NREL
Transforming ENERGY

Value of EV Managed Charging to Bulk Power Systems

Luke Lavin

June 12, 2023

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

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

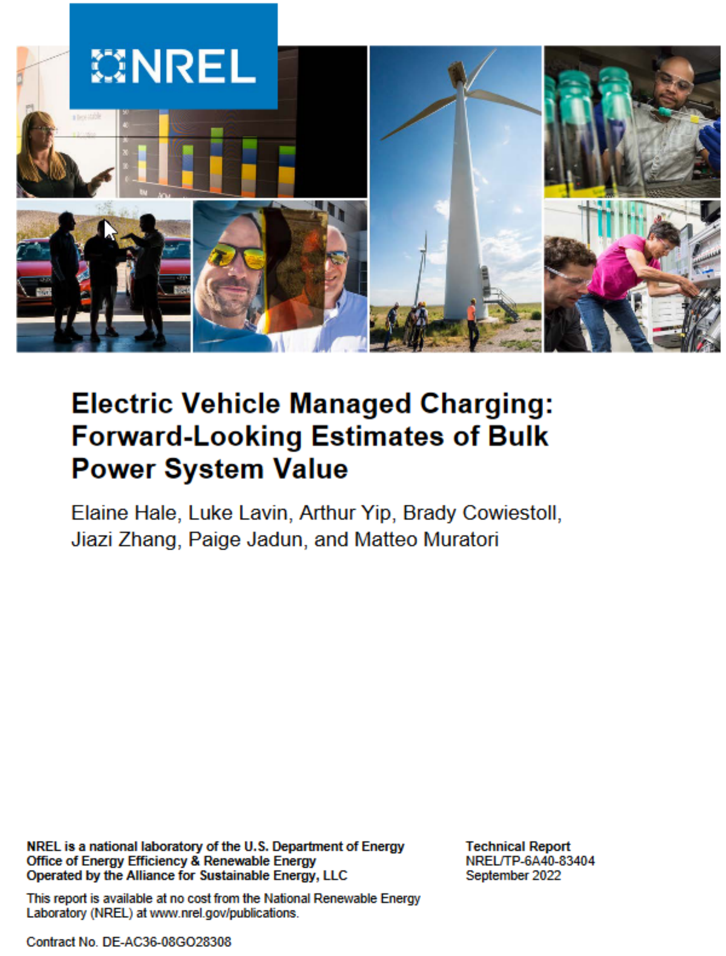
Bulk power systems – generator plant capacities in **MW,** system capacities in **GW**

Research Question

What is the 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?


NREL

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

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

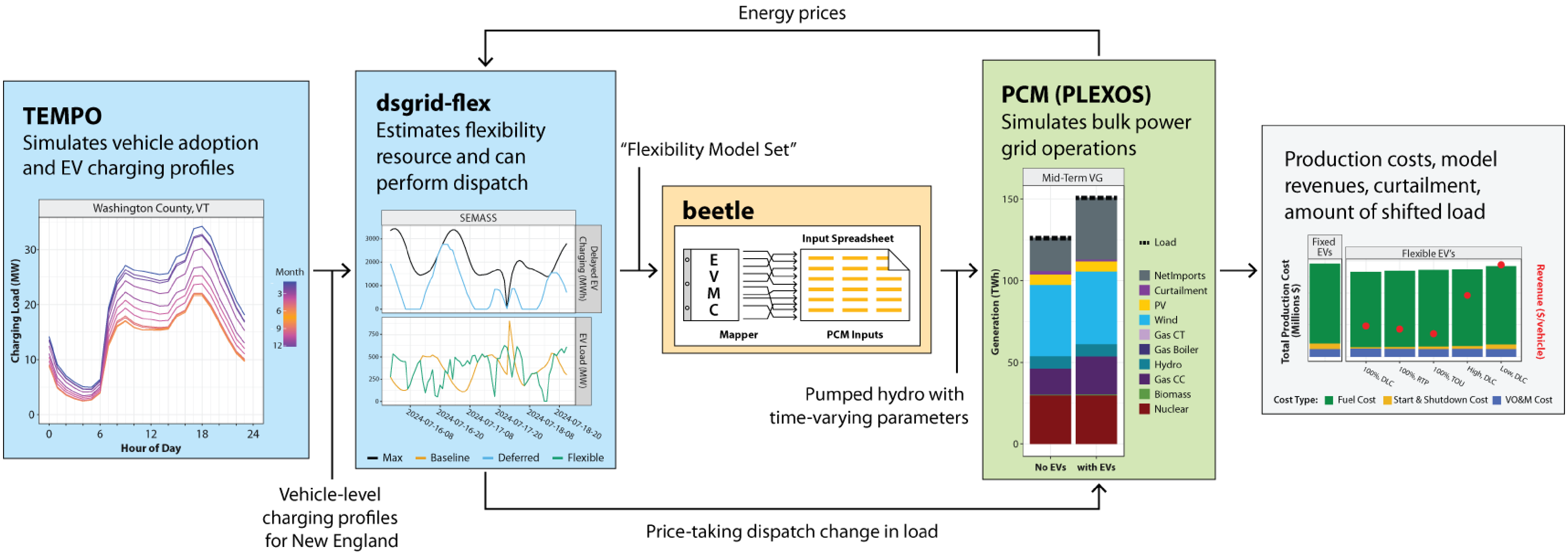
This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-6A40-83404
September 2022

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

Analysis Approach
New high-resolution modeling capability



Phase 1 – Completed work

PUBLIC

Study Setting

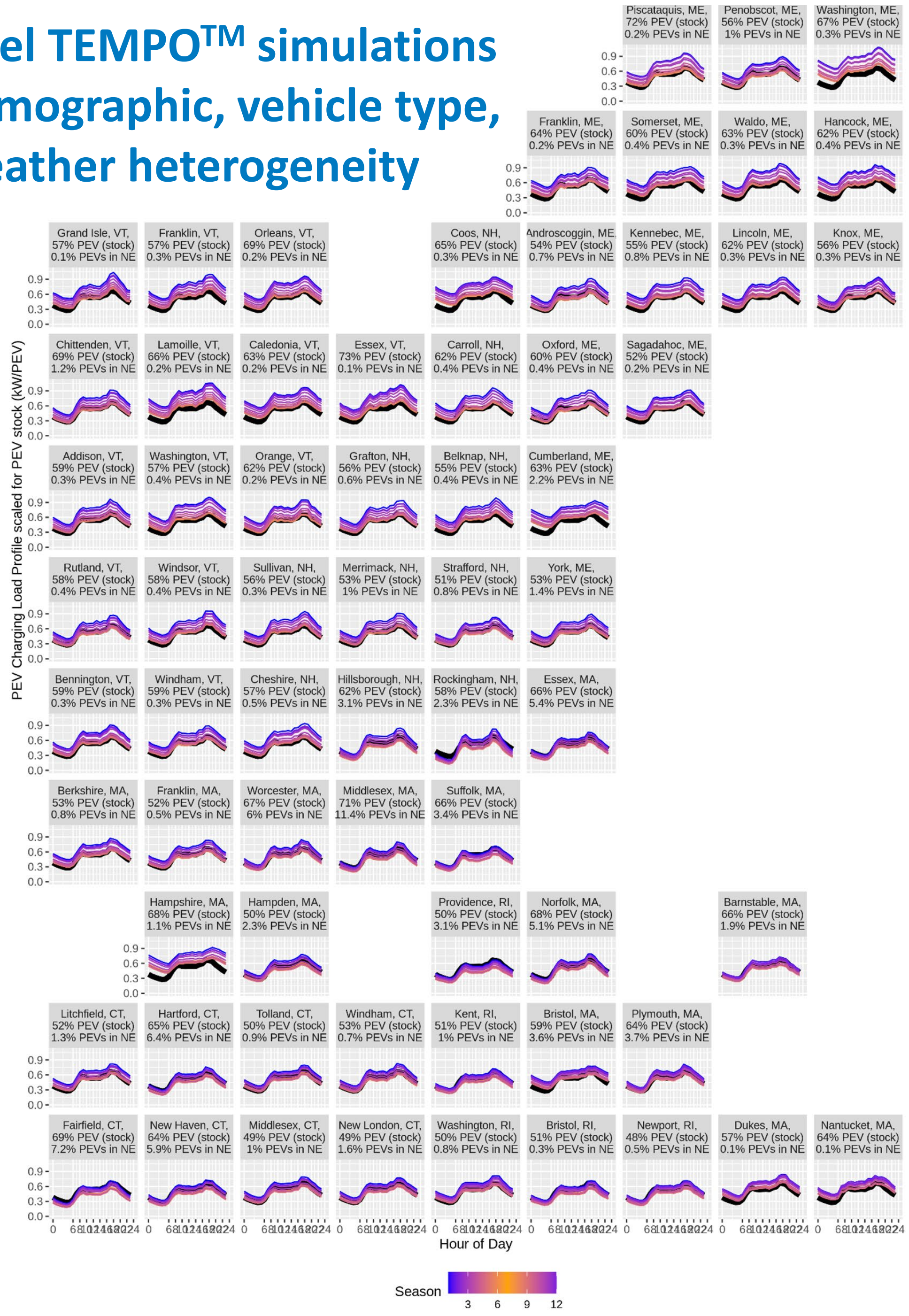
County-level TEMPO™ simulations capture demographic, vehicle type, and weather heterogeneity

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

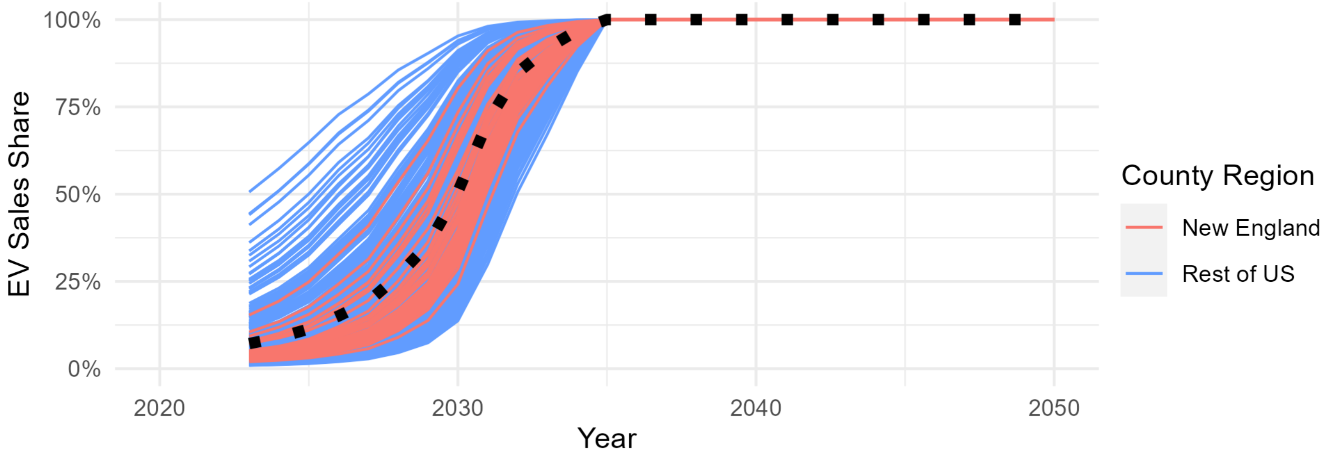
Charging flexibility (V1G) estimated from 101,000 sample vehicles' charging profiles

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

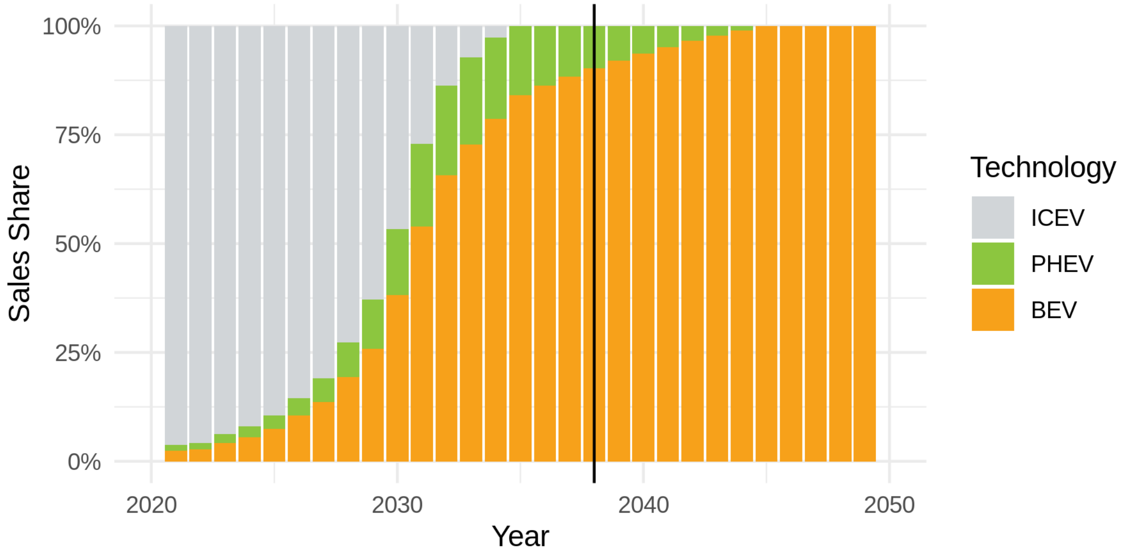


Analysis Approach
All EV Sales by 2035 Adoption Scenario from TEMPO

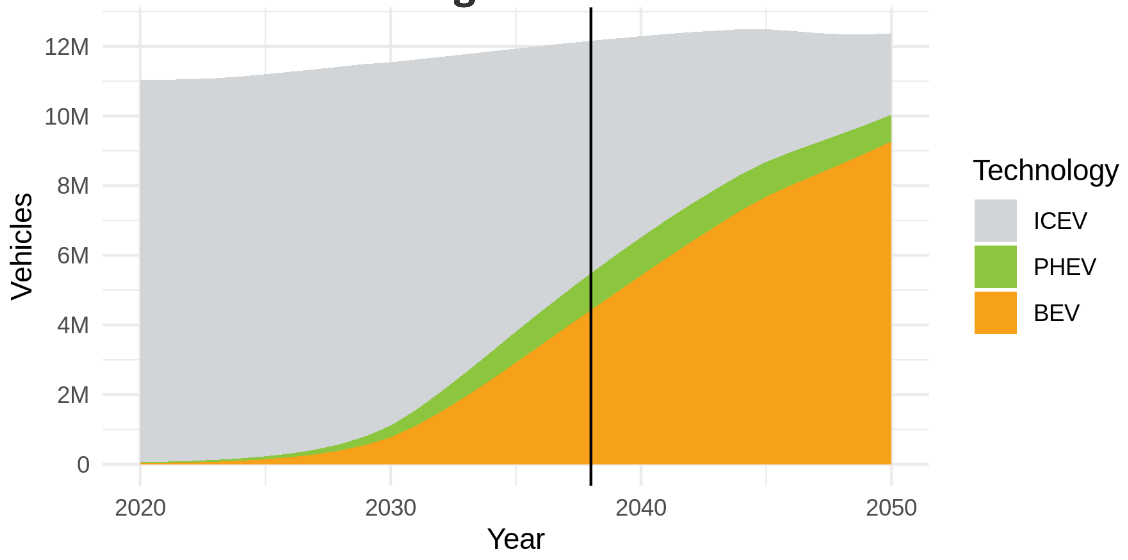
EV Sales Share of Passenger Light-duty Vehicles (LDVs) for All Counties in the Contiguous U.S.



Sales Share by Vehicle Type in New England



New England LDV Stock

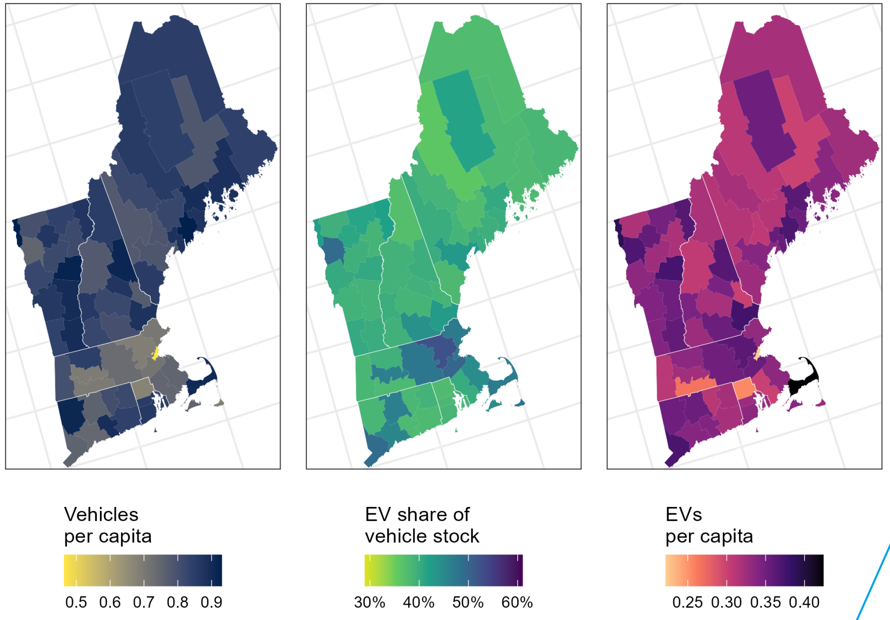


2038 Scenario

- 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

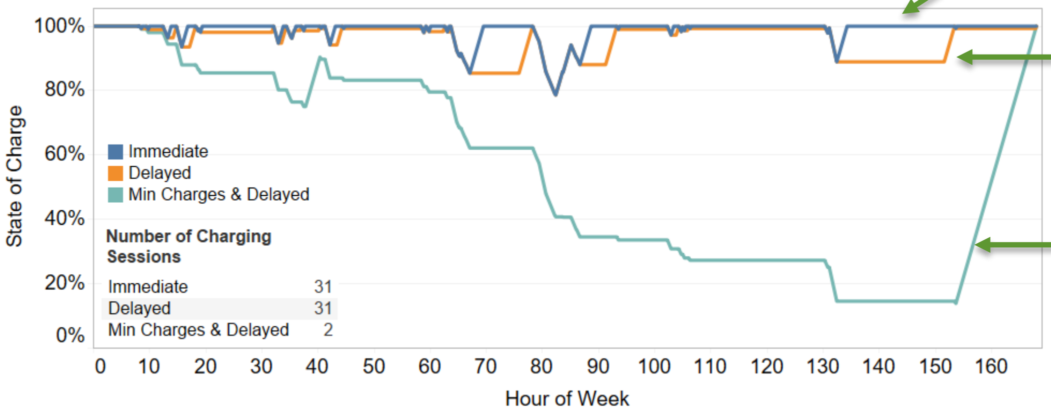
Analysis Approach
Heterogeneous, vehicle-level modeling with TEMPO

County-level demographic and weather patterns



+

Sample-vehicle charging simulations

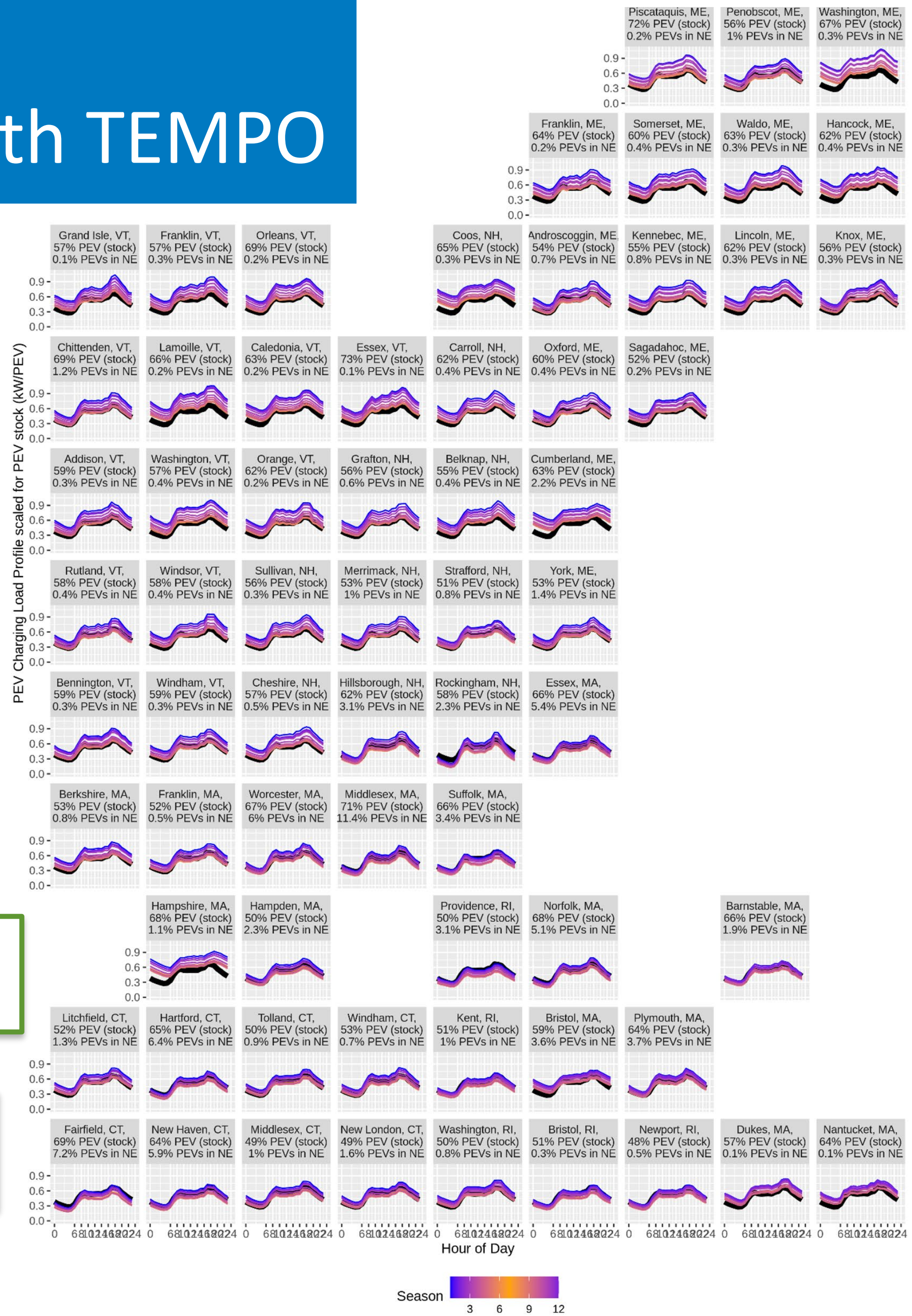


As-early-as possible, un-managed charging

As-late-as possible for within-session flexibility

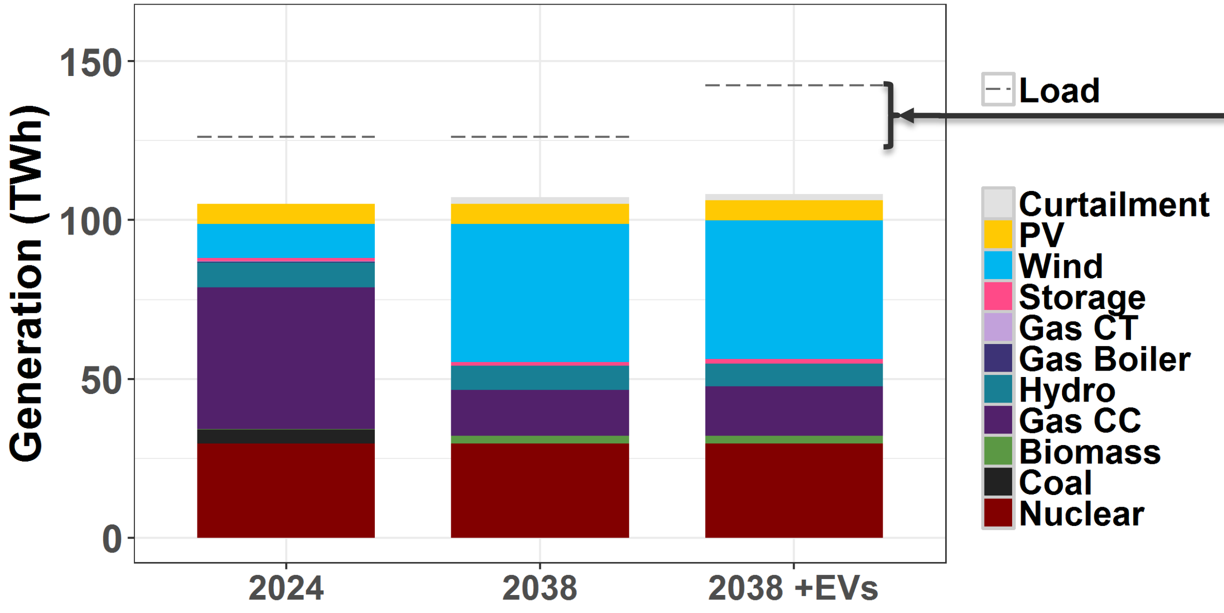
As-late-as possible for within-week flexibility

=



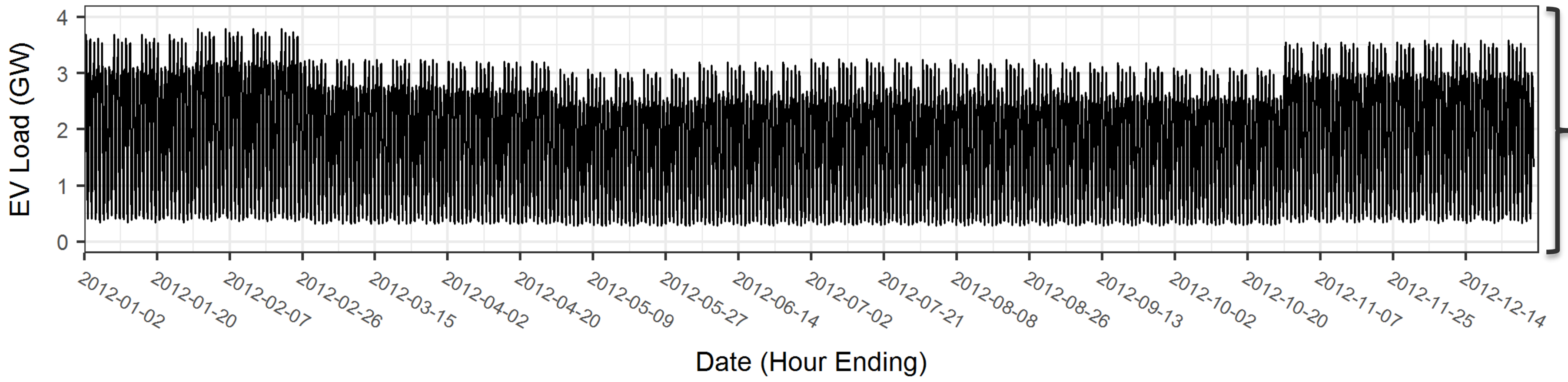
Analysis Approach
A cleaner New England grid in 2038

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



~12% of load is EVs at ~45% LDV electrification

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



Research question revisited – comparison of different dispatch mechanisms key to results

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?

NREL

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

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

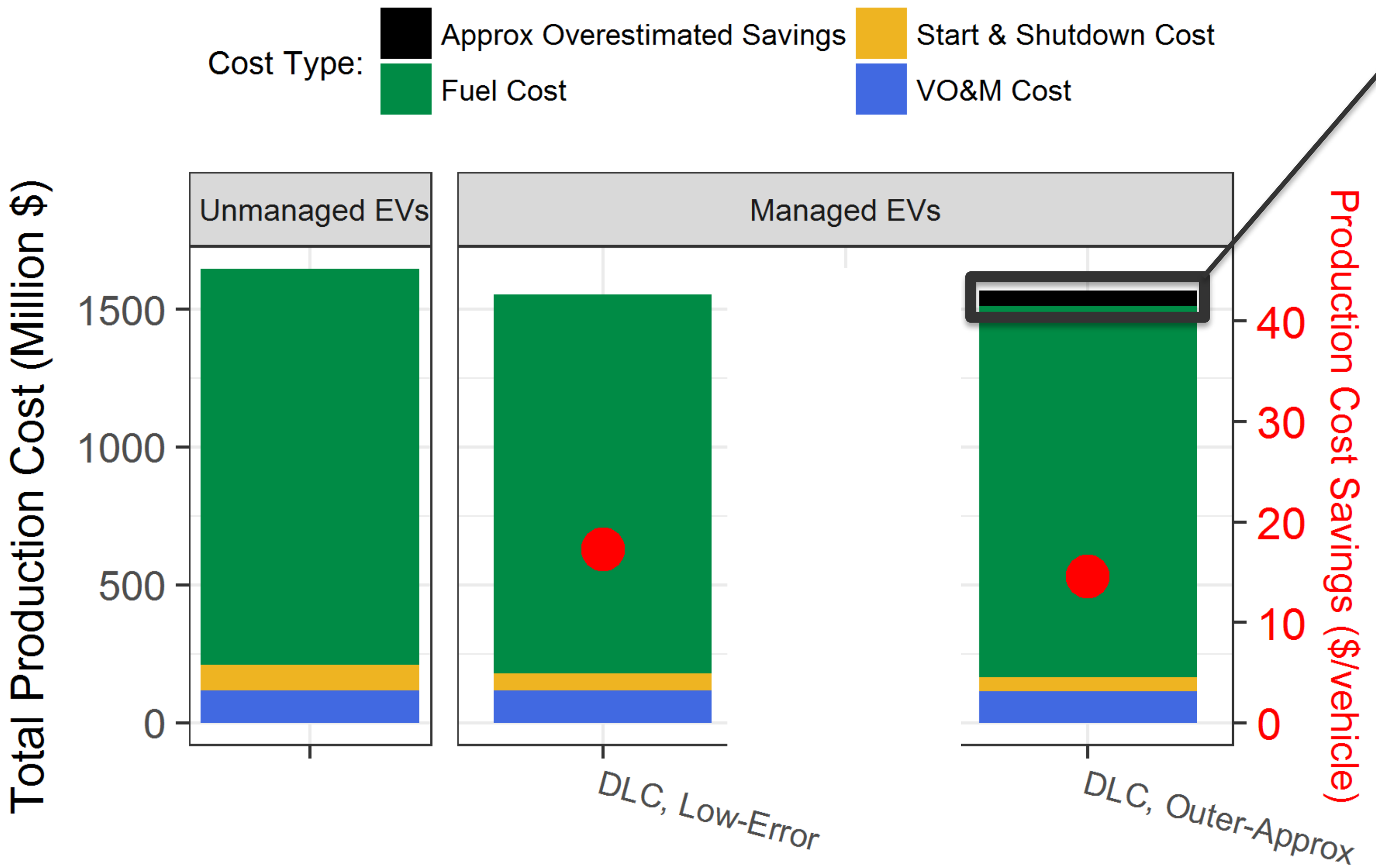
Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-6A40-83404
September 2022

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

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

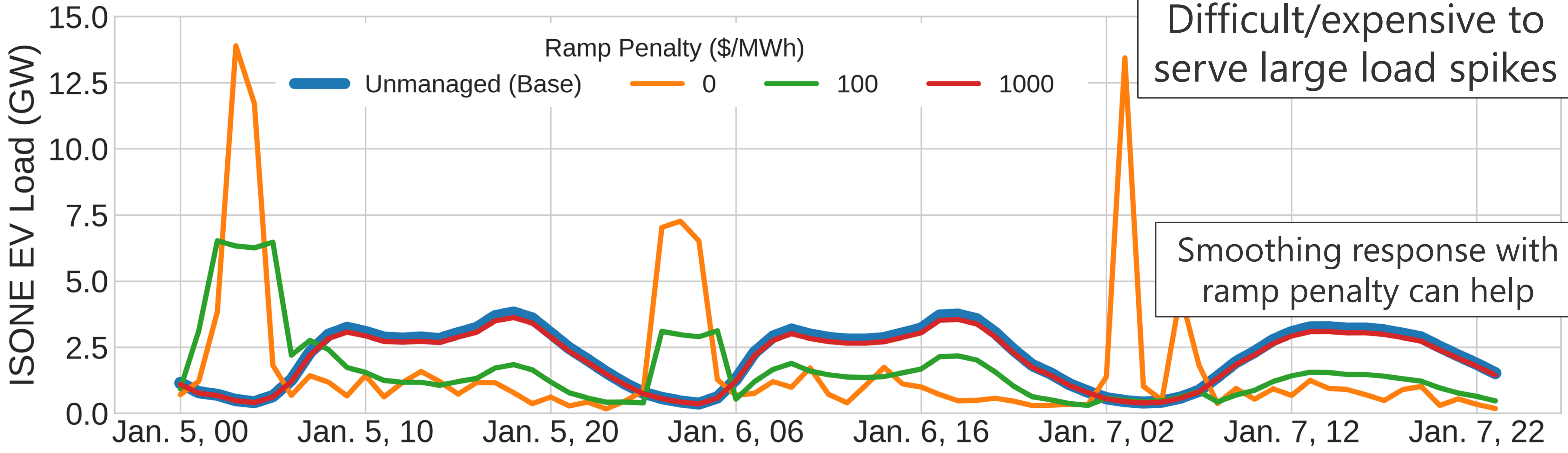


Naïve (“outer-approx”) aggregations effectively assume that one already-fully-charged vehicle’s ability to increase load can be paired with another already-charging vehicle’s ability to accept more charge.

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)



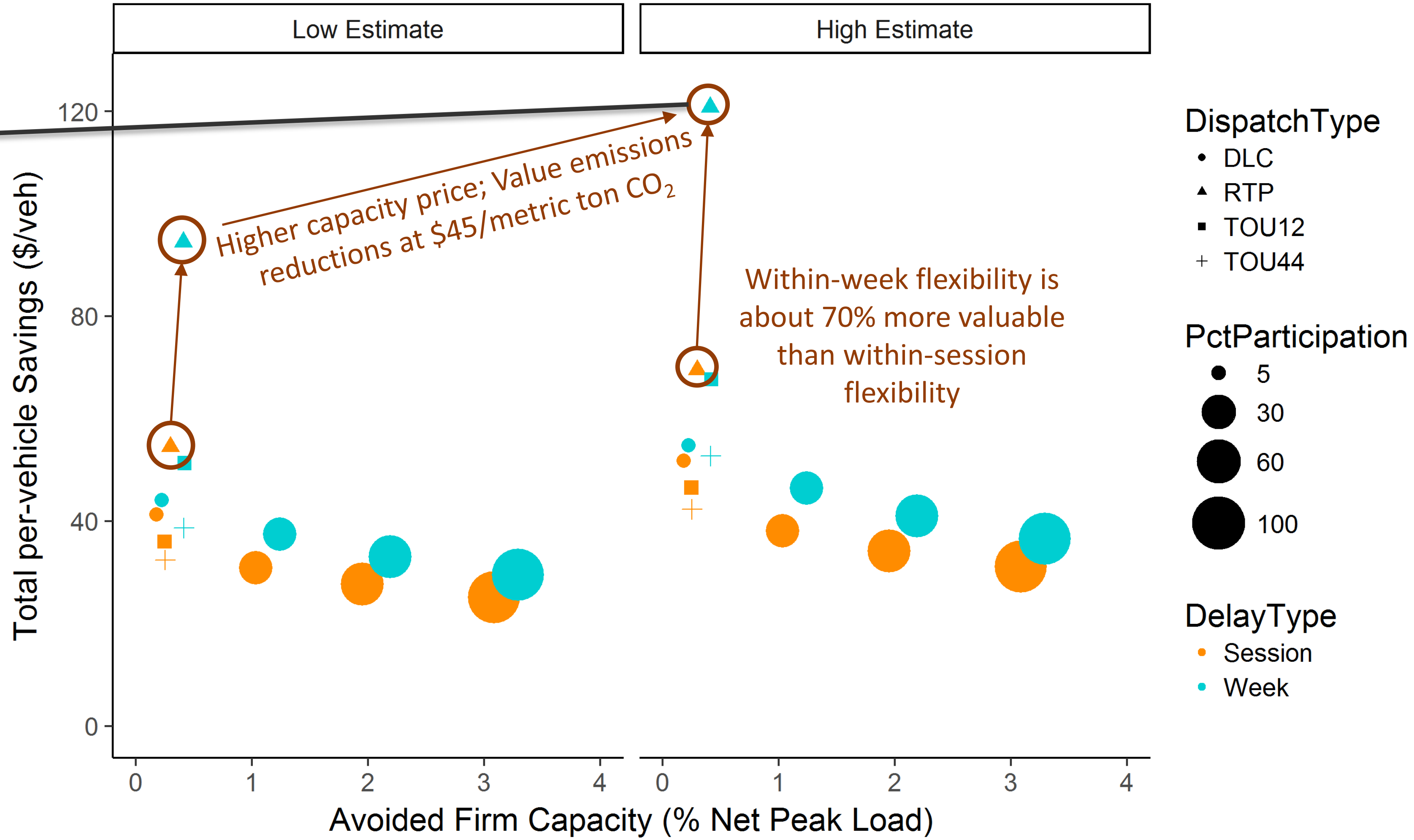
Difficult/expensive to serve large load spikes

Smoothing response with ramp penalty can help

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

The highest per-vehicle value tops out at about $10/month

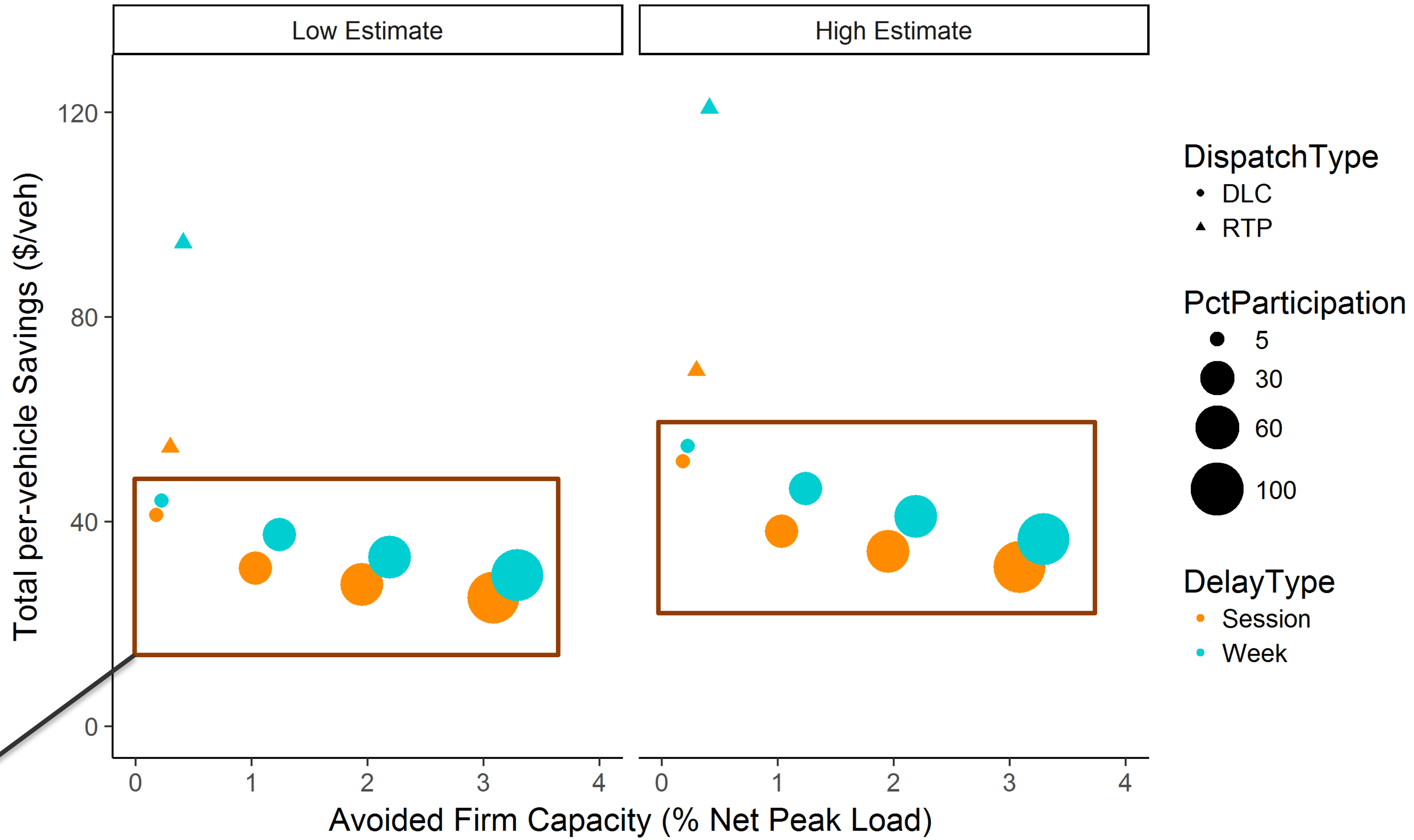
All-in value of production cost savings, capacity savings, and emissions reductions



Key Finding: Higher participation levels require coordination with DLC

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



Summary: Managed EV charging can reduce bulk system cost 4-7% but requires coordination and low per-vehicle enablement costs

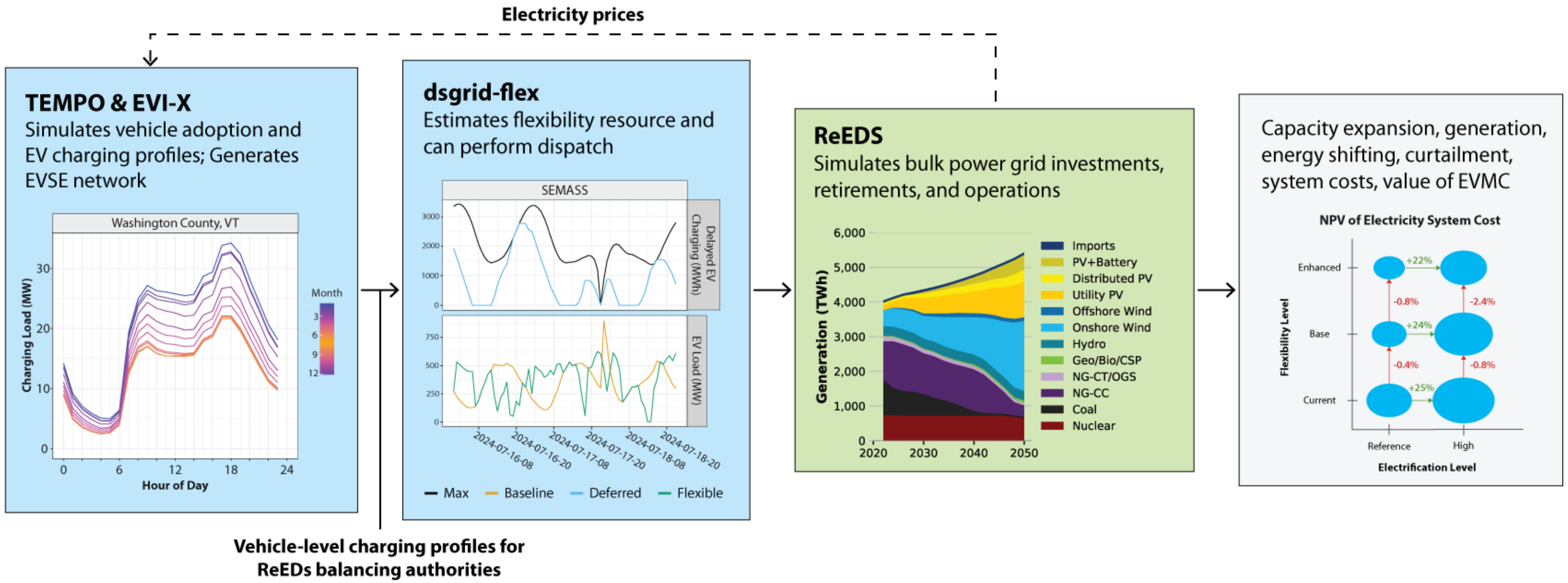
- Coordination of EVMC response is required starting at modest participation levels (~2-3% of total load EVMC) and comes at an aggregation feasibility cost
- Highest per-vehicle value is achieved at low participation levels responding to time-varying price
- Within-week flexibility more valuable than within-session flexibility
- If all EVs fully participate through 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 work!

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!

Luke.lavin@nrel.gov

Elaine.hale@nrel.gov

NREL

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

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-6A40-83404
September 2022

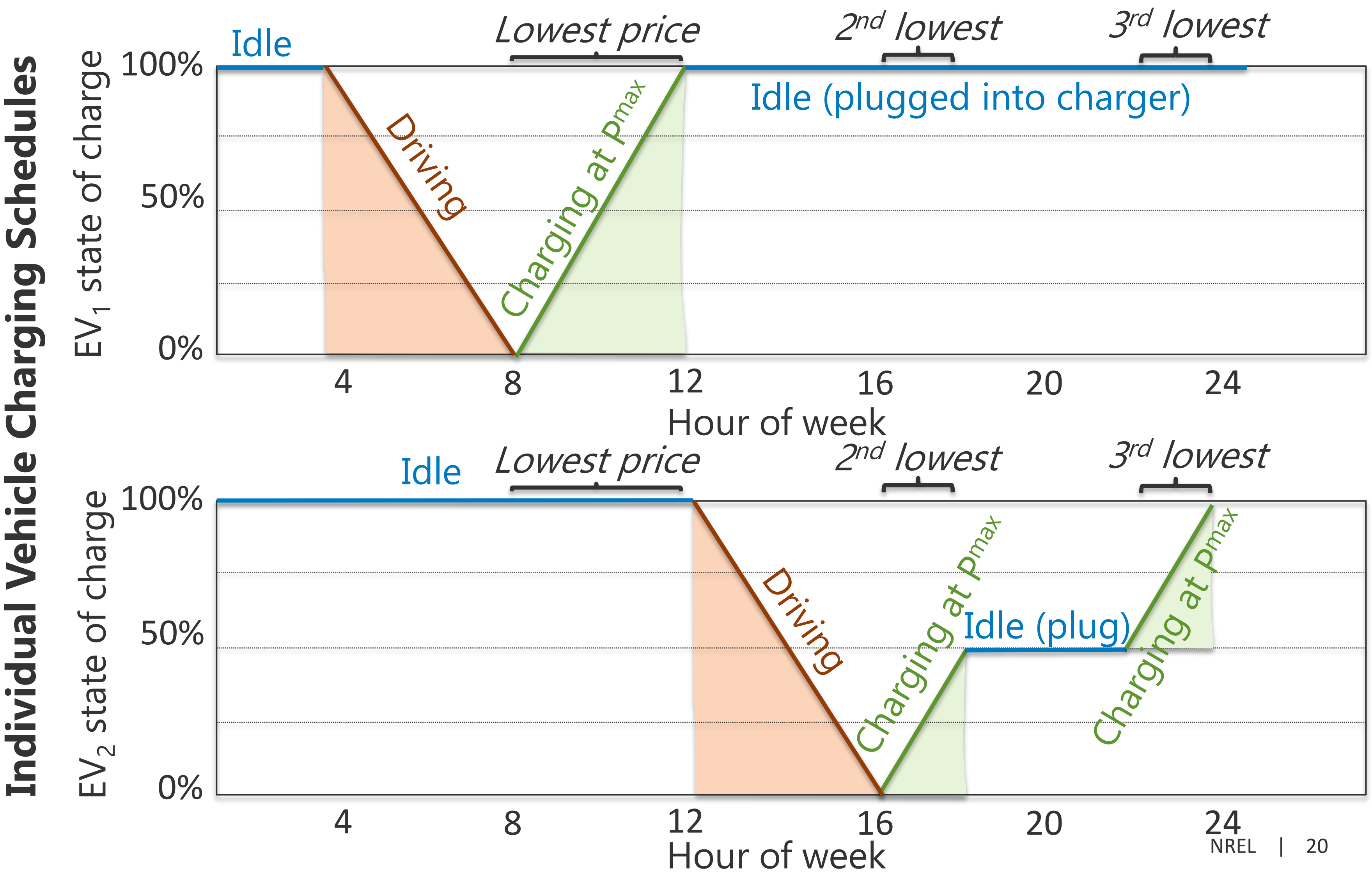
https://www.nrel.gov/docs/fy22osti/83404.pdf

Backmatter

Aggregation feasibility

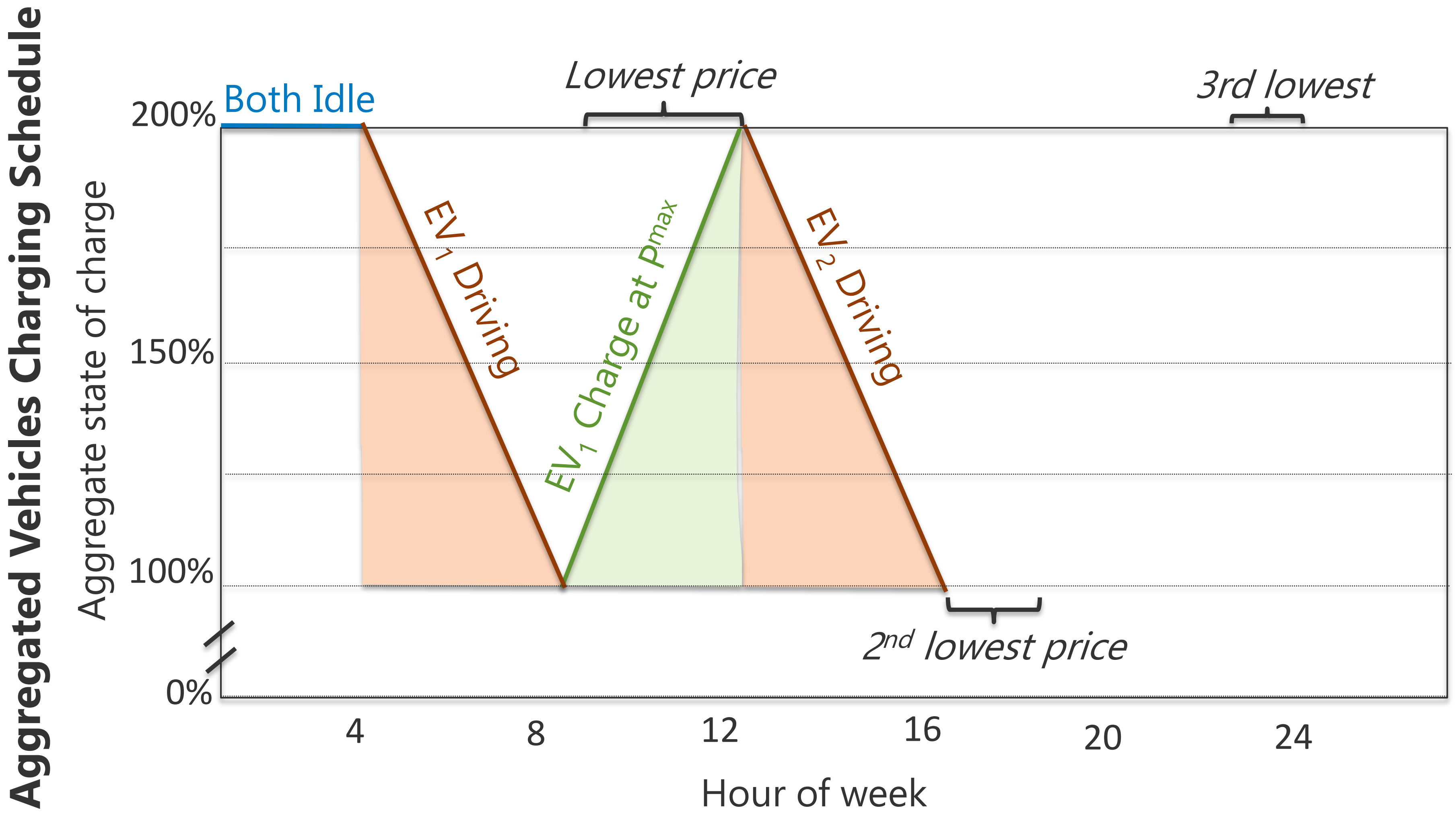
Methodological Finding: Energy and capacity bounds of EV aggregations *cannot* be naïvely added

- 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



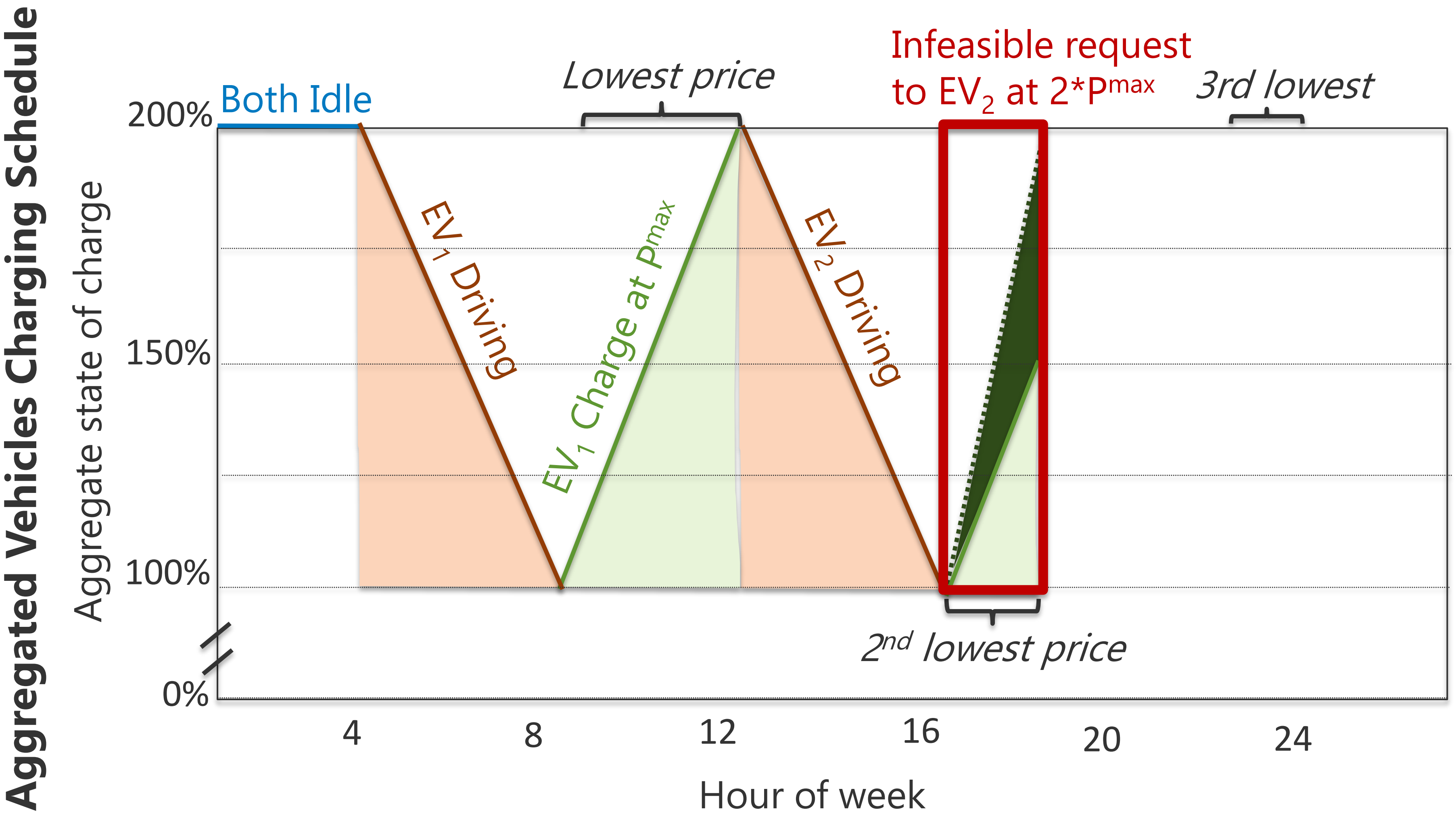
Methodological Finding: Energy and capacity bounds of EV aggregations *cannot* be naïvely added

- Aggregation needed for EVs to participate in wholesale electricity markets (>0.1 MW), but simple addition of individual vehicle flexibility overestimates resource

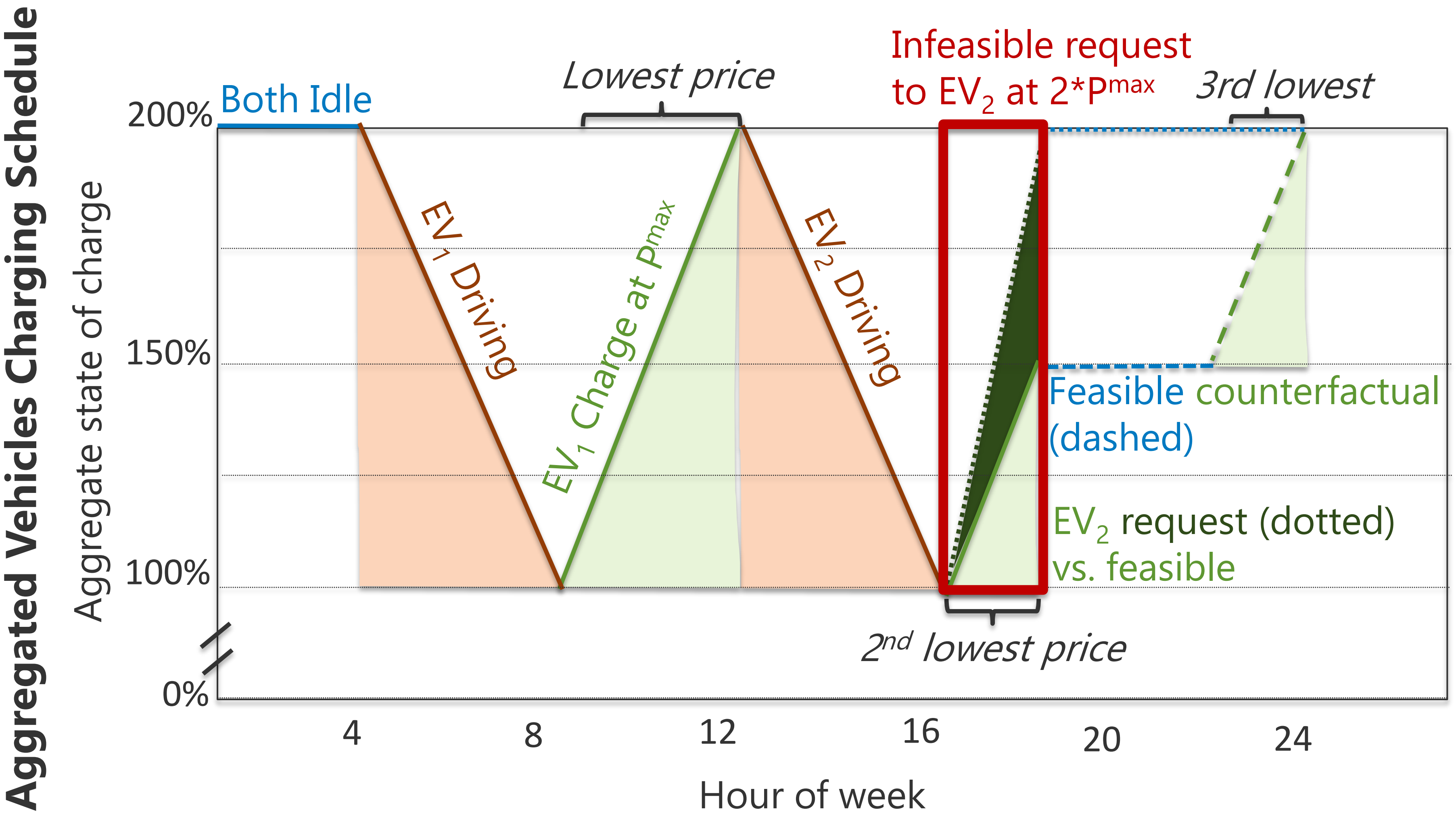


Methodological Finding: Energy and capacity bounds of EV aggregations *cannot* be naïvely added

- **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 naïvely added



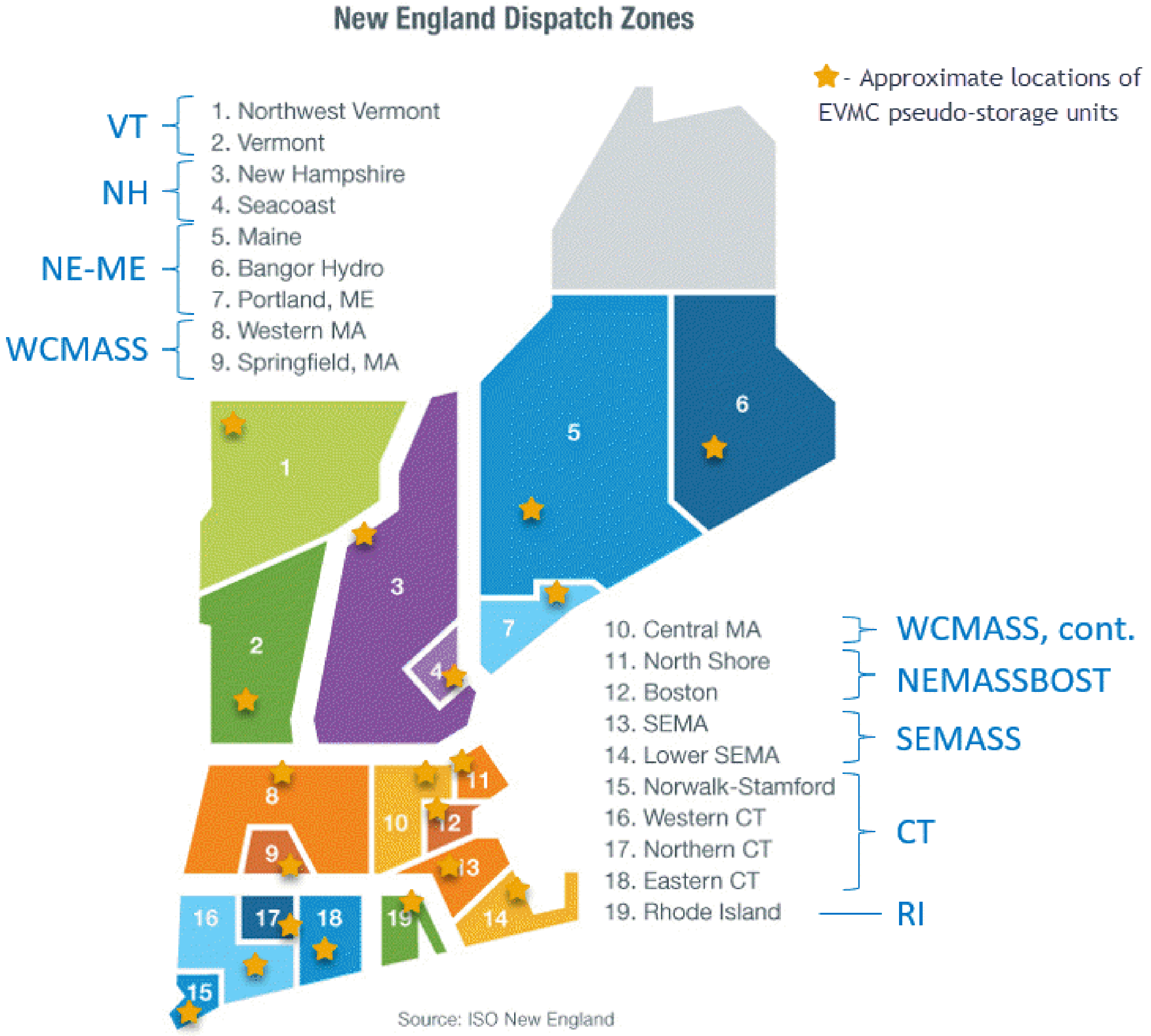
- **Question:** How feasible is Direct Load Control?

Backmatter

Other information

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 CO_2 (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



Analysis approach

Construct TOU rates for comparison to RTP and DLC mechanisms

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

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

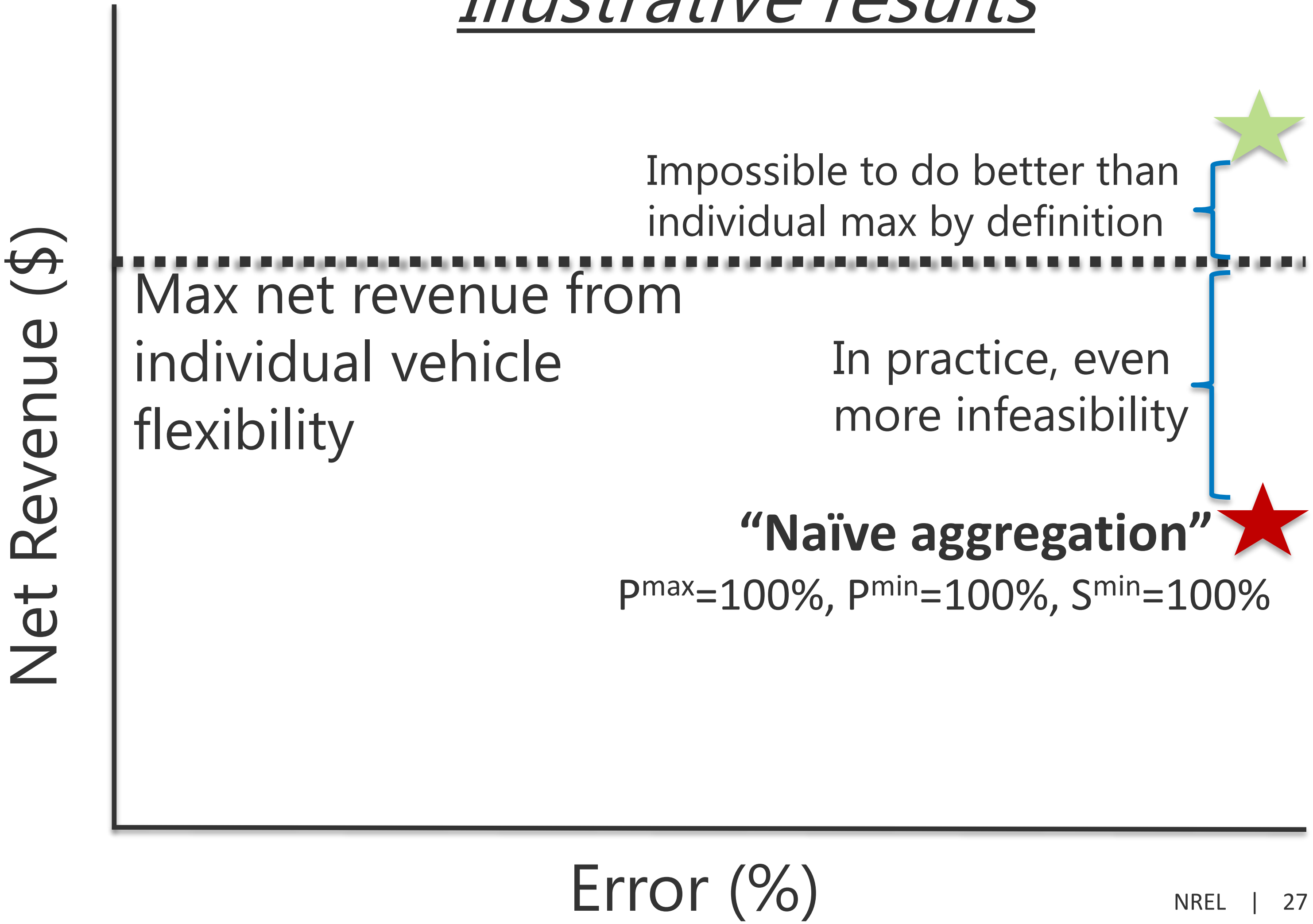
S^{min}: max quantity of deferred load in each time period

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

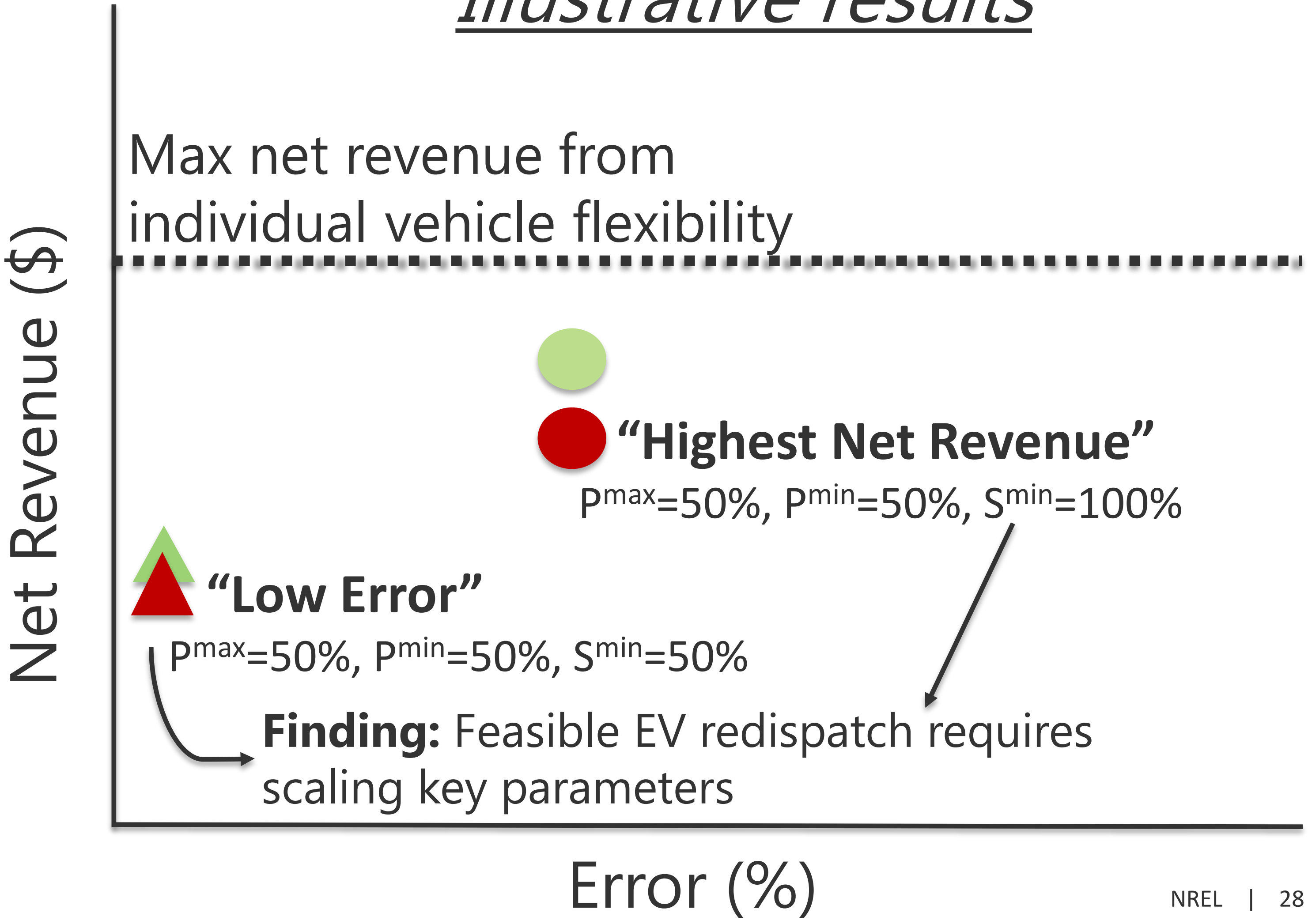
S^{min}: max quantity of deferred load in each time period

Red: Revenue under feasible re-dispatch to individual EVs

Green: Revenue if aggregate request was fulfilled

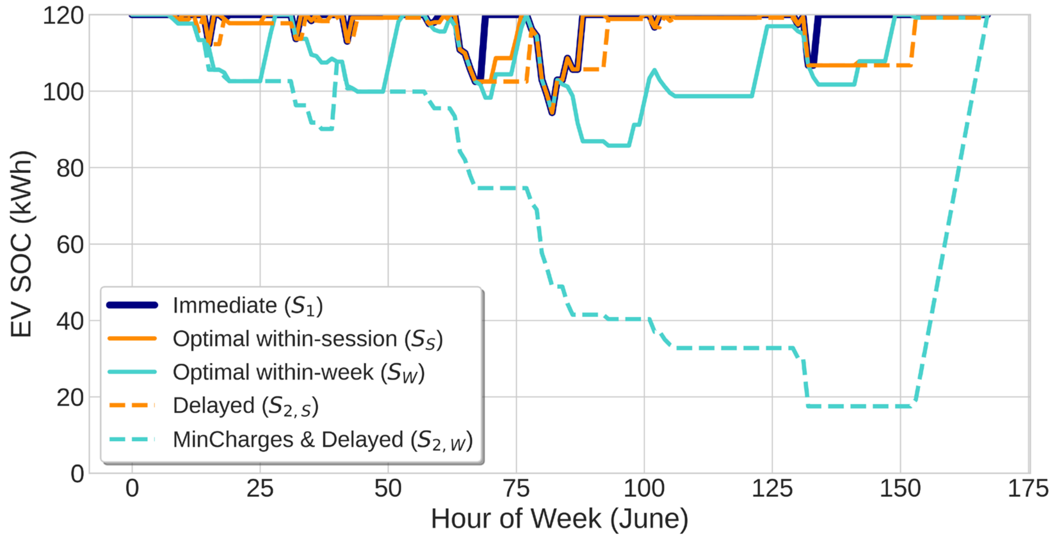
▲●★: Three different objectives

Illustrative results

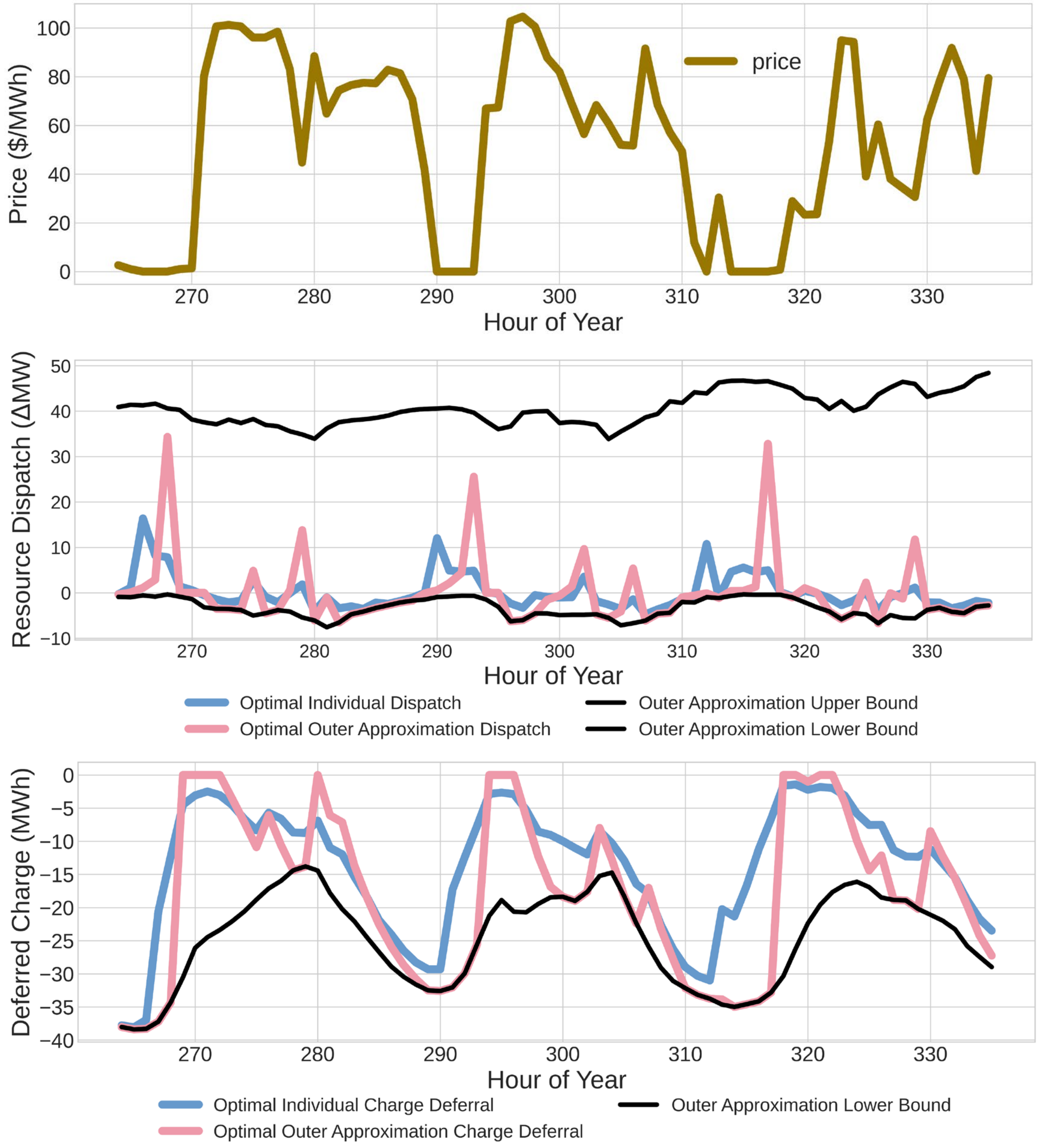


Analysis Approach
Deep dive into aggregation

Dispatch Individual Vehicles within Power and Energy Envelopes

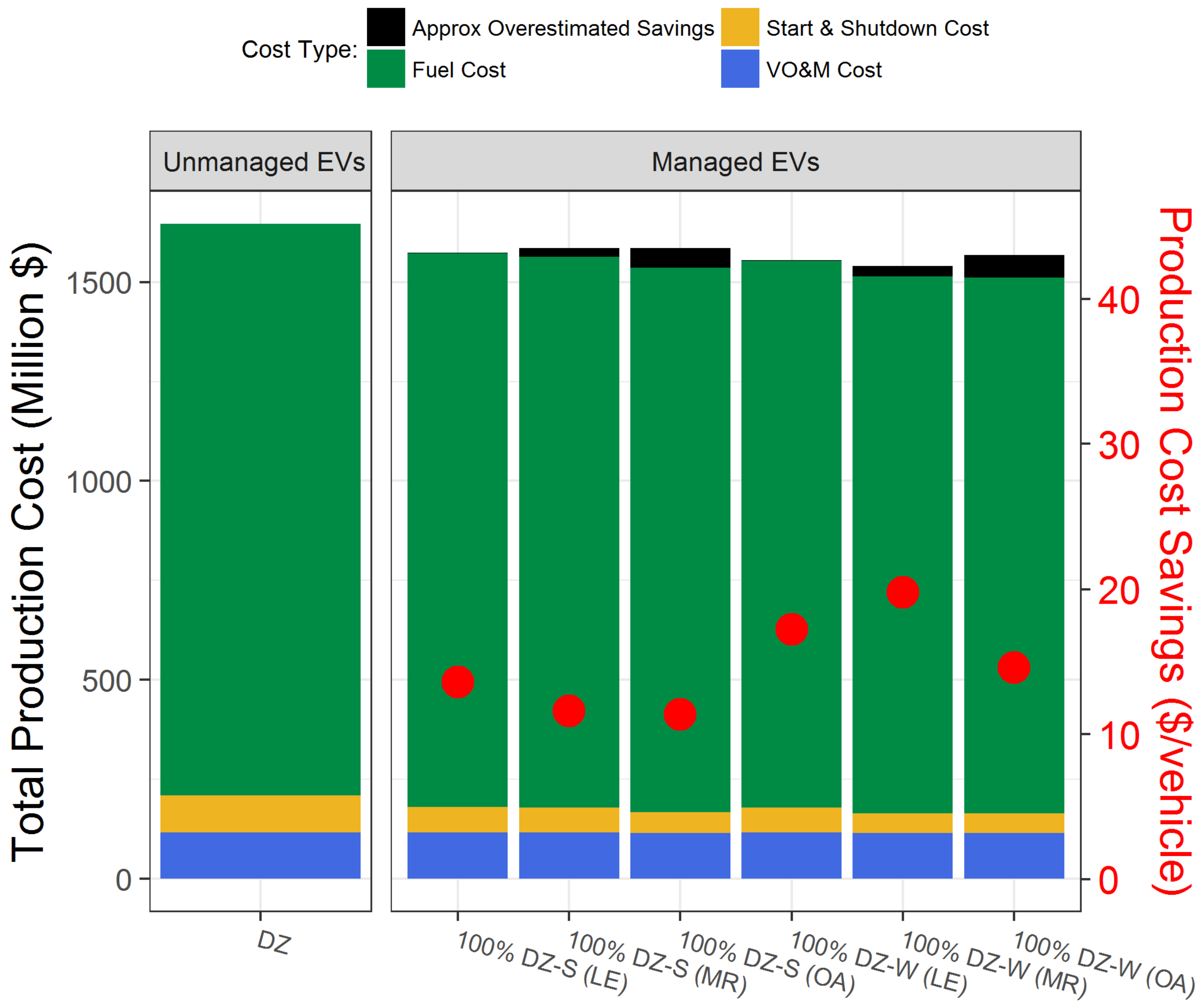


Simply Summing Power and Energy Bounds Overestimates Flexibility



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 outer 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)

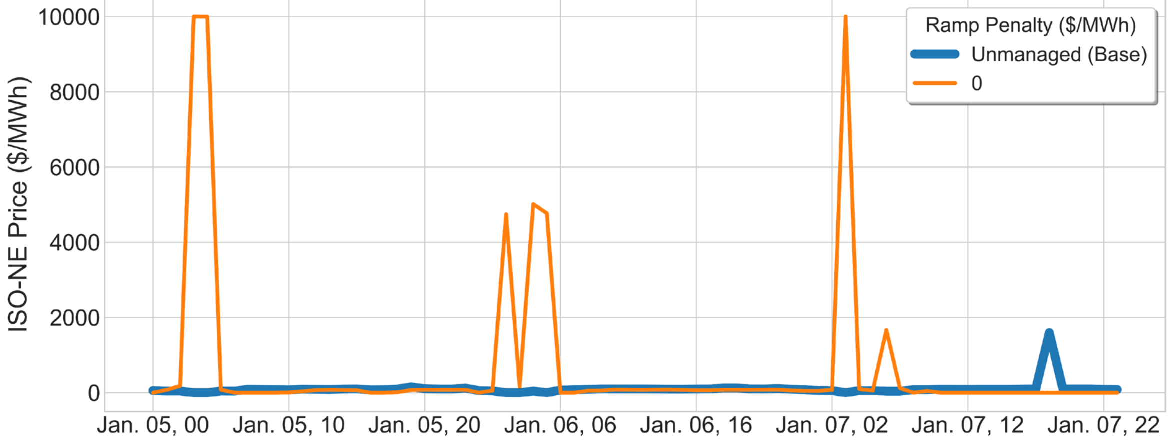


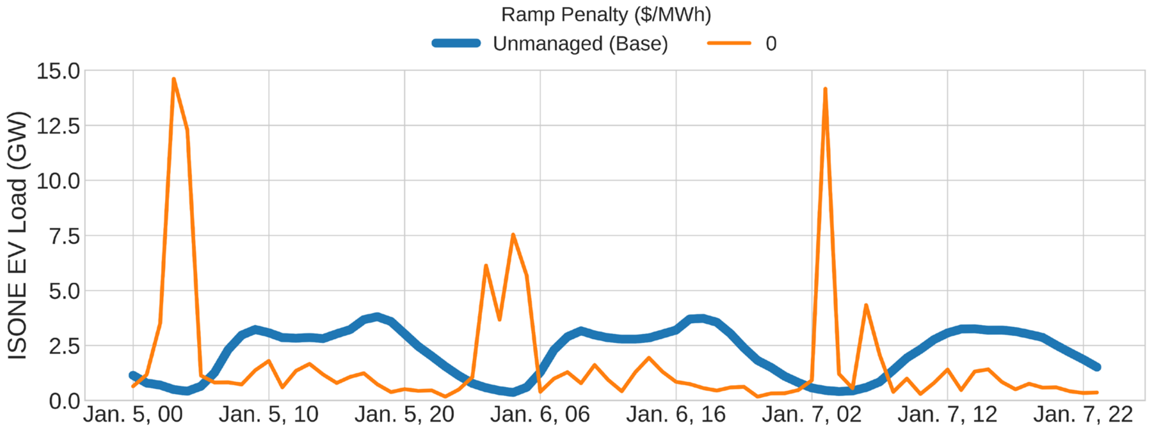
Analysis Approach
Testing the Limits of Price-taking

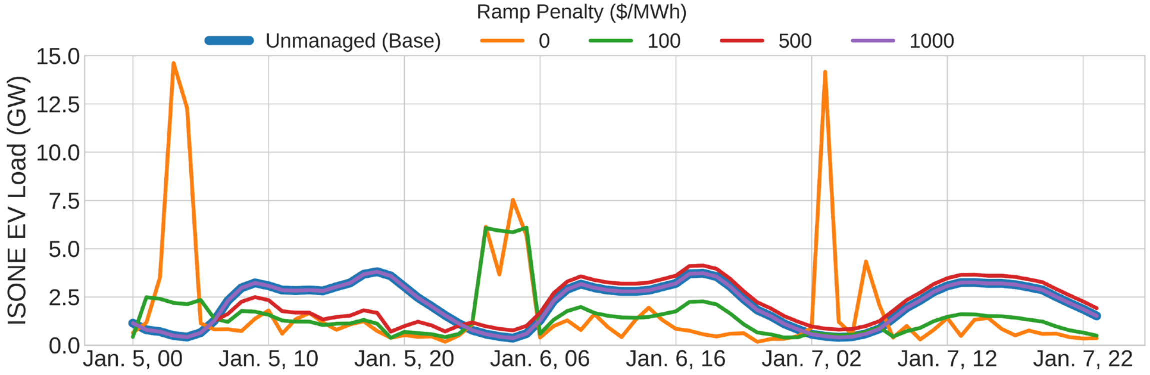
- Price-taking approaches are simpler than DLC, and let vehicles respond directly with their full flexibility
- However, too much flexible EV load chasing the same prices eliminates old, but creates new, price spikes
- Applying a penalty to aggregate ramps mutes response
- Simply muting response is not 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 RTP	TOU-4-4	TOU-1-2	Within-week 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