Unintended Consequences of Time-of-Use Rates: EV Charging and Distribution Network Constraints

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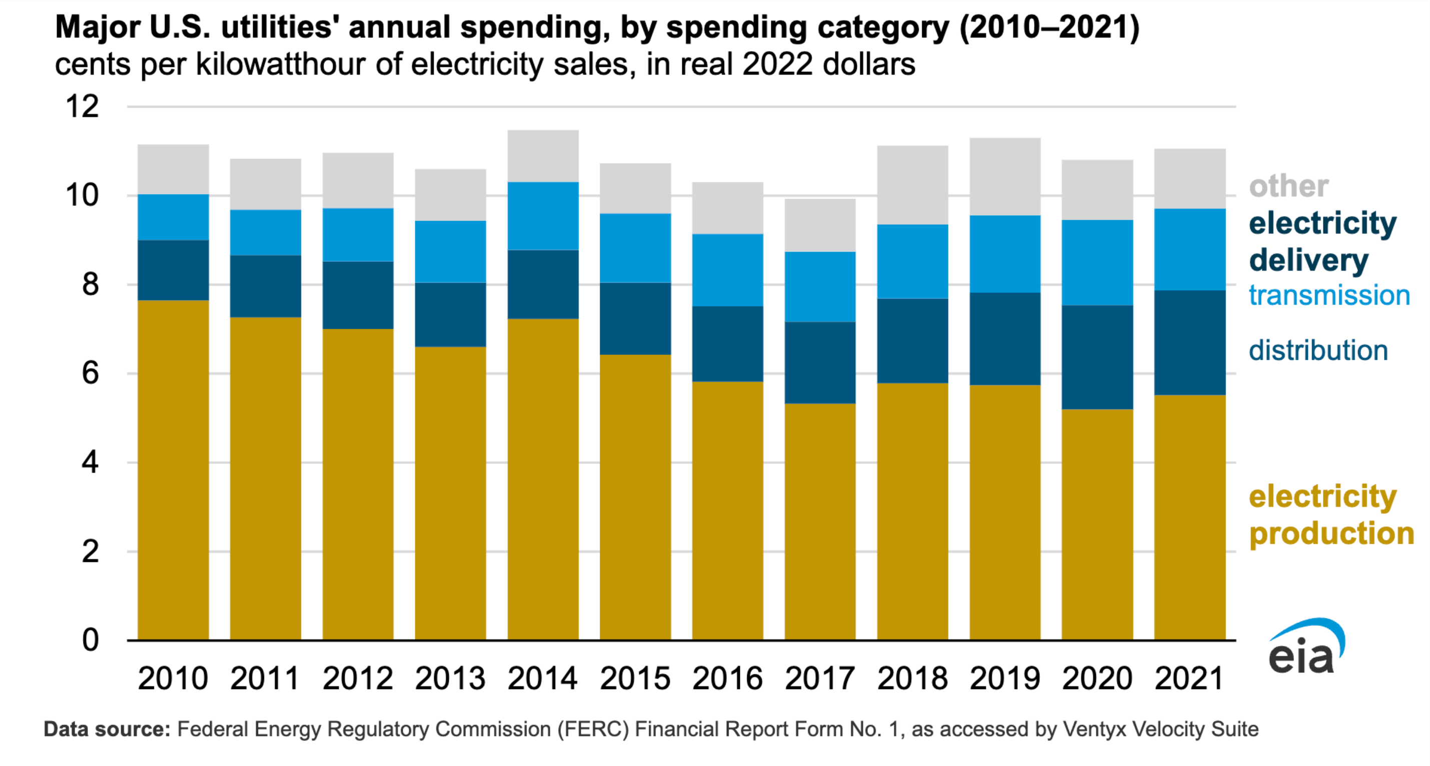
Some motivating trends…

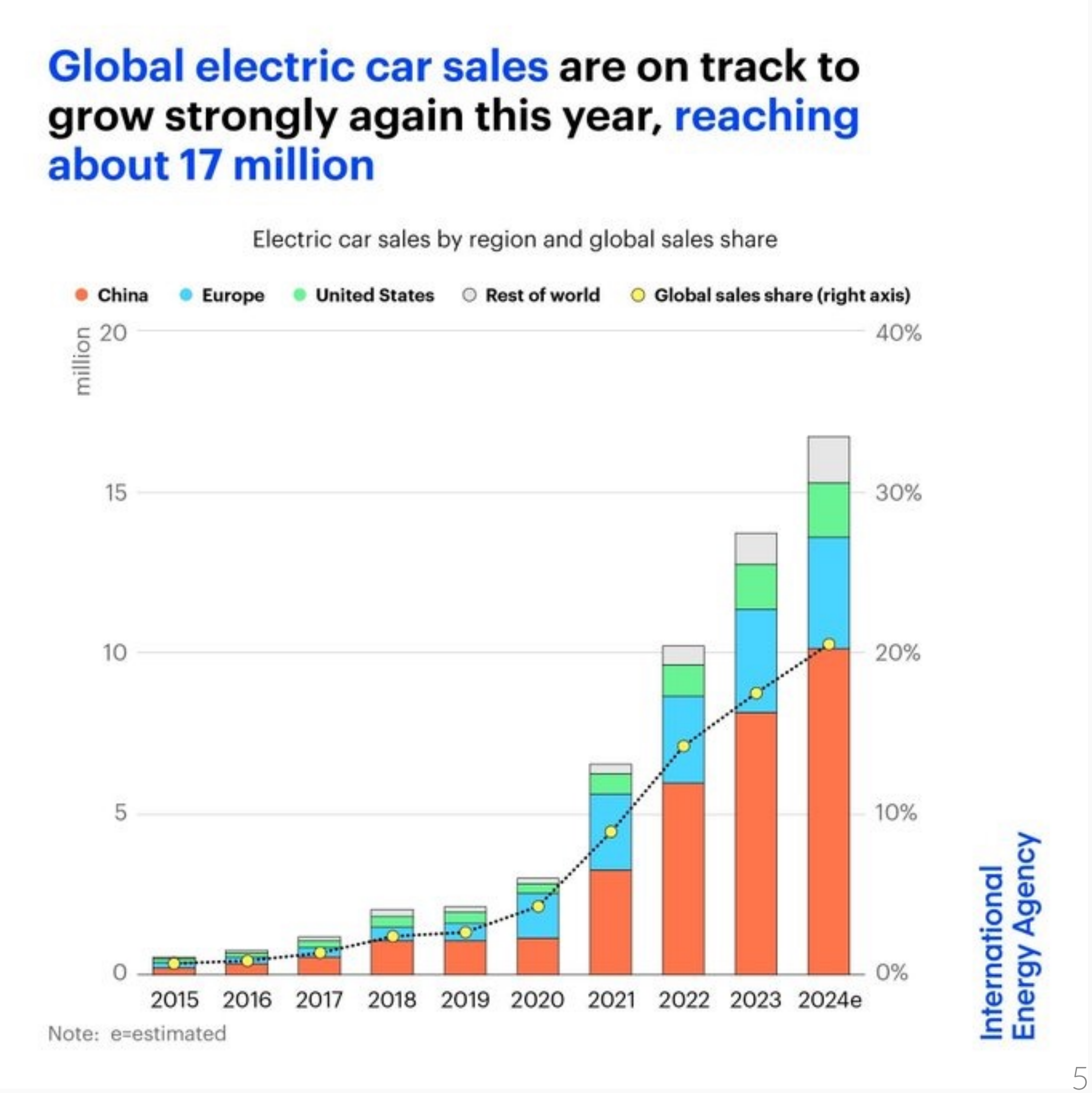
#1. Distribution costs are rising

- T&D share of total costs is rising
- Since 1990, annual spending (in real $ terms) on the distribution system has more than doubled (EIA, 2023)



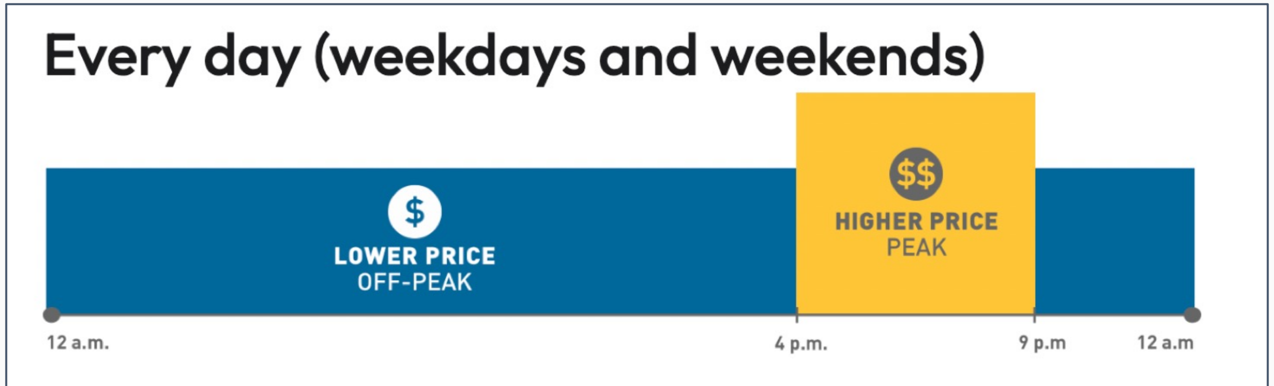
#2. Electric vehicle sales are rising

- EV sales continue to grow
- And… EV charging loads can be <u>large</u>
  - Level 2 (240V): 5-12kW
  - Compare to AC, dryer, oven: 1-3kW



#3. Increasing use of Time-of-Use (TOU) rates

- TOU is now the default rate in many US states
- Goal: Shift consumption away from peak demand periods



PG&E – TOU-C (2024)

VANCOUVER SUN

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B.C. Hydro launches new optional time-of-day pricing

Customers who choose to use electricity during off-peak hours can save money by opting into the new rate system

Joseph Ruttle

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How will EVs affect the electricity system?

In terms of…

1. **Energy** (level of demand)
2. **Capacity** (timing of demand)

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1. **Energy** (level of demand)
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a. **the bulk energy system**

b. **local distribution systems**

EV charging will affect different parts of the electric system differently

More granular (less diversity in average load profile)

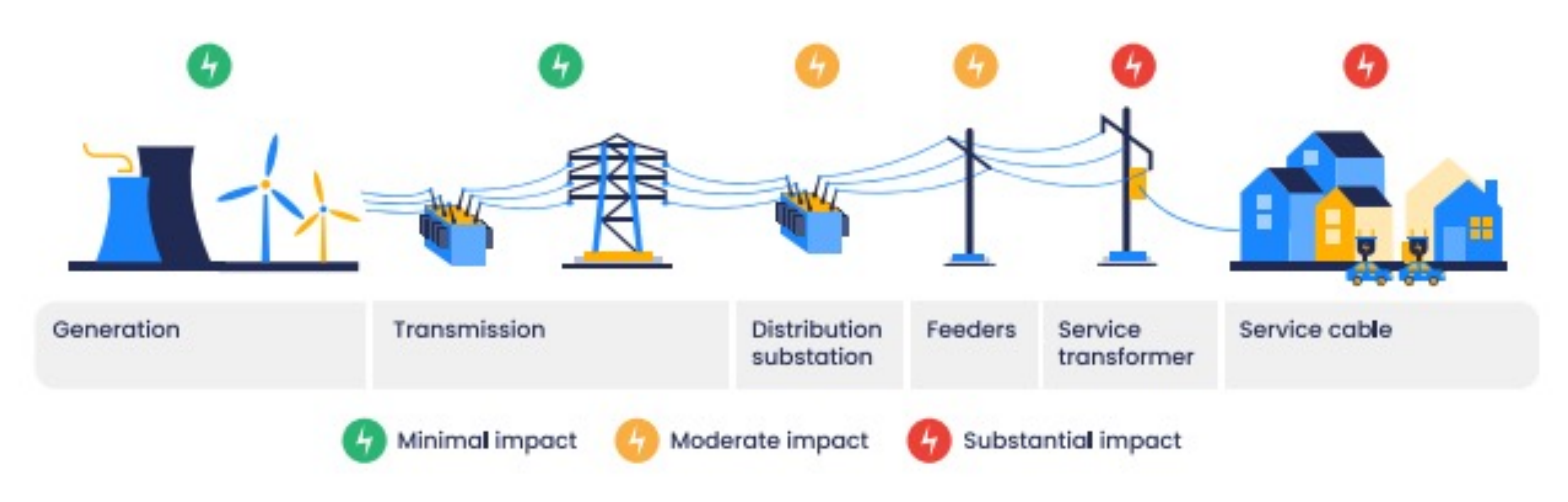

Image from EnergyHub (2023)

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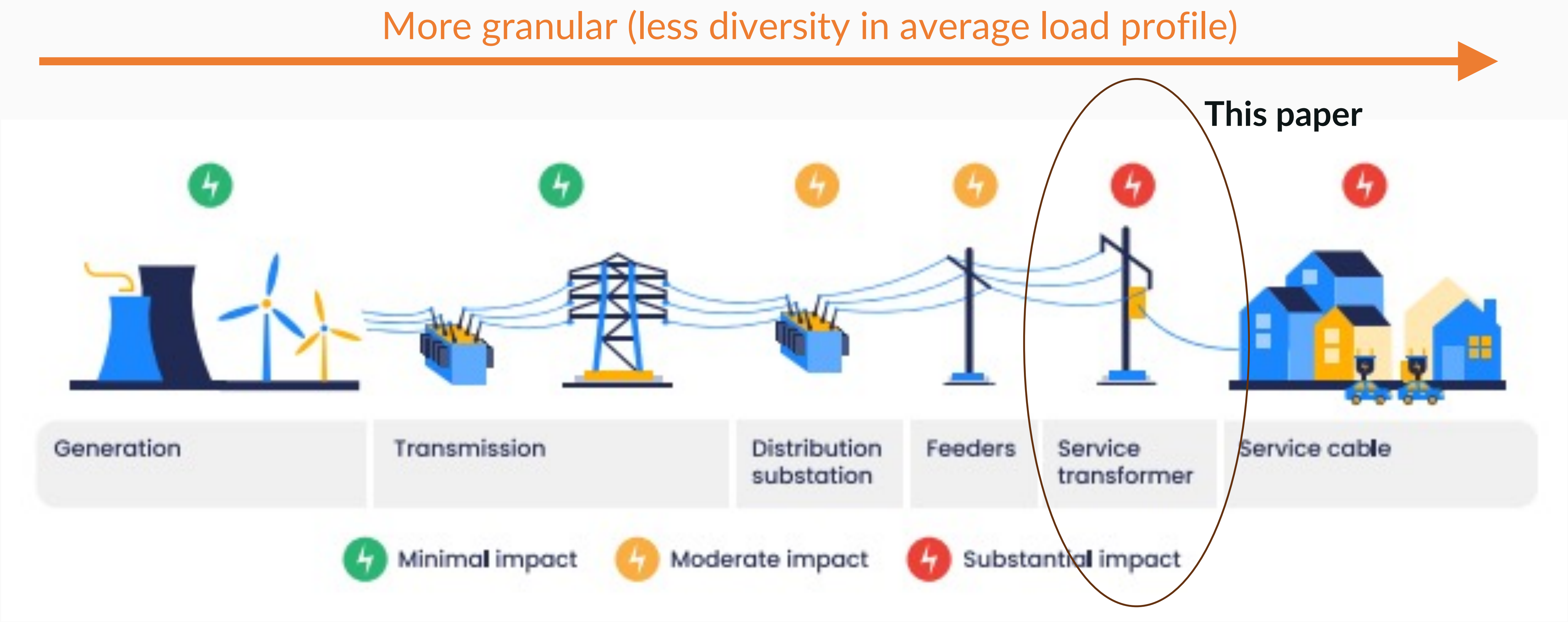
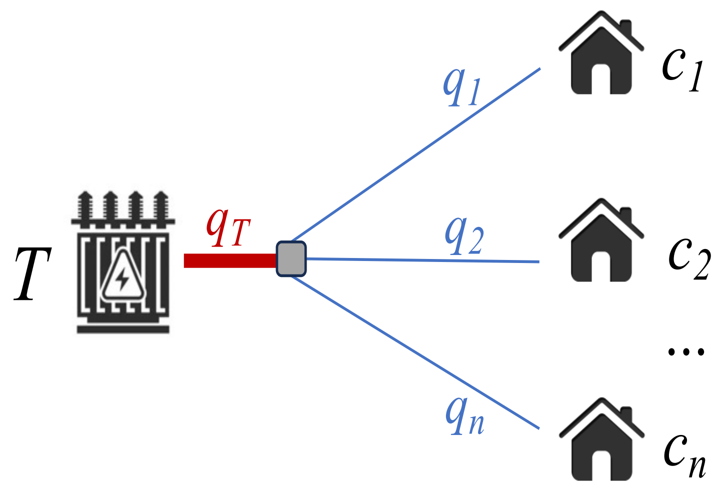


Image from EnergyHub (2023)

The Distribution Network Challenge

- ***We follow a simple conceptual model from Boiteux and Stasi (1964)***

- Consider a distribution transformer, T, serving a set of individual household loads, c_i, $i=1..n$
- The transformer must be sized, q_T, to allow sufficient power flow to serve the aggregate of all downstream loads, q_i



How to size the transformer, q_T?

- If all q_i were known, this problem is simple:

$$q_T = \sum_i \max q_i$$

- But q_i are uncertain and thus the flow requirement can be viewed as a draw from a distribution of aggregate loads. The transformer is sized to the average draw plus an "irregularity margin":

$$q_T = \bar{q} + \lambda\sigma$$

- One more step… the aggregate distribution stems from individual loads. It matters whether individual irregularities are **correlated** with one another:

$$\boldsymbol{q_T = \sum_i (\bar{q}_i + \lambda K_i \sigma_i)}$$

Factors that affect transformer size (and cost)

$$q_T = \sum_i (\overline{q_i} + \lambda K_i \sigma_i)$$

This expression provides intuition for transformer capacity size (and thus costs):

1. q_T increases with average peak demand $\overline{q_i}$
2. q_T increases as individual irregularities, σ_i, increase
3. q_T increases as the correlation across irregularities, K_i, increases

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In our EV context:

- EV charging increases total demand (increases $\overline{q_i}$)
- Level 2 charging is large kW (increases σ_i)
- **Our study looks at how TOU rates affect the correlation of load irregularities (?? K_i)**

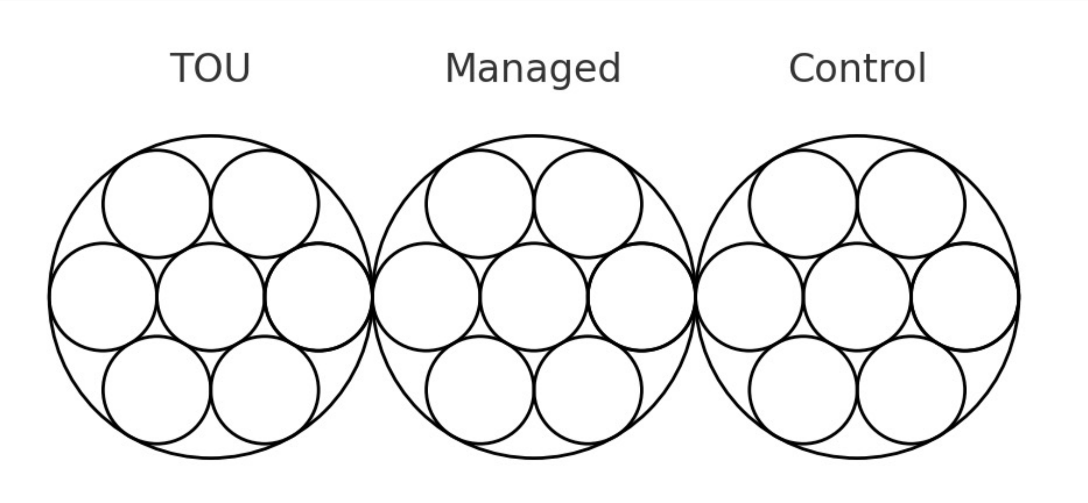
The Field Experiment: What we do

- Partnered with **FortisAlberta**, a local distribution company in rural/suburban Alberta
- Worked with **Optiwatt**, a software company
- Recruited approx. **200 EVs**
- Monitor all vehicles pre-intervention and then **randomize** to treatment arms

The Treatment Groups

1. **TOU**
   - receive 3.5c/kWh reward for all off-peak charging
     (Off-peak: 10 AM - 2 PM; 10 PM - 6 AM)
2. **Managed Charging**
   - receive a 3.5 ¢/kWh reward for all managed charging at home
3. **Control**
   - no additional messaging

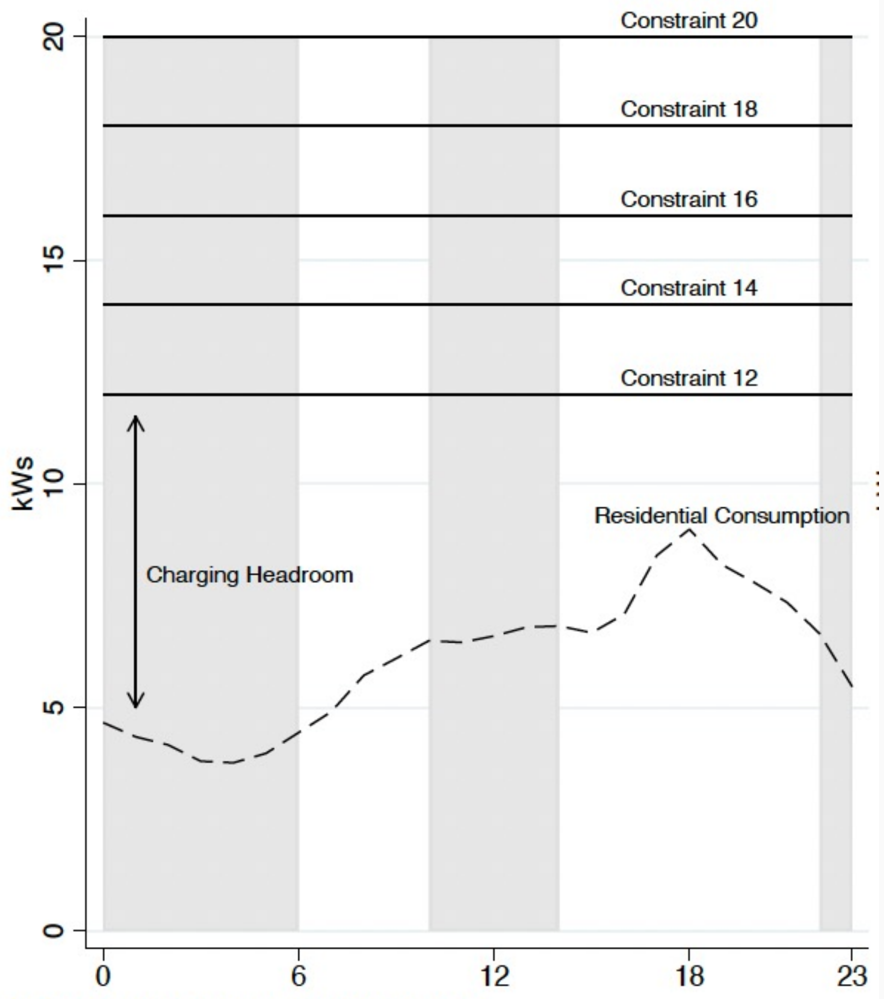
Going beyond individual behaviour



- Further randomized into "**virtual transformer groups**" of 10 EVs
- Monitor aggregate loads on each virtual transformer group
- Assign distribution constraint limits for virtual transformers
- Key metric: **<u>Violations of transformer constraints</u>**

Transformer Constraints and Charging Headroom

- Virtual transformers (10 EVs)
- Set a range of constraints
- Use representative non-EV load shape
- Charging headroom =
  transformer constraint – non-EV load



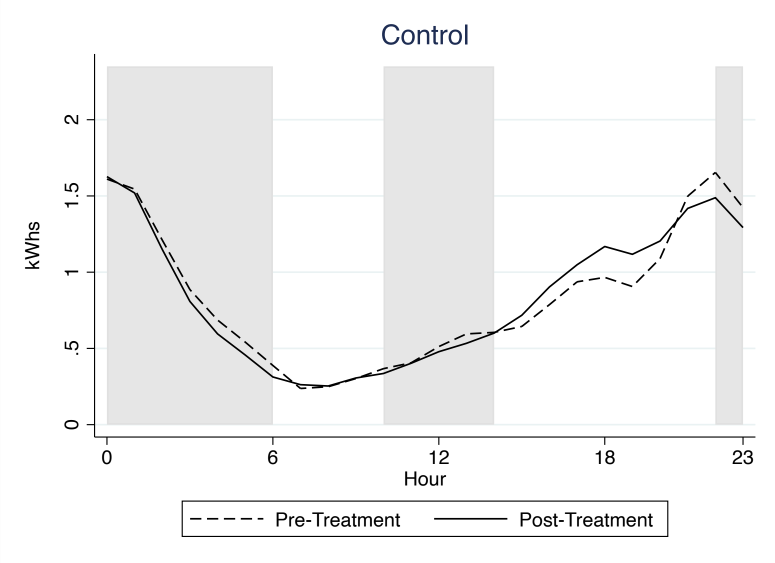
Notes. Shaded region reflects off-peak hours.

How Managed Charging works

- EV drivers set desired state-of-charge and departure time
- Optiwatt **sequences** charging to:
  a) satisfy charging preferences
  b) subject to remaining within the available "Charging Headroom"
- EV owner can override managed charging by pushing a button on the App ("Boost")

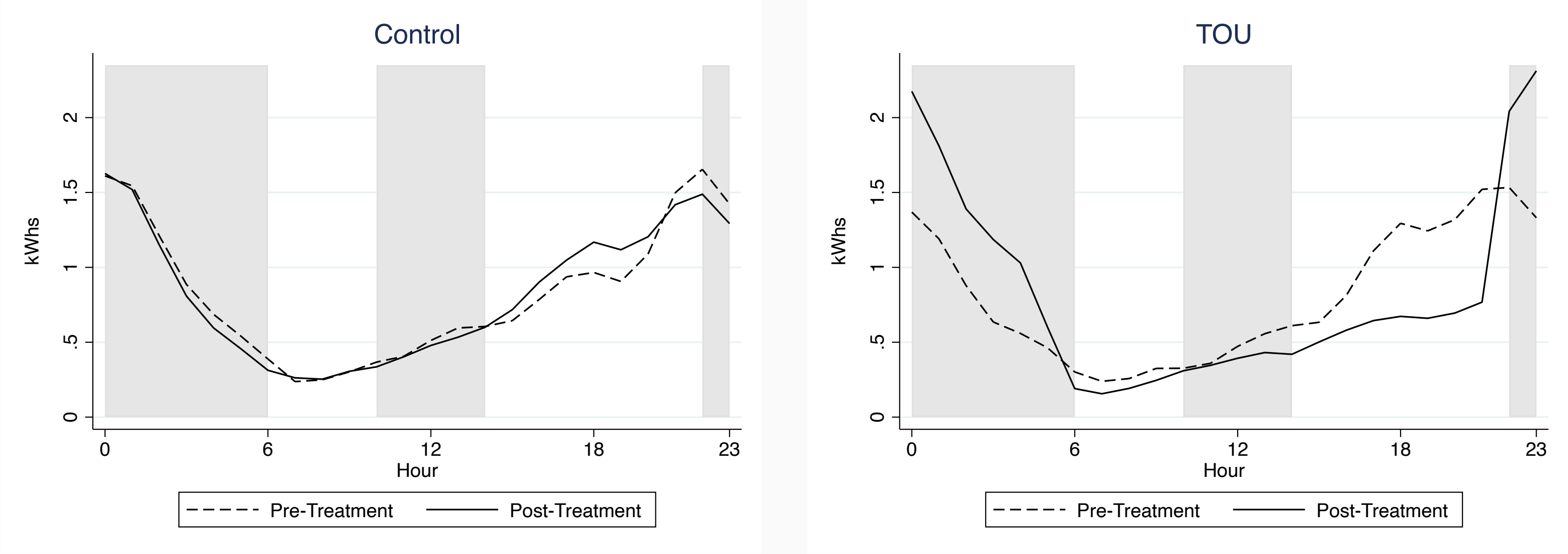
What we find

Average Hourly Load Shape



- No change to **Control**

Average Hourly Load Shape



- No change to **Control**
- Large shift to **TOU** shape

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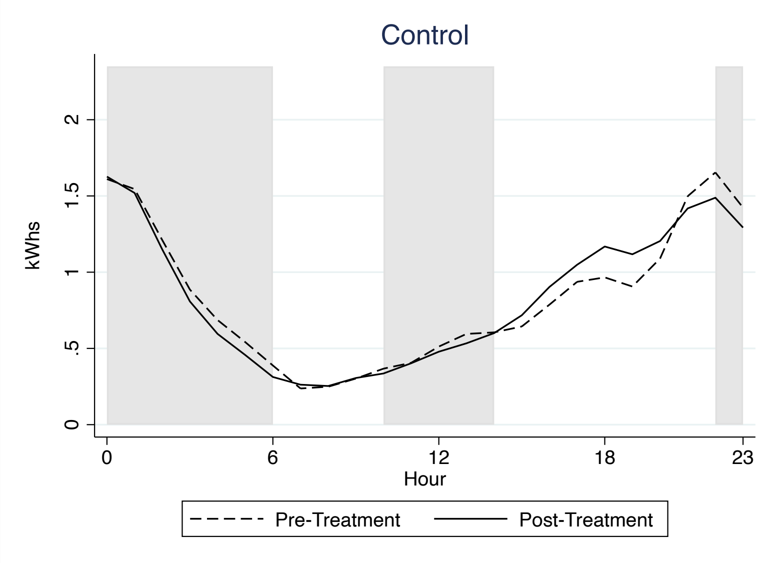
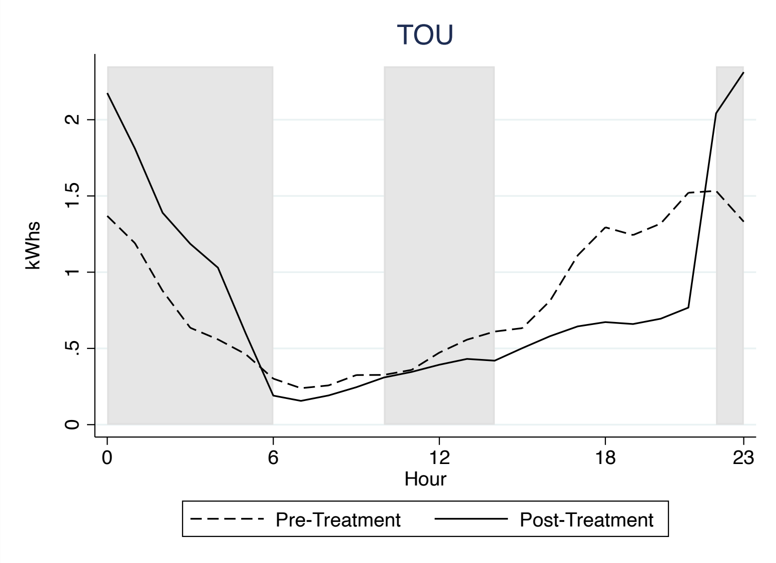
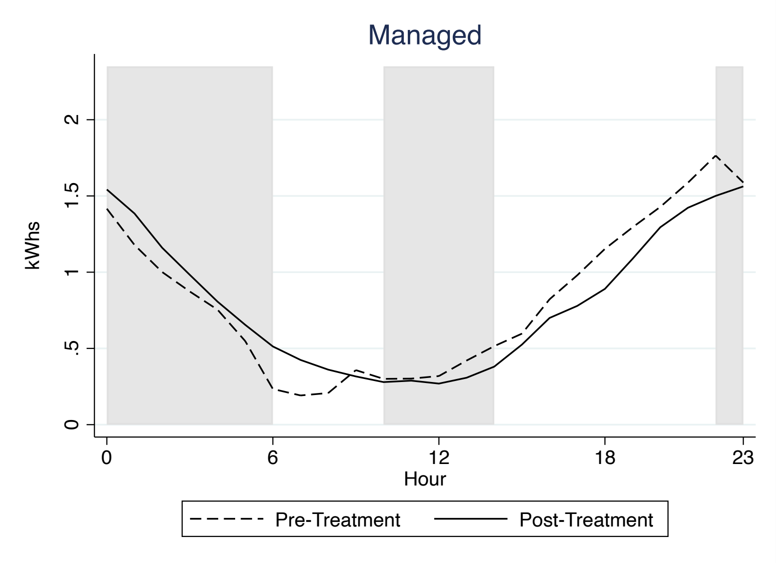
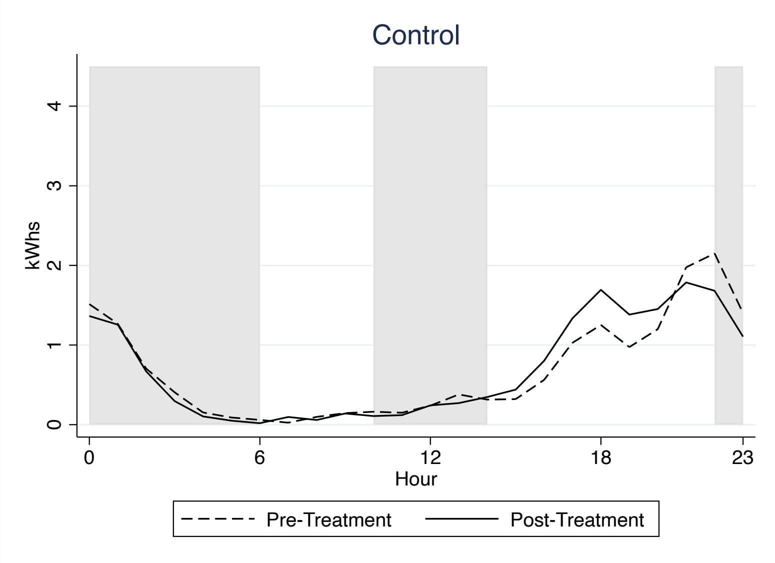






- No change to **Control**
- Large shift to **TOU** shape
- No change to **Managed** shape

Average Hourly **Transformer Violations**



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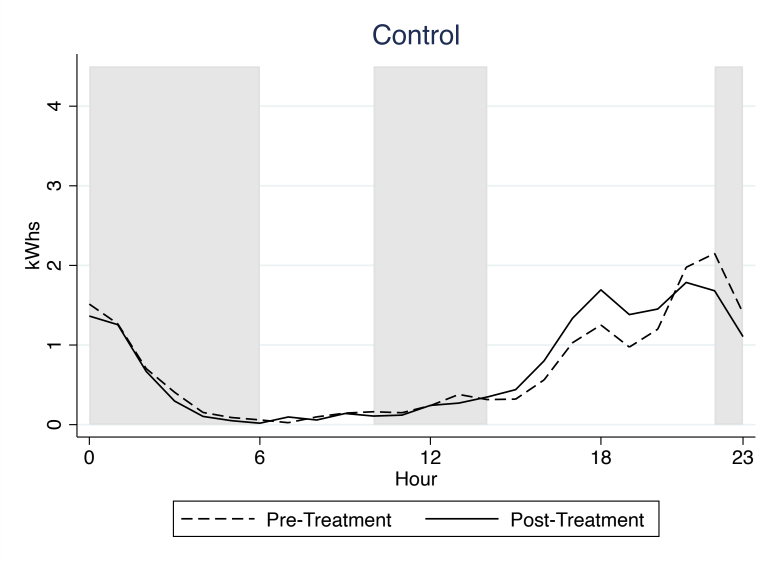

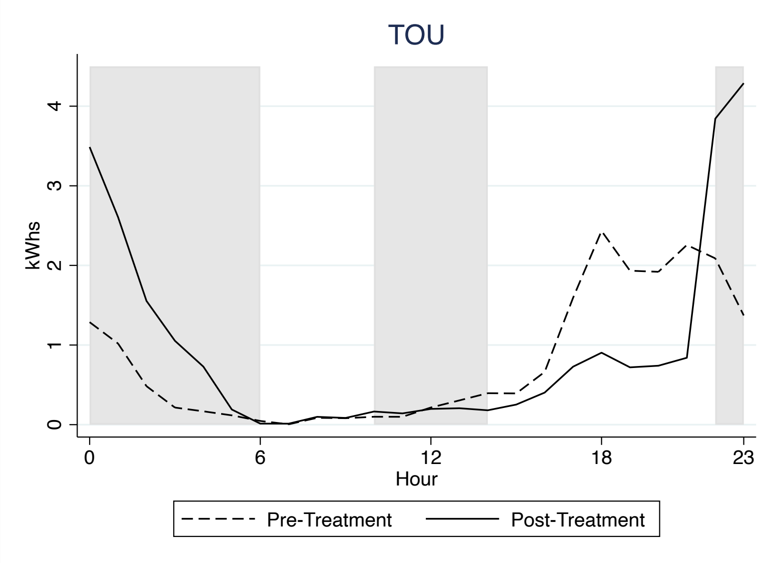

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- Larger violations for **TOU**
- **New "Shadow" peak**

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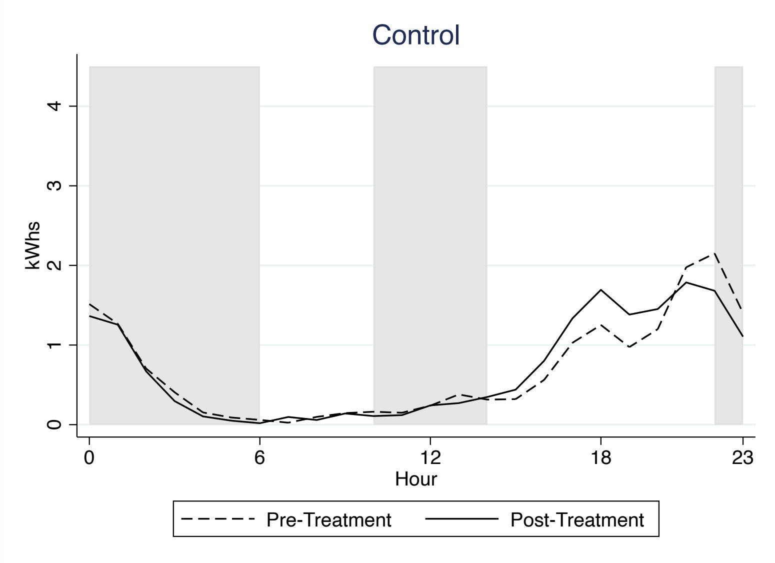

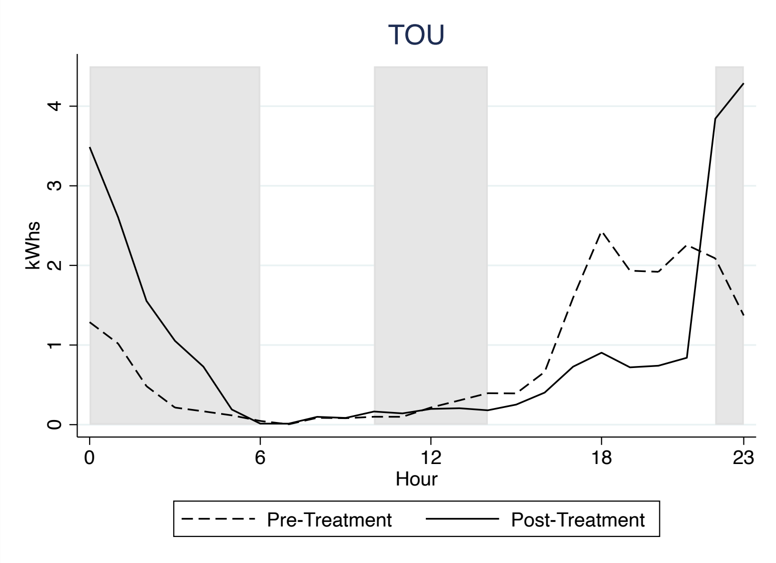

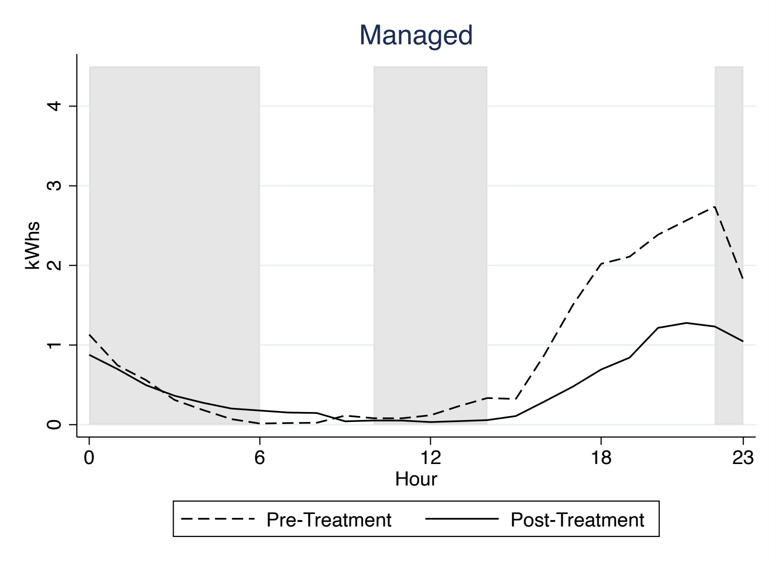

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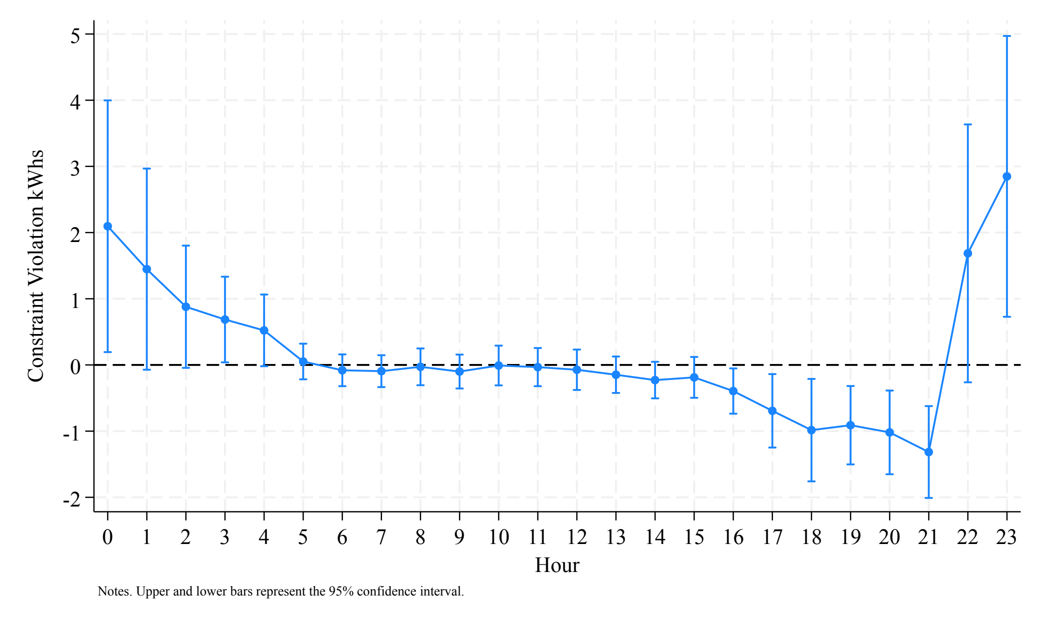
- Reduced violations for **Managed**

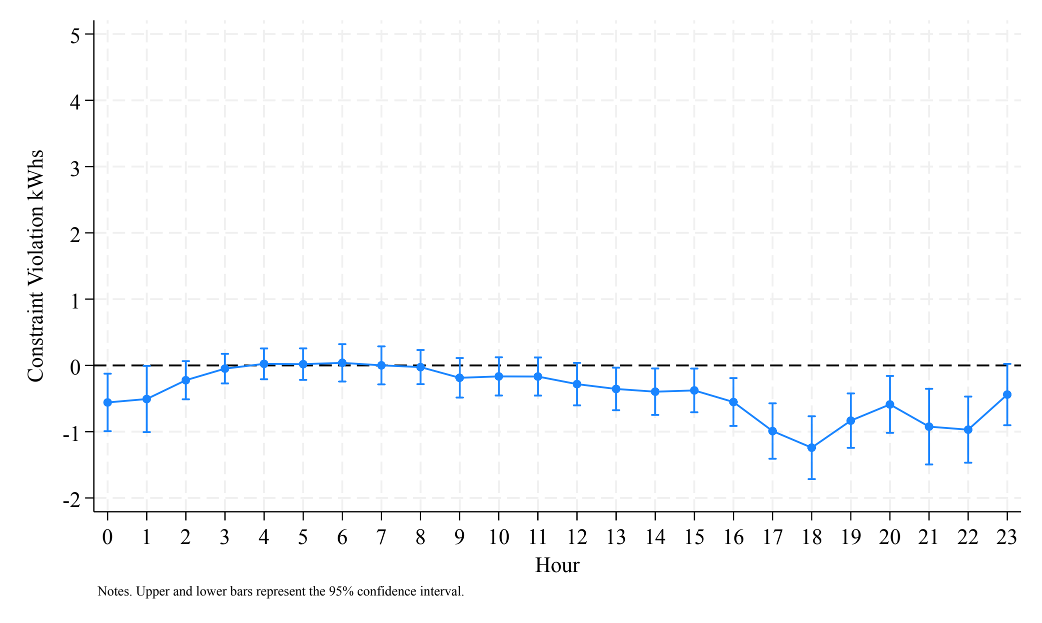
Regression Results

TOU Group



- Increased violations in off-peak
- Slight reduction in peak

Managed Group



- Reduced violations in most hours

Summary of Main Findings

Time-of-Use:

- Effective at shifting load to off-peak
  - Off-peak charging ⬆️ 64%
- But… ***TOU <u>increases</u> transformer violations***!
  - Peak violations ⬇️ 47%; Off-peak violations ⬆️ **138%**

Managed Charging:

- Reduces transformer violations by spreading charging more evenly
  - Peak violations ⬇️ 49%; Off-peak violations ⬇️ 45%
- Limited “boosting”
  - Less than 1% of charge-days over-ridden by EV owners

Key Implications

1. Need to rethink TOU as a solution to EV charging
    - *Likely to* ***increase*** *distribution costs with large EV adoption!*
2. Dynamic ("realtime") pricing makes it worse
    - *Concentrates charging into narrower time window, increases* K_i
3. Pricing solution requires more complex prices
    - *Household-time specific*
4. Managed charging can resolve the coordination challenge
    - *… but how to get people comfortable with it?*

Thank you!

Questions?

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