energy Transition**

Severin Borenstein, Meredith Fowlie, and James Sallee

February 2021

VS.


CBS LOS ANGELES   NEWS   WEATHER   SPORTS   VIDEO   MORE   61°

**State utility bills may see a change with a fixed-rate based on income**

KCAL NEWS

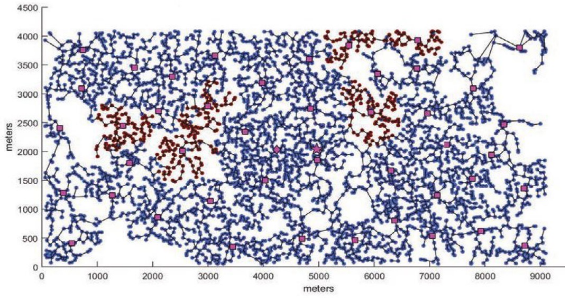
BY KCAL-NEWS STAFF
APRIL 15, 2023 / 9:03 AM / KCAL NEWS

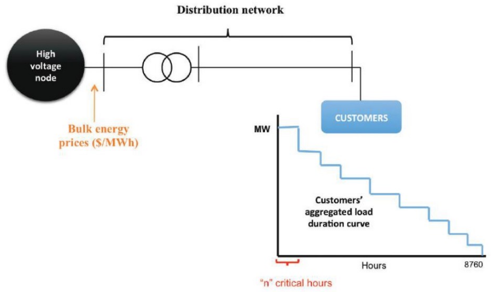
Details of the proposal are as follows:

- Households earning less than $28,000 a year would pay a fixed charge of $15 a month on their electric bills in Edison and PG&E territories and $24 a month in SDG&E territory.

…

- Those with incomes above $180,000 would pay $85 a month in Edison territory, $128 a month in SDG&E territory and $92 a month in PG&E territory.




ACER

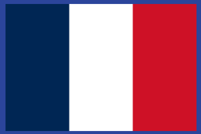
European Union Agency for the Cooperation of Energy Regulators

**Report on Distribution Tariff Methodologies in Europe**

February 2021

*"While capacity charges, often also referred to as demand charges, rare in the US for residential and small commercial consumers, 13 of the 27 member states of the European Union had capacity charges in place in 2021."*

# What can we learn from our friends across the pond?

| |  |  |  |
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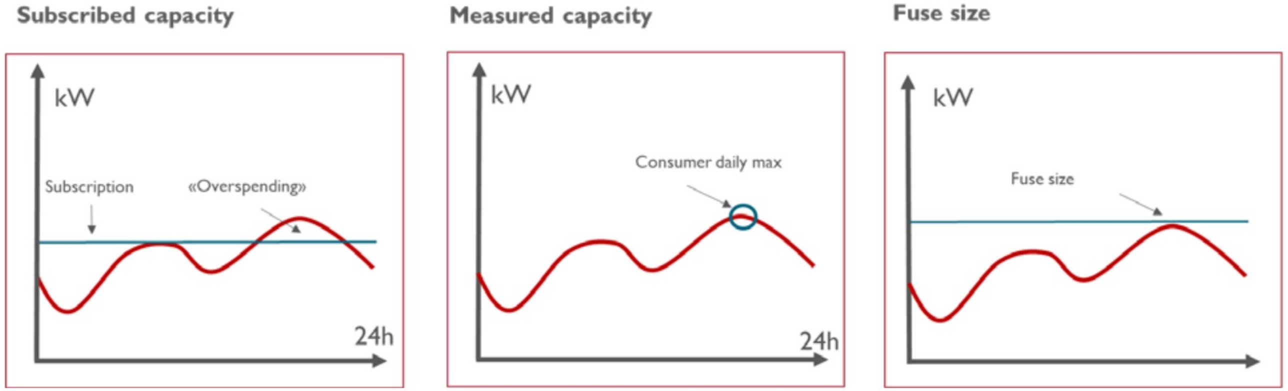


# Can we get more realistic? A 3-part subscription

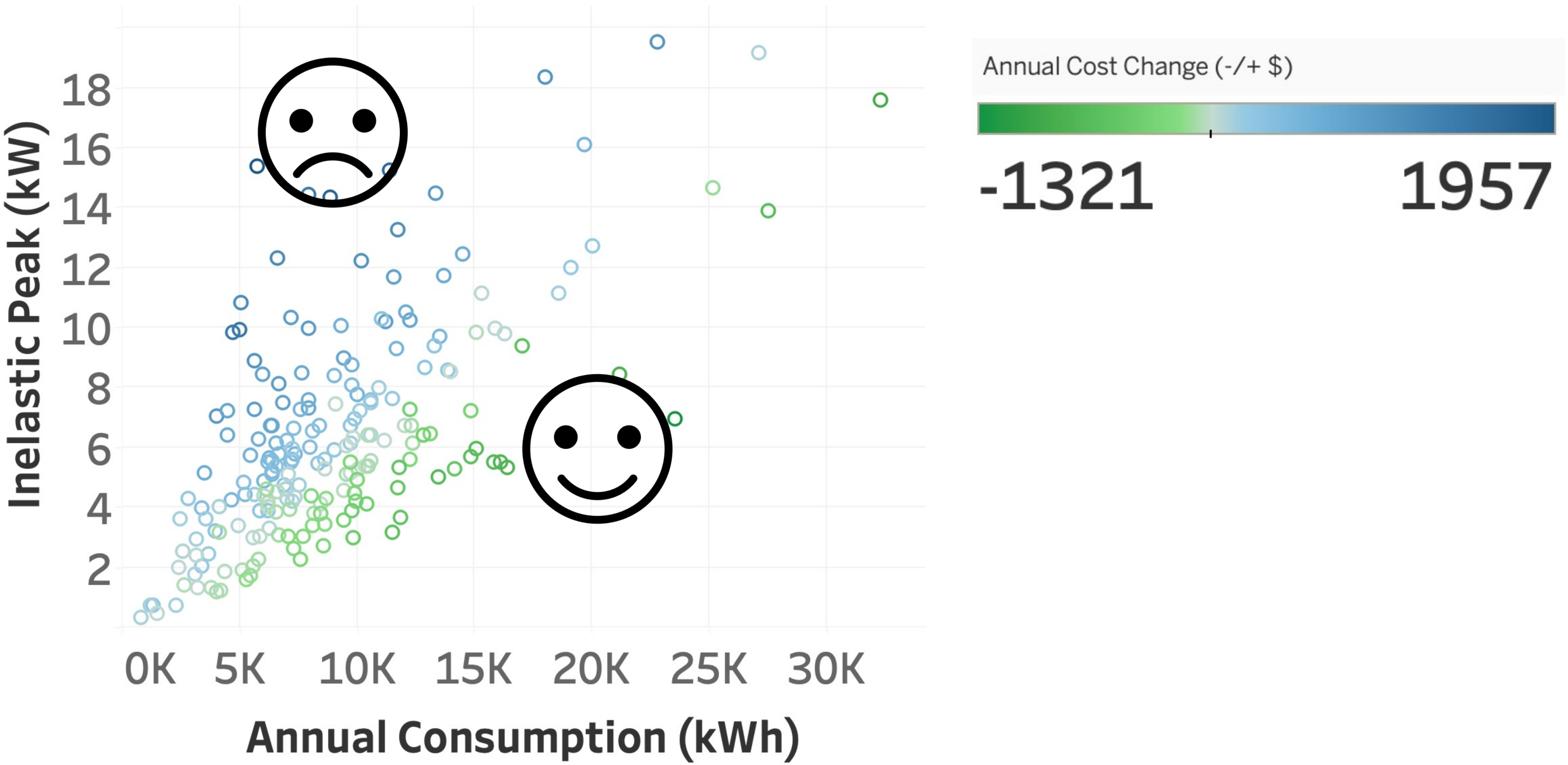
Methodology:

1. We run the optimization as for the 3-part capacity charge
2. We determine per consumer the peak usage in each of the 3 time-windows
3. Subscription value= peak usage + 1kW “buffer”
4. Run the optimization for each consumer again but now with a hard physical cap equal to the subscription value per time period

- Idea is that this is the “exercise” a consumer would do to determine its subscription
- Sensitive to the “buffer” value
- Easier for consumers to understand than ex-post capacity charge

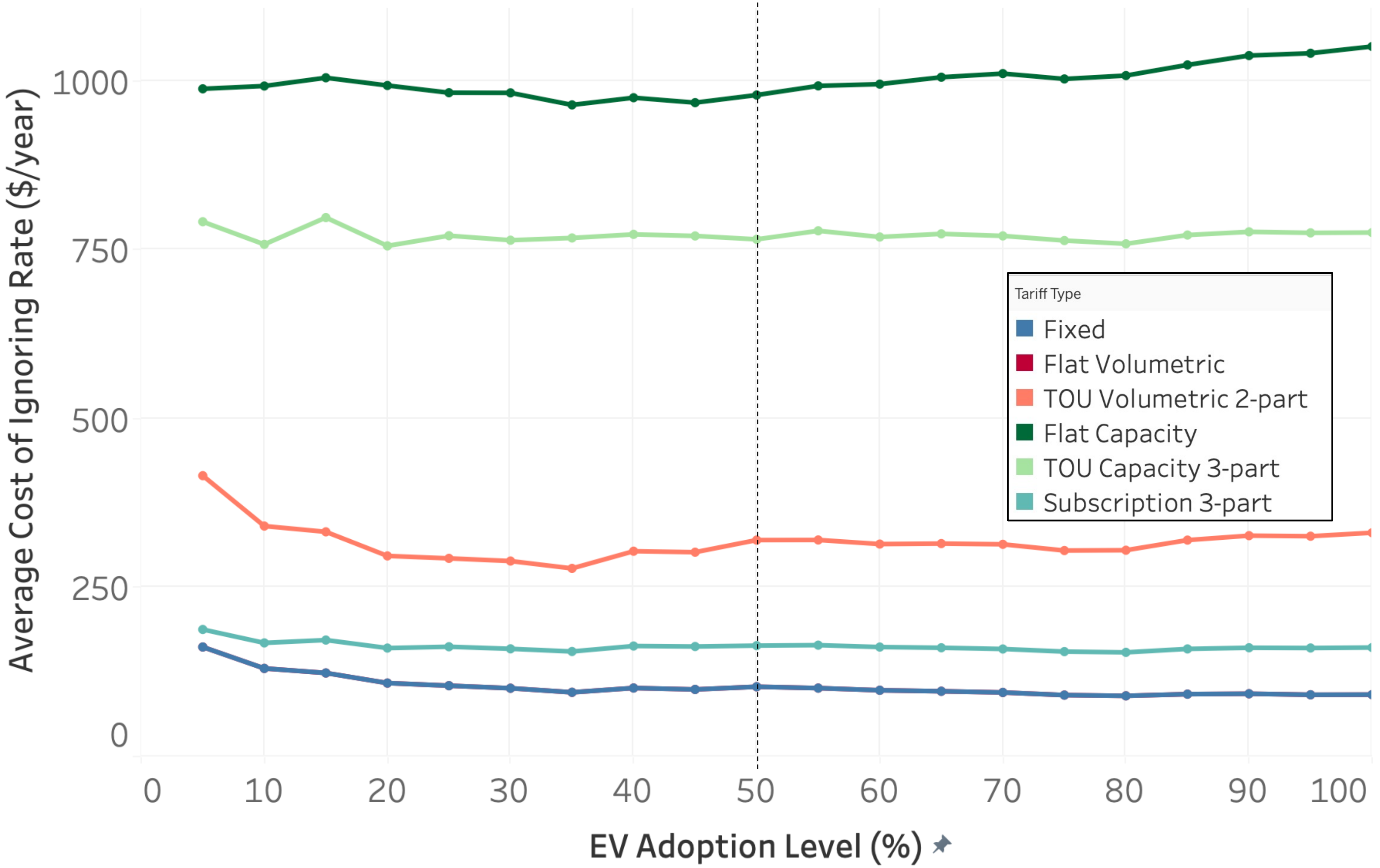
# Are non-electrified households impacted uniformly?

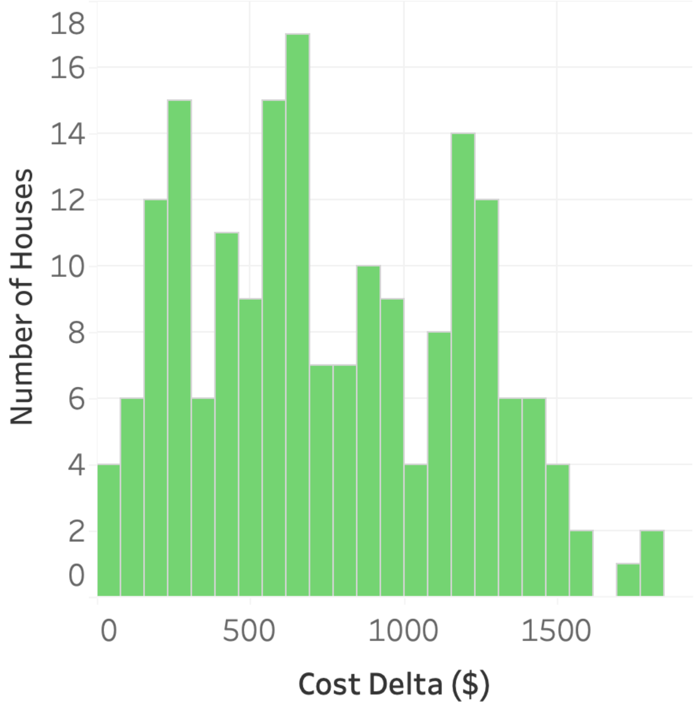
## *Subscription 3-part seasonal tariff at 50% electrification*

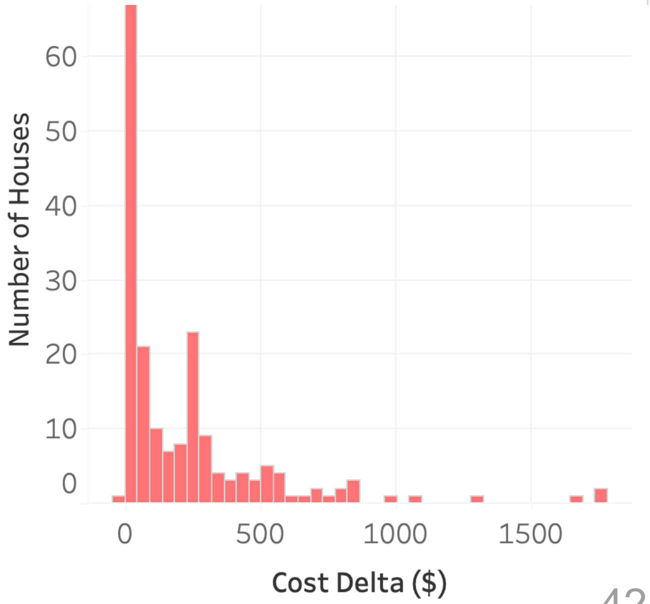


# What is the cost of not ignoring rates?

## Directly Full charging when plugged in



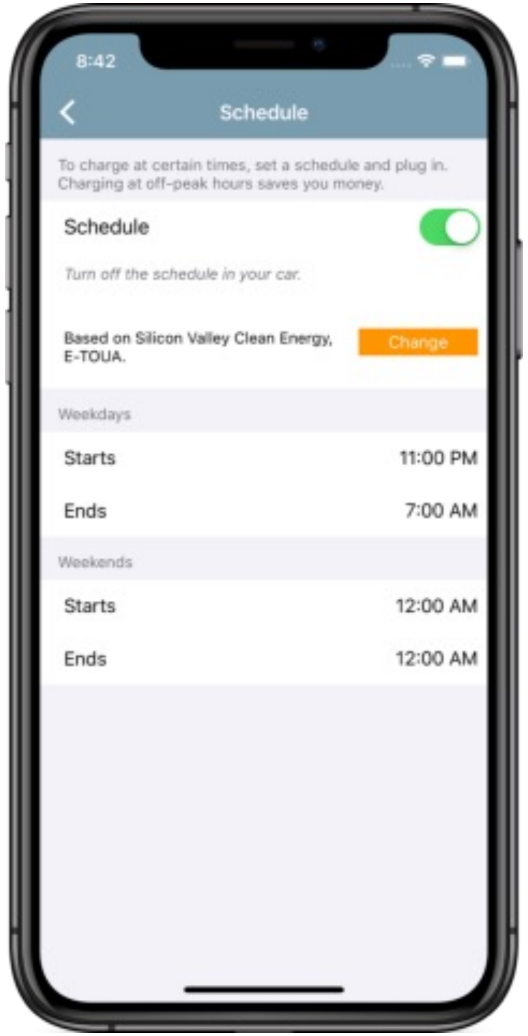



# How do we model EV response to price signals?

- Mixed integer linear program to minimize each user's cost of EV charging
- Tuning parameter: level of EV adoption
  - 0 – 100% with 5% steps

***EV charging load assumed to be flexible (perfectly price-responsive)***



# What are the assumptions & constraints of the optimization?

- Assign battery capacity based on driving profile: {40, 60, 90, 120} kWh (typical EV battery sizes)

***If drive short distances, more likely to buy a smaller (& cheaper) EV***

- Heterogeneous inelastic home profiles, unique & uncorrelated driving profiles
- No public/workplace charging & perfect foresight
- TOU energy price
  - peak: 8am-9pm weekdays, the remainder off-peak (ratio 2:1)
- EV charging constraints
  - Max 7.2 kW (30 A, 240V)
  - Nudge to leave the house each day with 100% battery charged
  - Battery state of charge cannot go below 10%

# Which standard tariff designs do we test and how are they structured?

## Magnitudes under 0% of EV adoption

| Tariff Type | Cost |
|---|---|
| Fixed charge | $ 1000 per year |
| Flat volumetric (baseline) | $0.11/kWh all hours[a] |
| TOU volumetric 2-period | $0.07/kWh off-peak[b]<br>$0.18/kWh peak[b] |
| Flat capacity | $158/kW-year |
| TOU capacity 2-period | $57/kW-year off-peak[b]<br>$111/kW-year peak[b] |

*As we add EVs, revenue requirement increases proportional to annual coincident peak over the 400 households*

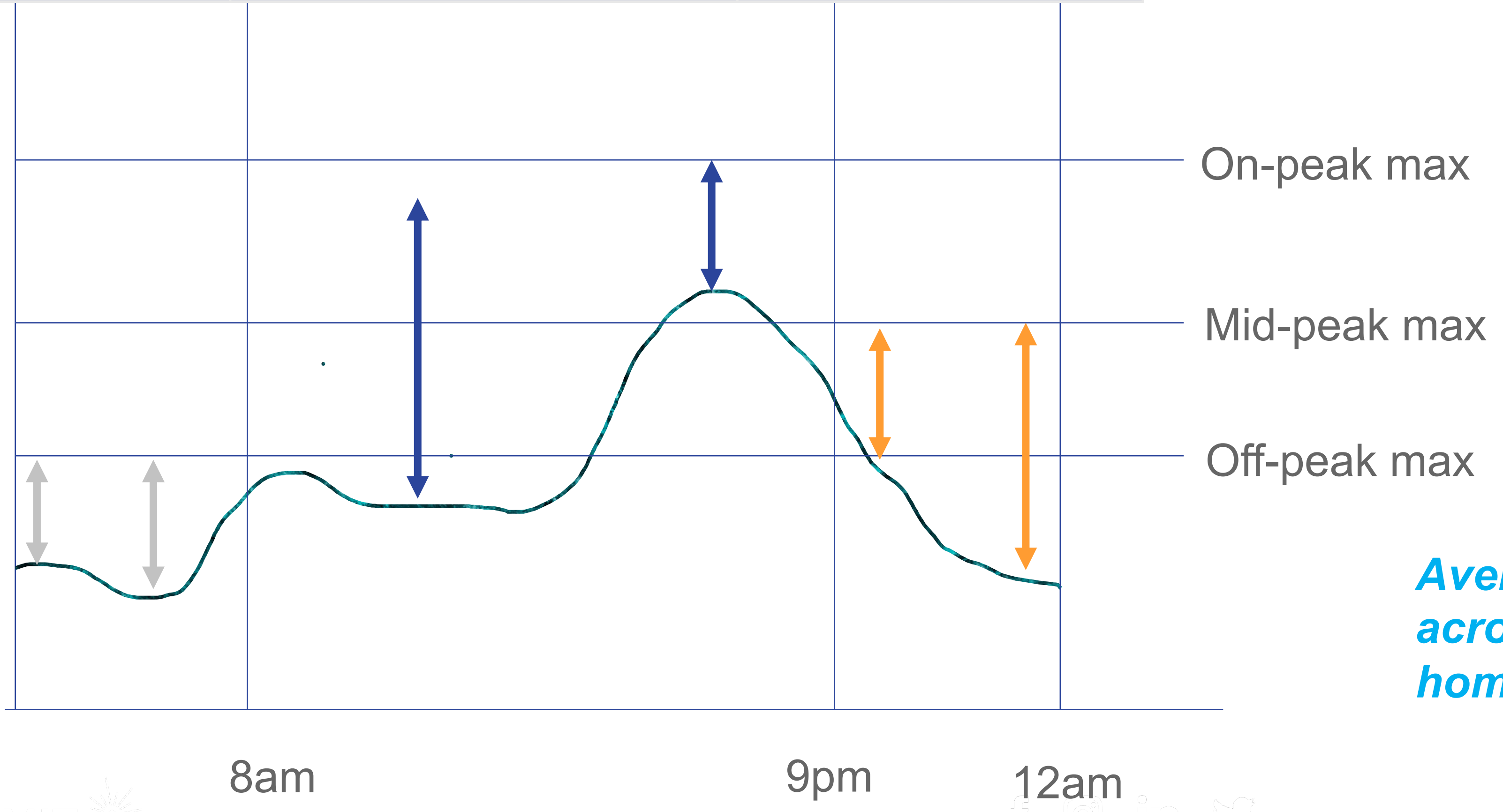
| Incremental peak cost | +$100/kW |
|---|---|

*Equilibrium reached when response does not deviate & full revenue requirement is collected*

[a] Eversource network charge as of March 2023
[b] Peak hours are M-F 8am-9pm, on-peak set at 2x peak based on National Grid rate G3

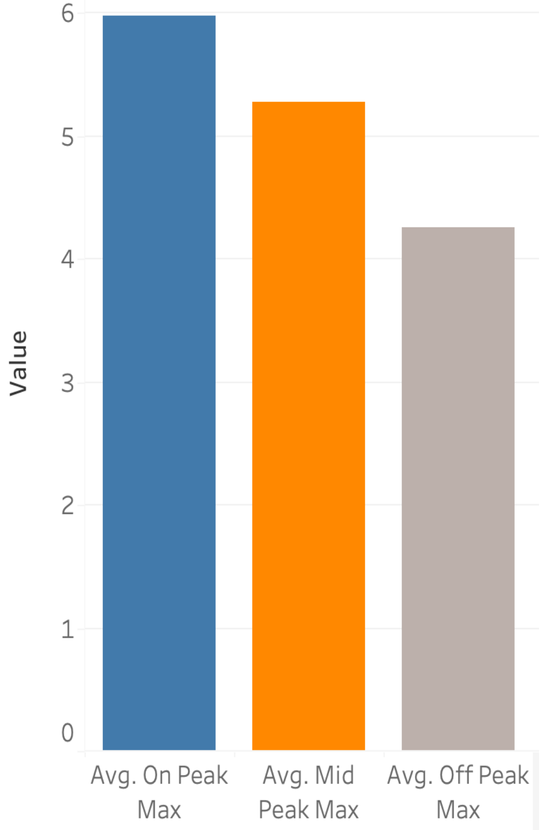
# Can we do better? The three-part capacity tariff

| Block | Time | Revenue share |
|---|---|---|
| On-peak | Weekdays 0800-2100 | 1/2 |
| Mid-peak | Weekdays 2100-0000 | 1/3 |
| Off-peak | Weekdays 0000-0800 | 1/6 |

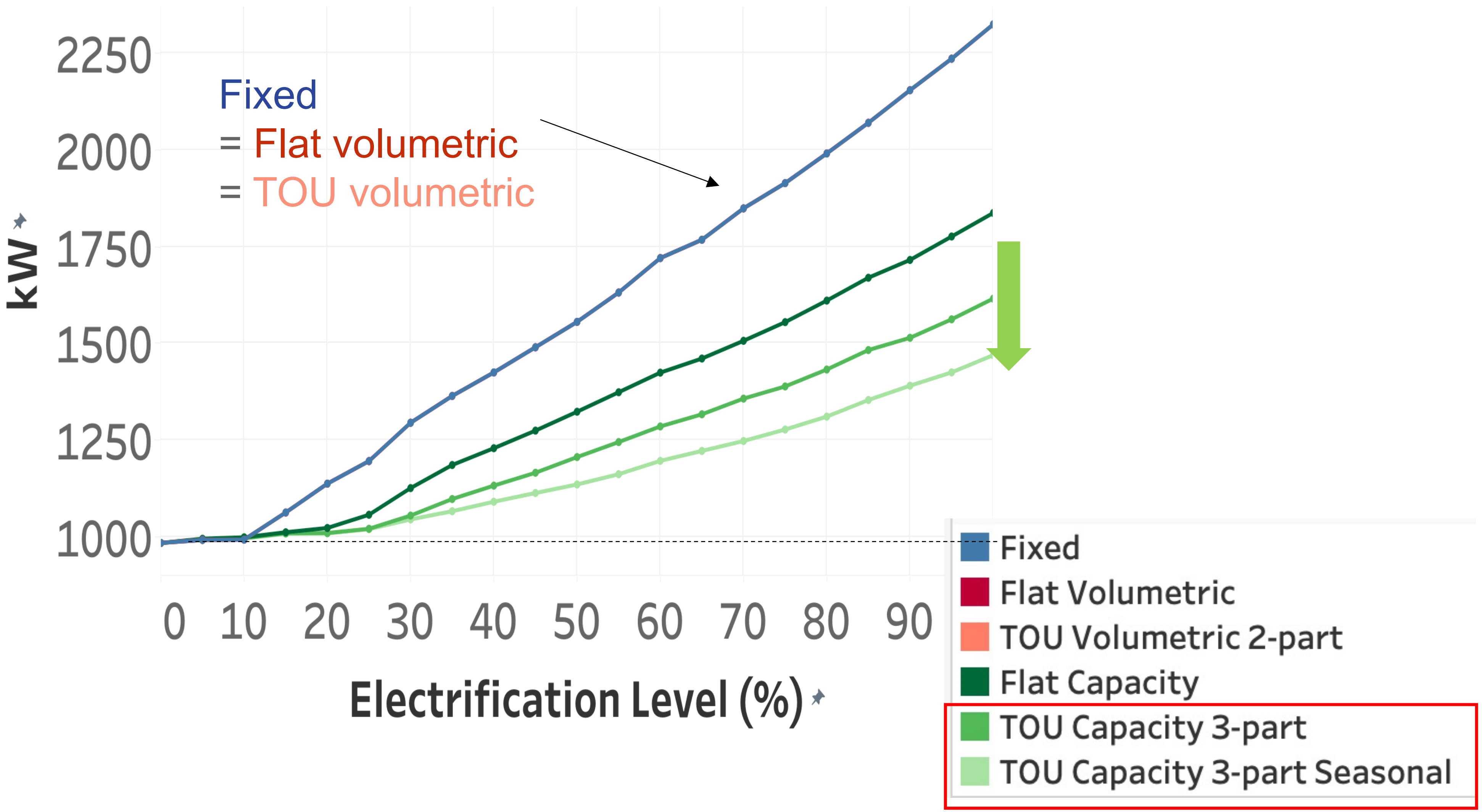



***If we have 3 separate capacity charges, midnight-8am is likely the MOST restrictive because has the lowest inelastic peak***

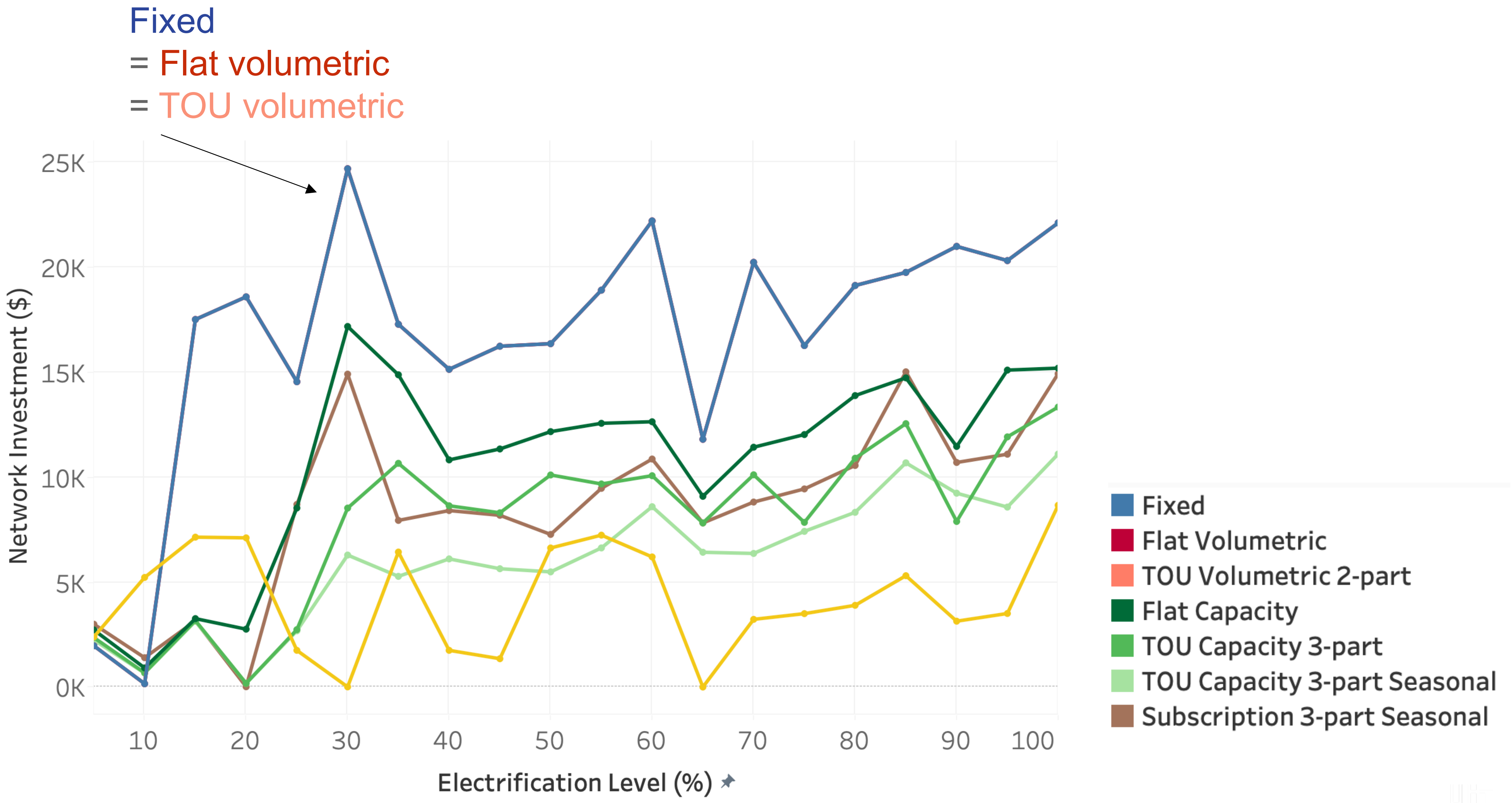
***Average across all homes***



# Can we do better with time/seasonal differentiation?



# What is the incremental network investment in each step?

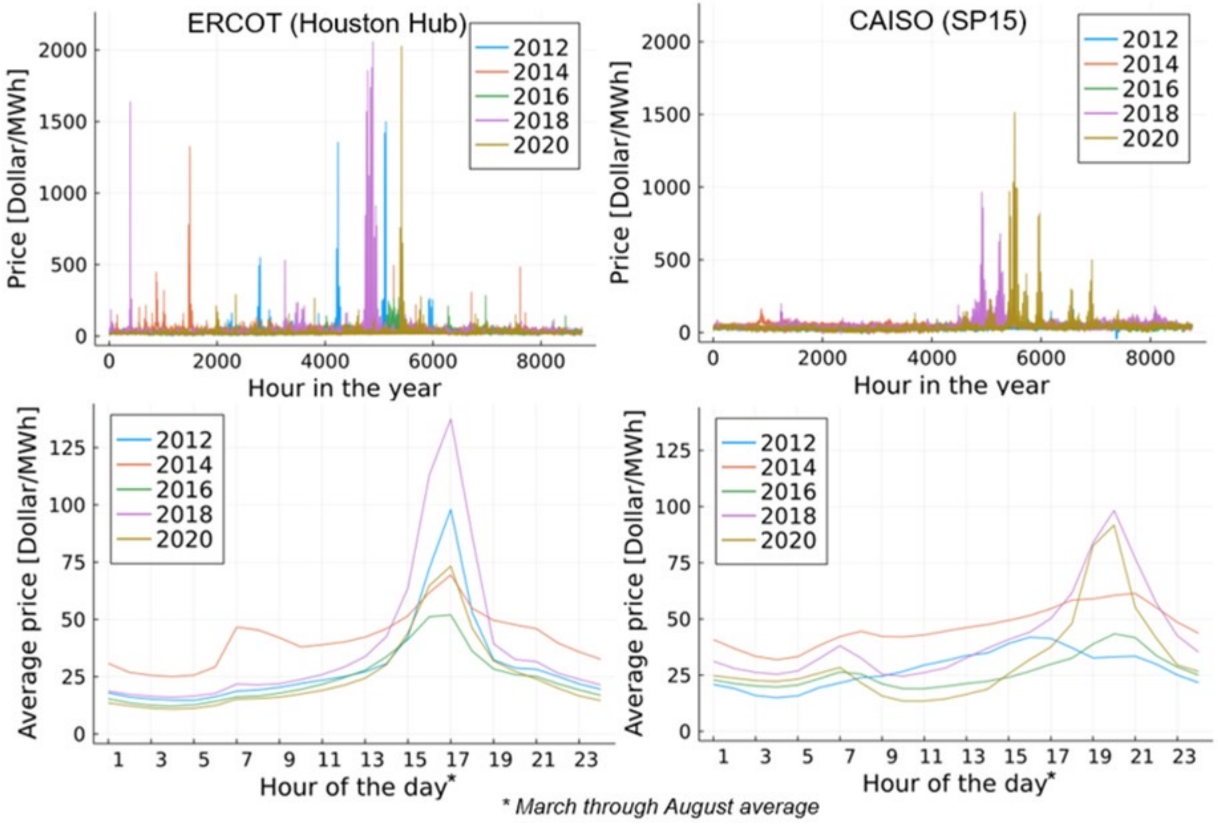


# What we are thinking of investigating next?

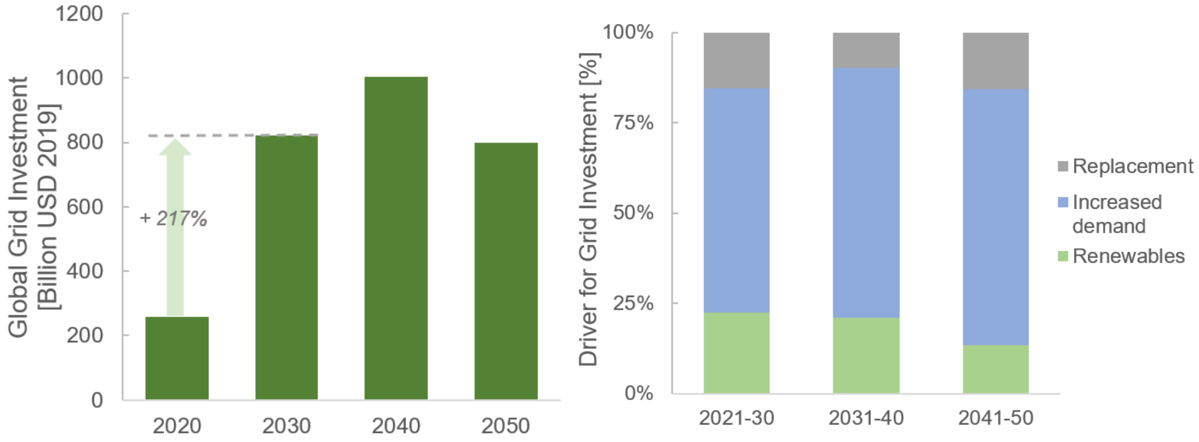
- Addition of elastic heat pump load; don't want technology-specific rates; rates should work for both HP and EV
- Look at how load control complements network charge design
- Introduction of (differentiated) fixed charge to mitigate distributional impacts and carry part of the distribution costs (capacity charges are now very high and not related to LRMC)
- Look deeper into seasonal capacity charges (rather than annual) & creation of "noise/bandwidth" to relax the perfect foresight condition
- Test robustness against different TOU energy pricing regimes
- Look deeper into results with dynamic pricing (wholesale prices won't be exogeneous anymore)

# Two big pieces of the retail rate puzzle

1. Retail customers do not see the often-substantial hour-to-hour variation in the marginal cost of electricity supply, reflected in spot wholesale prices

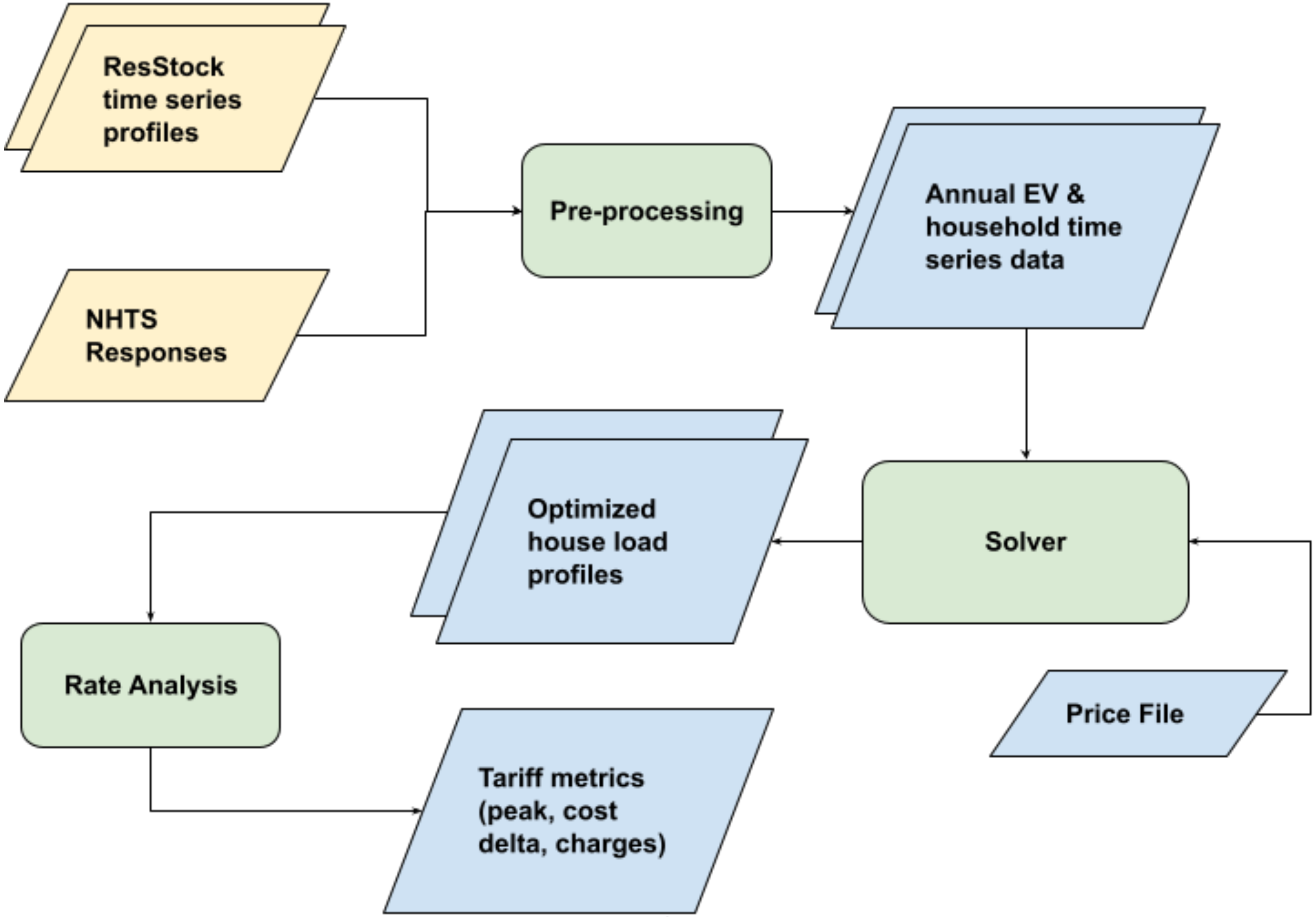



2. Investment-related costs are embedded into volumetric rates while in the short-run these costs are fixed and do not vary with instantaneous consumption




*IEA 2050 Net Zero Emissions scenario (IEA, 2022)*

# High-level overview methodology



# High-level overview methodology

- We model 400 households with unique hourly load profiles during one year
- We vary the rate of electrification over the households; each EV has a unique driving/plug-in schedule:
  - EV load responds rationally to price signals when plugged-in (perfect foresight) – MILP
- We assume the **energy prices to be exogeneous and reflected via a simple two-period TOU tariff** (peak: 8am-9pm weekdays, the remainder off-peak), no other distortions
- We test **four standard formats network tariff designs**: fixed, volumetric, capacity with and without time differentiation, and subscription
- We assume those 400 households are connected to one feeder and increases in the annual aggregated coincident peak demand lead to linearly increasing network costs
- The revenue requirement equals the base case network costs (no electrification) plus a constant (≈ LRMC) multiplied by the delta in coincident peak demand relative to the base case (iteration until equilibrium = cost recovery)
- We asses the results based on **three metrics**: annual aggregated coincident peak, levelized cost of charging, and change in the network costs for non-EV households