A Highly Efficient Control Framework for Centralized Residential Charging Coordination of Large Electric Vehicle Populations

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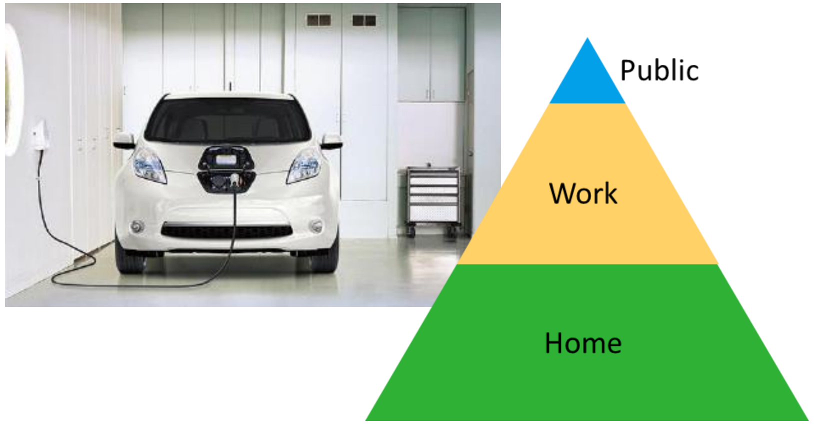
Introduction

- Significant portion of plug-in electric vehicle (PEV) charging occurs at residences

- Important to understand the potential impacts of PEV charging on residential electric distribution systems

- Negative impacts from residential charging may include:
  - Increased peak demand
  - Transformer aging
  - Distribution system congestion
  - Reduced power quality



Objective

- The purpose of this work is to develop a charging coordination strategy to mitigate negative impacts of residential PEV charging at scale

Approaches to Residential PEV Charging Coordination

- *Decentralized approaches*
  - ✓ Low computational complexity
  - ✓ Limited communication needed
  - × Impossible to achieve system-wide optimum
- *Centralized approaches*
  - ✓ Systematically allocate energy across a large population of PEVs for global optimum
  - ○ Network-wide communication required
  - × Computational complexity increases quickly as PEV population size increases

Focus of This Work

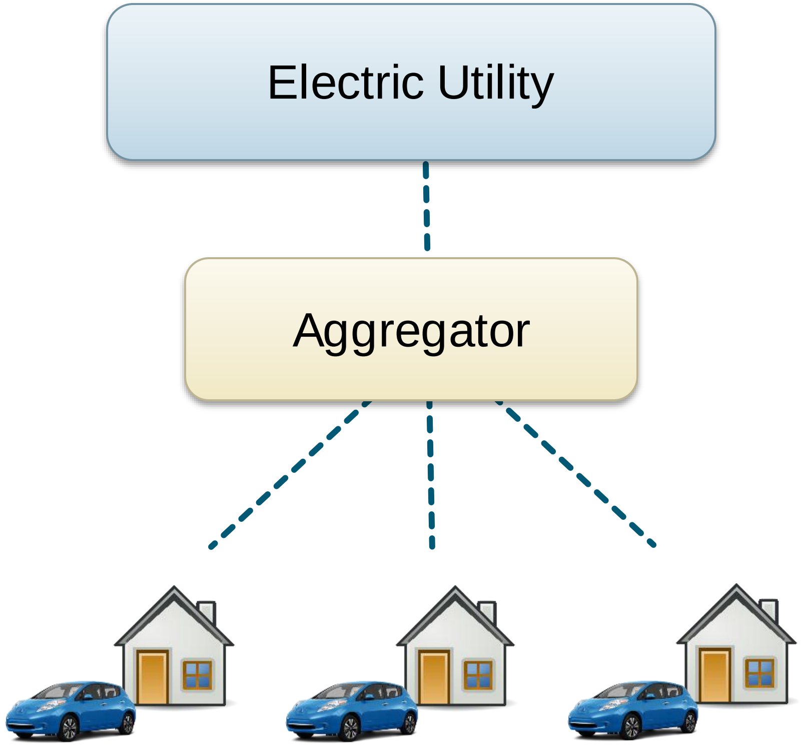
- This work focuses on overcoming a major barrier to centralized charging coordination for large PEV populations: high computational complexity of existing methods

- The computational barrier is overcome with a novel approach:
    - Receding horizon control with a two-stage hierarchical optimization routine

Note: solutions for overcoming other barriers to centralized control, such communications system requirements, are the subject of other works

Methodology

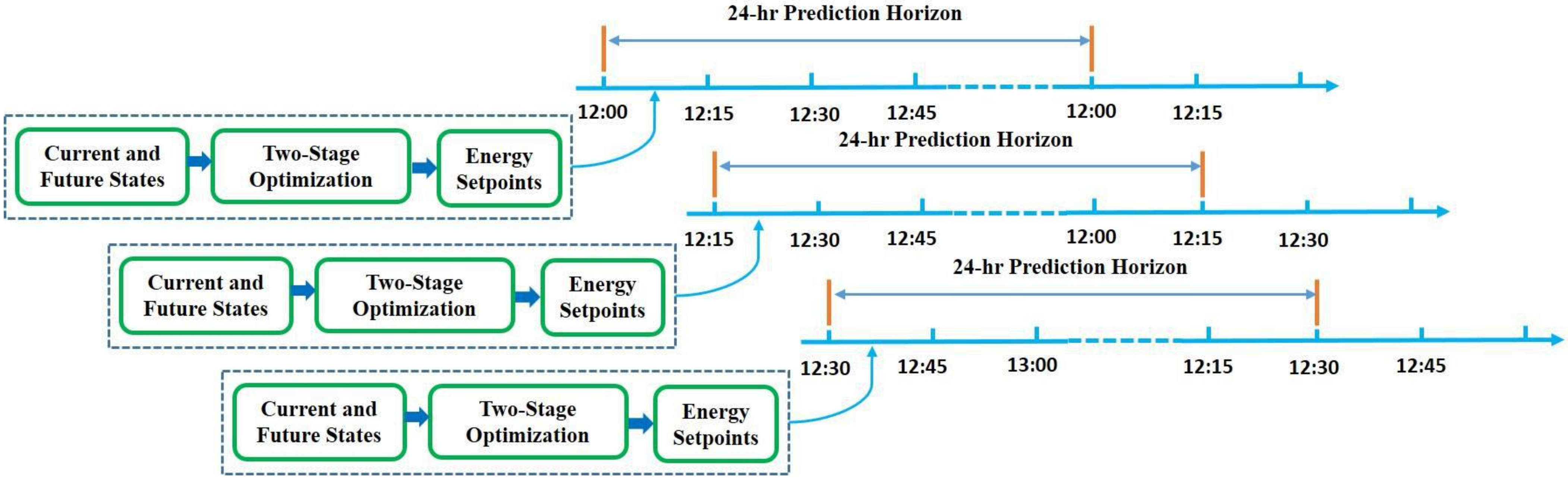
- A third-party aggregator concept is employed to centrally coordinate charging at the vehicle level in response to the needs of the grid
- The aggregator uses receding horizon control with two-stage hierarchical optimization to shift PEV charging loads to integrate them with non-PEV electricity demand (e.g., to flatten the system load)
- Individual vehicle charging needs are prioritized as constraints to ensure that vehicle owners' transportation needs are met



Receding Horizon Predictive Charging Coordination

For each time step (e.g., 15 minute interval), the aggregator follows these steps:

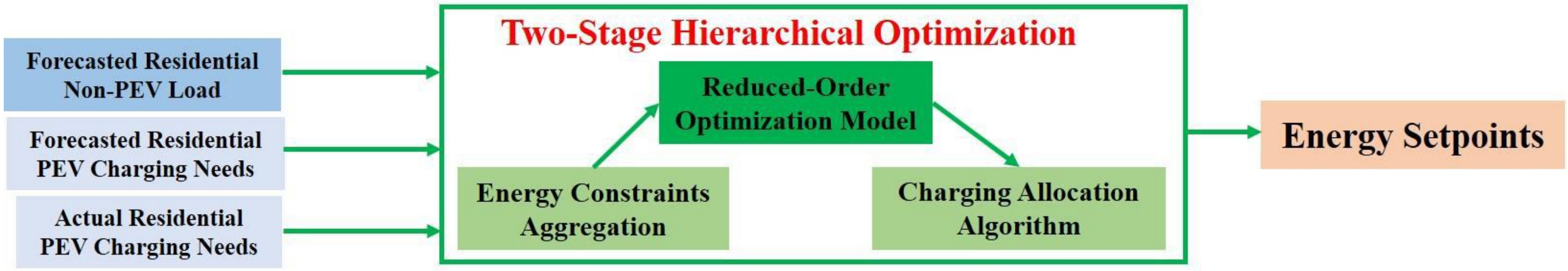
1. Evaluate current and future PEV charging and non-PEV loads over 24-hr prediction horizon
2. Perform optimization to meet system objectives
3. Determine energy set points for each plugged-in PEV to follow in the next time step
4. Move to next time step
5. Shift prediction horizon forward by one time step
6. Repeat



Two-Stage Hierarchical Optimization Routine

Optimization is performed for each time step as follows:

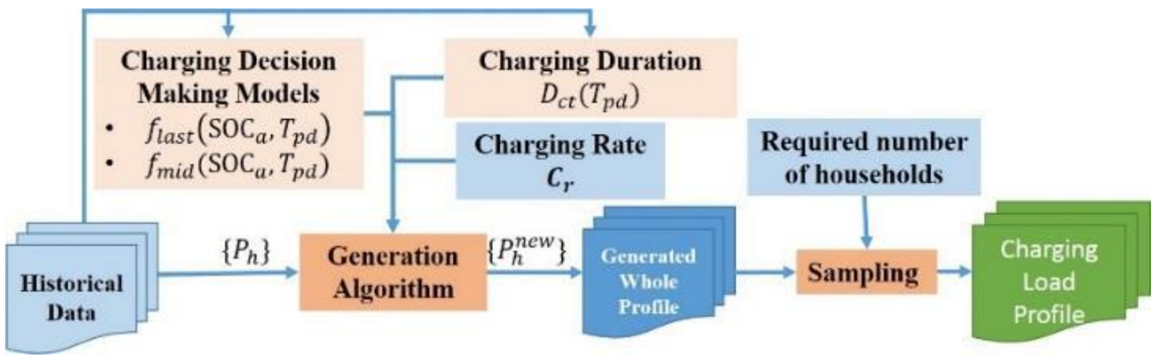
1. Reduce the problem by aggregating individual PEV charging constraints into a single set of constraints
2. Determine total PEV charging load to meet system needs within constraints
3. Allocate charging load across all PEVs
4. Send energy set point requests to individual PEVs



Data-driven Simulation for Concept Validation

- Real-world, residential PEV parking and charging behavior data from *The EV Project*[1] was input into machine learning models to construct charging decision-making and charging duration models

Framework for the residential PEV charging load profile generation



This framework can generate residential PEV charging load profiles for vehicles and charging equipment with different charging rates to simulate different control scenarios

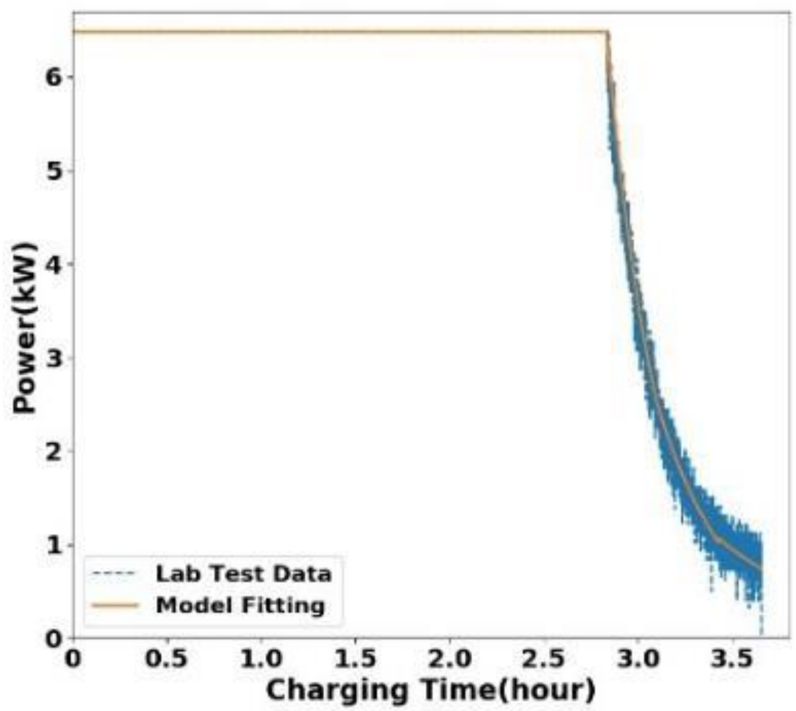
Sample residential PEV charging load profiles

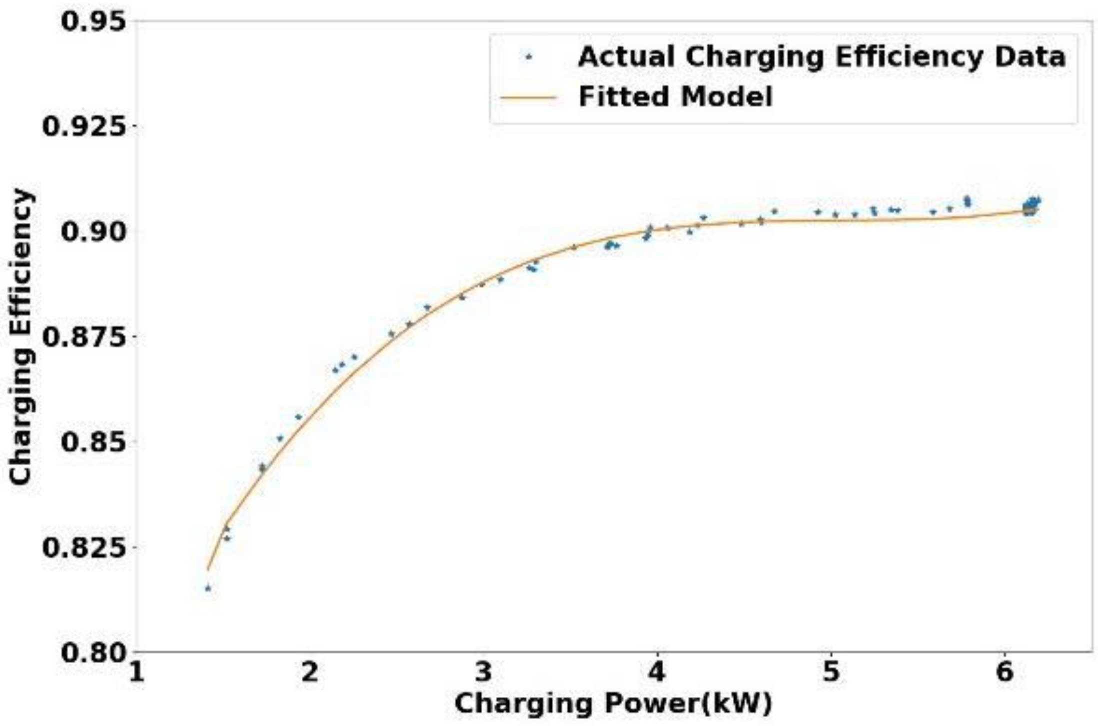
PEV ID	Vehicle Make /Model	Arrival Time (hours)	Departure Time (hours)	Arrival SOC (%)	Requested Departure SOC (%)
9225	2015 Nissan Leaf	23.36222	35.07194	47	100
9290		11.73722	31.92917	88	100
9373		17.41000	31.08056	85	100
10202		12.58722	36.09194	40	100
17905		14.94639	15.64944	57	74
17905		16.20389	30.47972	69	100
43003		17.33333	30.67083	68	100
50497		13.74528	14.79139	72	94
50497		16.70583	31.52083	70	100

[1]The EV Project included data collection over 3 years from over 4,000 privately-owned Nissan Leafs

High-Fidelity Simulation Platform

- PC-based simulation platform included the aggregator model, machine learning models, and a high-fidelity charging model of the 2015 Nissan Leaf





Charging model shows good correlation with the actual charging power profile (left) and charging efficiency data (right) from testing of a 2015 Nissan Leaf

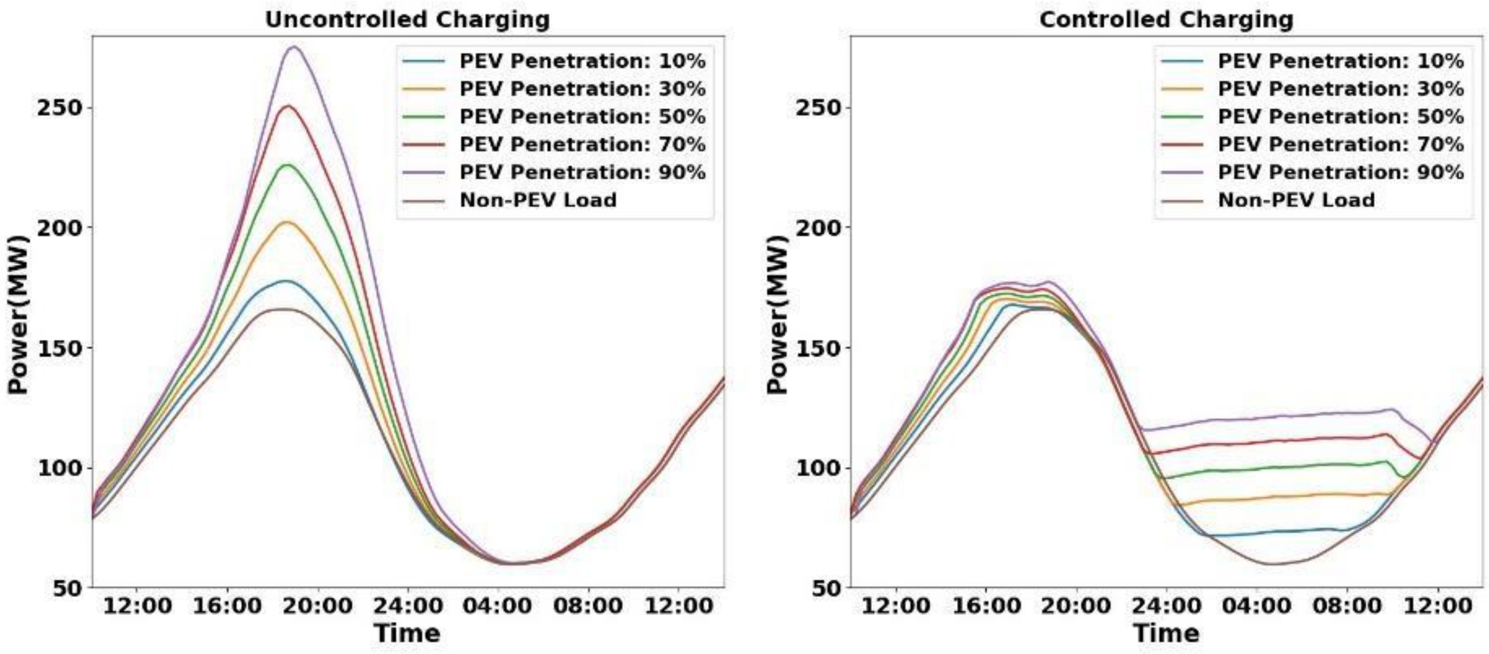
Simulation Scenarios

- Uncontrolled and controlled charging scenarios were simulated for five different penetration levels of Nissan Leafs in 100,000 households on the same residential feeder
- Capacity deferral through PEV load shifting was the objective of the controlled scenarios

Total number of households: 100,000	
Approximated PEV penetration	Number of charging events in simulated day
10%	9,744
30%	29,286
50%	48,978
70%	68,769
90%	88,482

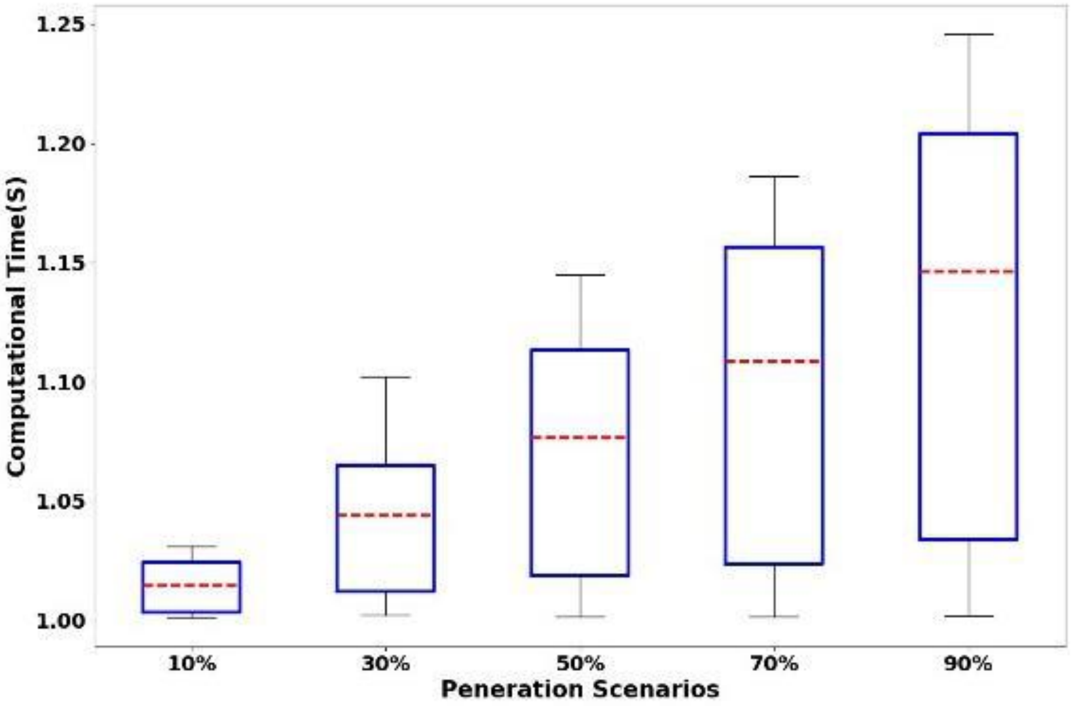
Simulation Results

- Residential feeder load profiles were generated for uncontrolled and controlled charging under five different PEV penetrations and for only non-PEV load (baseline)
- Results show that centralized charging coordination by the means of an aggregator significantly reduces PEV contribution to the system peak and shifts the majority of the PEV load to off-peak hours
- All PEV charging needs were also met



Computational Time

- Computations during each time step were completed in less than 1.25 seconds, for a simulation with only 96 time steps (15-min time step over 24-hr period)
- This compares to simulation run times of hours or days for existing centralized approaches
- An additional simulation of 500,000 PEVs was run for comparison
- Time steps of 1 to 4 seconds



Conclusions

- This work introduces a ***receding horizon control framework*** for highly efficient residential charging coordination of a large fleet of PEVs
- A ***two-stage hierarchical optimization routine*** was designed to facilitate the dynamic control framework
- The dynamic PEV charging control strategy was validated on a ***high-fidelity simulation platform***
- Simulations were conducted using ***real-world charging behavior data*** from Nissan LEAF drivers in The EV Project
- Case study results show that our framework can successfully coordinate large-scale residential PEV charging to minimize the system peak in an ***extremely efficient*** manner
- Future work should focus on overcoming additional barriers to implementing centralized charging control: forecasting and communication