Demonstrating the Full Value of Managed Electric Vehicle Charging

BASED ON A REAL-WORLD TRIAL OF ENERGYHUB'S EV SOLUTION

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JANUARY 2026

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Disclaimer and Acknowledgements

This report was prepared by The Brattle Group for EnergyHub. It is intended to be read and used as a whole and not in parts. The report reflects the analyses and opinions of the authors and does not necessarily reflect those of The Brattle Group's clients or other consultants.

The authors would like to thank the EnergyHub team, including Frederick Hall, Paul Hines, and Stephanie Ross, for their contributions, insight, and leadership throughout this study.

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Demonstrating the Full Value of Managed Electric Vehicle Charging

1. Executive Summary

Study Overview

The purpose of this study is to demonstrate with real electric vehicle (EV) drivers the value of various strategies for managing EV charging, with a focus on deferring distribution system upgrades and reducing wholesale costs.

STUDY SCOPE

This study summarizes the results of a trial of EnergyHub's EV managed charging solution with EV drivers in the state of Washington. Data from the trial was used to estimate the value of managed charging in avoiding electric system costs and to assess the differences in value between active and passive managed charging strategies.

WHAT IS "ACTIVE" MANAGED CHARGING?

Active managed charging refers to control algorithms implemented by distributed energy resource (DER) solution providers that use telematics to optimize EV charging by minimizing customer and/or electric system costs. In most implementations, the active managed charging algorithm ensures that the EV reaches its target state of charge by the time the customer needs it. Customers can override curtailment signals ("opt-out") when needed.

WHAT IS "PASSIVE" MANAGED CHARGING?

Passive managed charging uses price signals set by the utility to indicate when EV charging may be more or less expensive for the electric system to serve. The most common implementation in the US today is in the form of time-of-use (TOU) rates, which have a higher "on-peak" price when bulk system peak demand usually occurs and a lower "off-peak" price at other times. Customers generally respond to these price differences by setting schedules for their EVs to charge at night, soon after the on-peak window ends.

Defining Features of the Study

- Based on a real-world trial of strategies for active management of EV charging
- Illustration of the value of active managed charging relative to two baselines – unmanaged charging and passive managed charging
- Analysis of value to the bulk system based on historical wholesale market prices and marginal transmission costs
- In-depth analysis of impacts on the distribution system, including at secondary transformers
- Forward-looking estimation of value to the distribution system based on how impacts could change as EV penetration grows over time
- Gathering of customer feedback on managed charging strategies

EV Managed Charging Strategies

This study evaluates two active managed charging strategies for reducing electric system costs of EVs and compares them against two baseline strategies commonly used today.

BASELINE CHARGING STRATEGIES

- **Unmanaged Charging:** The charging behavior observed when drivers charge as needed, without optimization or time-varying pricing.
- **Passive TOU Rate:** The charging behavior observed when customers are on a TOU rate schedule with on-peak and off-peak rates. This is referred to as a “passive” strategy in the sense that it relies on the customer to respond rather than any active control of EV charging.

ACTIVE MANAGED CHARGING STRATEGIES

- **TOU + Load Limit:** EV charging is actively controlled and optimized to *minimize customer electricity bills*, assuming a TOU rate schedule. Load limits are applied across customer groups served by the same distribution assets to reduce the local distribution system peaks caused by coincident charging.
- **Wholesale + Load Limit:** EV charging is actively controlled and optimized to *minimize energy, generation capacity, and transmission system costs*. Load limits are applied across customer groups served by the same distribution assets to reduce the local distribution system peaks caused by coincident charging.

EnergyHub’s Active Managed Charging Capabilities

EnergyHub’s EV solutions coordinate EV charging to protect distribution assets, minimize wholesale costs, preserve driver readiness, and reduce driver bills.

Value stacking: Optimizes and stacks multiple value streams, including distribution protection, wholesale and transmission cost reduction, rate-based bill savings, and incentive/dispatch participation.

Multi-level distribution optimization: Maps each vehicle to substation, feeder, feeder section, and transformer assets, and enforces charging limits across all levels.

How it works: Runs a charging schedule optimization that recalculates in real time for plug-ins, early departures, and overrides to meet state of charge targets while managing for grid constraints and minimizing wholesale or TOU rate costs.

OEM integrations: Built on API-based integrations with EV manufacturers.

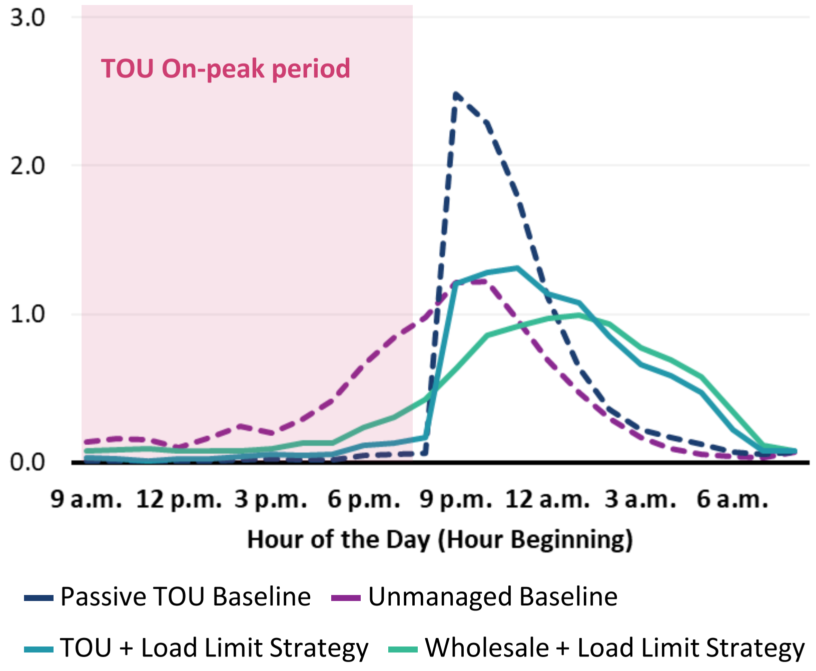
Shaping Charging with Active Management

Both active and passive management can shift charging out of the electric grid's peak demand periods. However, active management mitigates the TOU snapback effect and reduces aggregate peak charging loads.

	Strategy	Description	Aggregate Peak per EV[1]	% of Charging in Peak Window[2]
BASELINES	Unmanaged Charging	Charging behavior observed when drivers charge as needed, without optimization or time-varying pricing.	2.2 kW	31%
BASELINES	Passive TOU	Charging behavior observed when customers are on a TOU rate schedule with on-peak and off-peak rates.	3.3 kW	3%
ACTIVE MANAGEMENT	TOU + Load Limit Strategy	EV charging optimized to minimize customer electricity bills, assuming a TOU rate schedule, with load limits applied to reduce aggregate EV charging peaks.	1.7 kW	5%
ACTIVE MANAGEMENT	Wholesale + Load Limit Strategy	EV charging optimized to minimize bulk system[3] costs, with load limits applied to reduce aggregate EV charging peaks.	1.5 kW	12%[4]

AVERAGE DAILY CHARGING LOAD SHAPE UNDER EACH CHARGING STRATEGY

Avg. kWh per EV across 58 EVs



1: Refers to the aggregate peak hourly load of the participating group of 58 EVs divided by 58.
2: Refers to the percentage of charging energy consumed in the on-peak period (from 9 a.m. to 9 p.m. on weekdays) relative to total vehicle charging at any time.
3: "Bulk system" refers to generation capacity, energy, and transmission.
4: The Wholesale + Load Limit Strategy is based on dynamic system cost signals, so it does not factor in the TOU rate's on-peak vs off-peak periods when optimizing charging.

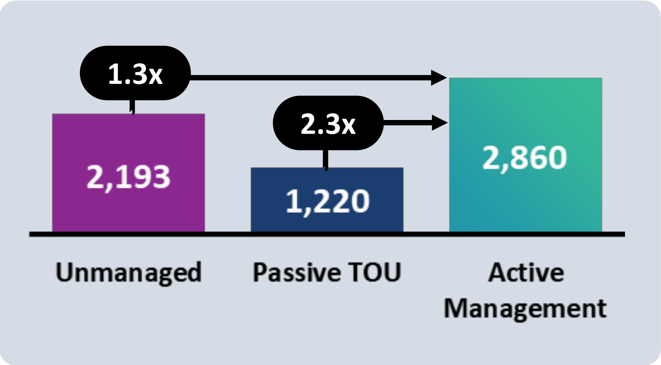
Distribution System EV Hosting Capacity Benefits

Active managed charging[1] allows distribution grid assets to host 1.3x to 3.2x more EVs. Our modeling illustrates how deployment could allow planners to defer grid upgrades by up to 10 years in a location facing EV-driven capacity constraints.

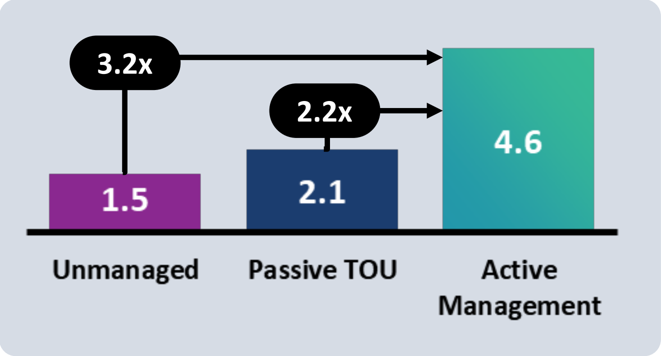
EV HOSTING CAPACITY
Number of EVs

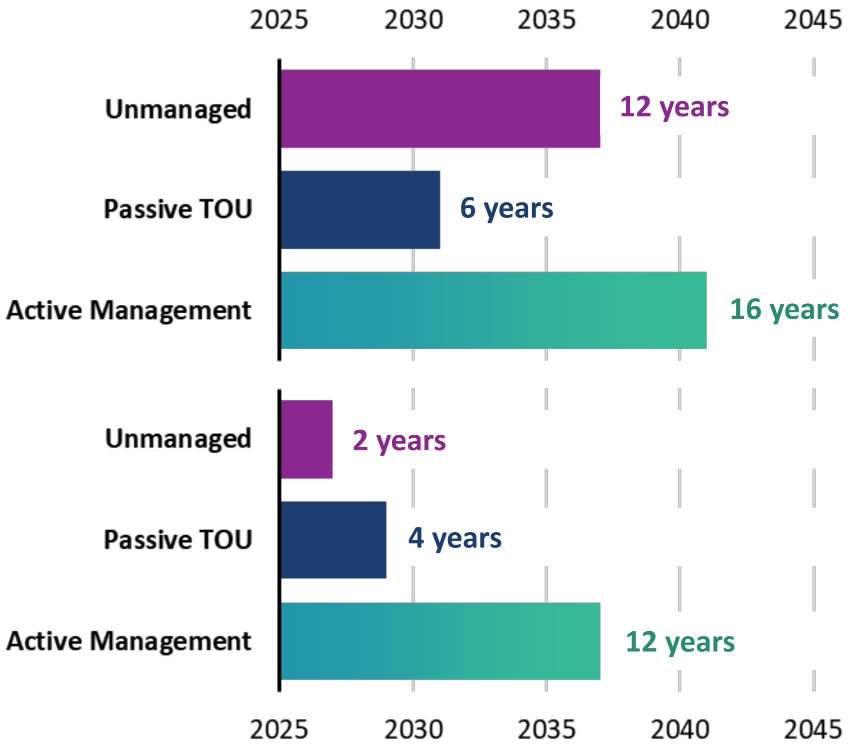
YEARS TILL GRID UPGRADE
In a scenario where 25% of annual vehicle sales are EVs

Primary Distribution System
5,000 customers served by a 13 MVA feeder loaded to 75% of capacity without EVs



Secondary Distribution System
11 customers served by a 37.5 kVA transformer loaded to 75% of capacity without EVs





1: Both the Wholesale + Load Limit and TOU + Load Limit strategies are shown as "Active Management" on this page for conciseness and provide very similar distribution system benefits.

Value of Deferring Distribution System Capex

Active management improves utilization of the existing grid in EV adoption hotspots and reduces distribution grid costs by up to $230 per EV per year in the long run.

Active managed charging increases the EV hosting capacity of existing distribution system assets, thereby deferring capital expenditures relative to unmanaged charging and the Passive TOU strategy.

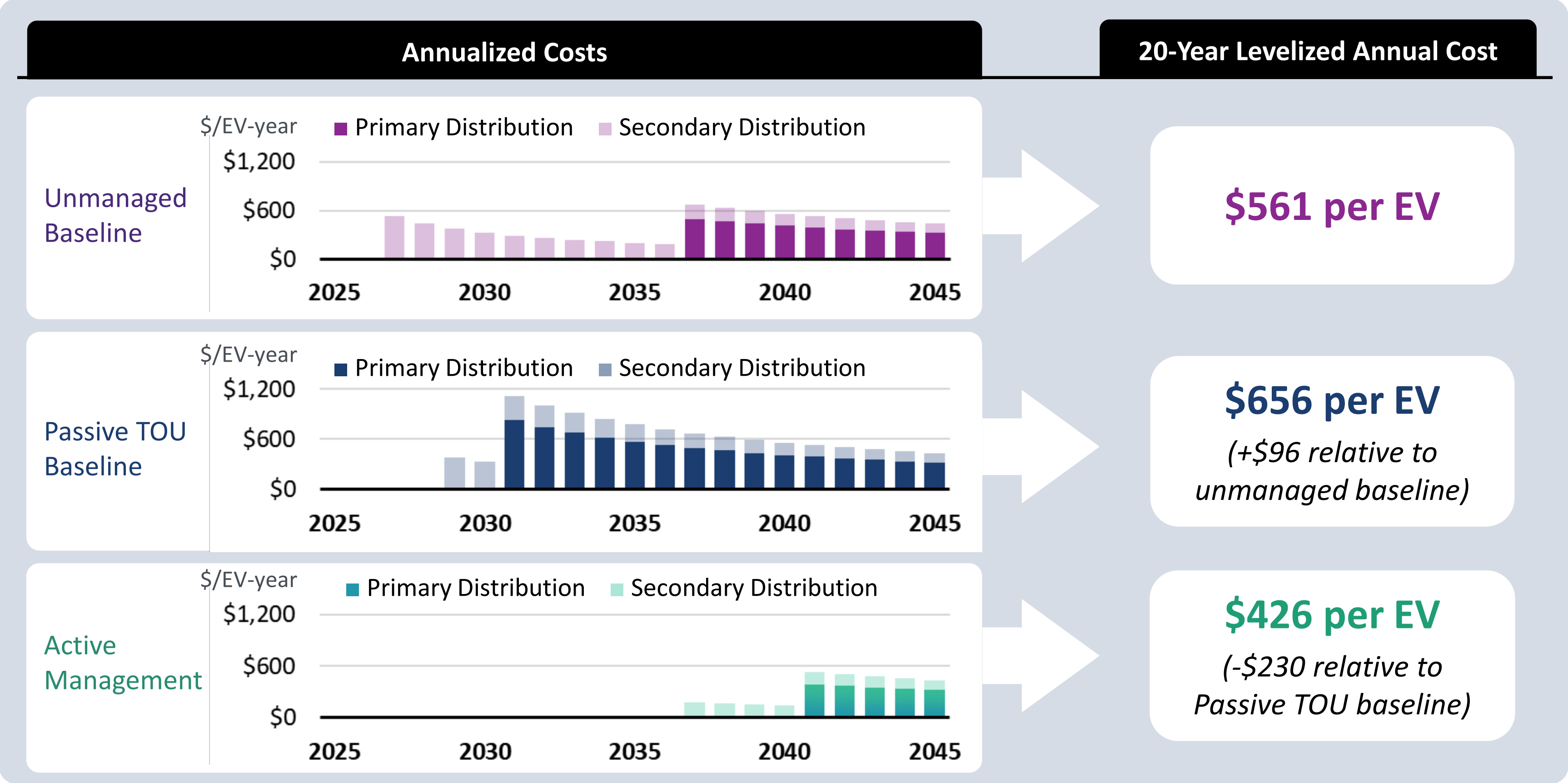
This has three major benefits to utilities and ratepayers:

- **Delaying rate impacts** through deferral of capital expenditures (capex)
- **Reducing rate impacts** by deferring capex until there are more EVs and thus spreading the costs (when they are eventually incurred) over a larger number of EVs
- **Providing utilities more flexibility** in allocation of their limited capital to serve other important purposes

1: Both the Wholesale + Load Limit and TOU + Load Limit strategies are shown as “Active Management” on this page for conciseness. The two active management strategies provide very similar distribution system benefits.

DISTRIBUTION SYSTEM UPGRADE COSTS

In a location where grid assets are loaded to 75% of capacity in 2025 and 25% of annual vehicle sales are EVs



Value of Active Managed Charging – Range Across US Regions

The cost of serving new EV load varies widely across the US due to differences in bulk system costs and distribution system hosting capacity. We extrapolate the findings from EnergyHub's trial to various regions and estimate that the value of active managed charging that optimizes distribution system loading can be as high as $400 per EV per year.

	Savings from Active Managed Charging *($/EV-year)*	Cost of Unmanaged Charging
Energy Wholesale market cost of electricity purchases	$30 – $40	$60 to $230
Generation Capacity Cost of ensuring adequate generation availability	$20 – $130	$25 to $155
Transmission Capacity Cost of load-driven transmission upgrades	$15 – $50	$20 to $60
Primary Distribution Capacity Cost of upstream distribution system upgrades	$0 – $95	$0 to $580
Secondary Distribution Capacity Cost of local distribution system upgrades	$0 – $85	$0 to $210
Full "value stack" (sum of the above)	**Total Savings: $65 to $400**	**Total Costs: $105 to $1,235**

Note: Refer to page 36 for details on which regions' costs were used to develop the cost ranges.

Key Findings on Active Managed Charging

Reduces EV charging peaks by

up to 55%

Active management smooths EV load at the service transformer and feeder levels, reducing distribution grid congestion.

Reduces distribution grid costs by roughly

$200/year per EV

Managed charging provides significant benefits to utility ratepayers.

Increases the distribution grid's EV hosting capacity by

up to 3.2x

Optimizing charging allows service transformers to support roughly 3.2 times more EVs before requiring upgrades.

Provides reliable performance with only

2.3 session opt-outs per month

Drivers overrode control signals 2.3 sessions per month, on average.

Could defer distribution grid upgrades by

up to 10 years

Utilities can substantially delay costly investments while maintaining service quality in EV adoption hotspots.

Does not compromise EV driver needs

100%

of EVs that plugged in with sufficient time to charge reached their desired target state of charge by the end of the optimization window.

A Robust Addition to the Managed Charging Knowledge Base

This study adds to the industry's knowledge base using a robust methodology grounded in real-world data.

- Several studies recently have estimated the value of managed charging, with a wide range of results
- This study adds to industry's knowledge base by:
  - Comparing multiple strategies for active managed charging
  - Conducting a real-world trial to measure the performance of each strategy
  - Proving in-depth analysis of the impacts on distribution system hosting capacity
  - Assessing long-term distribution system upgrade costs based on granular, asset-level modeling rather than system average marginal costs
- The results of this study provide a realistic view of the capabilities of managed charging based on a trial conducted with real customers
  - The study reflects the impacts of operational challenges such as customer opt-outs and EV communication issues

- Building on the findings from the active managed charging trial, areas for further study could include:
  - Incorporating real distribution network data, including information on other customer loads and distribution asset loading
  - Testing of grid-aware active management strategies, which use real-time distribution network data, with a comparison of performance against grid-unaware strategies
  - Extrapolation of results to a full utility service territory, accounting for locational hosting capacity variances and network characteristics
  - A longer study period and a larger sample of vehicles to gauge the persistence of observed effects and potential improvements in performance at scale
  - Comparison to a real-world implementation of the Passive TOU strategy rather than a synthetic baseline

2. Introduction

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OEM integrations: Built on API-based integrations with EV manufacturers.

Trial Structure and Data Collected

TRIAL PARTICIPANTS

- 58 EV drivers in Washington State
- Participants received a $100 upfront enrollment incentive and $10/month for limiting opt-outs to three or fewer charging sessions in a month
- All participants were confirmed to be on flat volumetric rates to ensure that their behavior is not influenced by time-varying rates.
- All participants had L2 chargers, with ratings as high as 12 kW.

TRIAL DURATION (2025)

TOU + Load Limit Strategy: 4 weeks (March 17 to April 15)

Wholesale + Load Limit Strategy: 4 weeks (April 16 to May 15)

Unmanaged Baseline: 4 weeks (May 17 to June 16)

Note: Passive TOU strategy was not trialed due to the difficulty of sending customers price signals potentially misaligned with their actual rates. Instead, EnergyHub modeled the impact of a TOU rate on charging behavior based on observed plug-in times and available data on the observed behavior in jurisdictions with Passive TOU rates (see page 17).

ASSUMED COST SIGNALS

TOU + Load Limit Strategy: EnergyHub managed charging under the assumption that the customer rate schedule was Xcel Energy MN's Residential Electric Vehicle Service TOU rate.

Wholesale + Load Limit Strategy: EnergyHub managed charging under the assumption that system costs are represented by hourly wholesale energy and capacity prices from a selected node in Minnesota.

Unmanaged Baseline: No cost signal.

DATA COLLECTED

- Charging energy (15-minute intervals)
- Vehicle state of charge
- Plug-in status
- Opt-out flag
- Owner-selected "need by" time and target SOC
- Driver engagement: Real-time feedback through surveys, with iterations of communication touchpoints to refine the experience for drivers.

Managing Based on Wholesale Costs and Retail Rates

Charging was optimized in the trial based on assumed hourly cost signals.

TOU + LOAD LIMIT STRATEGY

This solution is designed to allow EV customers to minimize their bills, while limiting distribution system peak loads. In the trial, this strategy was represented by optimizing charging behavior with respect to the assumed retail TOU rate.[1]

WHOLESALE + LOAD LIMIT STRATEGY

This solution is designed to minimize bulk system costs, while limiting distribution system peak loads. In the trial, this strategy was represented by optimizing with respect to assumed hourly system marginal costs. We developed this marginal cost metric based on hourly energy prices and by allocating annual generation and transmission capacity costs to the peak load hours of the "high-priced week."

Each strategy was implemented for four weeks of the trial.

1: *Xcel Energy MN's Residential Electric Vehicle Service TOU rate*

HOURLY COST SIGNALS UTILIZED IN THE TRIAL

Teal line is the ***retail TOU rate*** *used in the TOU + Load Limit strategy*

Stacked bars show the ***energy*** ***generation capacity*** ***transmission capacity*** *costs used in the Wholesale + Load Limit strategy*

Managing Based on a Multi-level Distribution Load Limit Scenario

The active management strategies targeted load limits across different groups of trial participants to illustrate how active management can be used to optimize distribution system loading, in addition to bulk system cost minimization.

Distribution network assets serve different numbers of customers at different levels of the grid. The most upstream assets, such as substations and feeders, can serve thousands of customers. The most downstream assets, such as service transformers, may serve around 10 residential customers or one large customer. Managing the loading of distribution assets at different levels of the grid requires mapping customers served by each asset into different groups and managing group-level loads to ensure that asset capacity ratings are not exceeded.

Though the trial participants were in different locations, likely not served by the same distribution assets, they were assigned to hypothetical asset groups to enable demonstration of the multi-level load limiting capabilities of EnergyHub's active management solution in a distribution load limit scenario.

Level 3

The entire trial group of 58 EVs was considered to be a Level 3 group, intended to represent effects at all upstream parts of the distribution grid (a feeder and substation). Though upstream assets serve thousands of customers, load diversity impacts (i.e., aggregate peak load per customer) generally converge at group sizes over 50 customers. Therefore, analysis of managed charging effects for the 58-customer group is informative on the effects that can be expected at the feeder or substation level of the distribution network.

Level 2

23 EV drivers were assigned to a Level 2 group, intended to represent a group served by a section of a feeder that is served by a capacitor bank, voltage regulator, or thermally constrained cable.

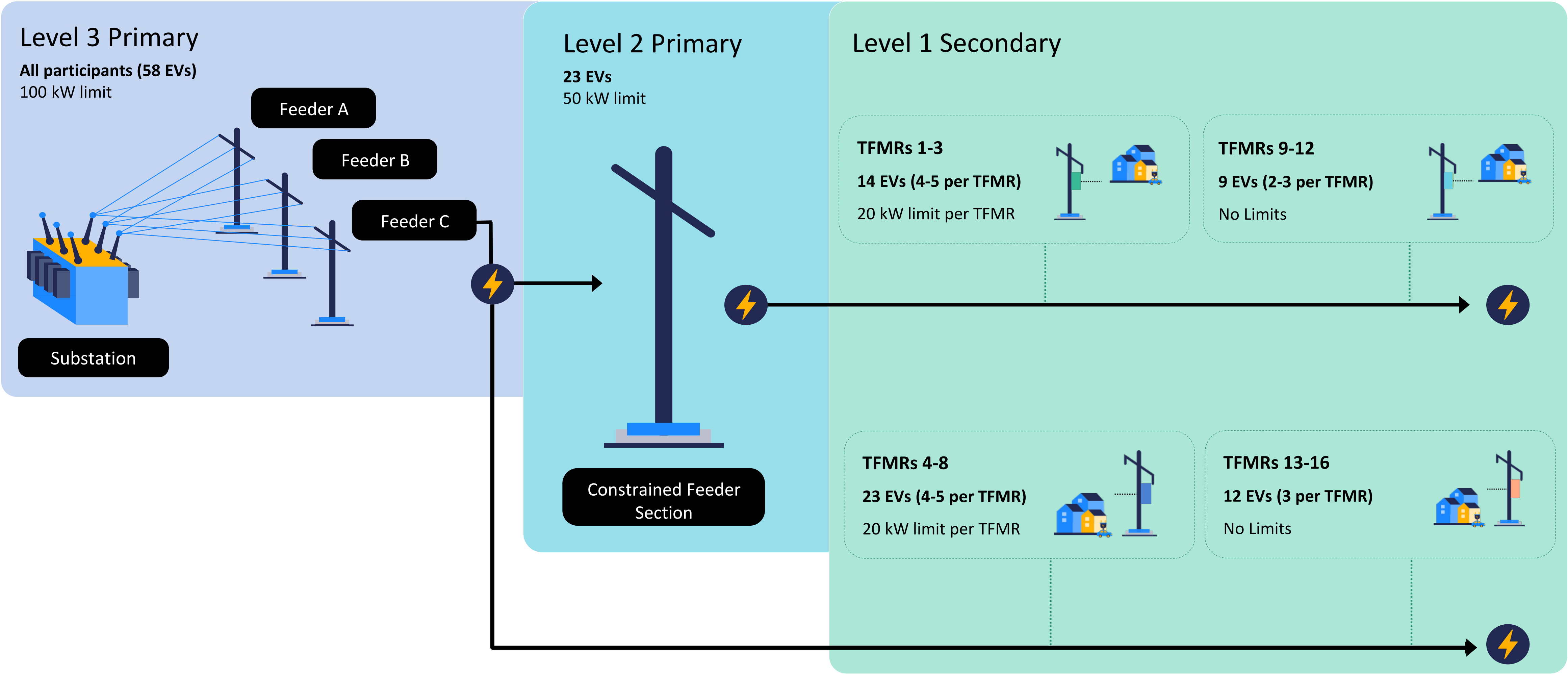
Level 1

The 58 participants were assigned to 16 Level 1 groups of up to 5 EV drivers each, intended to represent groups that could be served by 16 service transformers (abbreviated to TFMRs).

In the trial, the Wholesale + Load Limit and TOU + Load Limit Strategies managed each participant's EV load such that load limits were adhered to for all three of their assigned group levels.

Multi-level Distribution Load Limit Scenario

The mapping shown here was developed pre-trial and used to set the load limits for the active management strategies to target.



Development of a Synthetic Passive TOU Baseline

EnergyHub developed a modeled passive TOU baseline for each participating EV for every day of the trial. This baseline allowed evaluation of the active management strategies relative to the passive strategy that is most commonly employed by utilities today.

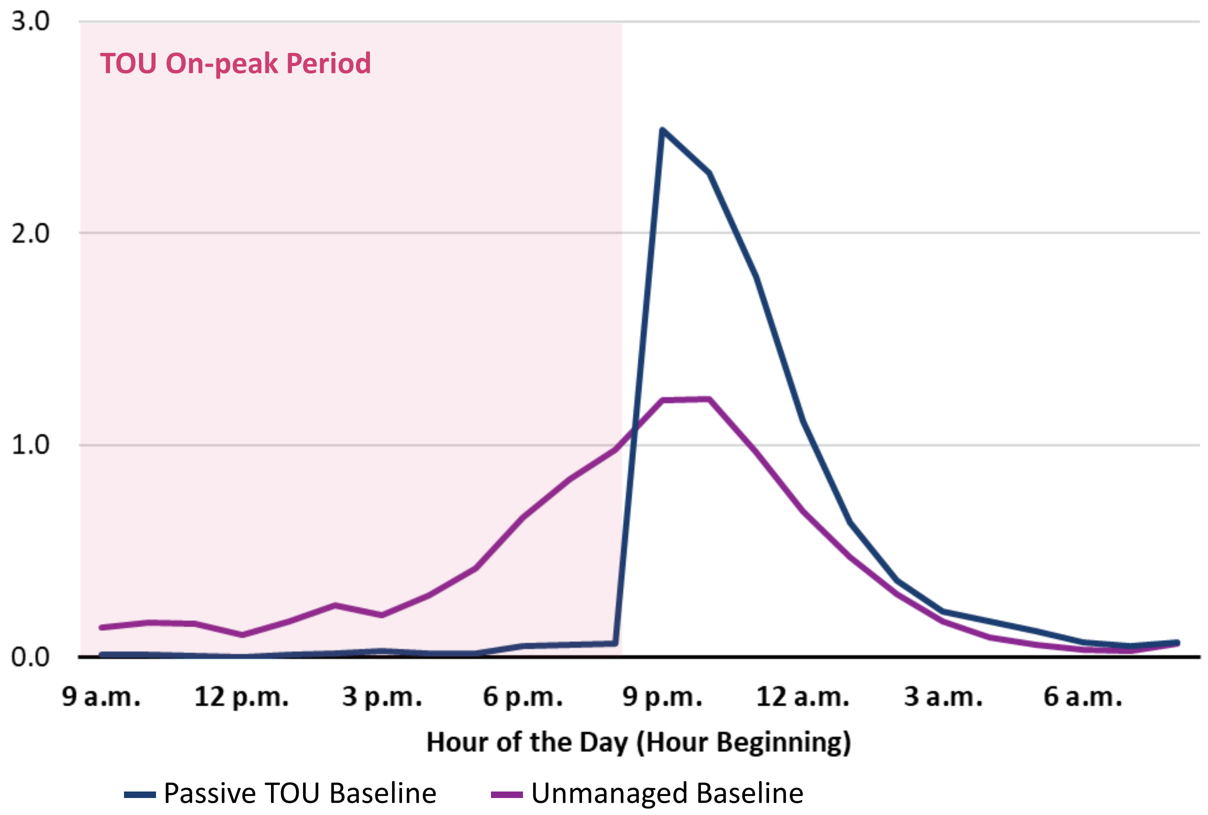
This study used a simple algorithm to develop a synthetic Passive TOU baseline for each vehicle using actual trial data and Xcel MN's EV TOU rate schedule (9 a.m. to 9 p.m. on-peak period).

This synthetic TOU baseline assumes charging begins at the first off-peak hour that a vehicle is plugged in and available to charge and continues until the vehicle completes the session's total required energy. On days when a vehicle opt-out was observed in the trial, the synthetic TOU baseline is also adjusted to follow the opt-out behavior, and no off-peak shifting is performed.

The resulting synthetic Passive TOU baseline has 97% of charging occurring in the off-peak period and a 9 p.m. snapback peak 104% higher than the unmanaged baseline's peak. These metrics align with observations from existing Passive TOU implementations across the US.

AVERAGE DAILY VEHICLE CHARGING LOAD

kWh per EV



3. Observed Performance of Managed Charging in the Trial

Overview

The trial showed that active managed charging is highly effective, both at shifting load out of the bulk system's high-cost periods and at limiting coincident peaks among different groups of EVs.

The passive and active managed charging strategies have similar effectiveness in shifting EV charging out of the bulk system's high-cost window. Relative to unmanaged charging, we observed that on-peak period (i.e., 9 a.m. to 9 p.m. on weekdays) charging was 59–91% lower with managed charging. The Wholesale + Load Limit active managed charging strategy provides additional benefits by further optimizing based on hourly energy prices.

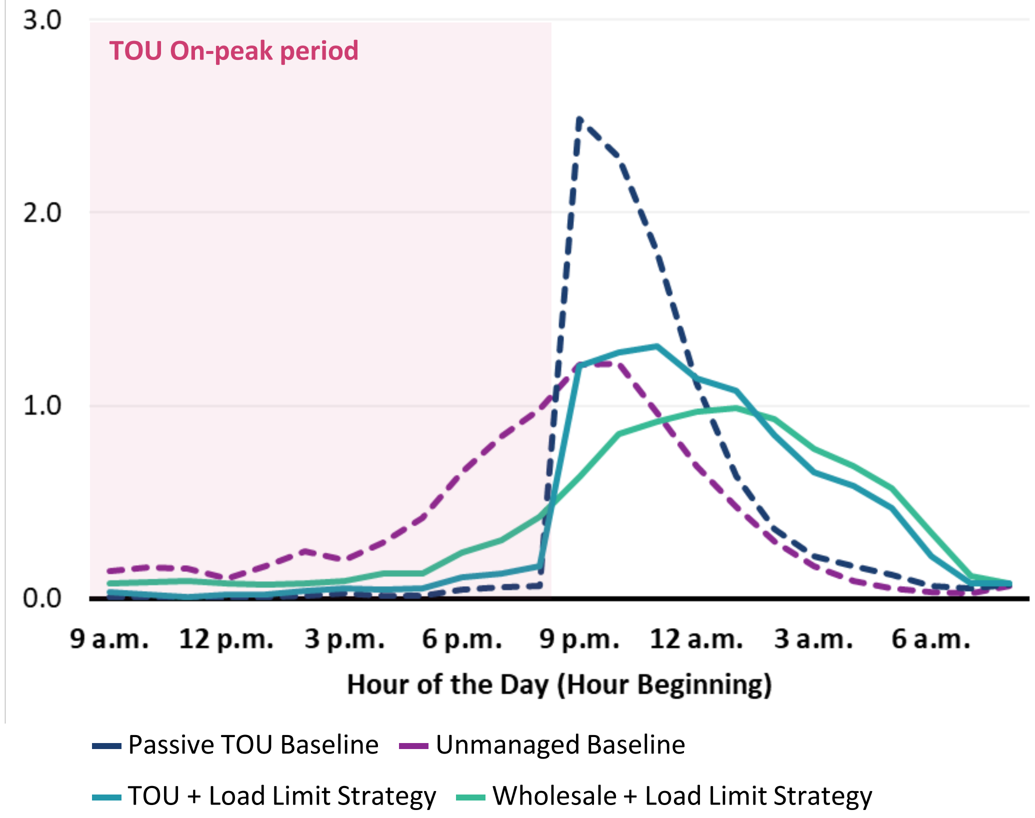
The active managed charging strategies' load limiting feature was shown to be effective at simultaneously managing groups of EVs to adhere to the multi-level load limits set pre-trial and intended to represent distribution asset capacity limits. The aggregate peak load of the trial group of 58 EVs was 33%–55% lower with active managed charging (85 kW with active managed charging, 127 kW with unmanaged charging, and 190 kW with the Passive TOU strategy).

This section summarizes the observed performance of managed charging in terms of several key metrics that have a bearing on electric system costs.

Changes to the Average Charging Load Shape

Both the active and passive management strategies shifted charging out of the bulk system's peak period. While the Passive TOU rate created a snapback peak at the start of the off-peak period, the active management strategies avoided this effect.

AVERAGE DAILY CHARGING LOAD SHAPE
kWh per EV



UNMANAGED BASELINE

Charging increases starting at 4 p.m. until reaching a peak around 9 to 10 p.m.

PASSIVE TOU BASELINE

Charging is low throughout the day until the off-peak period begins at 9 p.m. There is a snapback effect, where many vehicles begin charging immediately after the peak period ends.

TOU + LOAD LIMIT TRIAL

Charging is similar to the Passive TOU Baseline throughout the day. The optimization determines how many vehicles can begin charging at the end of the peak period, allowing the snapback effect to be mitigated due to the load limit.

WHOLESALE + LOAD LIMIT TRIAL

Charging is largely similar to the Passive TOU Baseline throughout the day, however there are some days where low wholesale prices coincide with the on-peak period and result in charging shifted to these periods. There is no snapback effect, as unlike with a TOU rate, there is no large step change in wholesale prices at 9 p.m.

Demonstration of Wholesale Energy Cost Optimization

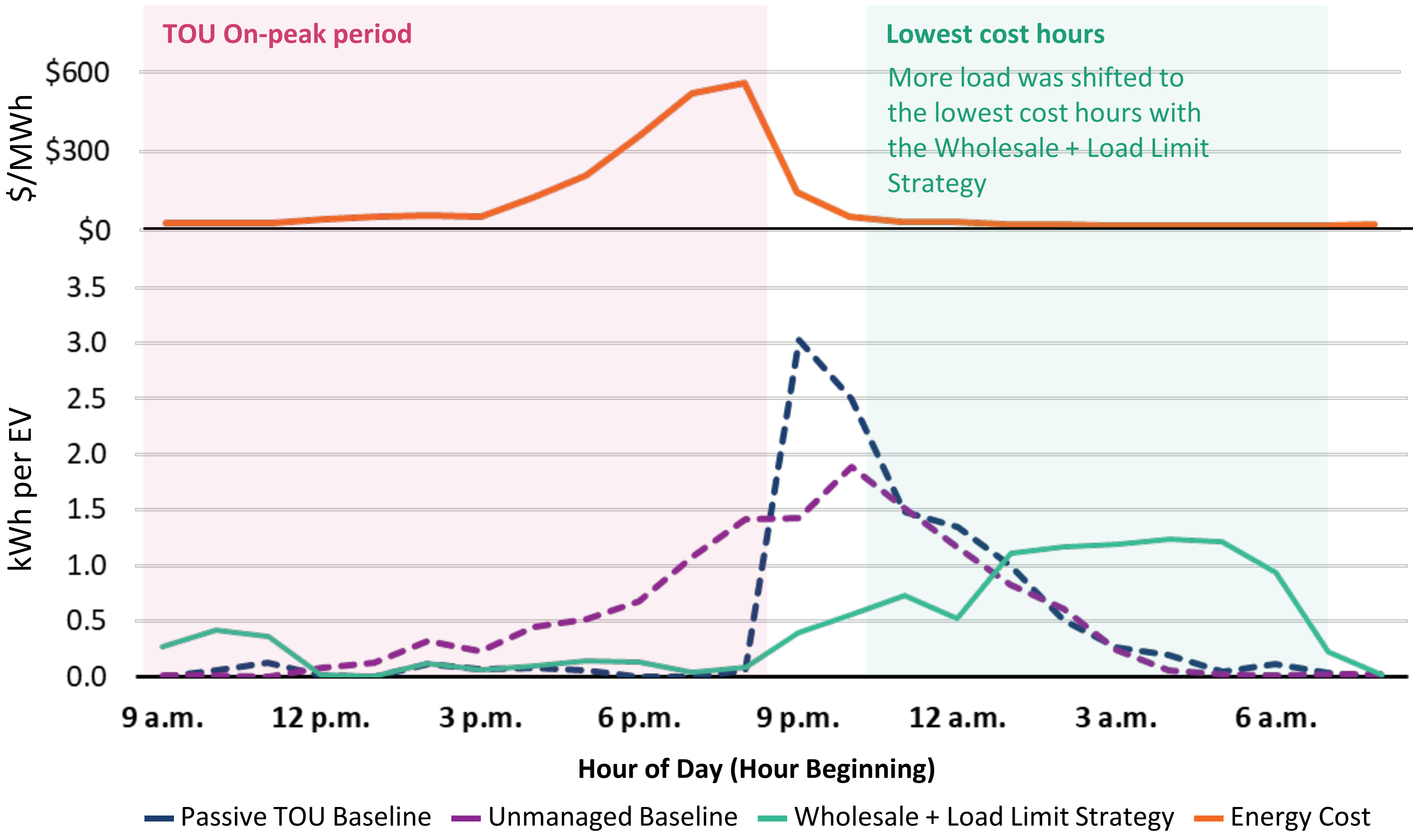
The performance of the Wholesale + Load Limit active managed charging strategy showed that dynamic management in response to wholesale energy prices can provide significant system cost savings by moving charging to hours with lower prices in a more targeted manner.

EnergyHub's wholesale cost optimization algorithm seeks to move charging out of the most expensive hours and into the cheapest hours, with more granularity and flexibility than the TOU rate's static peak and off-peak windows.

The cheapest hours are often overnight, aligning with the TOU rate's off-peak period, but the wholesale optimization goes a step further and finds the cheapest off-peak hours for vehicles to charge, while managing for load limits and driver charging targets. On the day of the trial shown here, the **Wholesale + Load Limit strategy resulted in wholesale energy cost savings of 79% relative to the Unmanaged Baseline and 40% relative to the Passive TOU Baseline.**

To maintain a positive customer experience, EnergyHub ensures that vehicles are fully charged by their inferred departure time and allows participants to override stop-charging signals when necessary.

ENERGY COSTS AND CHARGING LOAD ON A SELECTED DAY



Demonstration of Bulk System Capacity Cost Optimization

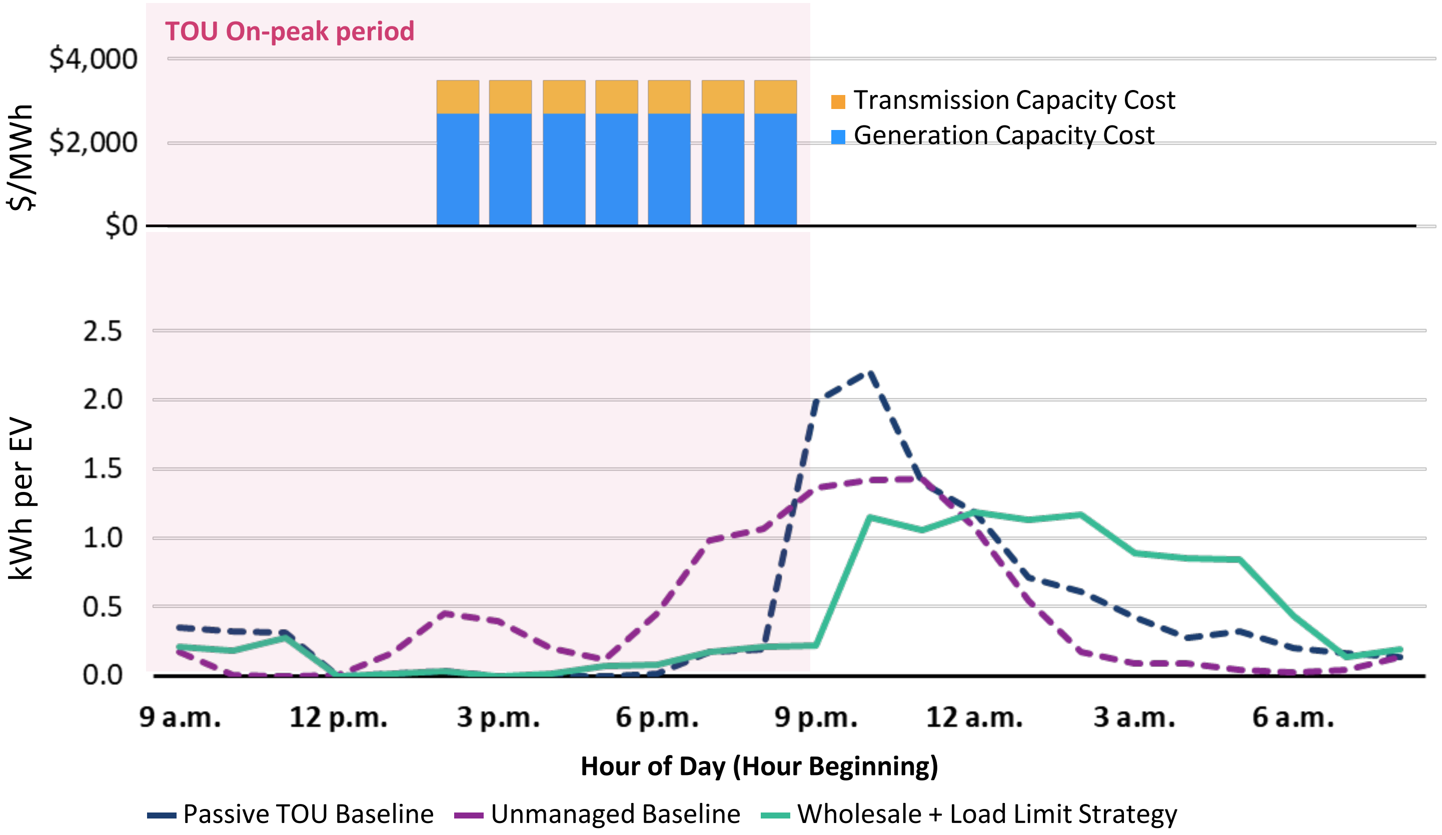
Both the passive and active managed charging strategies can contribute to resource adequacy by shifting charging out of the hours in which the bulk power system is most scarce on generation capacity.

Because the TOU rate's peak window is designed to reflect resource adequacy hours, both the Passive TOU and TOU + Load Limit strategies are effective at shifting charging away from these hours.

The Wholesale + Load Limit strategy moves charging to the cheapest system cost hours including energy, generation capacity, and transmission capacity costs. Because of the high generation capacity costs in resource adequacy hours, this strategy is also effective at shifting charging away from these hours.

In general, resource adequacy hours occur at similar times of the year and day, aligning with the on-peak period of the TOU rate. However, it is possible for scarcity conditions to develop during the TOU rate's off-peak period (e.g., due to extreme weather or generator outages). The Wholesale + Load Limit solution would be able to respond to dynamic signals that indicate these unexpected conditions, while the static TOU rate (and associated management strategies) would not be able to respond.

BULK SYSTEM CAPACITY COSTS AND CHARGING LOAD ON A SELECTED DAY



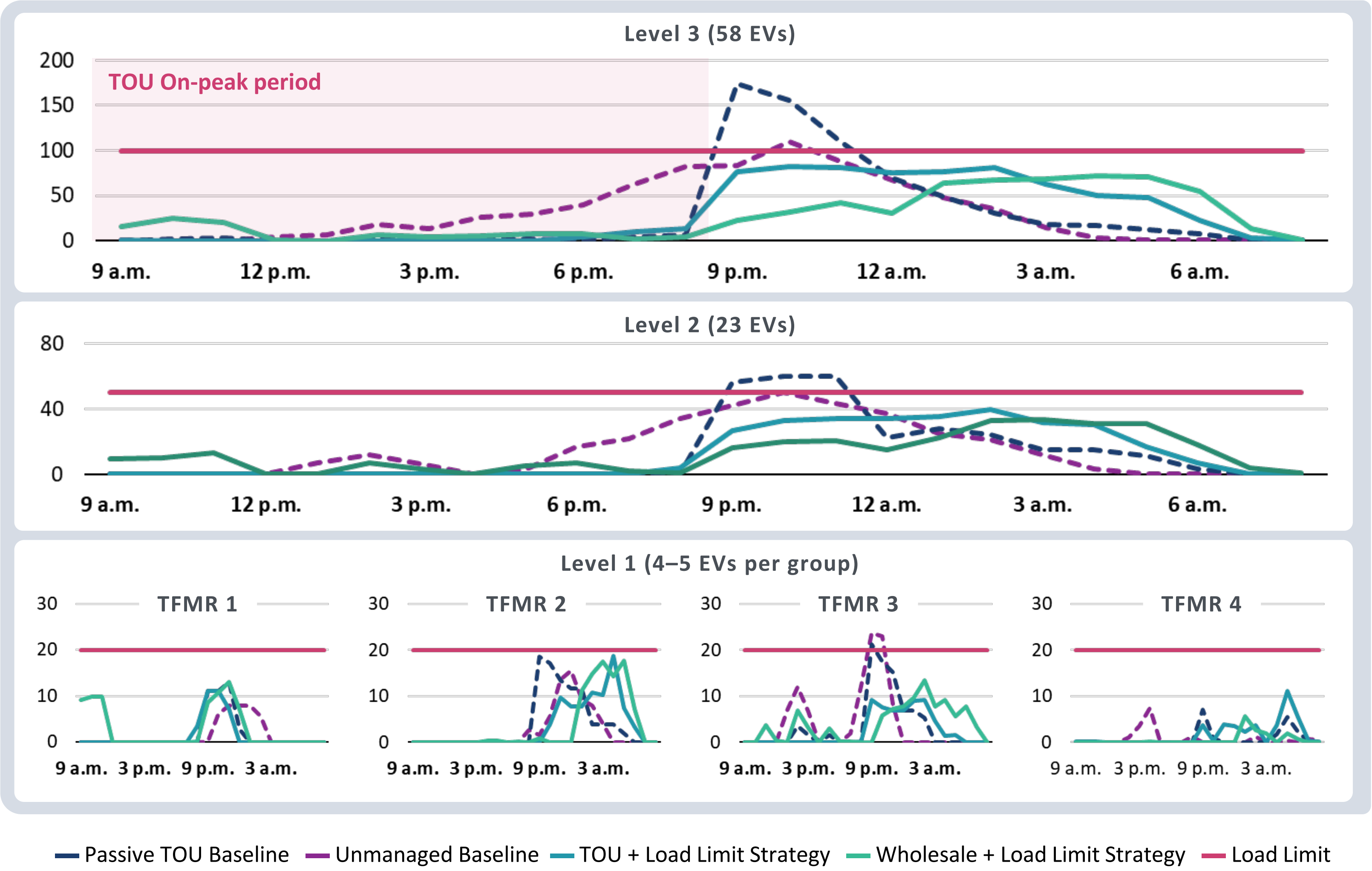
Demonstration of Multi-Level Distribution Load Limiting

The performance of the active management strategies shows that EnergyHub's solution can effectively limit EV charging peaks across different customer groups, while simultaneously optimizing for wholesale costs or customer bills.

Utilizing managed charging to defer distribution grid upgrades is likely to require managing groups of EVs to multiple levels of the primary and secondary distribution grid. The trial showed that active management can provide this type of granular, group-specific control at multiple distribution assets simultaneously.

In contrast, the Passive TOU rate's snapback effect results in much higher EV charging peaks even relative to unmanaged charging. This suggests that as EV penetration grows beyond a certain point, use of the Passive TOU strategy is likely to begin *causing* distribution system costs rather than avoiding them.

PERFORMANCE RELATIVE TO TARGETED LOAD LIMITS ON A SELECTED TRIAL DAY, *kW*



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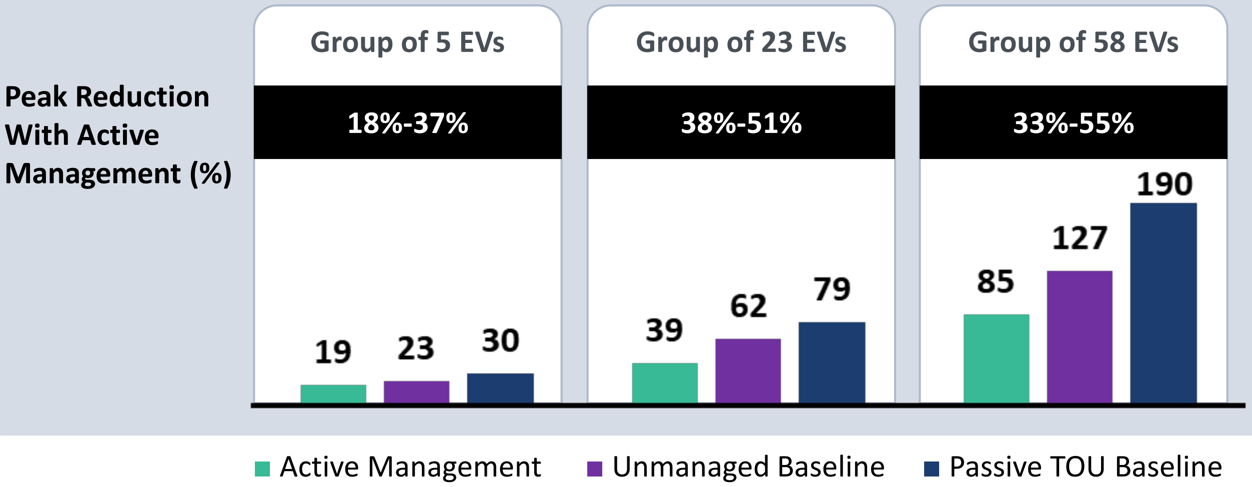
Aggregate Peak Charging Loads

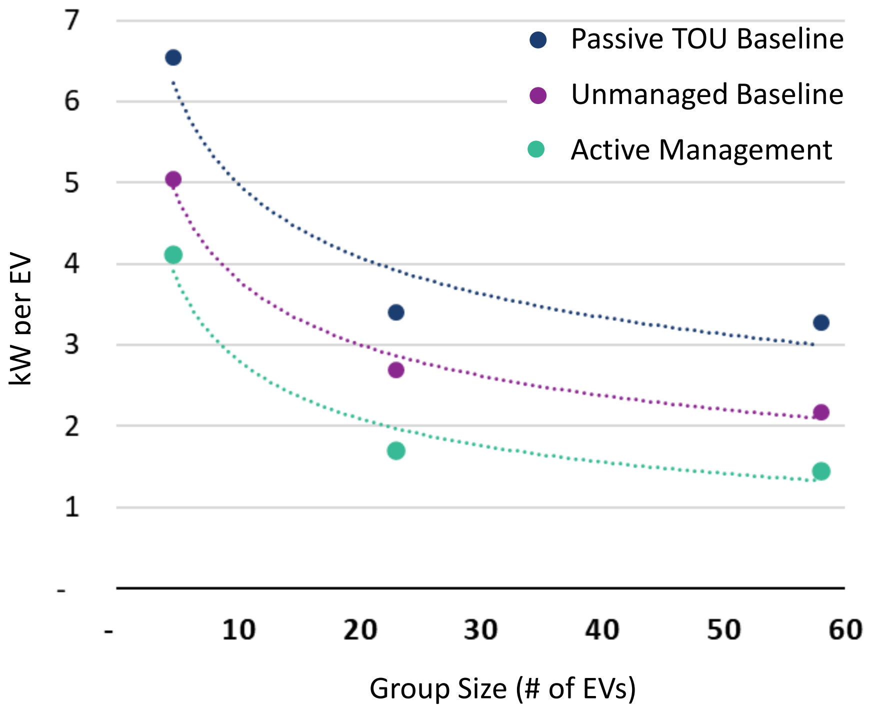
The active managed charging strategies resulted in significantly lower coincident peak loads per EV at all group sizes, particularly when compared to the Passive TOU Baseline.

AGGREGATE CHARGING PEAK LOADS OBSERVED IN THE TRIAL (kW)



EV LOAD DIVERSITY CURVE

Aggregate peak load per EV at different group sizes



- At small group sizes, the baseline strategies experienced coincident charging of the EVs at least once in the study period, driving coincident peak loads to over 5 kW/EV
- Active management reduced these peaks by targeting load limits for each group

- At larger group sizes, natural load diversity begins to reduce peaks under unmanaged charging
- Under Passive TOU, peaks are higher because the snapback effect reduces load diversity and causes more EVs to charge at the same time
- Active management reduced peaks for larger groups as well, particularly relative to the Passive TOU baseline

Customer Convenience Functionalities and Learnings

EnergyHub's EV managed charging solution has features that prioritize maintaining a positive experience for customers when load is being shifted. There were several learnings from the trial on how well the solution's customer convenience functionalities performed and the trade-offs between convenience and providing reliable power system services.

The solution successfully meets target need-by times

- 100% of EVs that remained plugged in and had sufficient time to charge during the optimization window reached their desired target state of charge

The solution handles TOU schedules and delivers bill savings

- Active managed charging can handle complex TOU rate schedules and deliver 95% of charging off-peak, which reduces drivers' EV charging bills by 50% compared to a flat residential rate.

Inferring need-by-times is critical to a positive driver experience

- Only 14% of drivers enter need-by times in OEM apps and rarely update these times to reflect changes in daily behavior, so explicit inputs are insufficient for reliably informing departure schedules.
- Inferring departure estimates with historical plug-out behavior helps ensure customers receive a full charge before departing, especially when they forget to update their need-by times. Compared to simply using the need-by times from OEM apps, this approach has avoided missed charge targets for 11% of charging sessions.

What drives vehicle response to optimization control instructions?

- On average, each driver overrode control signals in 2.3 sessions per month.
- About 5% of charging occurred in the on-peak period and opt-outs account for about 42% of these on-peak sessions. The other 58% of on-peak charging occurred for reasons unrelated to driver needs, such as data latency and errors. As EV data quality and connectivity improve, on-peak charging can be reduced even further.
- Customer feedback indicated that drivers often do not realize they had opted out, with some opt-out cases arising from competing charging controls set via a driver's charger or vehicle.

4. The Value of Managed Charging

Overview

Observed charging behavior from the trial was used, in conjunction with system marginal cost data from various US regions and the distribution network scenario, to estimate the value of active managed charging.

To provide a nuanced, long-term view of distribution system value, we developed a hypothetical network consisting of a substation, feeder, and service transformers serving a primarily residential area. We simulated how asset loading on this network could change with growing EV penetration. The results highlight how the load-limiting features of active managed charging significantly increase the hosting capacity of existing distribution assets and defer the need for system upgrades.

The active managed charging trial was run based on bulk system costs and retail utility rates from Minnesota. To provide a more representative view of the bulk system value of managed charging, a range of cost estimates were developed using wholesale market prices from various US regions. In addition to providing a range, a single case for the full “value stack” was modeled using prices from NYISO and CAISO to provide insights relevant to regions with high EV growth and ambitious decarbonization policies.

This section summarizes our estimates of the system value of managed charging, with a focus on the distribution grid value.

Electric System Costs of EV Charging

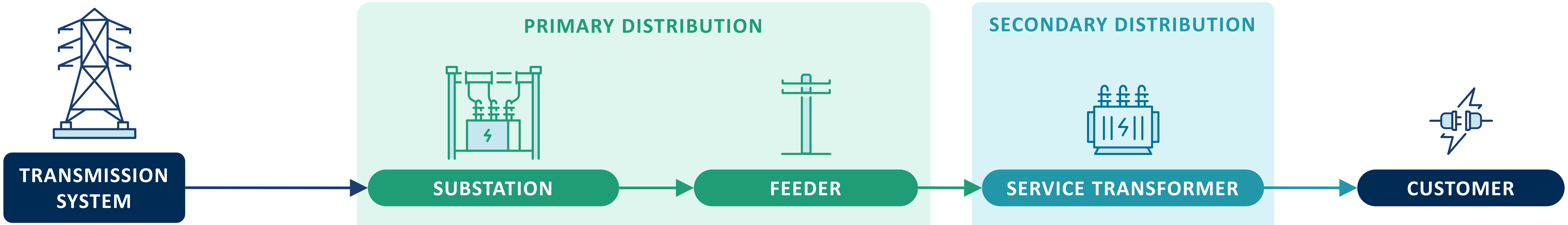
Electric system costs of EV charging include bulk system (energy, generation capacity and transmission) and distribution system costs. The value of managed charging comes from reducing these costs by shifting and shaping charging.

Marginal Cost Components	Description	Cost Drivers	How Costs Can Be Avoided
Energy	Marginal generators must ramp up supply to meet the energy demand of incremental EV charging loads.	Energy prices vary throughout the day depending on demand and available supply. Prices are typically higher in the evening hours, when renewable generation is low, and demand is high.	Shifting load from higher-priced hours to lower-priced hours mitigates volatility, reduces fuel costs, and aligns demand with renewable generation.
Generation Capacity	Bulk system planners must maintain available generation capacity to meet load at all times of the year.	Generation capacity needs are driven by peak demand and demand at times of generation scarcity (e.g., extreme weather events).	Investment need can be reduced by lowering seasonal bulk system peak demand.
Transmission Capacity	Transmission lines are used to deliver generated energy to load centers and to balance supply and demand in neighboring zones.	Transmission needs are driven by various factors, including peak demand, new generation interconnections, regional policies, and reliability needs.	The peak-driven portion of future transmission needs can be reduced in the long run by lowering system peak demand.
Primary Distribution Capacity	The distribution system delivers energy from the transmission network to customers. The upstream, higher voltage part of the distribution network is called the primary network.	Coincident peak load across the customer base served by distribution substations and feeders drives the need for primary distribution capacity.	Distribution upgrades can be avoided by lowering coincident peak demand and improving utilization of the existing system.
Secondary Distribution Capacity	The downstream, lower voltage part of the distribution network delivers energy from the primary distribution network to customer premises.	Each customer's service is sized to their total connected load. Service transformers are sized based on expected coincident peaks across the customers they serve.	Transformer upgrades can generally only be avoided through active management to ensure non-coincidence of customer loads.

Distribution Network Scenario Assumptions

We developed a distribution network scenario to illustrate value of distribution load optimization in managing the distribution system costs of EVs as adoption grows.

DISTRIBUTION NETWORK SCENARIO USED TO ILLUSTRATE THE VALUE OF MANAGED CHARGING



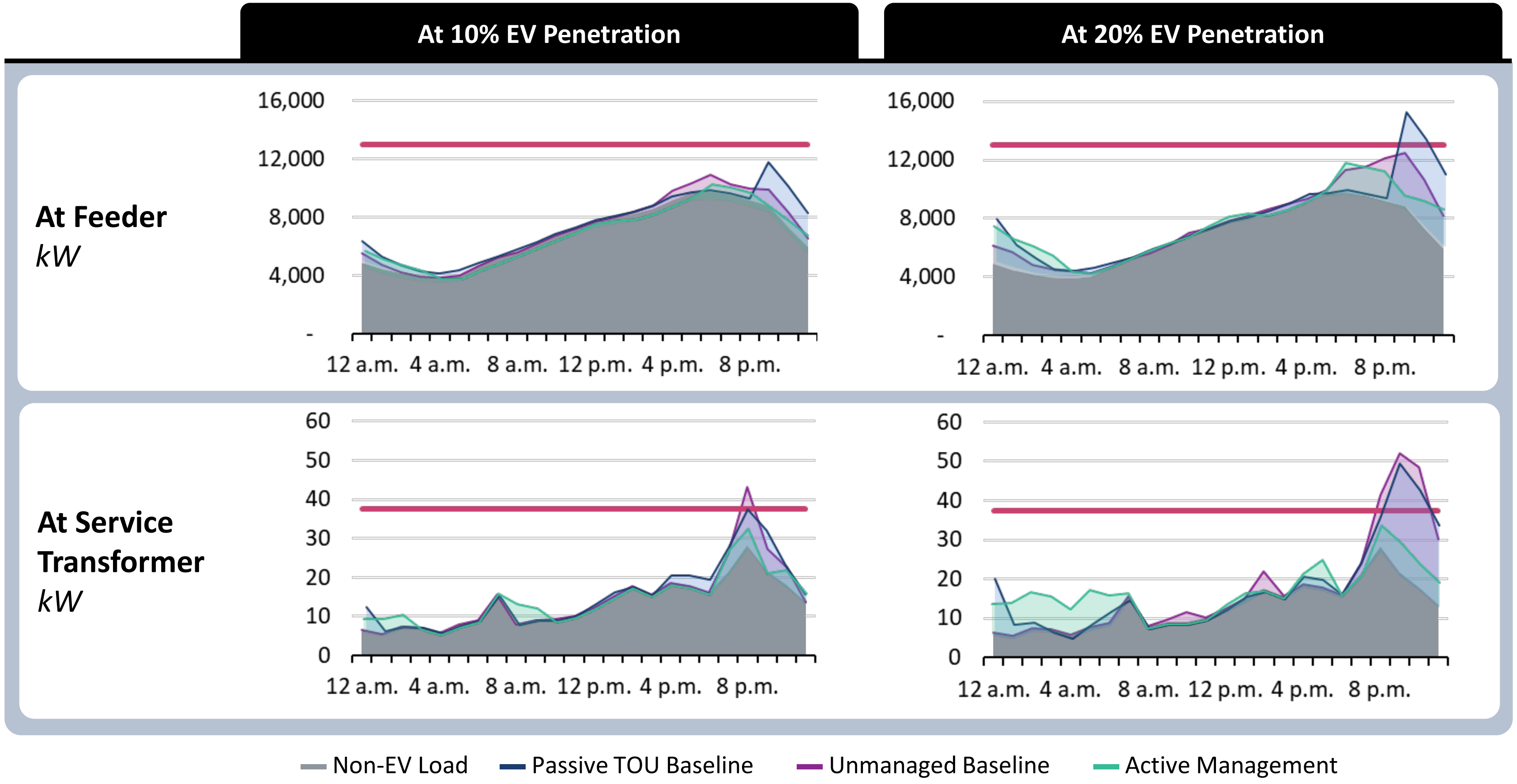
	Substation	Feeder	Service Transformer
Rating:	30 MVA	13 MVA	37.5 kVA
Existing Load:	75%	75%	75%
Customers:	13,000	5,000	11
Upgrade Cost:	$12 Million	$6.5 Million	$8,500
EV:	Growth from 1,050 EVs today to 8,000 EVs in 20 years	Growth from 450 EVs today to 3,500 EVs in 20 years	Growth from 1 EV today to 7 EVs in 20 years

Note: This EV adoption scenario reflects 1.8 cars per residential customer, of which 5% are EVs in 2025, with an additional 1 .7% being converted to EVs annually for 20 years. This growth rate reflects 25% of annual vehicle sales being EVs, roughly in line with observed EV sales levels in the states with highest adoption in the US in 2024.

Modeling EV Load Growth Based on Trial Data

We modeled distribution network peak load growth in the study scenario by adding the EV load shapes observed under different management strategies to a baseline residential load profile at each level of the network.

DISTRIBUTION NETWORK LOAD ON PEAK DAY UNDER EACH MANAGED CHARGING STRATEGY



Progressively adding EV load to the network's baseline load allowed us to develop various insights:

- How quickly EV load may begin to drive residential class peaks
- Which level of the grid (primary or secondary) faces overloads first and to what extent
- The EV penetration level at which each part of the network faces overload – i.e., the EV hosting capacity of each asset
- The additional EV hosting capacity created by the active management strategies

Note: This is a simplified abstraction of how load limiting could work as EV penetration grows. As the system gets closer to capacity limits, the load limiting algorithm would adapt to more effectively target coincident peaks rather than EV charging peaks.

Hosting Capacity Benefits – Primary Distribution System

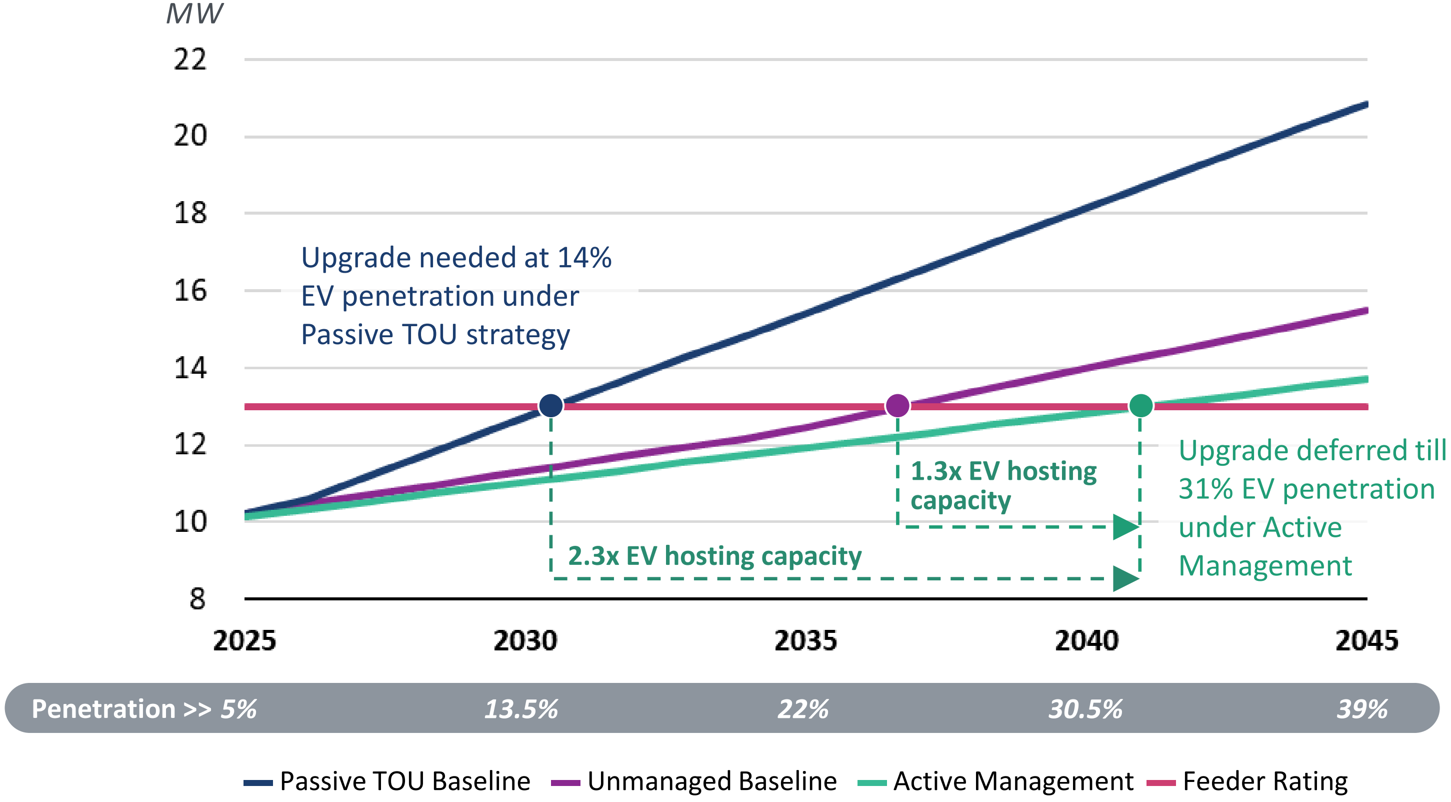
Active managed charging allows the primary distribution system to host 1.3x more EVs relative to unmanaged charging and 2.3x more relative to the Passive TOU strategy.

The Passive TOU strategy reduces load diversity among EVs. The snapback EV charging peaks at the beginning of the TOU rate's off-peak window begin to drive the peak loads of the residential customer class as a whole at around 10% penetration. In our modeled scenario, these peaks overload the feeder around **14% EV penetration.**

Unmanaged charging has natural load diversity stemming from randomness in charging. This leads to lower EV charging peaks than under the Passive TOU strategy, allowing the feeder to support up to **24% EV penetration** without an upgrade.

Active managed charging with load limiting significantly increases the feeder's hosting capacity, deferring the upgrade until **over 30% EV penetration**. In this EV adoption scenario, this is 4 to 10 years of deferral relative to the Passive TOU and unmanaged baselines. Active managed charging could perform even better than shown here under a grid-aware approach, where the solution provider receives real-time signals on the local grid's status and needs. The trial tested only the grid-unaware approach of managing to static load limits.

MODELED FEEDER PEAK LOAD AT GROWING PENETRATION LEVELS



Note: The Wholesale + Load Limit trial is shown as "Active Management" in this chart. TOU + Load Limit trial shows similar results.

Hosting Capacity Benefits – Secondary Distribution System

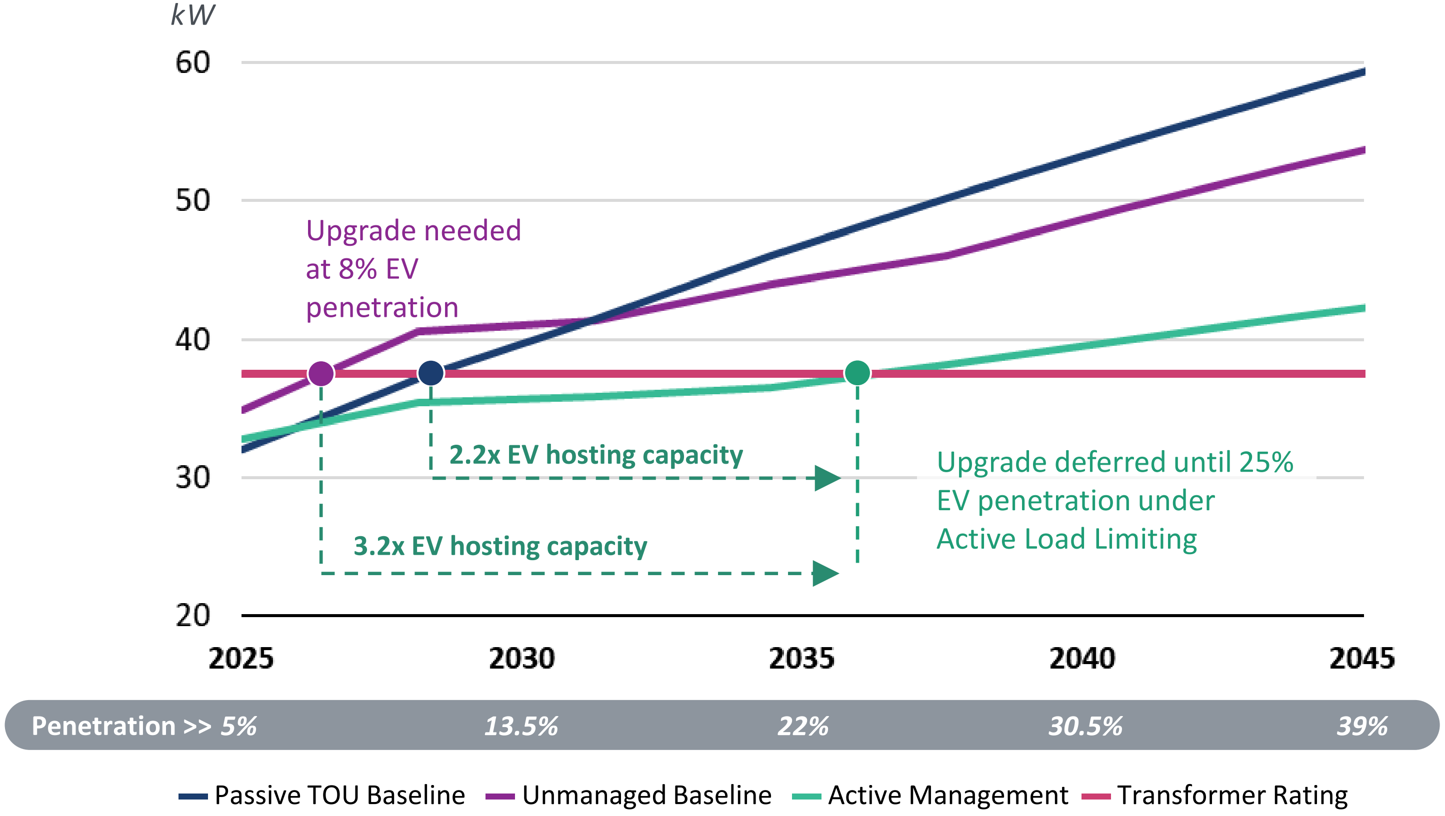
Active managed charging allows the secondary distribution system to host 3.2x more EVs relative to unmanaged charging and 2.2x more relative to the Passive TOU strategy.

There is limited load diversity at the small number of EVs served at the service transformer level, e.g., three neighbors with EVs are likely to charge at the same time at some point. Therefore, with **Unmanaged charging**, the service transformer is able to support only about **8% EV penetration (~2 EVs)** before it requires an upgrade.

The **Passive TOU strategy** serves to shift EV charging away from the times other residential loads peak, creating some benefits relative to unmanaged charging at low EV penetration levels and allowing **~1 additional EV** to be hosted before requiring an upgrade.

Active managed charging with load limiting significantly increases the transformer's hosting capacity, deferring the upgrade until about **25% EV penetration**. In this EV adoption scenario, this is 8 to 10 years of deferral relative to the unmanaged and Passive TOU baselines. Similar to the primary system level, active managed charging could perform even better than shown here under a grid-aware approach.

MODELED SERVICE TRANSFORMER PEAK LOAD AT GROWING PENETRATION LEVELS



Note: The Wholesale + Load Limit trial is shown as "Active Management" in this chart. TOU + Load Limit trial shows similar results.

Value of Deferring Distribution System Capex

Active management improves utilization of the existing grid in EV adoption hotspots and reduces distribution grid costs by up to $230 per EV per year in the long run.

Active managed charging increases the EV hosting capacity of existing distribution system assets, thereby deferring capital expenditures relative to unmanaged charging and the Passive TOU strategy.

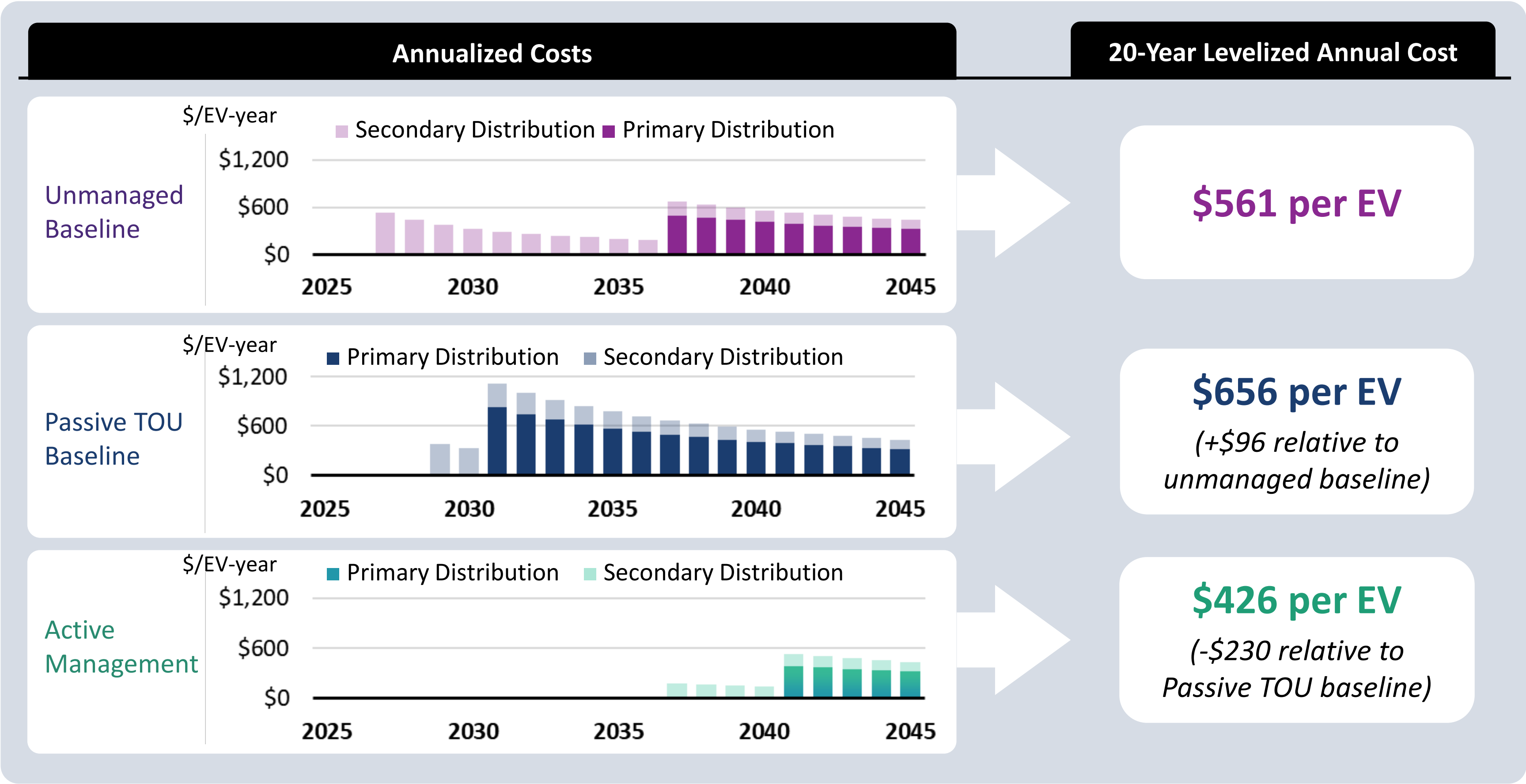
This has three major benefits to utilities and ratepayers:

- **Delaying rate impacts** through deferral of capital expenditures (capex)
- **Reducing rate impacts** by deferring capex until there are more EVs and thus spreading the costs (when they are eventually incurred) over a larger number of EVs
- **Providing utilities more flexibility** in allocation of their limited capital to serve other important purposes

1: The Wholesale + Load Limit Strategy is shown as "Active Management" on this page for conciseness. The two active management strategies provide very similar distribution system benefits.

DISTRIBUTION SYSTEM UPGRADE COSTS

In a location where grid assets are loaded to 75% of capacity in 2025 and 25% of annual vehicle sales are EVs



Modeling Bulk System Value of Managed Charging Based on Trial Data

We modeled the bulk system value of managed charging based on real EV charging data from the trial and assumed electric system marginal costs developed using data from various US regions.

Cost signals used in the trial to demonstrate performance of active managed charging

To demonstrate how active managed charging strategies would perform when optimizing against different objectives, the trial used a month of hourly, time-varying cost signals.

To align the two active management strategies and the Passive TOU baseline around the same region's costs, we utilized:

- **In the TOU + Load Limit trial:** The actual historical TOU rate structure and level from Xcel Energy MN
- **In the Wholesale + Load Limit trial:** The actual 2023 energy prices from a node in Xcel Energy MN's zone in MISO, generation capacity costs based on the 2023 Net CONE in the Xcel Energy MN zone, and representative marginal transmission capacity costs

Extrapolation from 4 weeks to annual value

Each strategy in the trial was in effect for four weeks. We extrapolated results from the four weeks to a year by weighting each week based on how often similar price levels occurred over the whole year at the selected MISO price node.

- **Week 1:** Low-Priced Week (Weight = 4%)
- **Week 2:** Lower Mid-Priced Week (Weight = 61%)
- **Week 3:** High-Priced Week (Weight = 6%)
- **Week 4:** Higher Mid-Priced Week (Weight = 29%)

Extrapolation to other regions

To develop a broadly applicable estimate of the value of managed charging, we extrapolated the annual results from the selected MISO node to various regions across the US. We extrapolated each component of the bulk system value stack based on the drivers of that value:

- **Energy:** Based on the price differential in each region between unmanaged charging hours and managed charging hours (more value in regions with more price volatility)
- **Generation capacity:** Based on differences in regional capacity prices
- **Transmission capacity:** Based on differences in the marginal cost of transmission service

Value of Active Managed Charging – Range Across US Regions

The cost of serving new EV load can be as high as $400 per EV-year and varies widely across the US due to differences in bulk system costs and distribution system hosting capacity.

Cost Component	Description	Cost to Serve New Load	Cost of Unmanaged Charging *$/EV-year*	Savings from Active Managed Charging *$/EV-year*	Notes
Energy	Wholesale market cost of electricity purchases	$25 to $60 per MWh	$60 to $230	$30 to $40	Low end based on MISO energy prices for Minnesota; high end based on CAISO energy prices.
Generation capacity	Cost of ensuring adequate generation availability	$55 to $330 per kW-year	$25 to $155	$20 to $130	Low end based on NYISO Zone K; high end based on NYISO Zone J.
Transmission capacity	Cost of load-driven transmission upgrades	$40 to $130 per kW-year	$20 to $60	$15 to $50	Range based on a review of marginal transmission cost of service estimates in five jurisdictions. Low end based on SDG&E; high end based on Con Edison.
Primary distribution capacity	Cost of upstream distribution system upgrades	$0 to $110 per kW-year	$0 to $580	$0 to $95	Low end assumes a location with adequate distribution hosting capacity for new load. Many parts of most utility systems have available hosting capacity today. High end based on a location with constrained hosting capacity, assuming EV charging would overload assets in the first year if unmanaged.
Secondary distribution capacity	Cost of local distribution system upgrades	$0 to $20 per kW-year	$0 to $210	$0 to $85	
Total Cost	Full "value stack" (sum of the above)	$25-$60/MWh + $95-$590/kW-year	**$105 to $1,235**	**$65 to $400**	Wide range of value based on regional bulk system cost variation and local distribution system hosting capacity.

Illustrative Value Stack in a Relatively High-Cost Location

This value stack of $245 per EV per year is illustrative of a location with relatively high electric system costs, representd using the modeled distribution network scenario and 2023–24 wholesale market prices from CA/NY. The value stack is likely to grow as system costs continue to rise.

Secondary Distribution costs are significantly lower with active management due to the increased hosting capacity of service transformers.

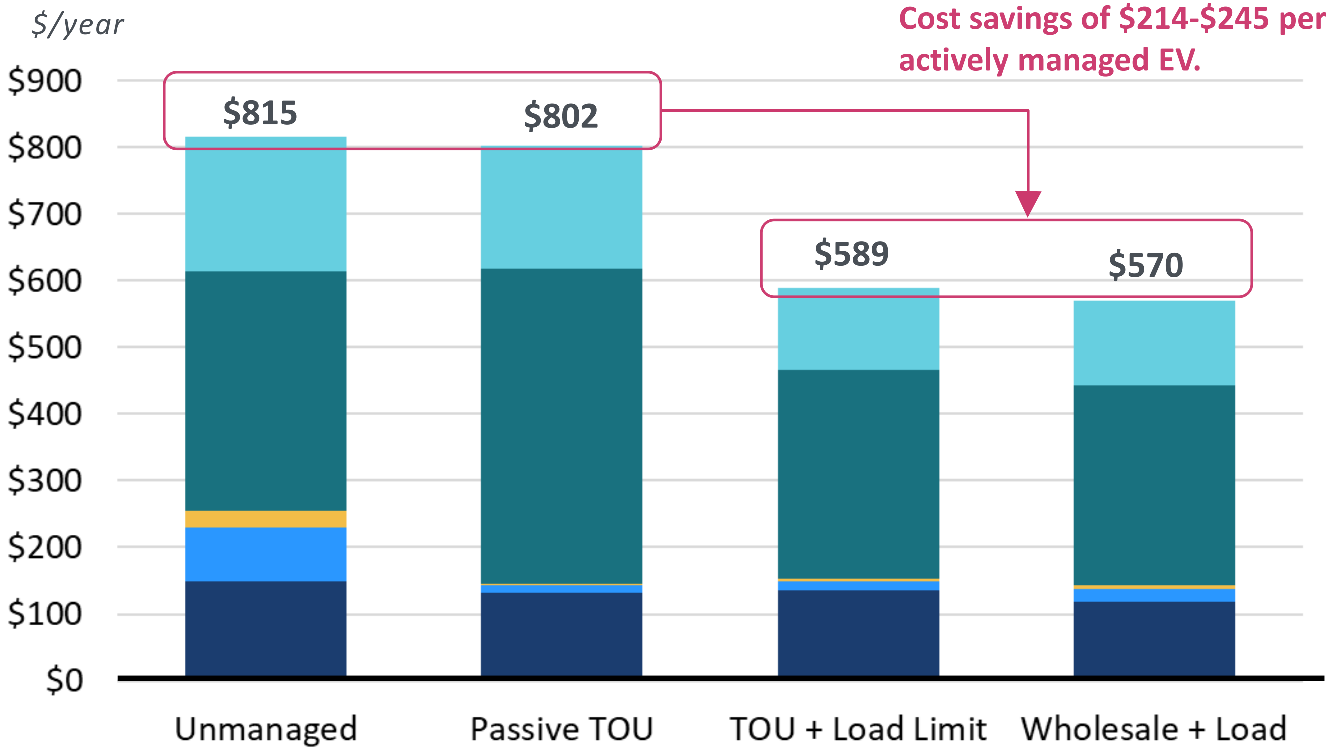
Primary Distribution costs are higher under a Passive TOU because the snapback effect causes earlier grid upgrades. Active management spreads out charging to increase hosting capacity and defer upgrades.

Transmission Capacity and **Generation Capacity** costs are effectively reduced by both the active and passive management strategies, with EV charging load being shifted out of bulk system peak periods.

Energy costs are also reduced by both active and passive management strategies. The Wholesale + Load Limit strategy provides incremental value relative to the other strategies by shifting charging to the lowest priced hours.

ELECTRIC SYSTEM COST PER EV

$/year



Note: This modeled case does not correspond to a specific region. It is based on a hypothetical distribution network scenario and bulk system costs from CA and NY.

5. Conclusion

Key Takeaways from the Study

Active managed charging delivers substantial system cost savings.

Active management of EV charging can reduce annual electric system costs by about 30% relative to passively managed or unmanaged charging. In a case where annual unmanaged charging costs were ~$800 per EV, active management was shown to provide annual savings of $245 per EV. Savings could be as high as $400 per EV in regions with higher system costs.

Active management reduces coincident EV charging and cuts EV charging peak load on the electric grid by roughly 30%–50%.

The load-limiting features of active management reduced the group-wide EV charging peak demand by 55% relative to the passive TOU strategy and 33% relative to unmanaged charging.

Active management can more than double the distribution system's EV hosting capacity.

The load-limiting features of active management were shown to increase service transformer EV hosting capacity by 2.2–3.2x and primary distribution assets' EV hosting capacity by 1.3–2.3x relative to unmanaged charging or the Passive TOU strategy.

Active management significantly outperforms passive management in deferring distribution system costs.

Passive management with TOU rates reduces load diversity and causes earlier overloads at feeders and substations. Active management effectively spreads EV charging, reducing peaks and deferring the need for grid upgrades. In a scenario where 25% of vehicle sales were EVs, active management was shown to defer distribution system upgrades by ten years relative to a Passive TOU strategy.

Both passive and active management are effective at reducing energy costs. The most targeted approach (active management to hourly wholesale prices) can double the savings.

Shifting charging out of higher energy price hours reduces energy costs by about 10%. Active management that optimizes based on hourly wholesale prices takes a more targeted approach and can double the energy cost savings, leading to a 20% cost reduction.

Both passive and active management strategies are effective at reducing generation and transmission capacity costs.

Managed charging shifts EV load out of the bulk system peak periods, reducing generation and marginal transmission capacity costs by over 75% relative to unmanaged charging. The value of this shifting is likely to grow over time as many parts of the US electric grid are becoming capacity-constrained due to rapid load growth from data centers.

How to Use This Study

Utilities

- **Designing Managed Charging Programs**
  The insights from this study demonstrate why active managed charging should be part of the utility toolkit for managing EV impacts, even at penetration levels under 10%. Utilities should consider how to integrate program offerings that can flexibly transition passively managed customers to active management.

- **Determining Locational Value**
  The study showed that EV charging can be a significant long-term cost driver even in locations that presently have load hosting capacity. Utilities can use the method illustrated in this study to estimate the location value of managed charging and target deployment in the most valuable locations.

- **Distribution System Planning**
  The study illustrates the impact of active managed charging on distribution system peak loads. Distribution capacity planners can use the coincident peak loads reported from the trial both to forecast unmanaged EV load and to plan for mitigation using managed charging programs.

- **Customer Service Sizing**
  The study showed how even two EVs charging coincidentally can overload a typical service transformer. Utility engineering teams that plan for customers' service adequacy can use these estimates of secondary distribution system loading to decide if connecting a new EV may require a transformer upgrade.

Regulators and Policymakers

- **Evaluating Utility Customer Program Portfolios**
  In many jurisdictions, utility development of new customer programs is driven primarily by regulatory directives. Regulators should consider directing utilities to introduce options for active managed charging based on expected EV growth rates in the region.

- **Considering Active Managed Charging Programs**
  Many utilities have begun solidifying plans for the implementation of a Distributed Energy Resource Management System (DERMS). Active managed charging is likely to be a key use case for DERMS, which will provide more visibility into the state of the grid and DERs, enabling real-time communication between these assets. Regulators can use the estimated system value from this study as a benchmark for the value that could be enabled by DERMS when evaluating the prudence of these investments.

- **Committing To Electrification Initiatives**
  The study shows that the industry is developing effective ways to manage and mitigate the electric system impacts of electrification. As states face affordability pressures on climate policies, policymakers should consider revising cost estimates to account for highly effective mitigation strategies such as active managed charging.

Recommendations for Program/Tariff Rollout

We recommend a proactive approach to managing EV grid impacts by deploying both TOU tariffs and active managed charging programs now, without waiting for grid needs to become imminent.

Near-Term Strategy
Under 5% EV penetration

- Deploy TOU rates, which are beneficial for managing non-EV loads and for managing EV loads at lower penetration levels.
- Design active management programs and deploy on an opt-in basis across the service territory. It takes time to deploy programs and scale enrollment, so there is value in acting now to get this infrastructure in place.
- For customers in active management programs, phase in optimized charging for distribution grid needs on a locational basis, as needs arise.
- Account for managed EV charging in integrated system planning to reduce bulk system costs.

Mid-Term Strategy
5%–20% EV penetration

- Begin incentivizing customers to transition EVs off TOU rates and onto the active management programs, while maintaining TOU rates for non-EV loads.
- Market programs through OEM channels (in-app experiences, dealership partnerships, email) to drive scale.[1]
- Use the experience gained from early deployment to more effectively integrate active managed charging into distribution system planning.

Long-Term Strategy
Over 20% EV penetration

- Consider default enrollment of EVs in active managed charging programs.
- Grow program capabilities, including through grid-aware approaches that can further optimize charging based on real-time data from local grid assets.
- Continue to allow customers to opt out of managed charging, while ensuring that they pay for their fair share of resulting grid upgrade costs.

1: Refer to Distributed Energy, Utility Scale: 30 Proven Strategies to Increase VPP Enrollment for a detailed set of program design and enrollment strategies.

For Further Information

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Clarity in the face of complexity

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