

Value of EV Managed Charging to Bulk Power Systems

Luke Lavin and Elaine Hale

March 28, 2023

Joint work with: Arthur Yip, Brady
Cowiestoll, Jiazi Zhang, Paige Jadun, and
Matteo Muratori

Research Question

What is the value of light-duty electric vehicle (EV) managed charging (EVMC) to the bulk power system and how does it vary with:

- Single-day vs. Multi-day flexibility
- Dispatch mechanism:
 - Direct load control (DLC)
 - Real-time pricing (RTP)
 - Time-of-use tariff (TOU)
- EVMC participation levels

What is the value in terms of bulk power system energy, capacity, and avoided emissions?



Electric Vehicle Managed Charging: Forward-Looking Estimates of Bulk Power System Value

Elaine Hale, Luke Lavin, Arthur Yip, Brady Cowiestoll,
Jiazi Zhang, Paige Jadun, and Matteo Muratori

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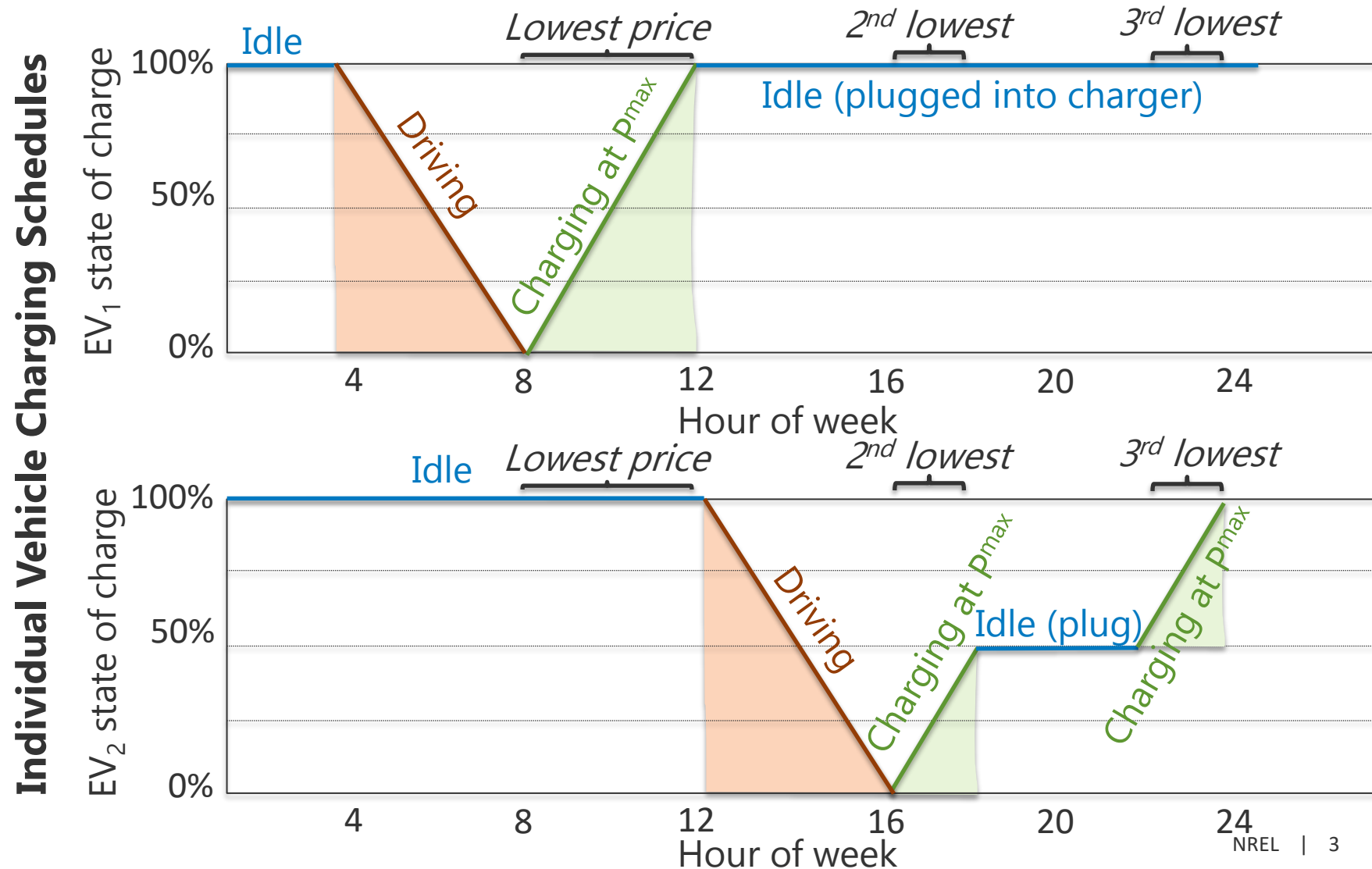
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Technical Report
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September 2022

<https://www.nrel.gov/docs/fy22osti/83404.pdf>

Methodological Finding: Energy and capacity bounds of EV aggregations *cannot* be naively added

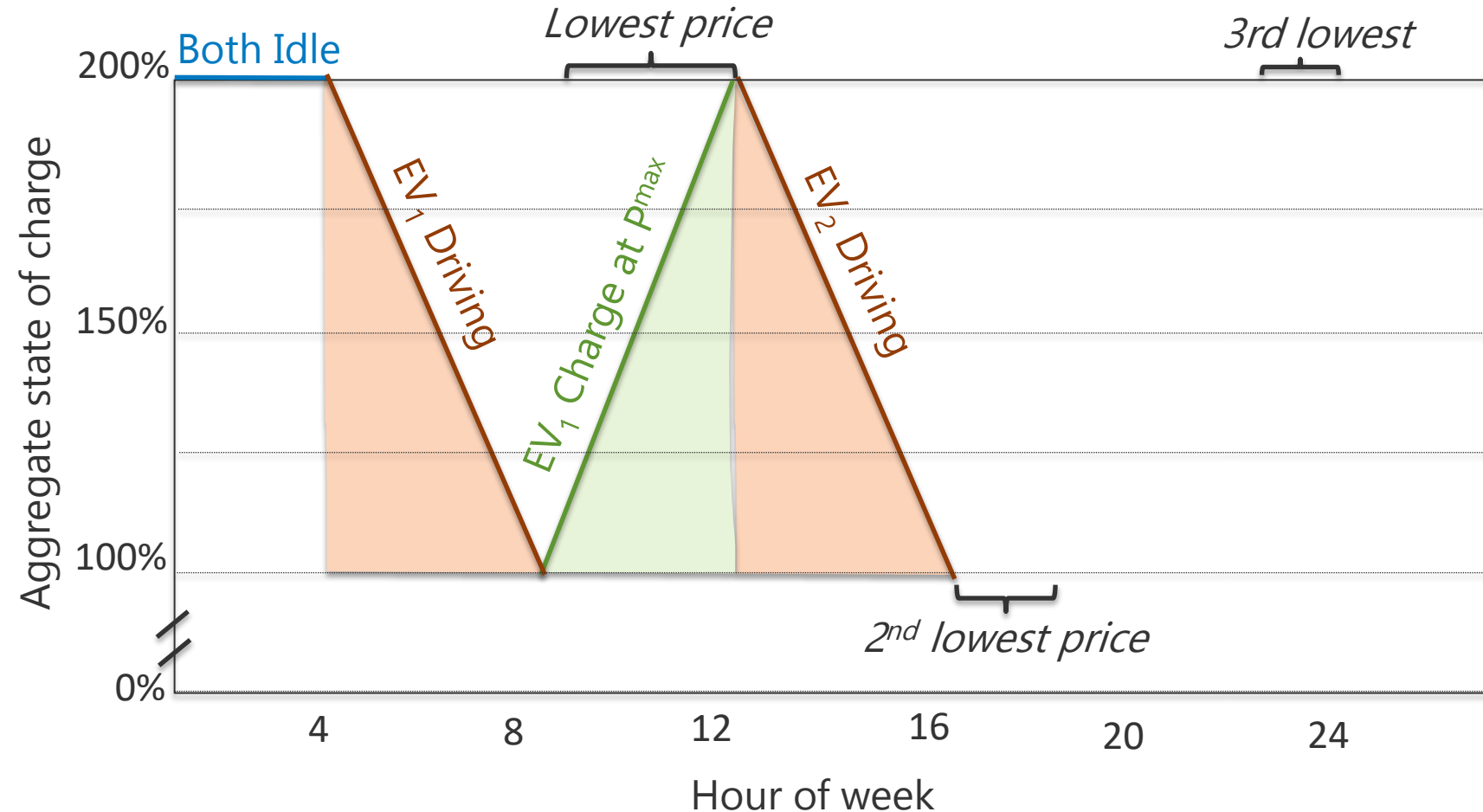
- Aggregation is needed for EVs to participate in wholesale electricity markets (>0.1 MW), but simple addition of individual vehicle flexibility overestimates resource
- **Why:** A fully-charged vehicle's ability to increase load can be paired with another vehicle's ability to accept more charge



Methodological Finding: Energy and capacity bounds of EV aggregations *cannot* be naively added

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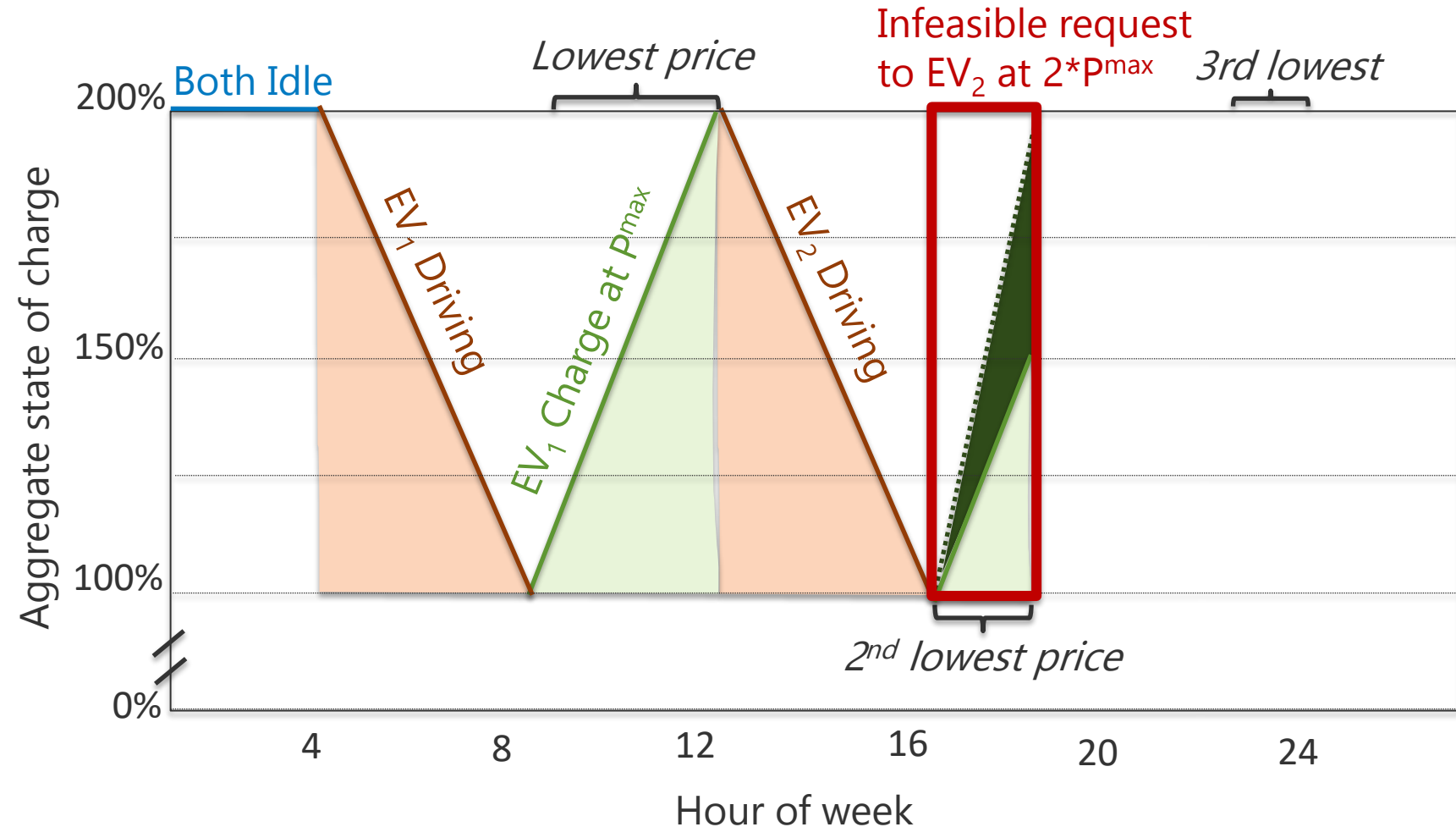
Aggregated Vehicles Charging Schedule



Methodological Finding: Energy and capacity bounds of EV aggregations *cannot* be naively added

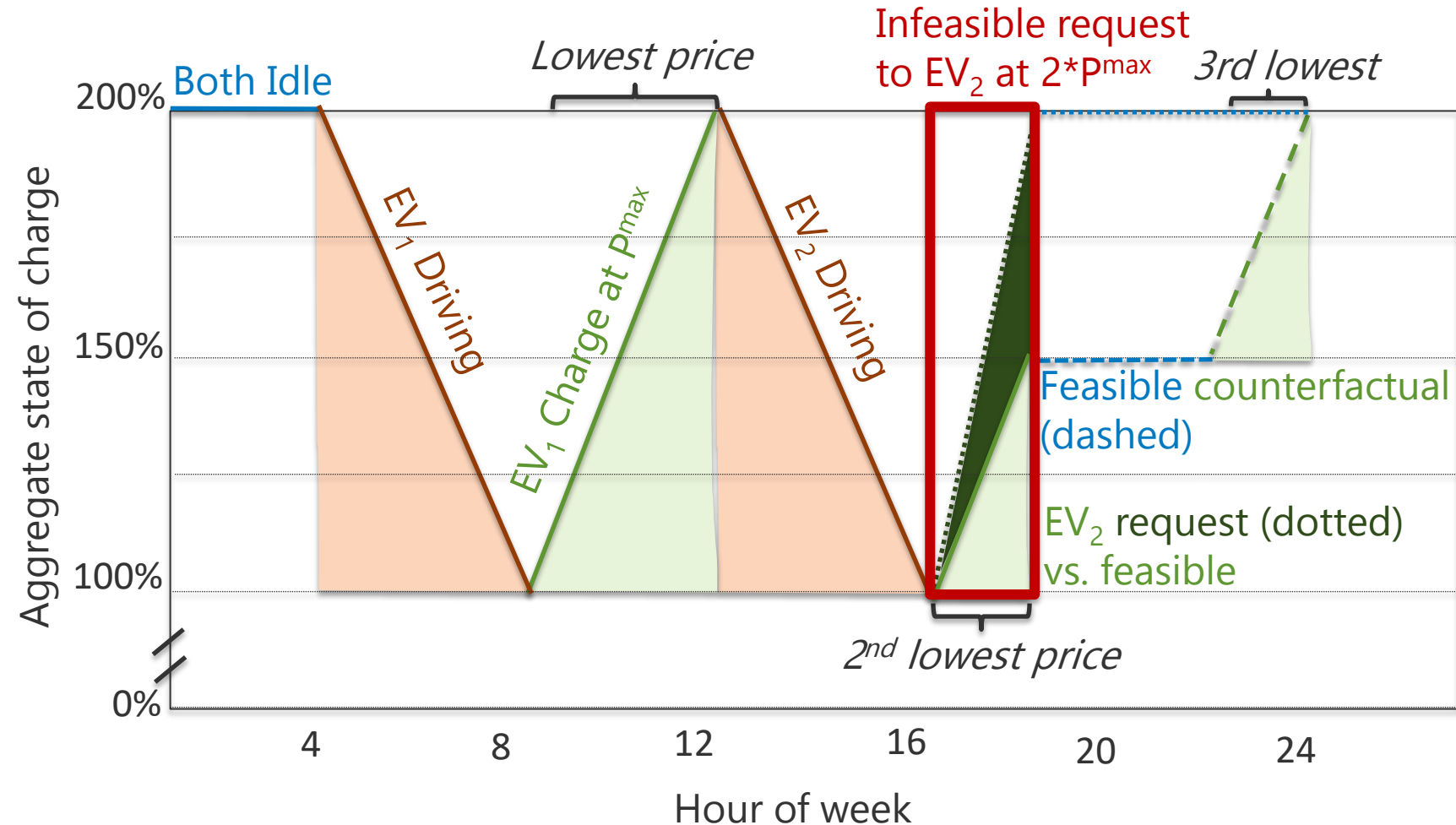
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Methodological Finding: Energy and capacity bounds of EV aggregations *cannot* be naively added

Aggregated Vehicles Charging Schedule



- **Question:** How feasible is Direct Load Control?

Tests show naïve aggregation produces highly infeasible charging flexibility requests

Legend

$P^{\max}$: upward charging flexibility in each time period

$P^{\min}$: downward charging flexibility in each time period

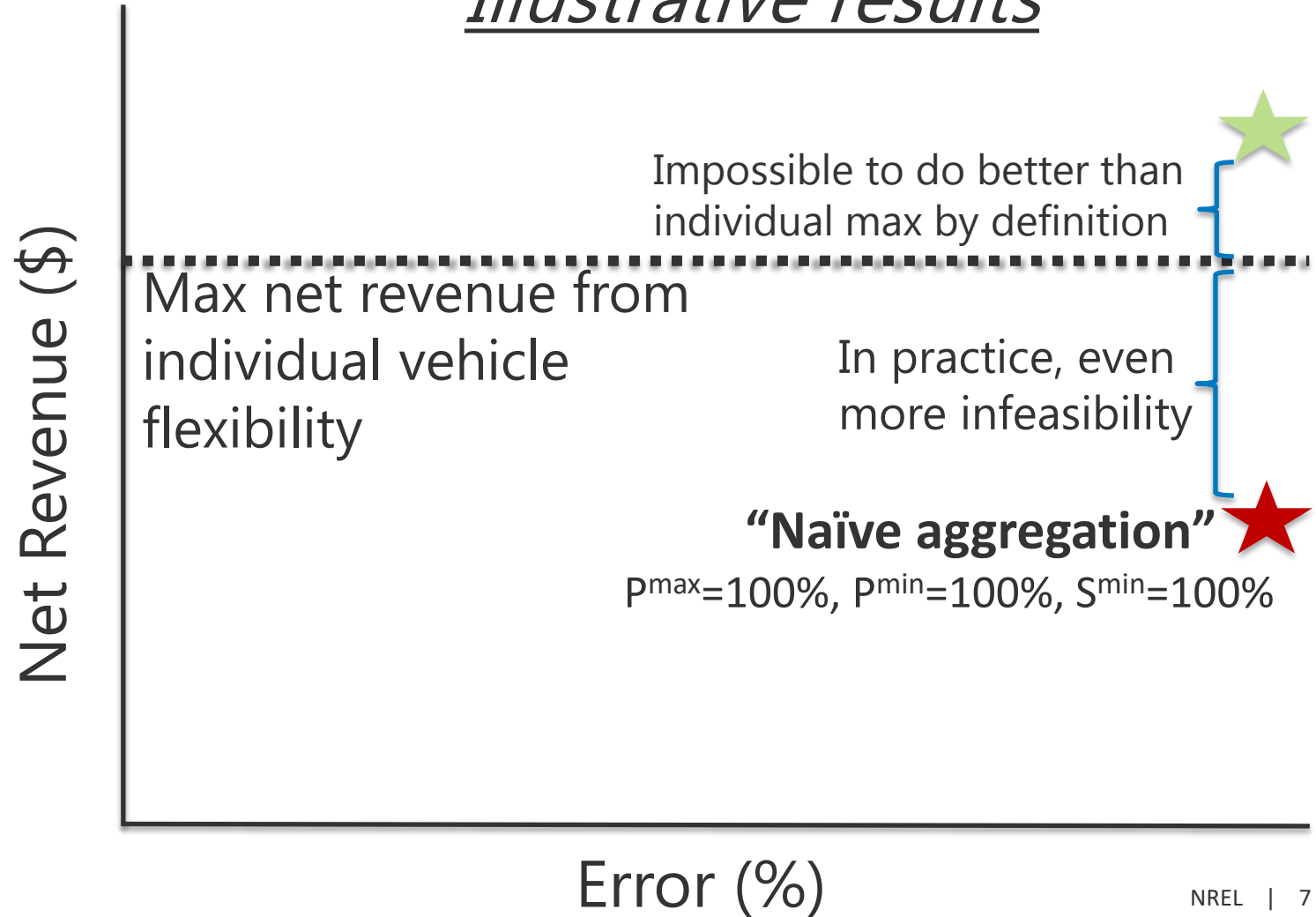
$S^{\min}$: max quantity of deferred load in each time period

Red: Revenue under feasible re-dispatch to individual EVs

Green: Revenue if aggregate request was fulfilled

▲●★: Three different objectives

Illustrative results



Feasible redispatch of aggregate managed EV resource requires scaling power and energy bounds

Legend

$P^{\max}$: upward charging flexibility in each time period

$P^{\min}$: downward charging flexibility in each time period

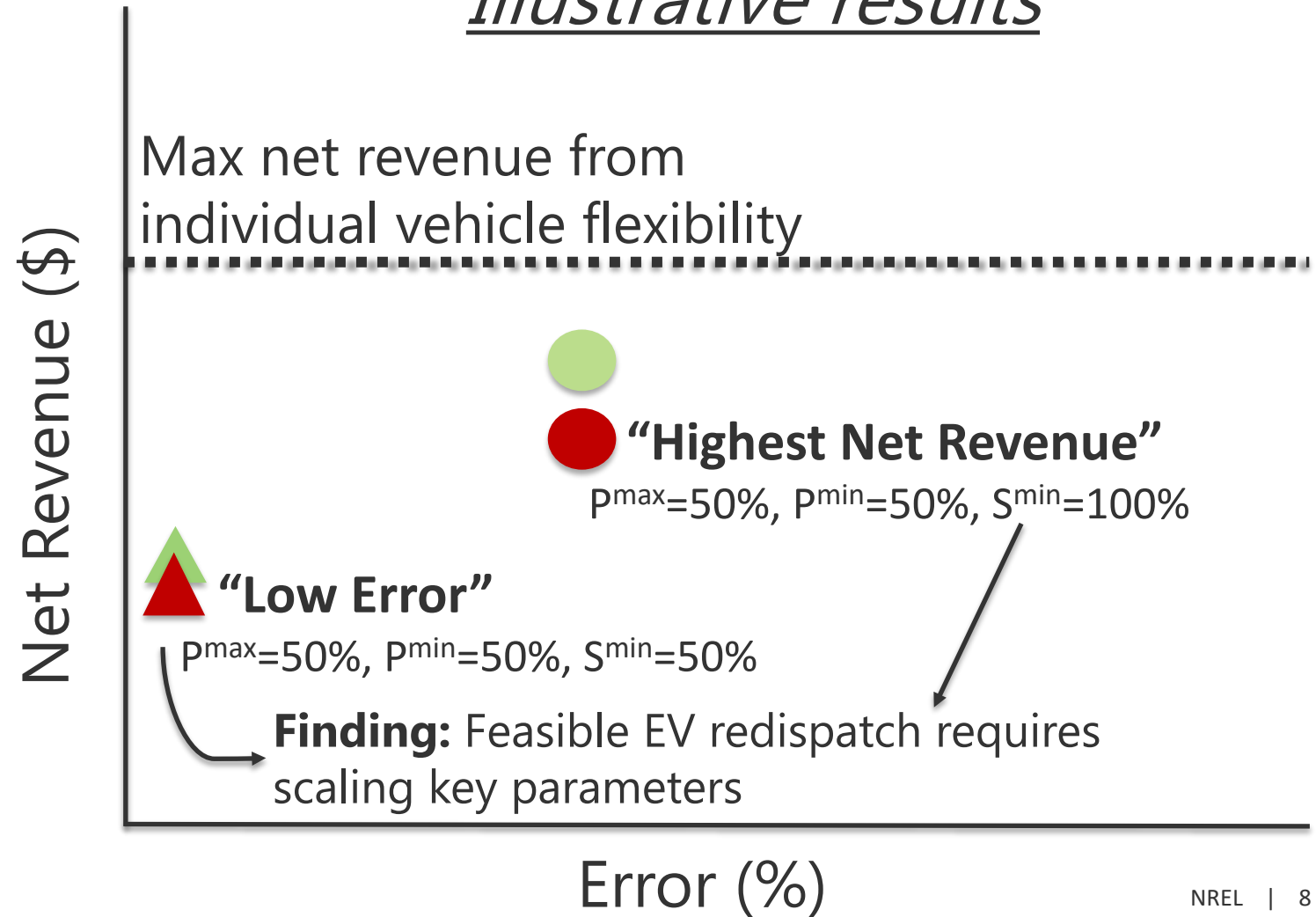
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Illustrative results



Study Setting

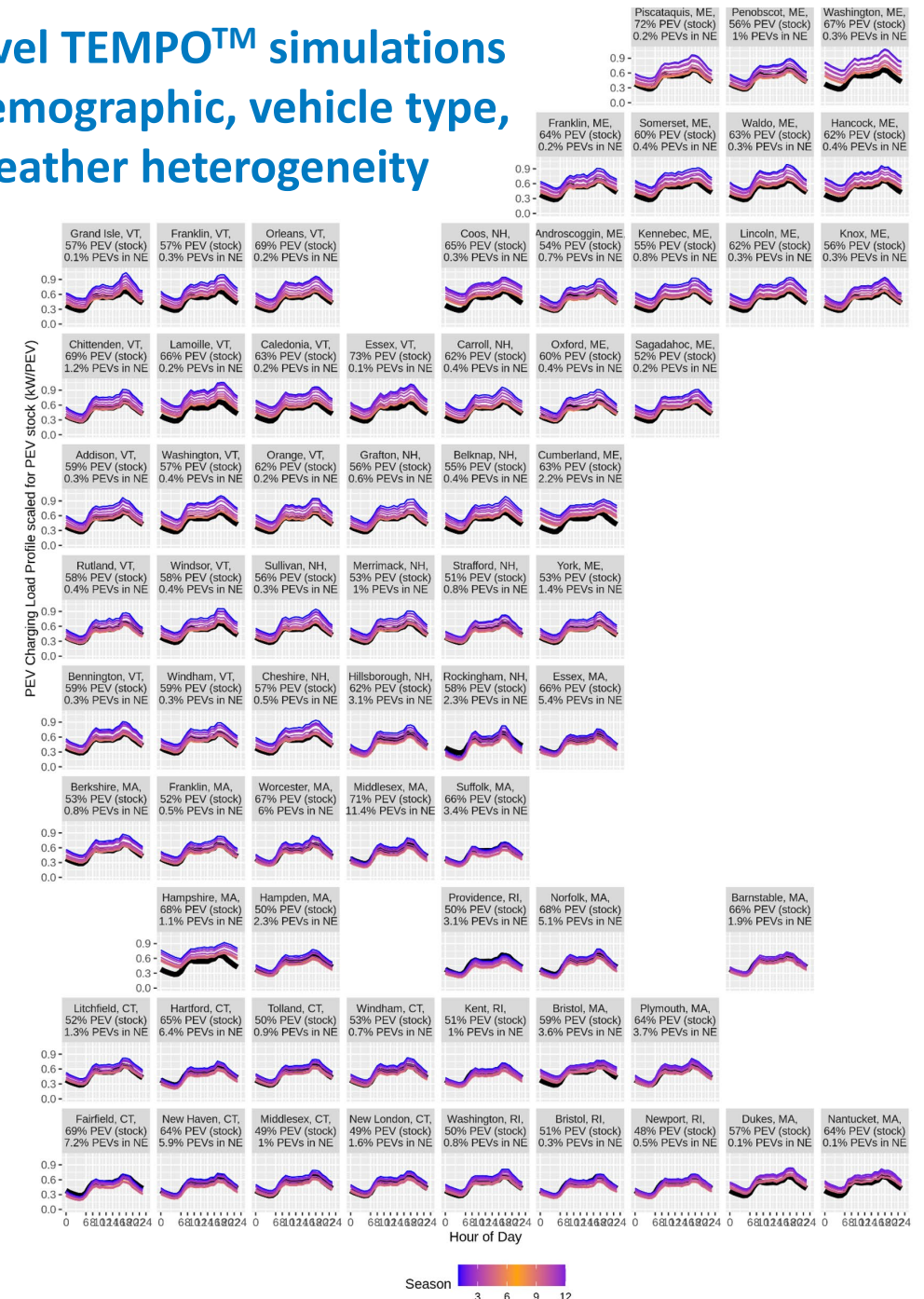
Hourly operational model of an envisioned 2038 New England Power System

- Peak load is 28.9 GW
(0.5 GW from EVs; compare to 25.8 GW in 2021)
- Within-ISO generation is 84% clean
(wind, solar, hydropower, biomass, nuclear)
- EVs are 45% of light-duty passenger vehicle fleet (100% of sales); 80% of EVs are battery electric vehicles

Charging flexibility (V1G) estimated from 101,000 sample vehicles' charging profiles

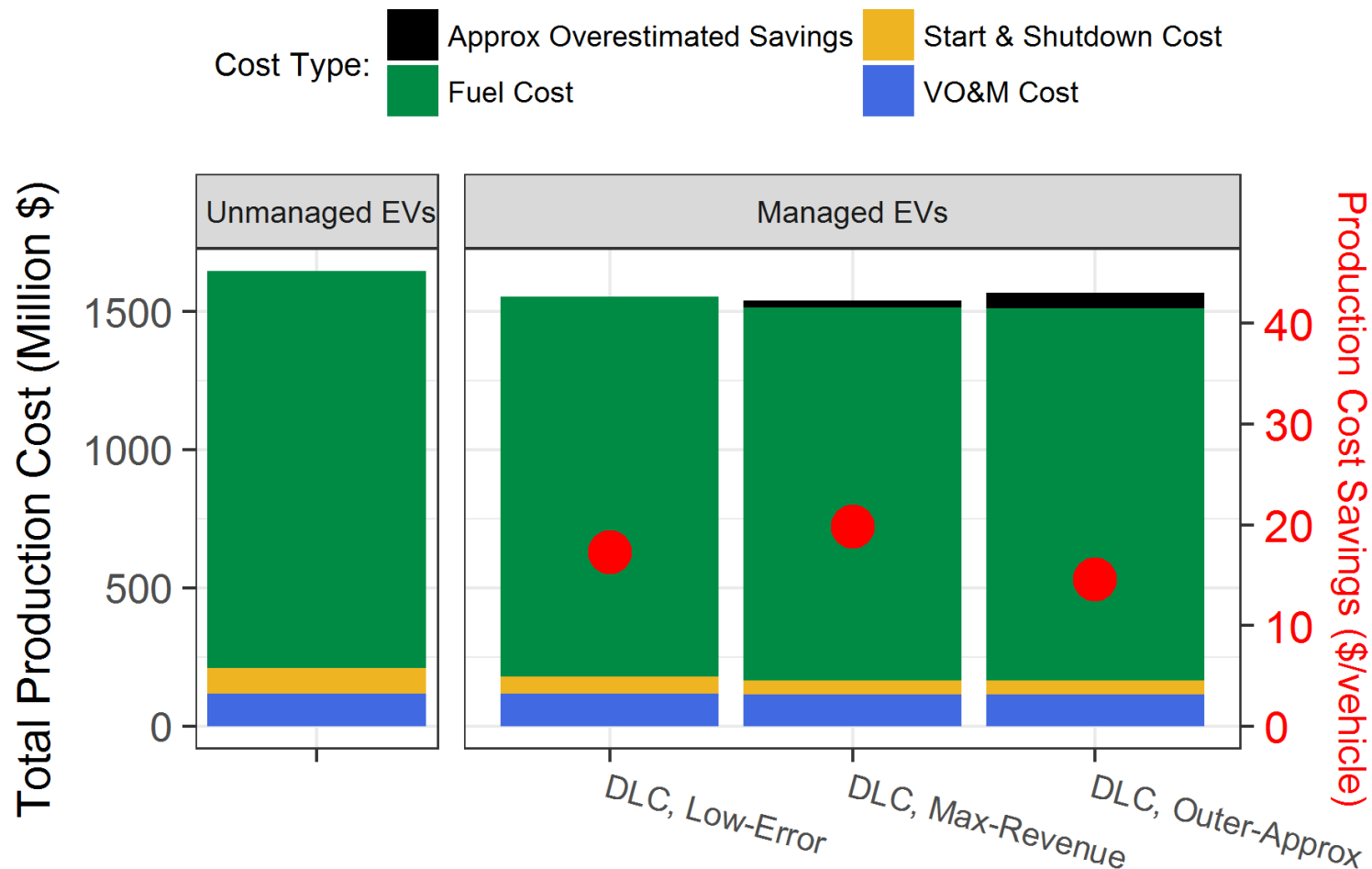
- Mobility service is preserved in all scenarios
- Ubiquitous charging assumption

County-level TEMPO™ simulations capture demographic, vehicle type, and weather heterogeneity



Key Finding: Aggregating vehicles for direct load control (DLC) comes at a feasibility cost

Estimated production cost savings for within-session aggregate flexibility models with different scaling factors

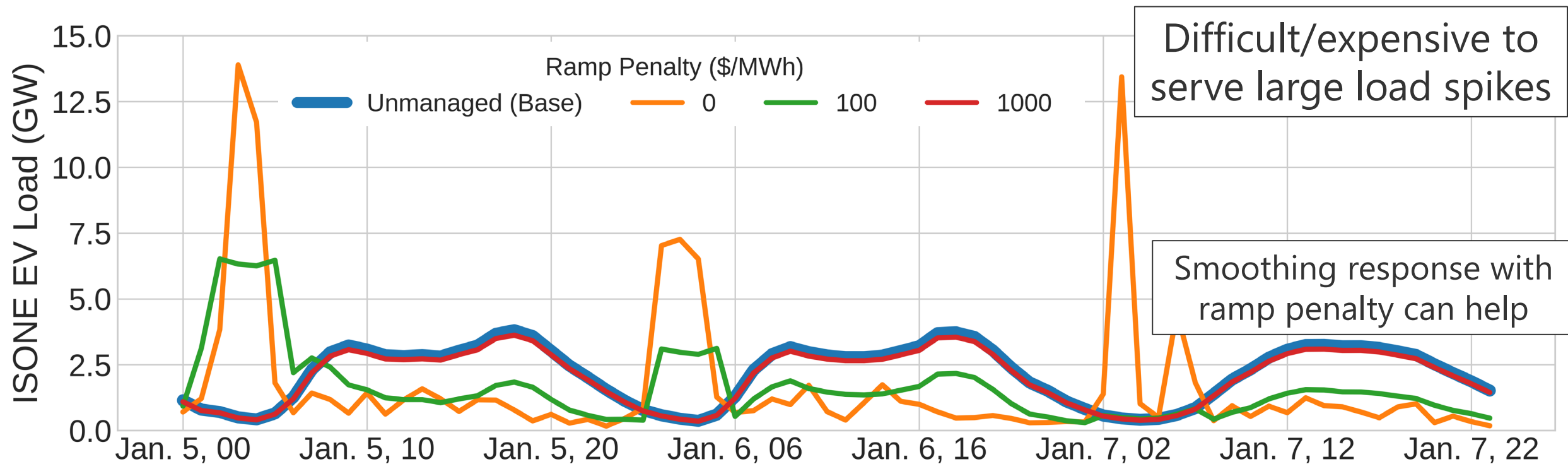


Recall: Naïve (“outer-approx”) aggregations effectively assume that one already-fully-charged vehicle’s ability to increase load can be paired with another already-charging vehicle’s ability to accept more charge.

Key Finding: Individual vehicles responding to price works for small numbers of vehicles, but is difficult to scale up

Charging profiles for the unmanaged case vs. vehicles responding to day-ahead energy prices

Energy prices were computed using the unmanaged profile as the EV load forecast (zero foresight of price-responsiveness)



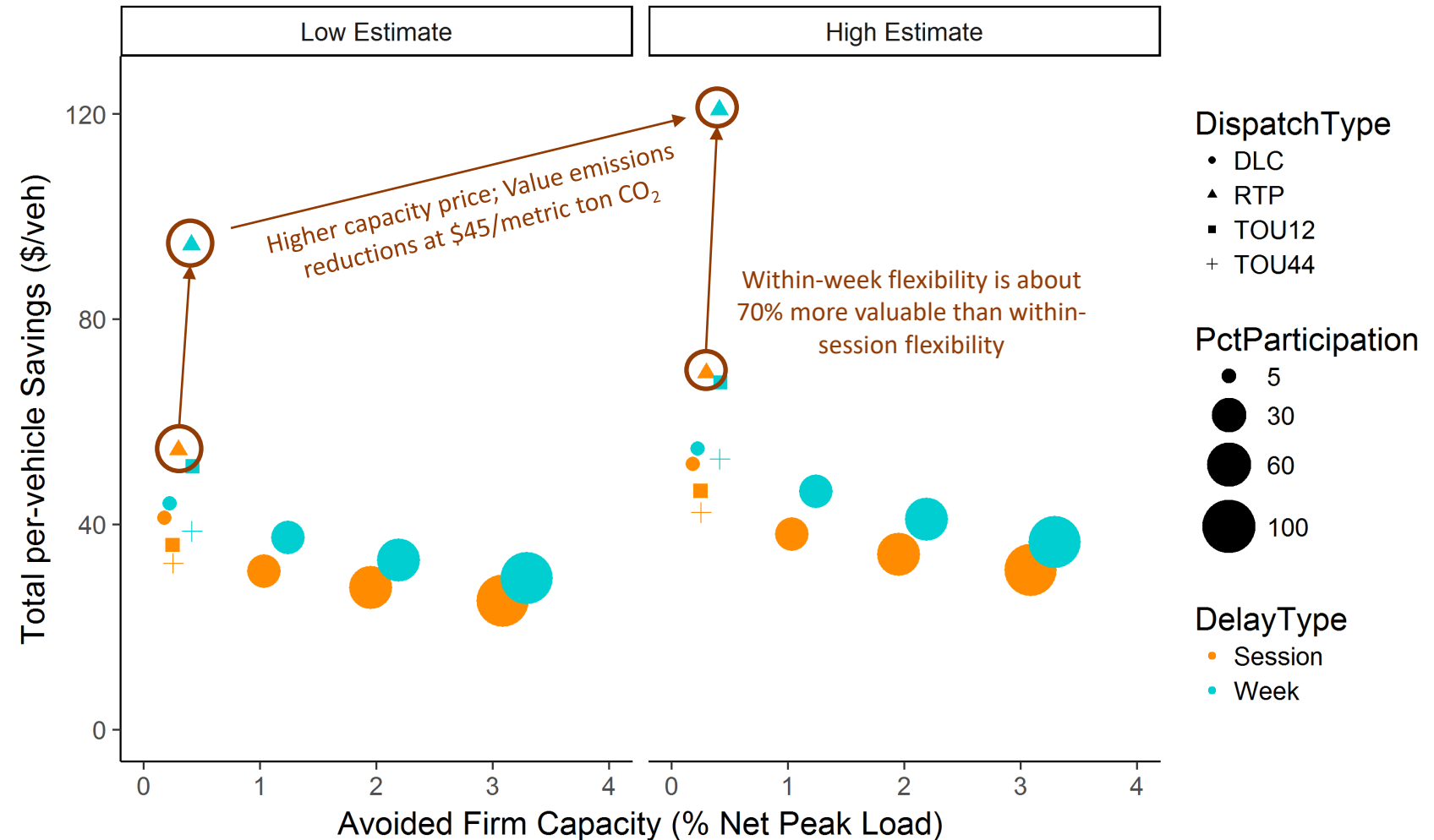
This is an extreme example, but we also find that the bulk system value of 2% of vehicles responding to an RTP is improved with a small ramp penalty (\$1/MW for within-session and \$10/MW for within-week).

Key Finding: Highest per-vehicle value from low participation, RTP

All-in value of production cost savings, capacity savings, and emissions reductions

The highest per-vehicle-year value is produced at low participation rates by individual vehicles responding to real-time prices computed in the day-ahead market

- Per-vehicle value tops out at about \$10/month, and that does not yet account for enablement and incentive costs
- Up to 1% of production costs and nearly 2% of within-ISO emissions can be avoided by about 2% of the 2038 LDV fleet actively participating in EVMC
- Price-responsive EVMC is not anticipated in the day-ahead unit commitment problem in this study (no foresight assumption)

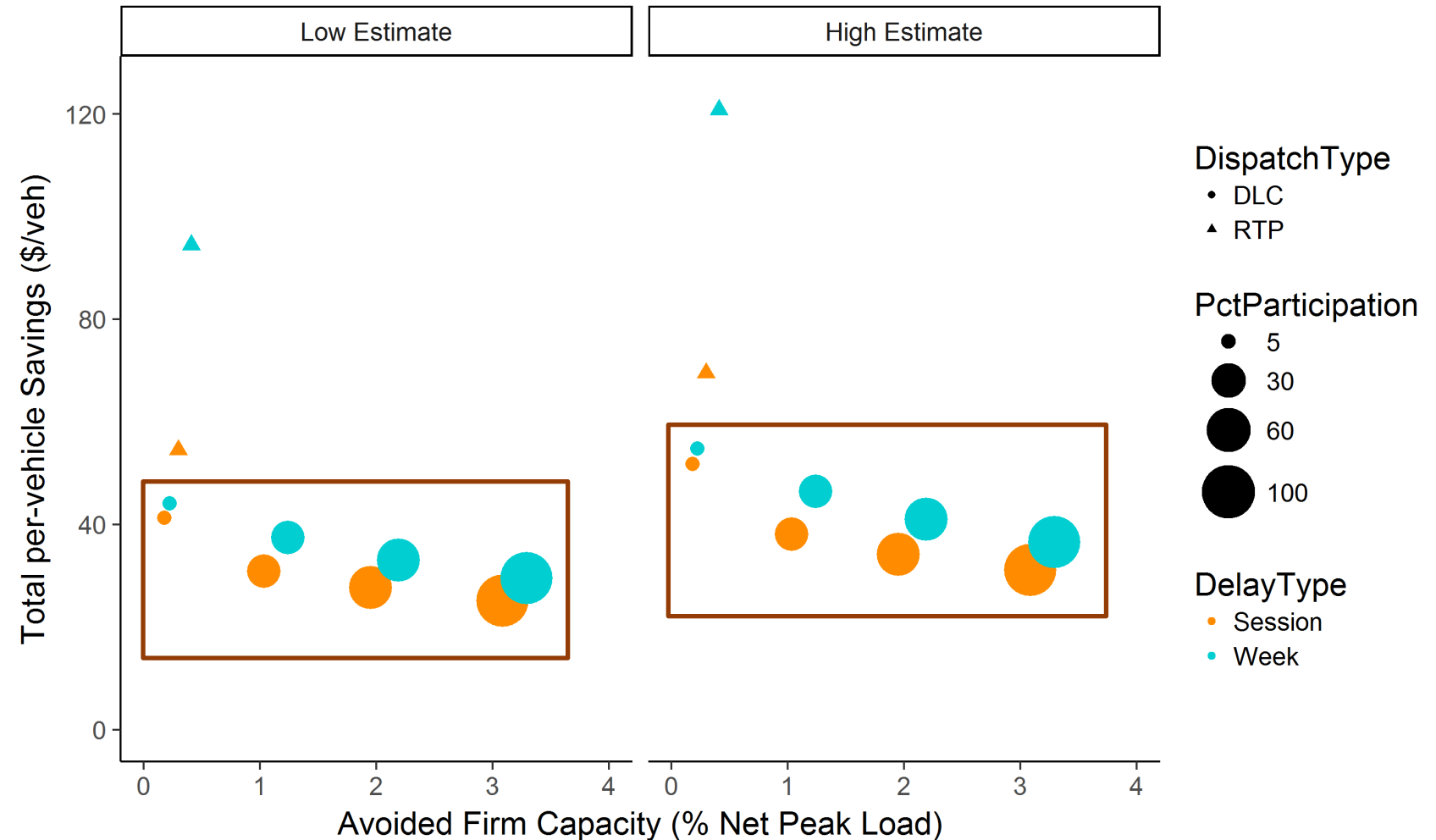


Key Finding: Higher participation levels require DLC and mute the advantages of multiday flexibility

All-in value of production cost savings, capacity savings, and emissions reductions

Only direct load control provided significant production cost savings for all participation levels. With low-error DLC:

- All EVs (45% of the LDV fleet) providing within-session flexibility reduces production costs 4.4% and within-ISO emissions 5.2%
- All EVs (45% of the LDV fleet) providing within-week flexibility reduces production costs 5.6% and within-ISO emissions 6.9%
- Within-week is 70% more valuable than within-session flexibility at 5% participation with RTP; For DLC, the within-week advantage is 20% at 30% participation and drops to 17% for 100% participation



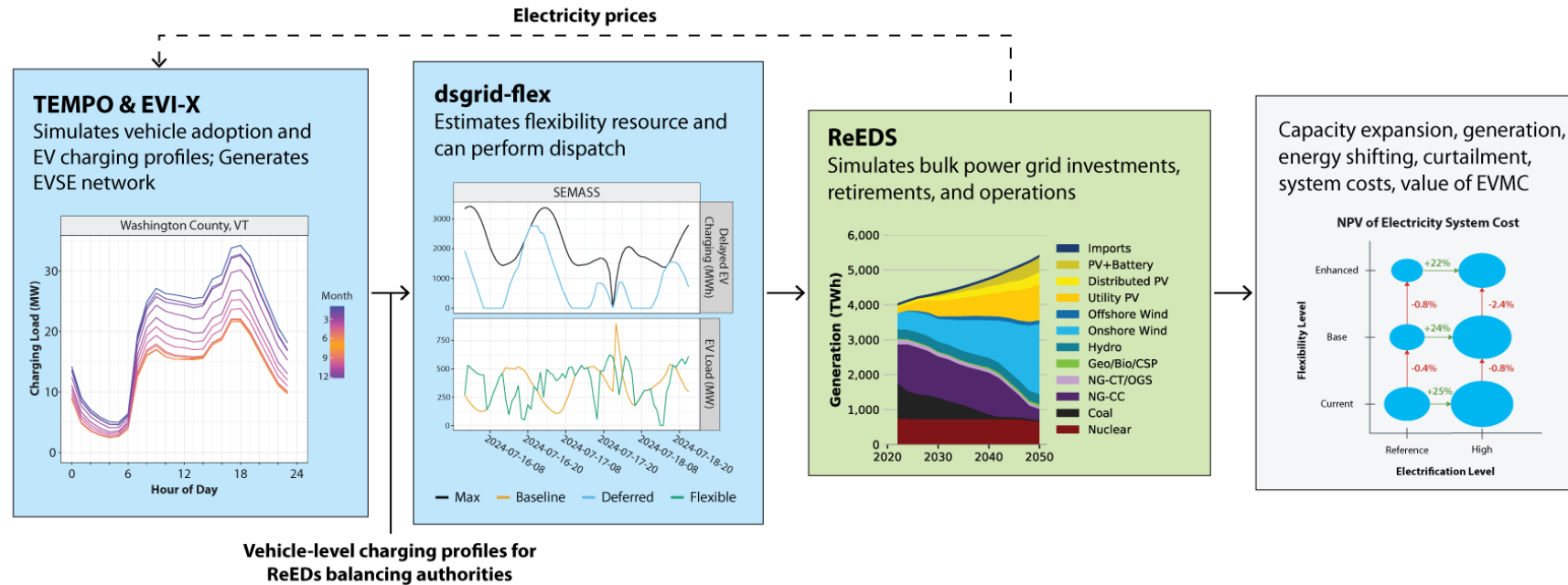
Summary of key findings

- Coordination of EVMC response is required starting at modest participation levels and comes at a cost
- Highest per-vehicle value is achieved at low participation levels responding to time-varying price
- Within-week flexibility is more valuable than within-session flexibility, but in our study the effect is muted at higher participation levels
- If all EVs fully participate through a low-error DLC mechanism, we estimate total system savings of:

Flexibility type	Production Cost Savings (%)	Power Sector Emissions Savings (%)	Firm Capacity from EVMC (MW)
Within-session (single day)	4.4	5.2	780
Within-week (multi-day)	5.6	6.9	830

yielding per-vehicle value estimates of **\$25/vehicle-yr to \$37/vehicle-yr.**

New Project: Managing Increased Electric Vehicle Shares on Decarbonized Bulk Power Systems



Building on the completed project's innovations around:

- Single and multi-day charging flexibility
- Exploration of aggregation and comparing direct control to price responsive dispatch

The new multi-year project, sponsored by the DOE EERE Vehicle Technologies Office (VTO), is extending the methodology to include:

- Capacity expansion modeling with EVMC as an investible resource
- Medium and heavy-duty vehicles
- Spatially resolved electric vehicle supply equipment (EVSE) and EV charging
- Fixed assets (e.g., EVSE scenarios) as management strategies
- Nationwide, path-dependent impacts on bulk power system costs and related metrics

Stay in touch!

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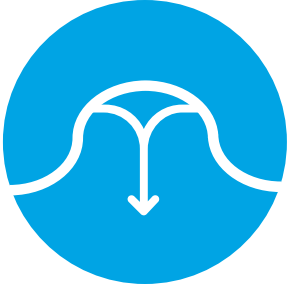
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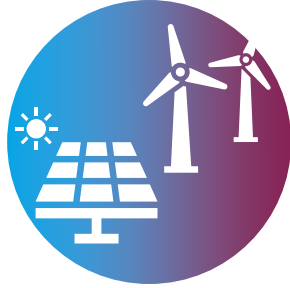
<https://www.nrel.gov/docs/fy22osti/83404.pdf>

Backmatter

General Problem Statement



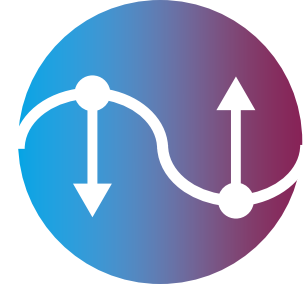
Demand response is a long-standing source of power system flexibility



Increased solar and wind generation increases net-load variability and uncertainty



Additional balancing needs and a desire for less carbon emissions at affordable costs **increases interest in more forms of demand-side flexibility**



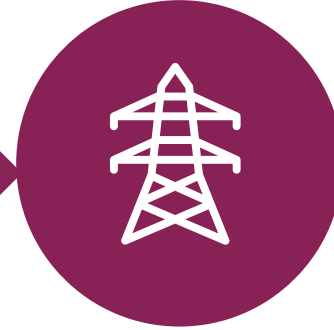
Demand response, ideally available year-round, can potentially **shift demand from high- to low-price times and reduce renewable energy curtailment**

Resource

Individual resources with equipment capacities in **kW**



What can aggregated electric vehicles contribute to power systems?



Target

Bulk power systems – generator plant capacities in **MW**, system capacities in **GW**

Research Question

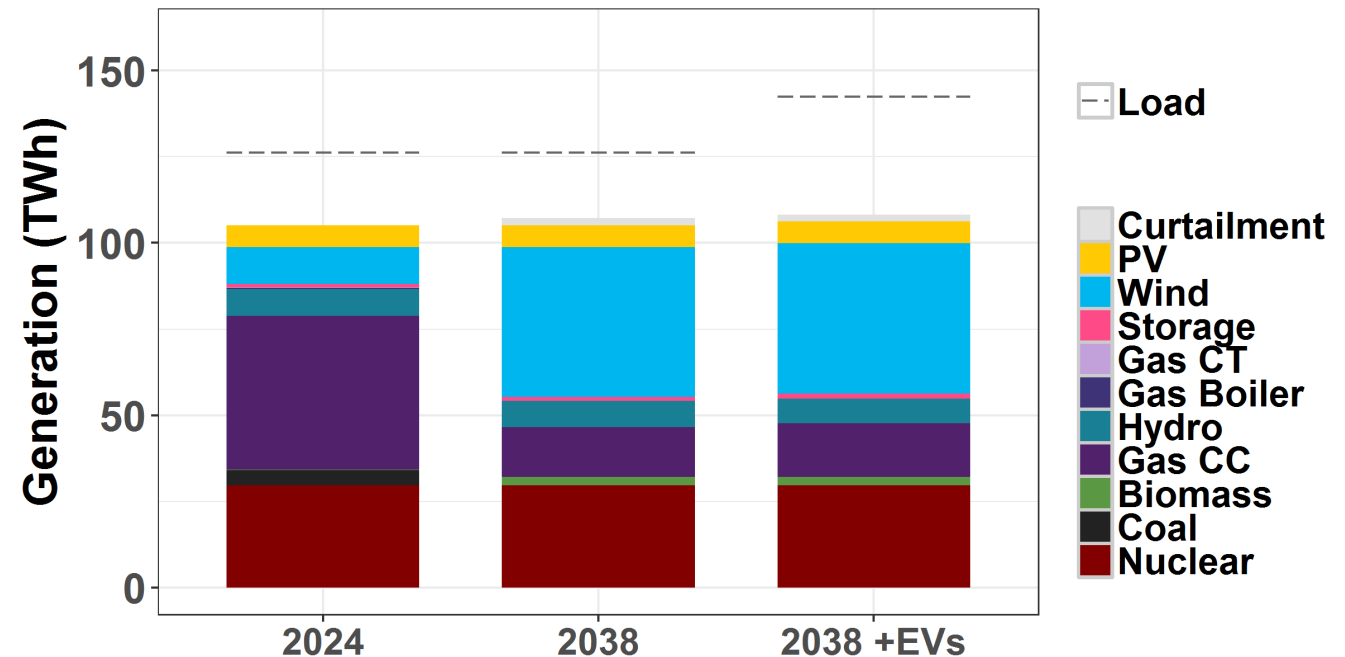
What is the potential value of EV managed charging (EVMC) and how does it vary depending on:

- Flexibility type (within-session or within-week)
- Participation level (5% to 100%)
- Dispatch mechanism (direct load control [DLC], real-time price [RTP], time-of-use [TOU] rate)

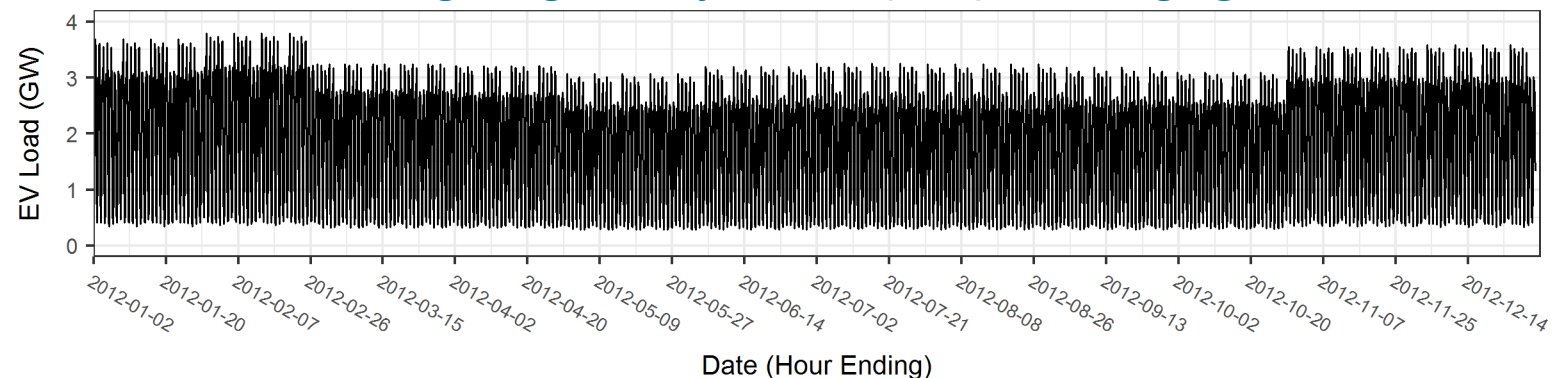
This study:

- Grid-to-vehicle (V1G)
- Constant mobility service
- Ubiquitous charging
- Technical potential (no costs for EVMC)
- Case study in an envisioned ISO-NE in 2038

ISO New England (ISO-NE) PLEXOS Models Based on SEAMS

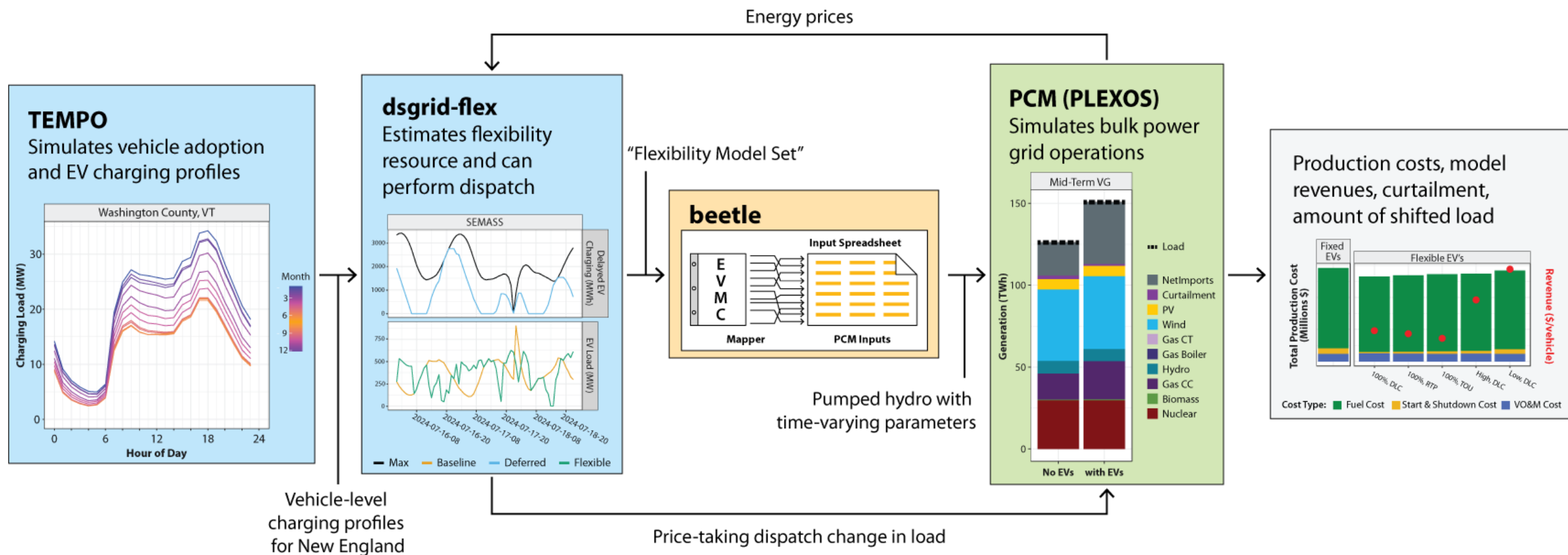


Personal Passenger Light-Duty Vehicle (LDV) EV Charging from TEMPO



Analysis Approach

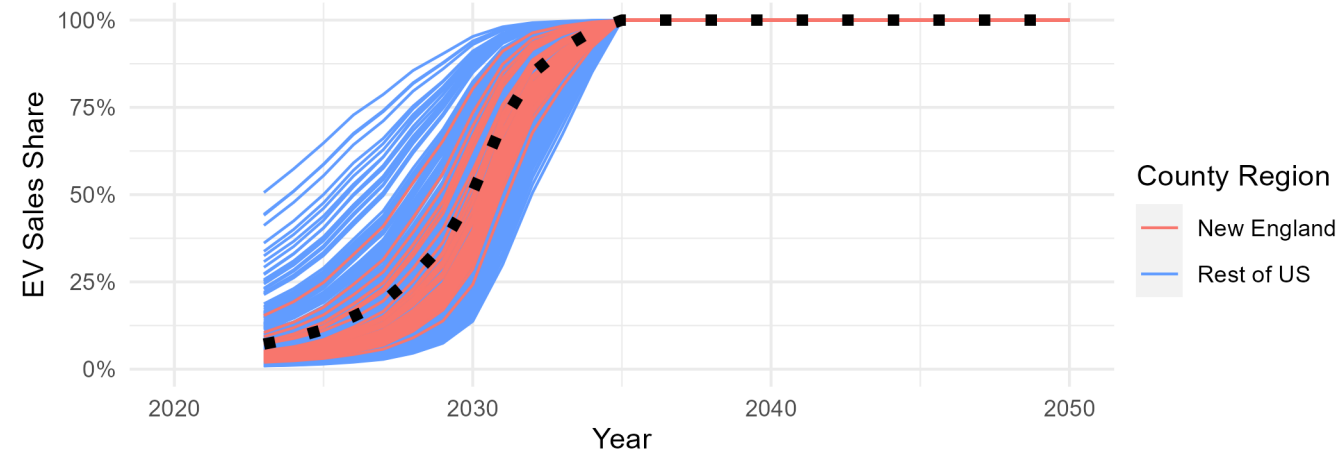
New high-resolution modeling capability



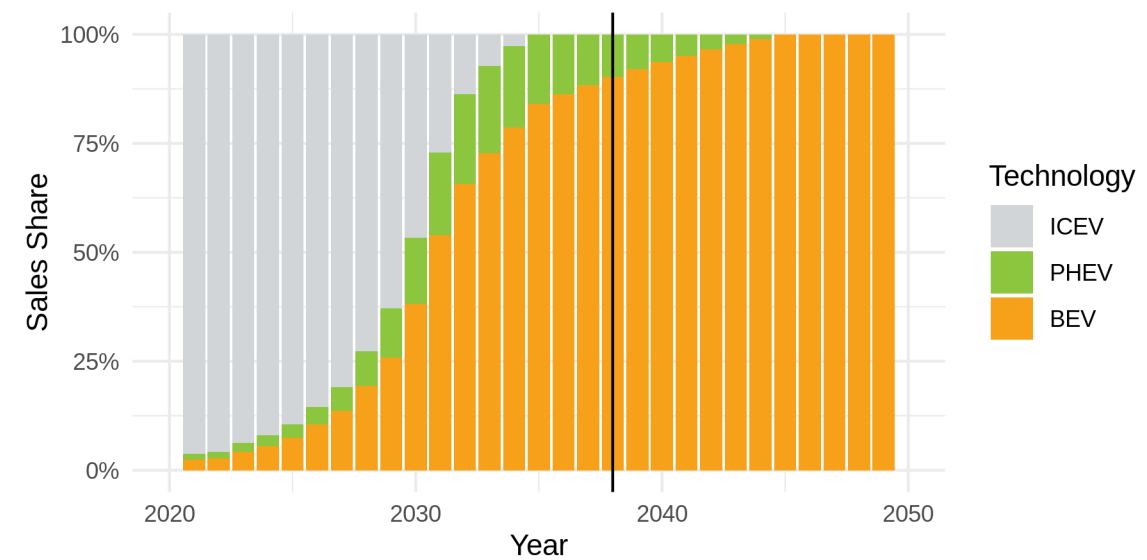
Analysis Approach

All EV Sales by 2035 Adoption Scenario from TEMPO

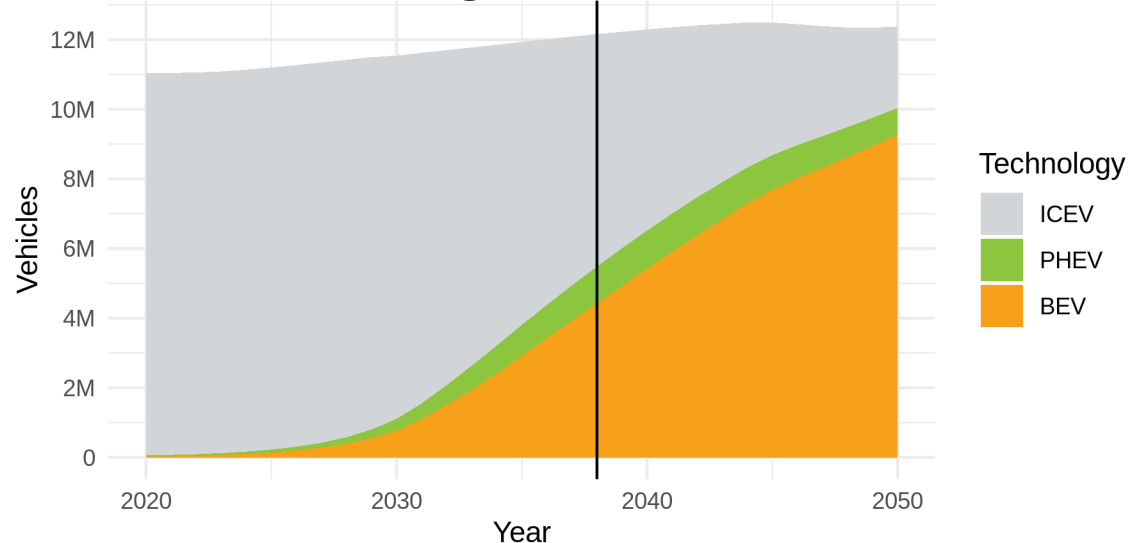
EV Sales Share of Passenger Light-duty Vehicles (LDVs) for All Counties in the Contiguous U.S.



Sales Share by Vehicle Type in New England



New England LDV Stock



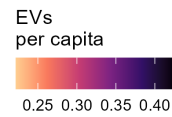
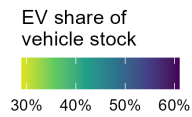
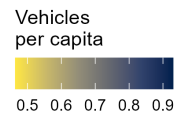
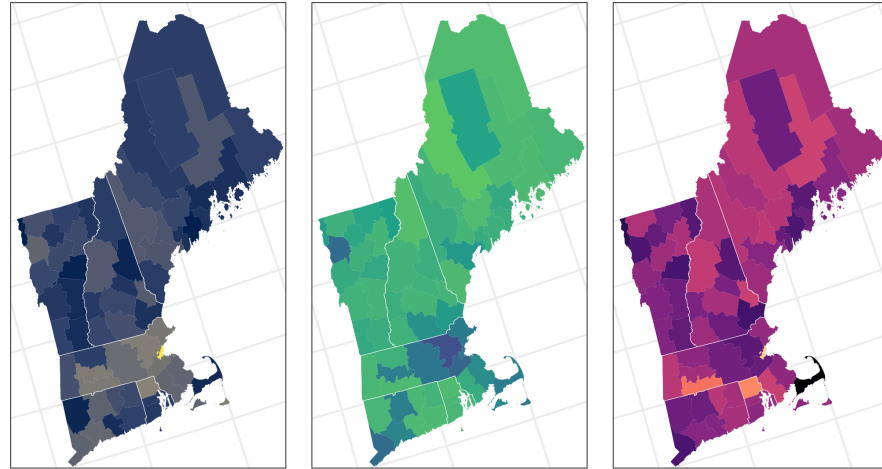
2038 Scenario

- 5.3 million EVs
- EVs are 45% of the LDV stock
- 80% of EVs are battery-electric vehicles (BEVs)
- 16.3 TWh/yr
- 3.79 GW unmanaged peak load

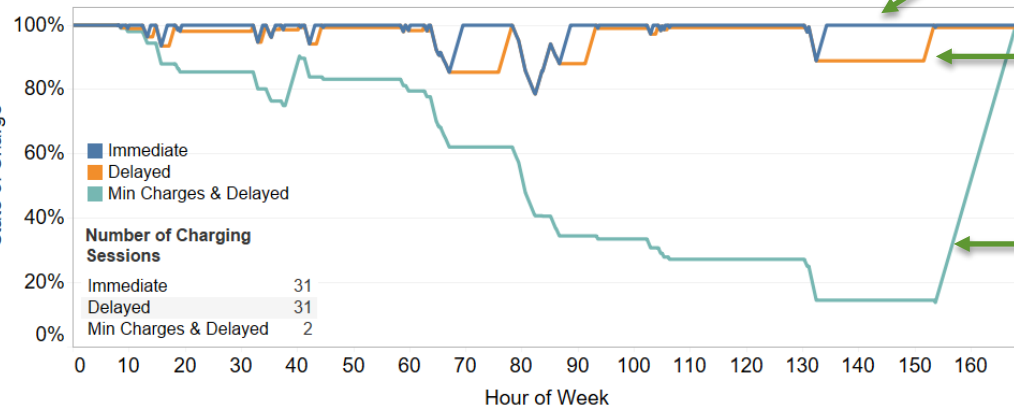
Analysis Approach

Heterogeneous, vehicle-level modeling with TEMPO

County-level demographic and weather patterns



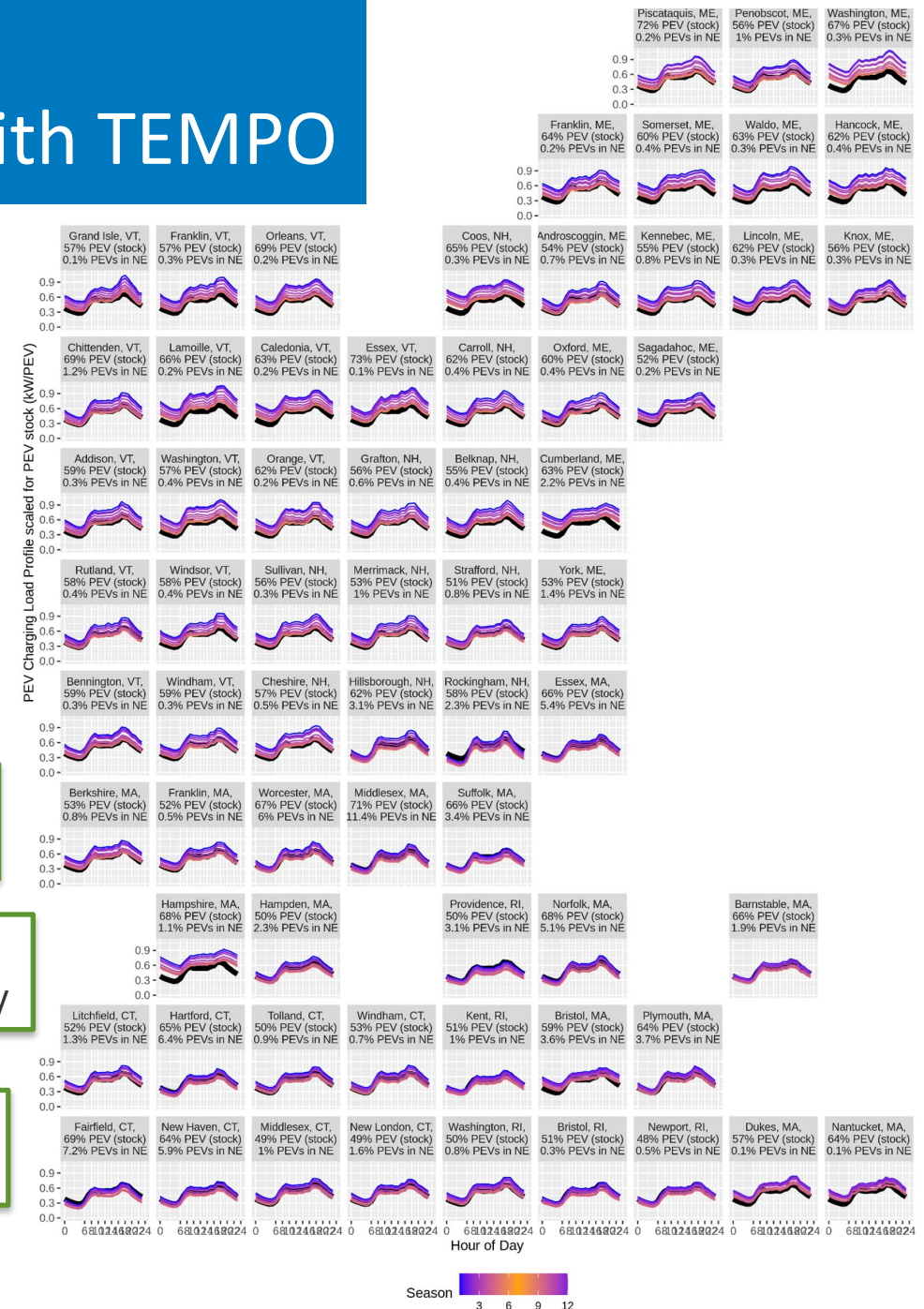
Sample-vehicle charging simulations



As-early-as possible,
un-managed charging

As-late-as possible for
within-session flexibility

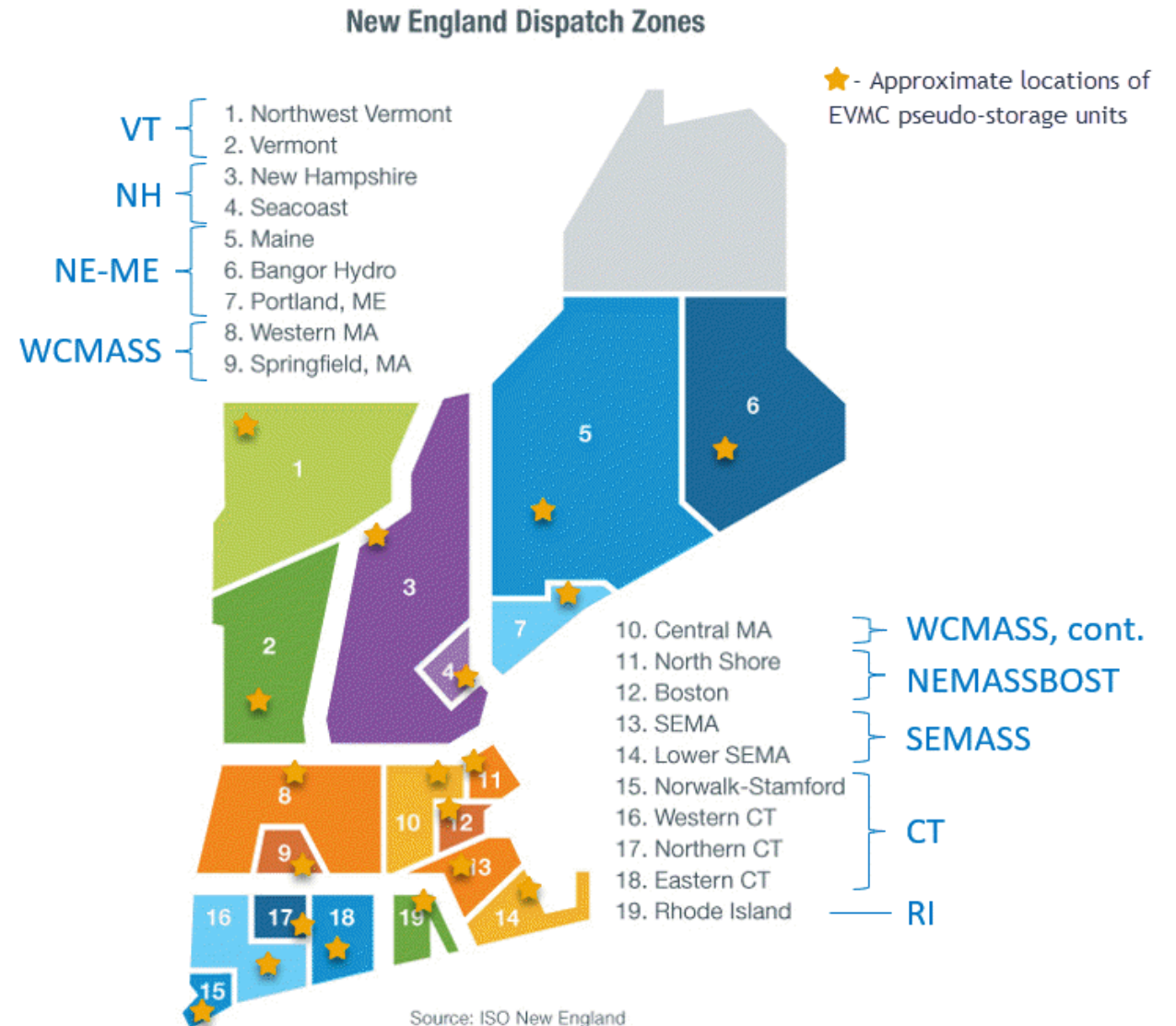
As-late-as possible for
within-week flexibility



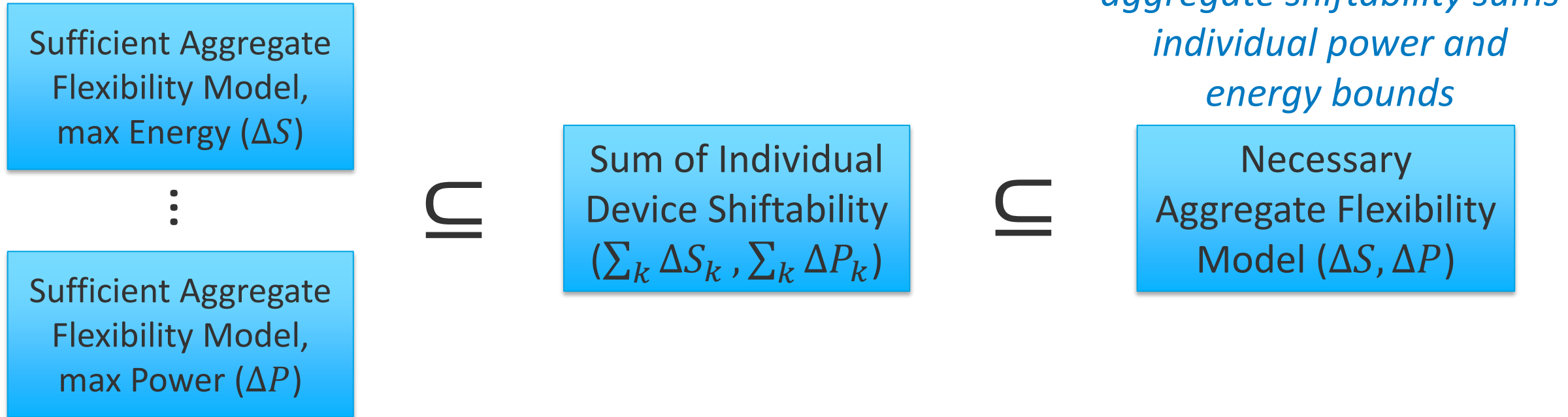
Analysis Approach

Nodal Production Cost Model with DC Powerflow

- Isolated ISO-NE from the Interconnection Seam Study (SEAMS) 2038 model
- Analyzed resource adequacy and determined that more generation capacity was not needed to support additional EV load
- Determined that additional transmission capacity was required and checked our revised assumptions with ISO-NE
- Cost assumptions from SEAMS include regionalized 2038 fuel prices from the 2017 AEO and \$45/metric ton CO₂ (emissions costs are included in the dispatch objective), **all in 2016\$**
- Un-managed EV load and realizations of EVMC in the real-time (RT) model are represented regionally and distributed to nodes with load participation factors
- EVMC DLC is modeled in the day-ahead (DA) unit commitment (UC) model as pseudo-storages, one per dispatch zone
- The DA model with un-managed EV charging is used to create an 8,760-hour RTP signal; Two TOU rates are constructed to mimic the RTP: TOU-1-2 and TOU-4-4



Aggregation: Inner and Outer Approximations



Inner Approximations are provably decomposable, conservative estimates that can be tuned to favor higher power or higher energy capacity (or something in between)

Concept described in, e.g., Hao et al. (2013)

Aggregation: Inner, Outer, and Scaled Outer Approximations

Outer Approximation is typically an infeasible overestimate of flexibility

Sufficient Aggregate Flexibility Model, max Energy (ΔS)

⋮

Sufficient Aggregate Flexibility Model, max Power (ΔP)

$\ll$

Sum of Individual Device Shiftability ($\sum_k \Delta S_k, \sum_k \Delta P_k$)

$\subset$

Necessary Aggregate Flexibility Model ($\Delta S, \Delta P$)

Inner Approximations might significantly underestimate resource

Sum of Individual Device Shiftability ($\sum_k \Delta S_k, \sum_k \Delta P_k$)

$\approx \begin{matrix} a^* \\ b^* \end{matrix}$

Necessary Aggregate Flexibility Model ($\Delta S, \Delta P$)

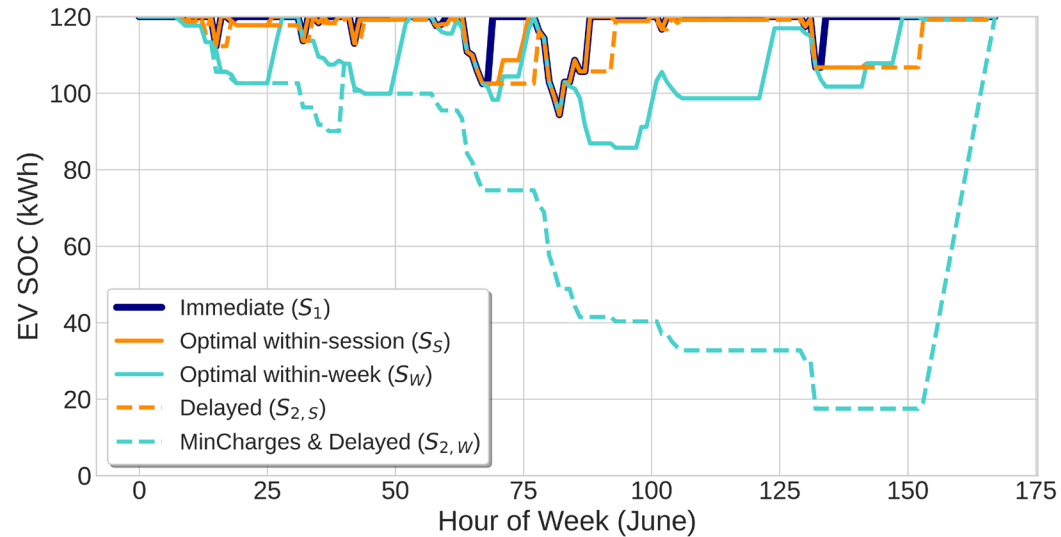
Scaled Outer Approximation can yield more accurate representation of resource, but still does not provide a feasibility guarantee

$$0 \leq a, b \leq 1$$

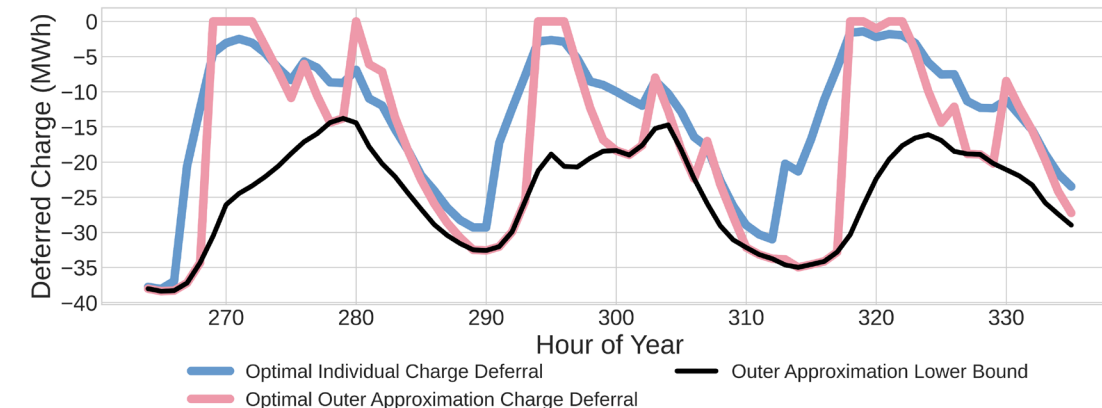
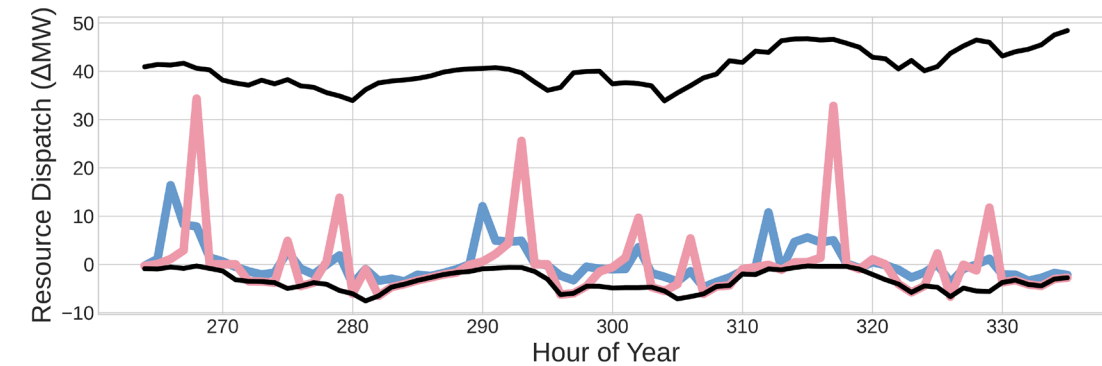
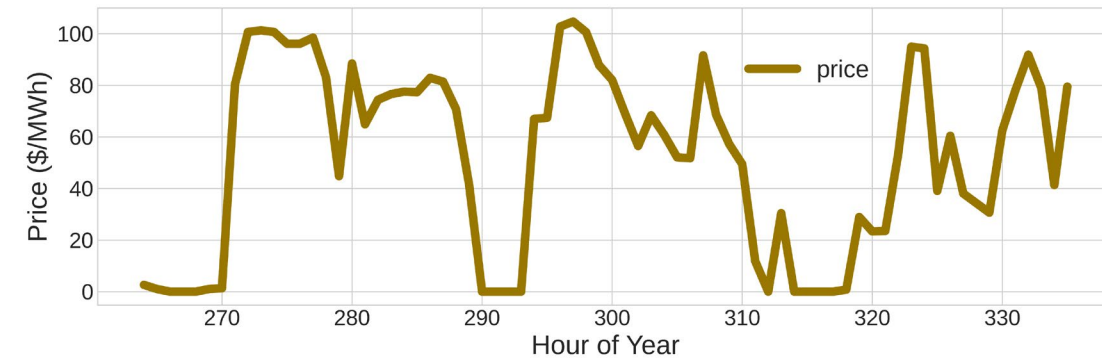
Analysis Approach

Deep dive into aggregation

Dispatch Individual Vehicles within Power and Energy Envelopes



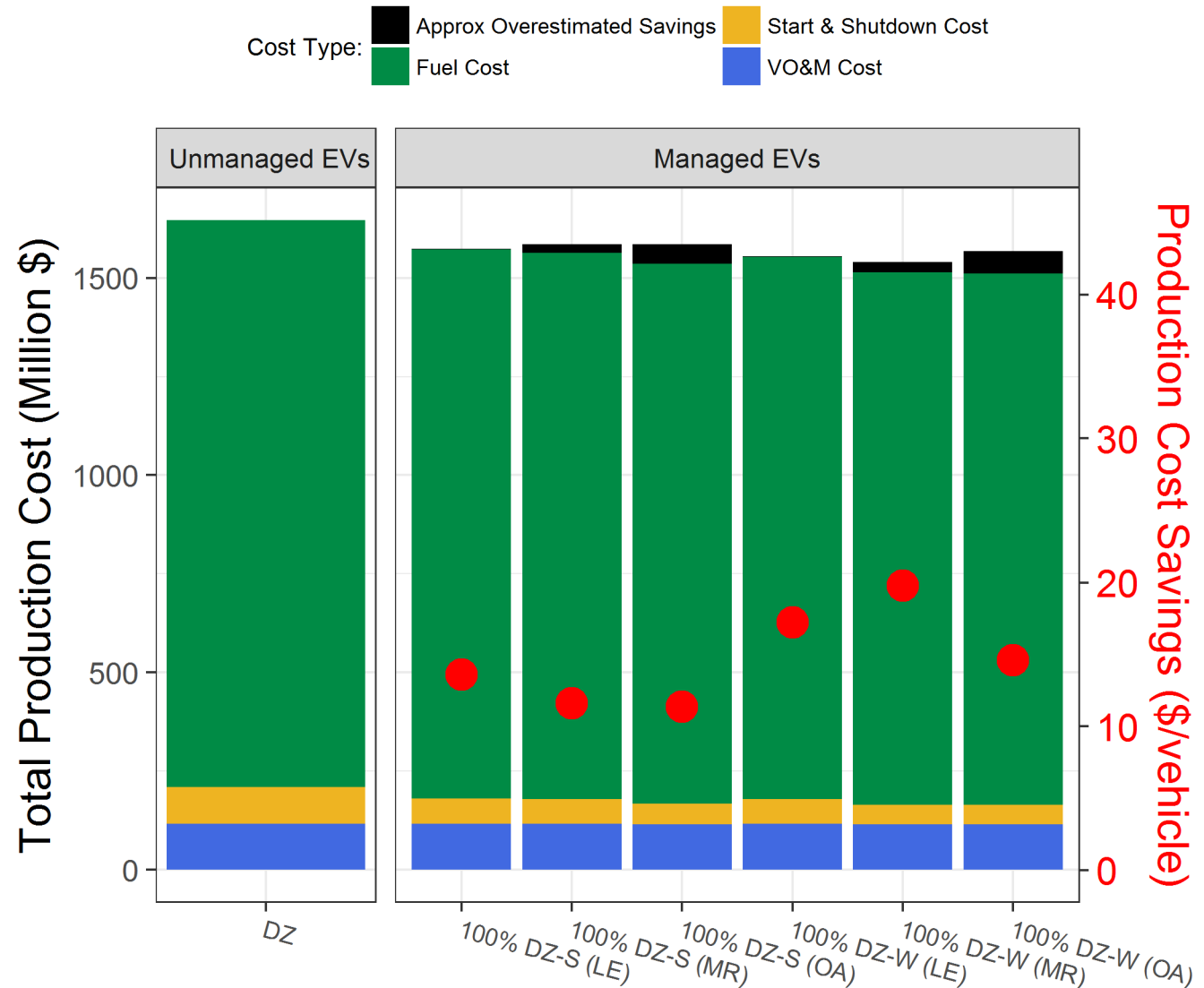
Simply Summing Power and Energy Bounds Overestimates Flexibility



Analysis Approach

Deep dive into aggregation

- Performed disaggregation experiments to
 - Estimate scaling parameters that produce “low error (LE)” or “maximum revenue (MR)”
 - Estimate to what extent each “scaled out approximation” overpredicts value
- Result of applying overestimated savings results from price-taking experiments to production cost simulations shown here
- The report mostly focuses on DLC-LE results, because the reported performance should be feasible and accurate without scaling
- DLC-LE scales all parameters by 50%; real-world aggregation should be able to achieve more cost savings/revenue (e.g., compare –W (LE) to –W (MR) in this plot)



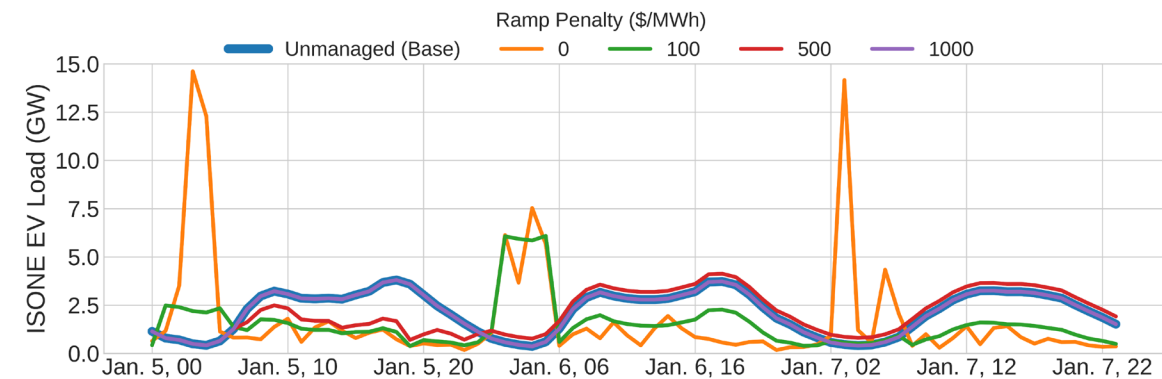
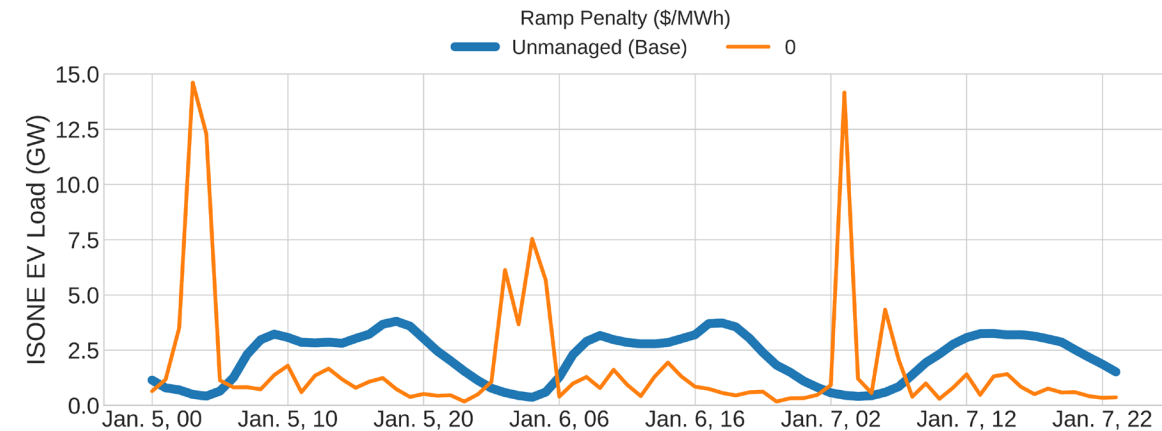
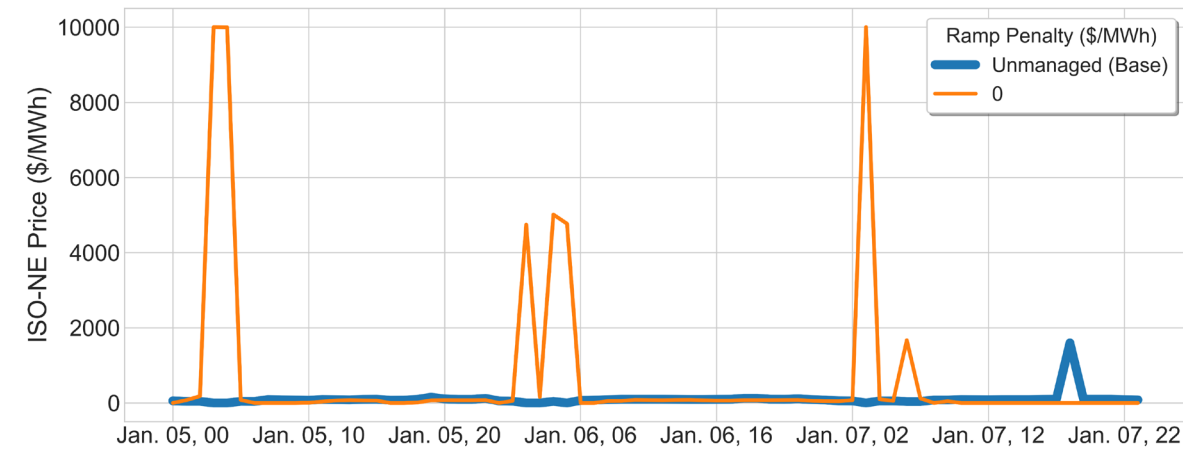
Analysis Approach

Testing the Limits of Price-taking

- Price-taking approaches are simpler than DLC, and let vehicles respond directly with their full flexibility
- However, too much flexible EV load chasing the same prices eliminates old, but creates new, price spikes
- Applying a penalty to aggregate ramps mutes response
- Simply muting response is not a sufficient strategy at moderate to high participation rates

Table 7. Optimal Ramp Penalties for the Price-taking Dispatch Mechanisms that Reduce Production Costs by at Least \$1/vehicle-yr. Combinations that do not yield sufficient production cost savings for any value of ramp penalty are indicated with dashes.

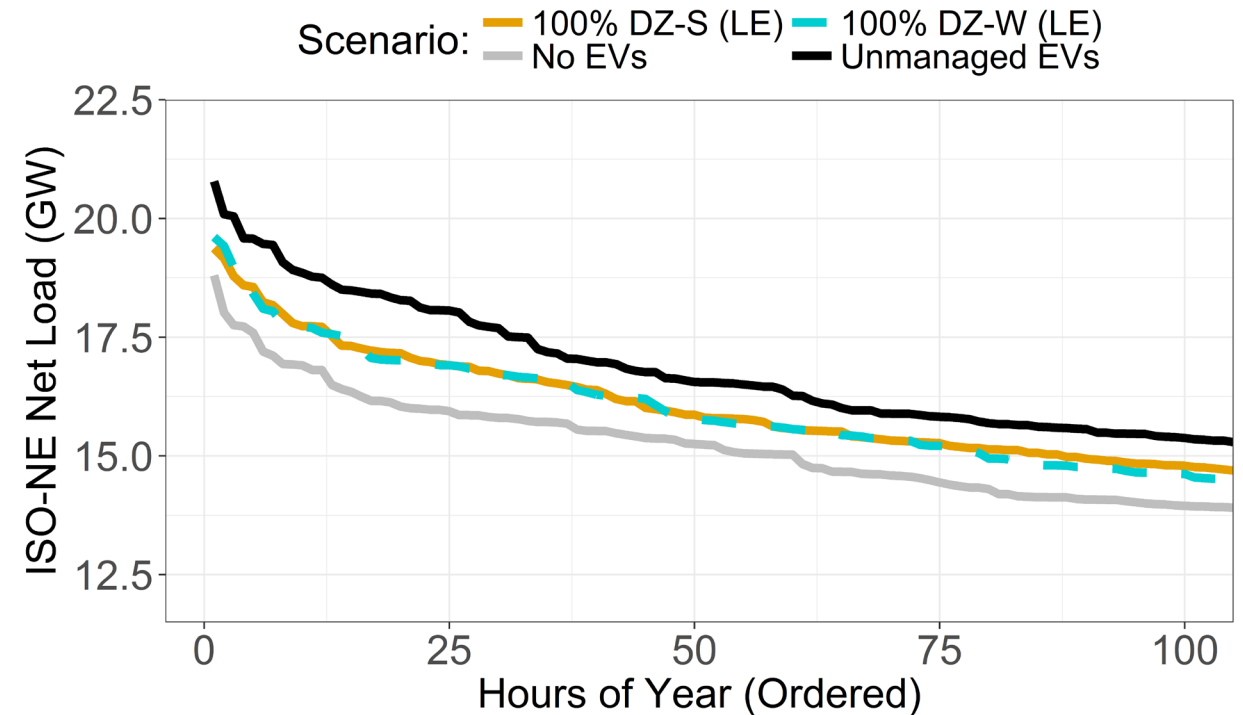
Participation (%)	Within-session			Within-week		
	RTP	TOU-4-4	TOU-1-2	RTP	TOU-4-4	TOU-1-2
5	1	10	1	10	10	1
30	100	100	-	-	-	-
60	-	-	-	-	-	-
100	-	-	-	-	-	-



Analysis Approach

Capacity value

- Previous work (Stephen, Hale, and Cowiestoll 2020; Jorgenson et al. 2021) identified average MW reduction of the top 100 net-load hours as a reasonable heuristic for firm capacity
- Capacity value is monetized using the 2021 [Cambium](#) data set, specifically 2038 ISO-NE capacity prices under the Mid-case 95% decarbonization by 2035 and by 2050 scenarios
- On average, unmanaged EV load adds 1,620 MW to the top 100 hours of net-load in this system
- DLC-LE EVMC with 100% participation reduces that amount by about half



Time-of-Use (TOU) Rates

Objective:

- Minimize difference in hourly revenue from day-ahead “real-time price (RTP)” and TOU rate *assuming load is fixed*

Parameters:

- Number of seasons
- Minimum length of season (days)
- Number of blocks
- Minimum length of blocks (hours)

Methods:

- Optimization problem is a mixed-integer linear program derived by linearizing a non-convex quadratic program—can solve for 1-2 months of data
- **Initial value computed using agglomerative clustering**—can be computed for the whole year and in test problems (1-2 months) results in a better objective value than the “optimal” solution

How many season-hour blocks are appropriate for TOU rates?

Feedback?

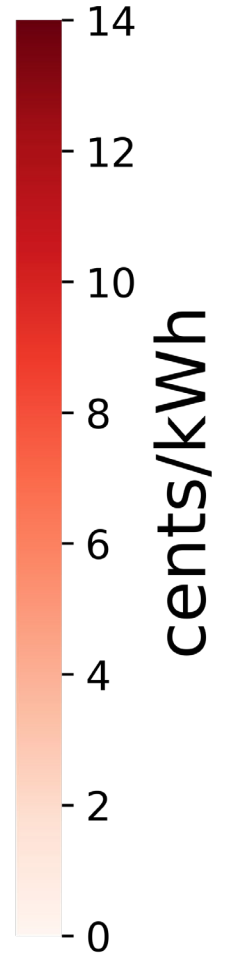
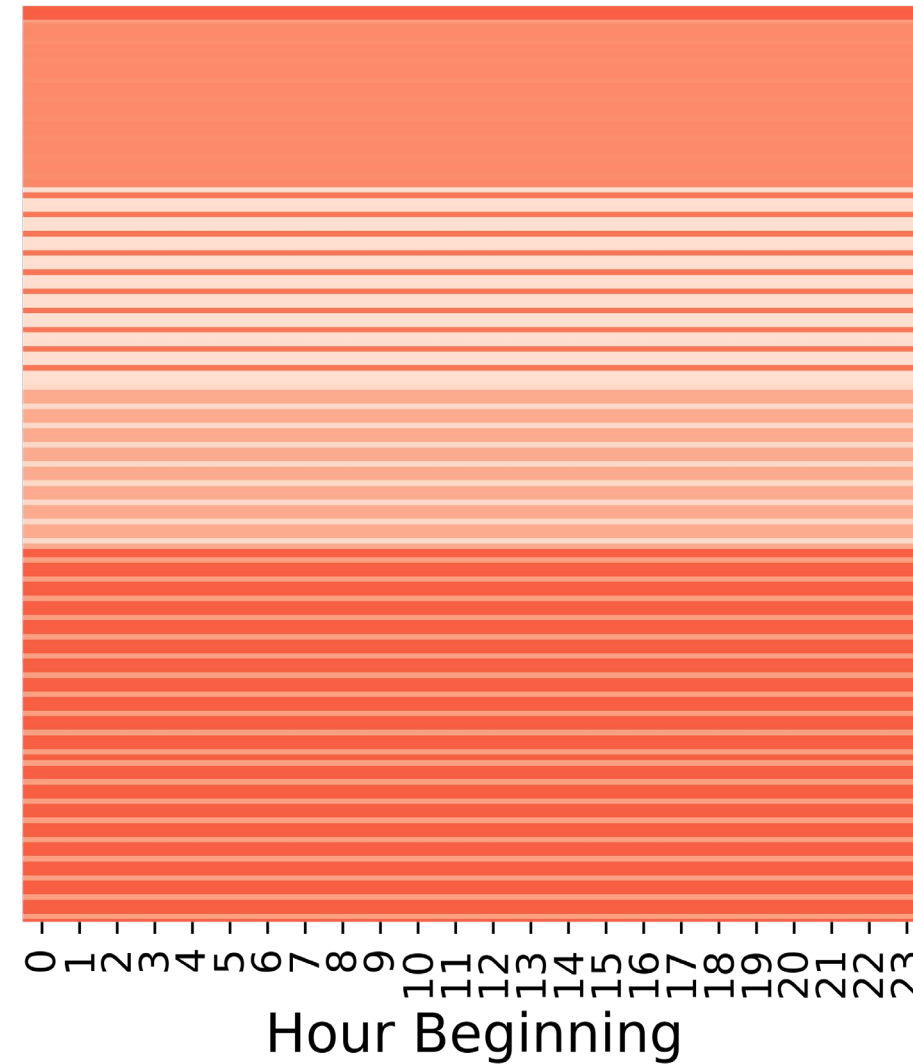
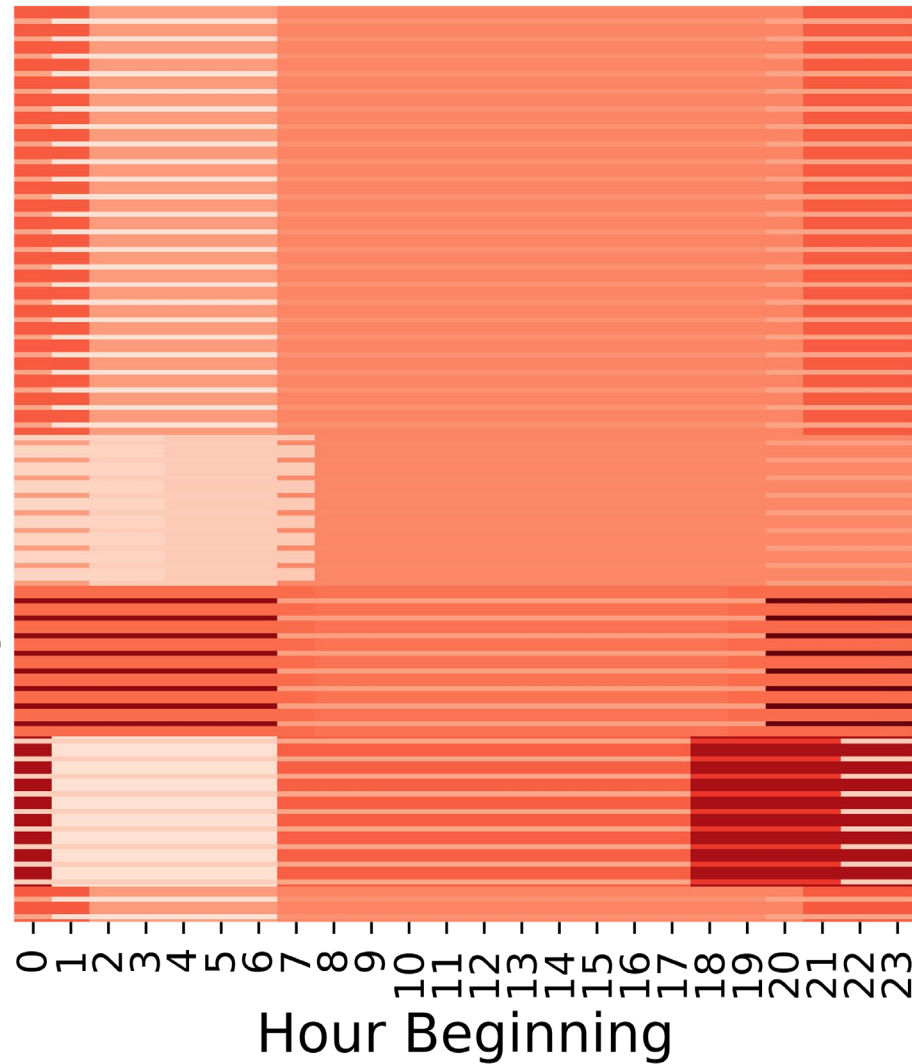
Seasons=4, Blocks=4

Seasons=4, Blocks=1

January

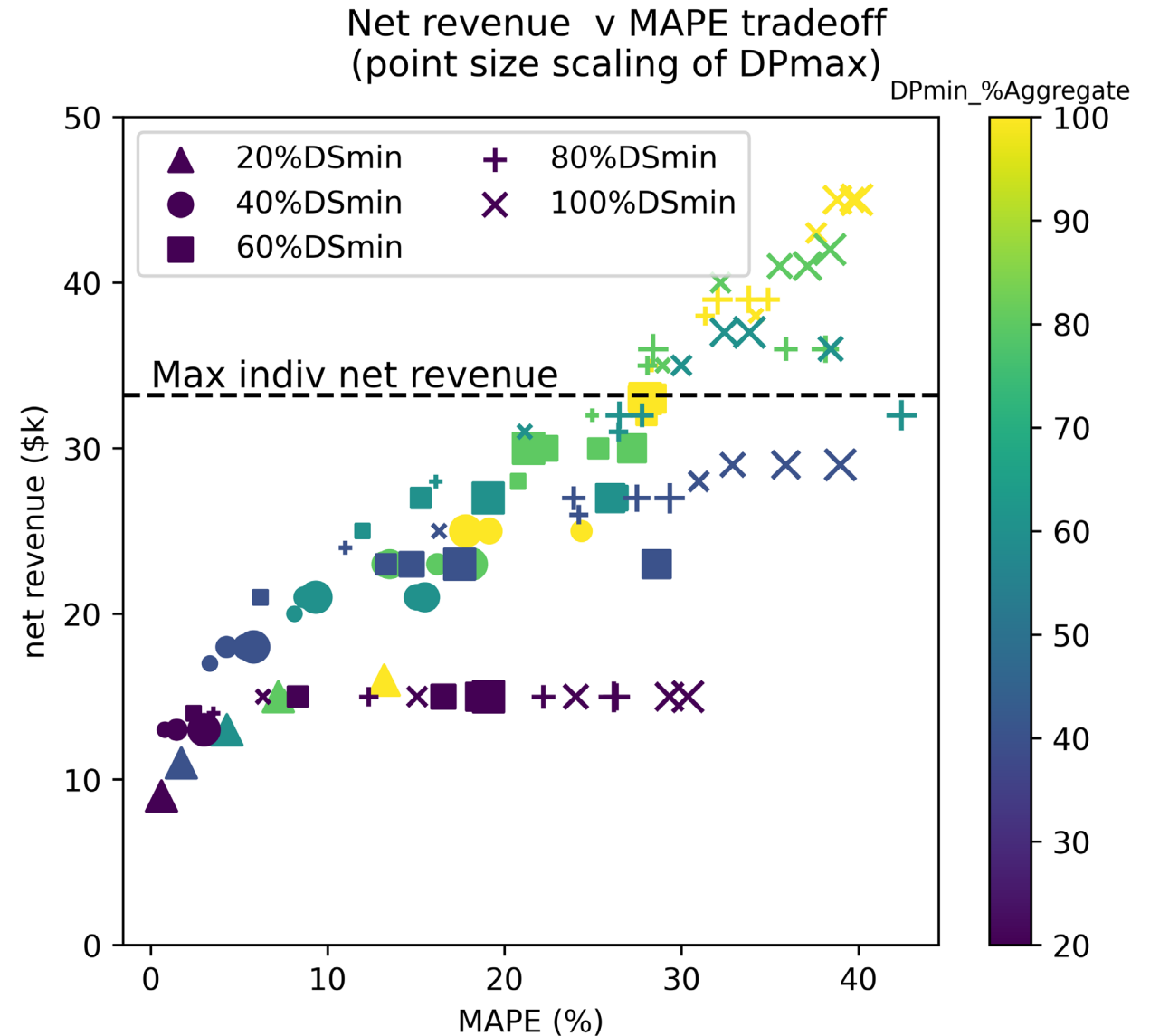
Day of Year (1-365)

December



What is the trade-off between feasibility net-revenue for **within-session** charging delays

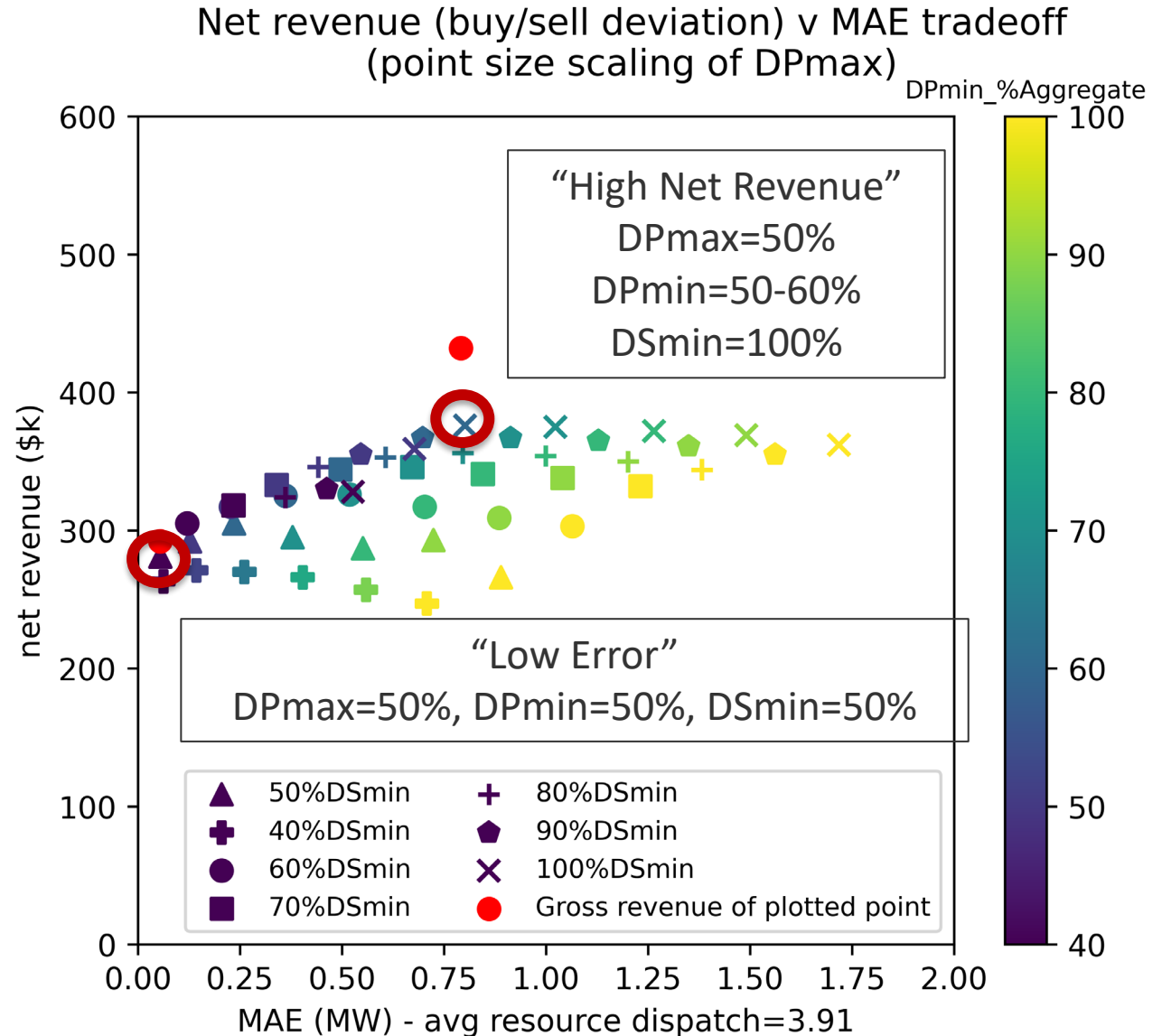
The net revenue shown is for the day-ahead aggregate plan, which is not actually feasible



Testing within-session delay scaled outer approximations

- Larger scaling test on 559 vehicle charging profiles
- DPmax scaling has little effect on revenue
- Run a “low error” and “high net revenue” point in PLEXOS DA based on DPmin and DSmin scaling

Feedback?



Phase 2 – ongoing work

Potential Learnings: Price-responsive can work at higher participation levels?

- Depends on management/forecasting approach for price-responsive load
- Results and participation rate ranges are largely illustrative; need to do research!
- **Hypothesis:** Randomization and incorporation of price-responsive EV load in load forecast can make price-responsive dispatch (particularly TOU) preferable to DLC at higher participation levels than in Phase 1 work

Legend

1

“Best” dispatch mechanism
(highest savings/lowest costs)

4

“Worst” dispatch mechanism
(lowest savings/highest costs)

Hypotheses: In Phase 1, price-responsive only preferable at low participation. Fixing TOU44 makes it second-best? In Phase 2, adding randomization, then perfect foresight allow price-responsive TOU to remain preferable at higher participation levels? Eventually, resource is large enough that DLC is best, even though aggregation is imperfect?

Dispatch Mechanism	Participation = 0-5%	Participation = 5-30%?	Participation = 30-60%?	Participation = 60-100%?
DLC	4	3	3	1
TOU12	3	1	2	2
TOU44	2	2	1	3
RTP	1	4	4	4