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State Key Laboratory of Internet of Things for Smart City (University of Macau)

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2026

电网约束下的电气化自动驾驶车队在线调度
Real-Time Operation of Electric and Autonomous Mobility Systems under Power Grid Constraints

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Jan 20, 2025

Main credits to my students:

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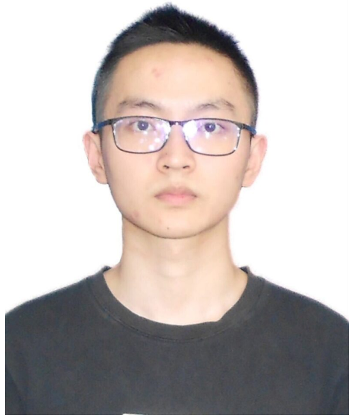
- PhD student at University of Macau (since 2022)
- Master in Electrical Engineering, Shandong University (2021)
- Bachelor in Electrical Engineering, Shandong University (2018)

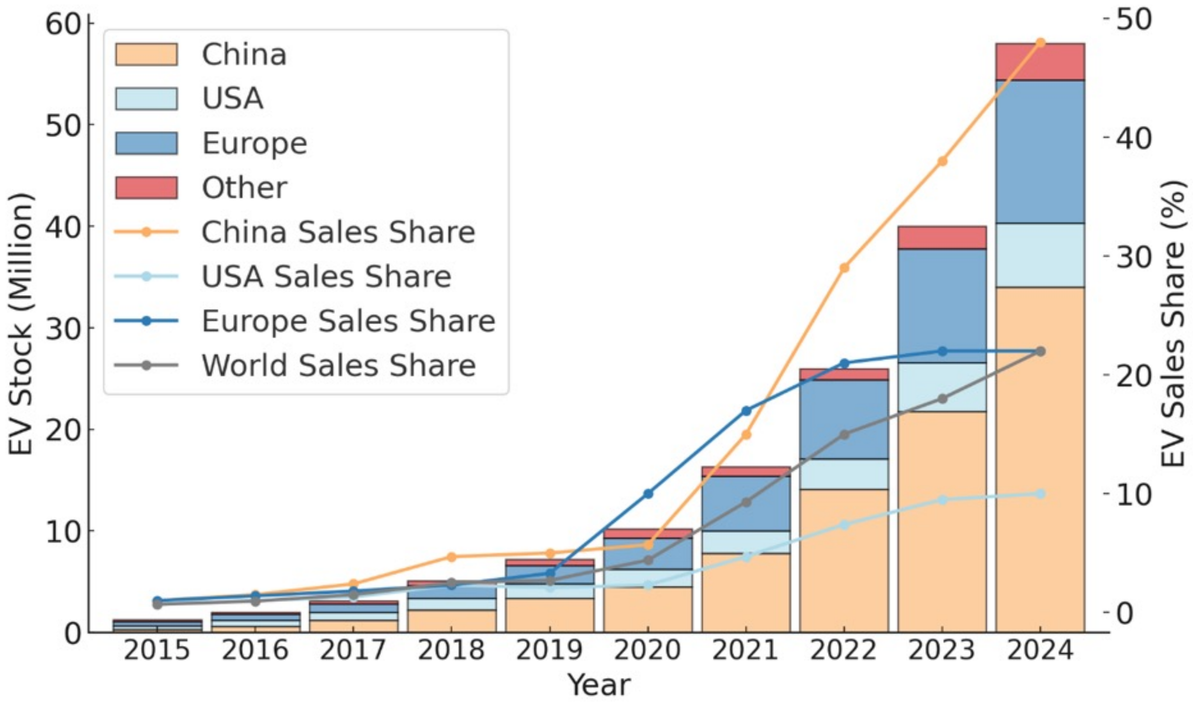


Lyuzhu PAN

- PhD student at University of Macau (since 2023)
- Master in Electrical Power Engineering, The University of Edinburgh (2023)
- Bachelor in Hydropower Engineering, Huazhong University of Science and Technology (graduation with honors, 2022)

Electric vehicles (EVs) are dominating future transportation systems

- By 2024, China's EV stock reached 31.4 million, accounting for nearly 50% of new vehicle sales
- In 2024 alone, newly added EV battery capacity in China is 548 GWh, equivalent to 5 times of the newly installed grid-scale energy storage (110 GWh, including pumped hydro)



Global EV stocks and sales share, 2015-2024

(China's stock is over 31.4 m, with close to 50% sales share)

Newly added EV battery capacity vs. grid-scale energy storage investment in China (2024)

EV: 548GWh

ES: 110GWh

An example in Zhongshan, Guangdong

100MW/200MWh energy storage, Zhongshan, Guangdong, 2025

≈

2,500 BYD taxis*

or

460 BYD trucks

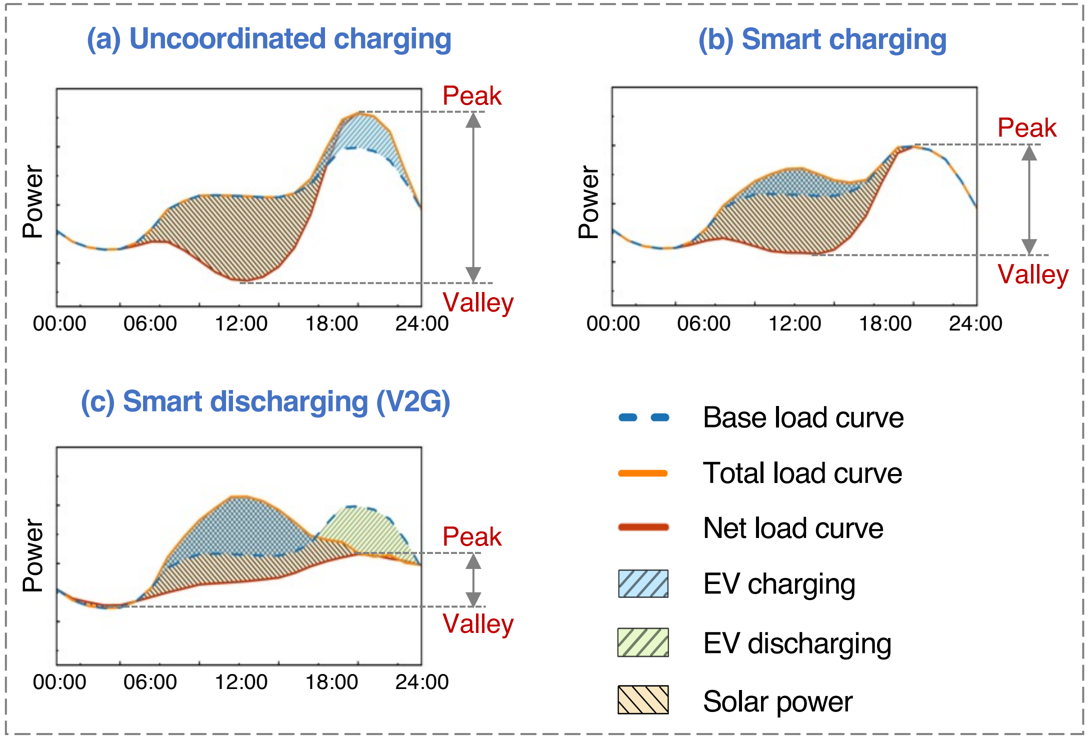
*Note: Zhongshan has over 1.64M cars, with over 15 k taxis.

[1] Beijing News, "China's new energy vehicle market share continues to rise," Jan. 13, 2025.
[2] ESS News, "China's new energy storage capacity surges to 74 GW, 168 GWh in 2024, up 130% YoY," Jan. 23, 2025.

With vehicle-to-grid technology, EVs can provide services to power grid

- **Vehicle-to-grid (V2G)**: manipulating EVs' charging & discharging to provide power grid services
- **Strong policy momentum** & **advancing technologies** is scaling up V2G applications nationwide

Conceptual diagram of V2G application



(a) uncoordinated charging increases peak-valley differences;
(b) smart charging reduces peak-valley differences;
(c) smart discharging (V2G) flattens load profile (thereafter promotes solar power integration & reduces carbon emissions).

Key milestones of China's V2G application

Government policy

- 2009, National "Ten City-Thousand EV Pilot" Program, first EV policy
- 2012, National "Energy-saving and New-energy Vehicle Development Plan", **first proposed** V2G study
- 2020, National "New-energy Vehicle Development Plan", promoting V2G as a **National Strategy**
- 2023, National "Implementation Plan on V2G", planning a V2G **technical standard** system
- 2024, Shanghai, "New Energy Storage Plan", 30k–50k smart V2G piles by 2030
- 2025, National "Notice on Large-Scale V2G ", developing **markets** to enable large-scale **V2G trading**
- 2025, Shandong, Chongqing, & Shanghai, Guangdong etc. issued **V2G price policies** to incentivize V2G applications

2009
2012
2018
2020
2023
2024
2025

Industrial application

- 2012, Dalian, China's first V2G discharge experiment
- 2018, Shanghai, first batch V2G demonstration station
- 2020, Beijing, first commercial V2G demonstration station
- 2023, Wuxi, **3MW** V2G center for peak shaving & backup power supply
- 2024, Shenzhen, V2G trial with **17k+** EVs and 760 charging stations
- 2025, Shanghai, large-scale V2G test with **20 MW** discharge capacity
- 2025, China Southern Grid, **world largest V2G trials** with **100K+ EVs**
- 2025, China's first batch of large-scale V2G pilots covering **9 cities** & **30 demonstration projects**

EVs’ emissions depend on their synergy with renewable generation

- EVs may emit more even with high-penetration of renewable generation

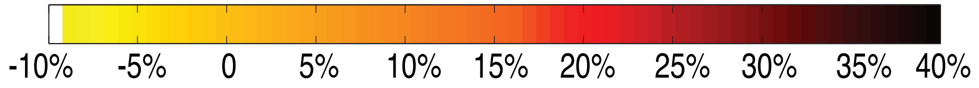
Vehicle emission with high penetration of wind in Jing-Jin-Tang

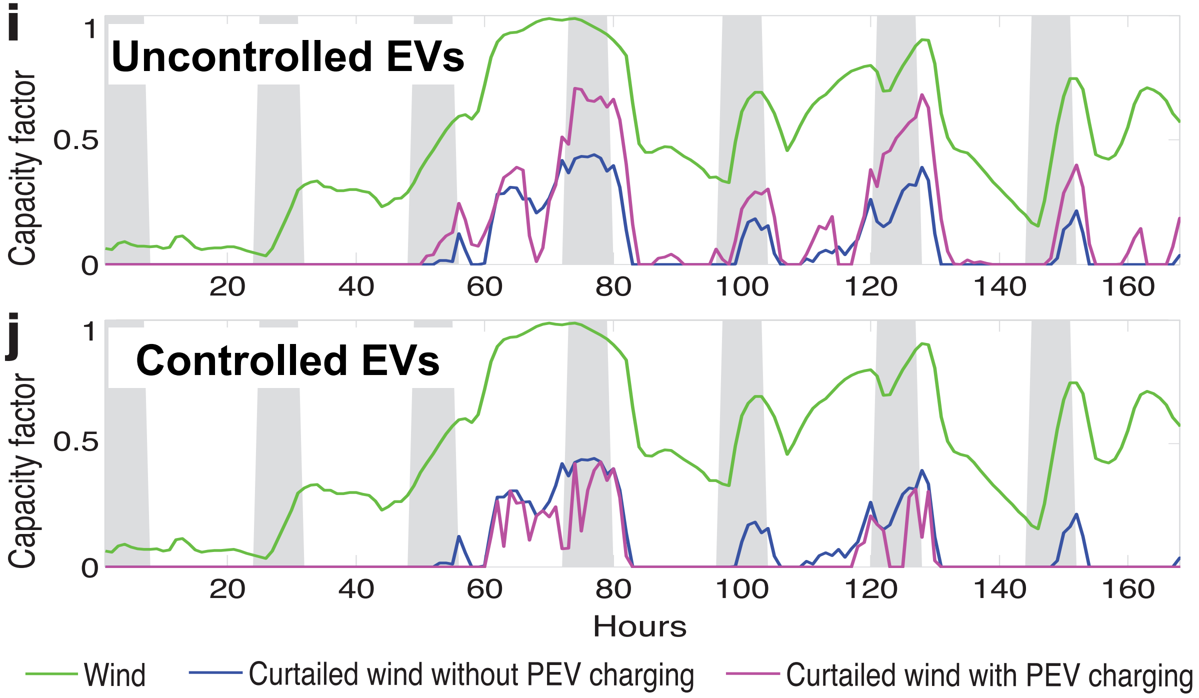
a CO_2 reductions

	Wind level 0%	10%	20%	30%	40%
ICEVs	0%	10%	19%	25%	29%
Uncontrolled EVs	-3.4%	6%	12%	17%	20%
Controlled EVs	-2.7%	8%	18%	26%	31%

b NO_x reductions

	Wind level 0%	10%	20%	30%	40%
ICEVs	0%	5%	9%	12%	14%
Uncontrolled EVs	11%	15%	18%	20%	22%
Controlled EVs	11%	16%	21%	24%	27%

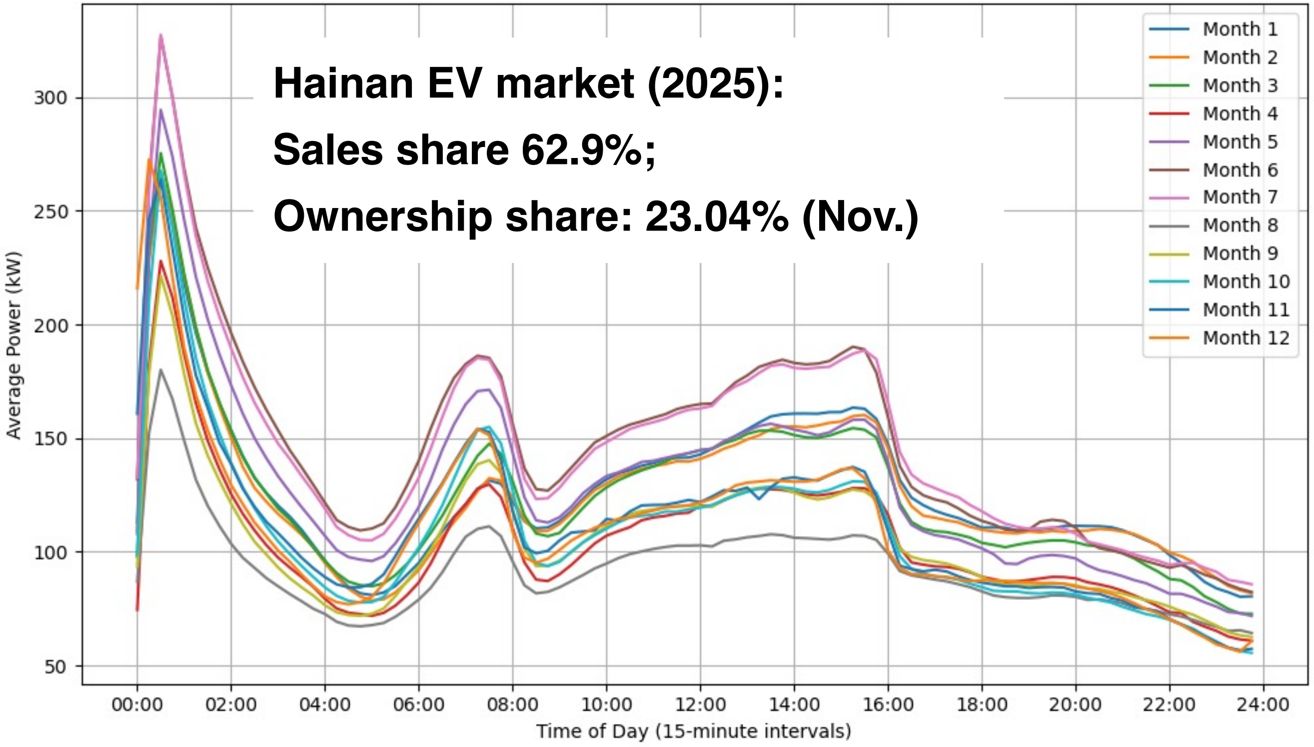




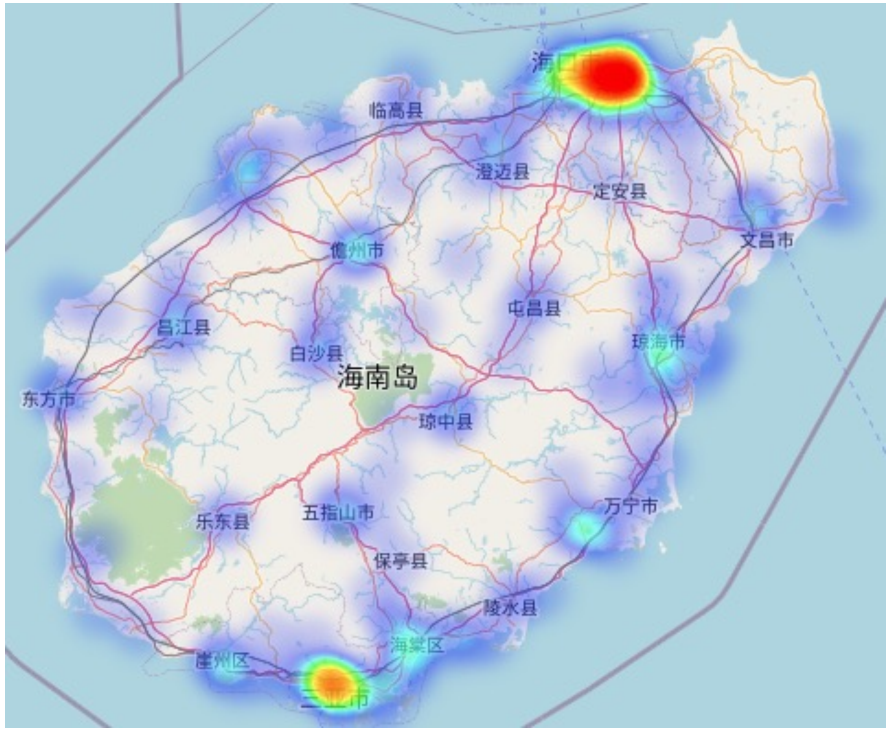
*X. Chen, **H. Zhang**, Z. Xu, C. P. Nielsen, M. B. McElroy, and J. Lv, “Impacts of Fleet Types and Charging Modes for Electric Vehicles on Emissions under Different Penetrations of Wind Power,” **Nature Energy**, vol. 3, pp. 413-421, 2018. DOI: [10.1038/s41560-018-0133-0](10.1038/s41560-018-0133-0)

A realworld example: EV charging in Hainan Province, China

- EV charging at midnight caused 5 (out of 6) times of historical province-level power peaks in 2024
  - Net EV charging load at midnight: 630 MW (7.8% of total demand)
  - EV charging load ramp rate up to: 75 MW/min
- In 2025, charging load is estimated to have hit 1200 MW, further stressing the power grid



Average daily EV load profiles per station in Hainan (2024)

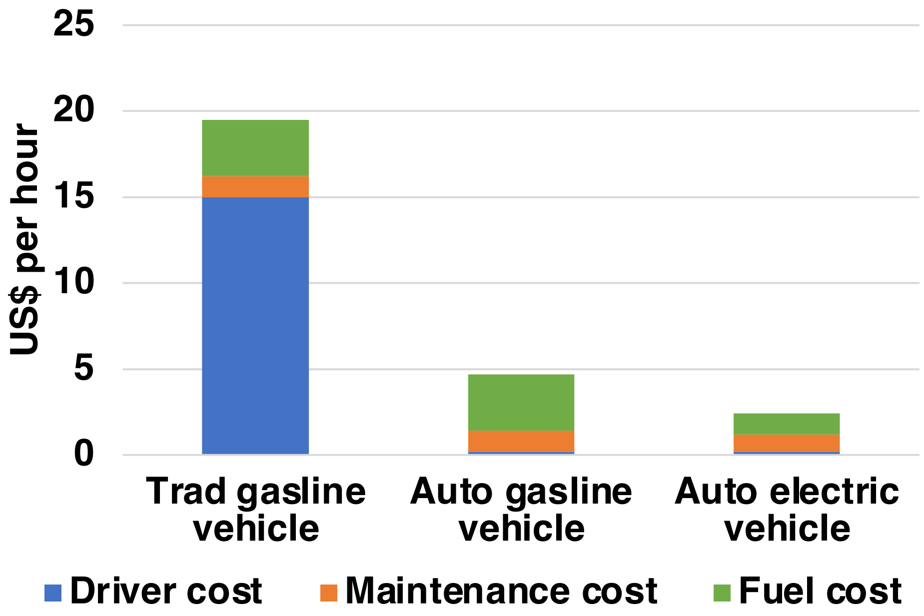


Hainan EV charging load heat map (2024)

Autonomous EVs (AEVs) have enhanced V2G capability

- Operational expense is **dominated by electricity costs** (**no driver time costs**)
- **Scheduled driving, parking, & charging behaviors** following dispatch signals (no driver decisions)
- Operable in **hazardous or inaccessible areas** (without risking driver safety)

Cost analysis of vehicle mobility*



*Note: fuel efficiency 0.32 kWh/mile for AEVs, and 30 mi/gallon for ICEVs; gas price 3.3 $/gallon; average driving speed 30 mile/hour.

萝卜快跑

WAYMO

ROBOTAXI

AEVs' key advantages

- ✓ **Coordinated operation**
- ✓ **Signal-driven dispatch**
- ✓ **Spatiotemporal flexibility**
- ✓ **Hazard-area access**

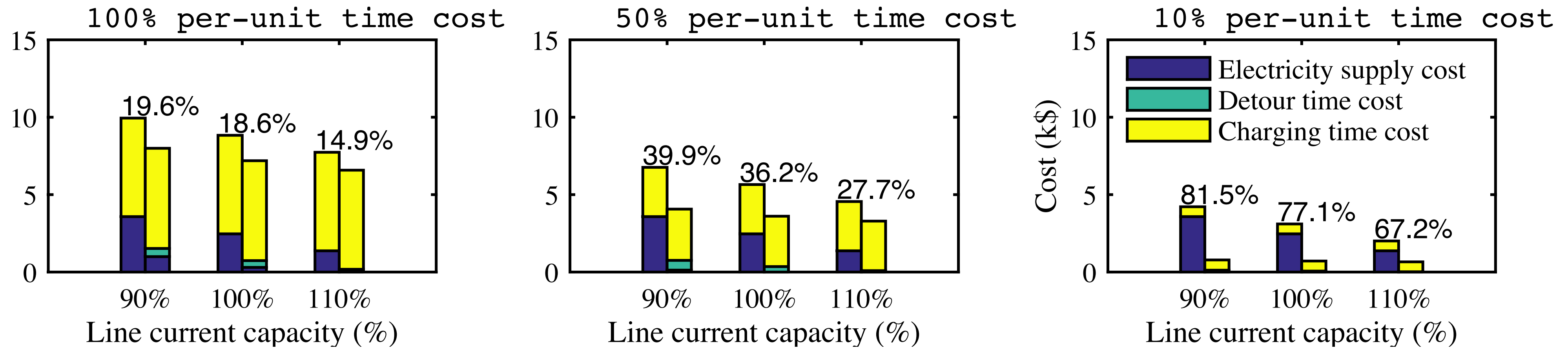
Autonomous EVs (AEVs) have enhanced V2G capability

- Autonomous EVs are more motivated to get charged with cheap & renewable electricity

Traditional EVs: Significant operation costs reduction (-20%) with mild detour

Case	Power generation and purchase (MWh)			Fueling costs (k$/h)				
	Electricity purchase	Conventional DG	Renewable DG	Electricity	Emission	Charging time	Detour time	Total
Shortest path	10.37	6.05	94.65	2.37	0.099	6.36	0	8.83
Strategic routing	1.14	0.86	113.98	0.29	0.012	6.45	0.44	7.19

Autonomous EVs: Enhanced benefits of strategic routing with lower per-unit charging time

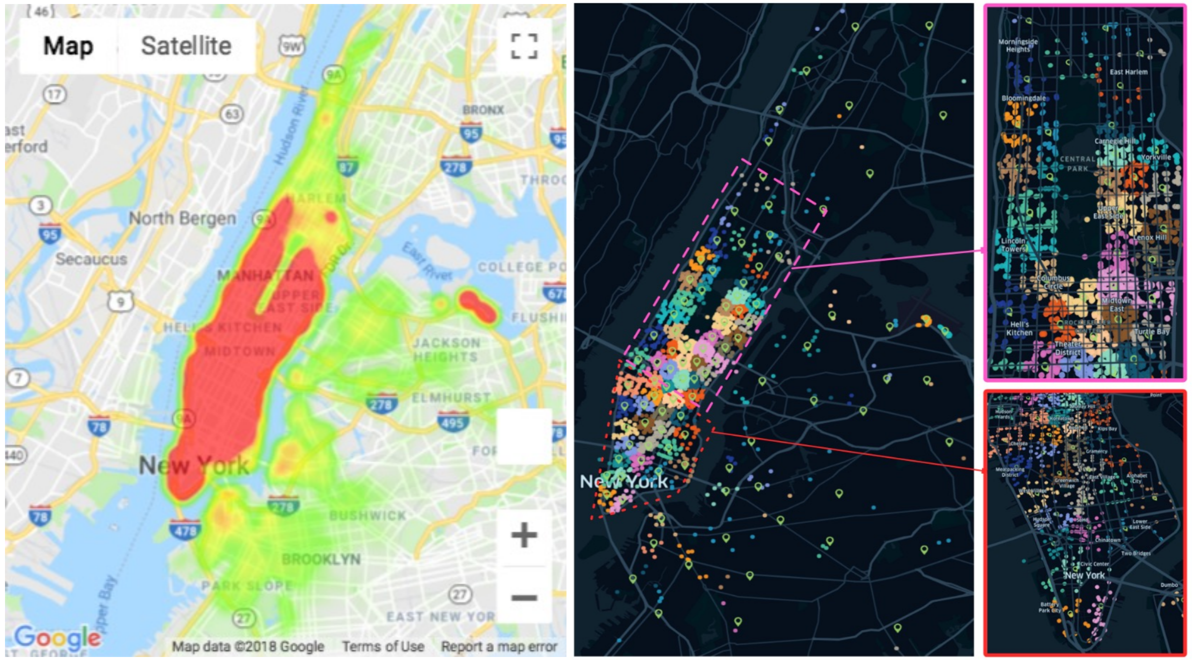


*H. Zhang, C. J. R. Sheppard, T. E. Lipman, and S. J. Moura, "Joint Fleet Sizing and Charging System Planning for Autonomous Electric Vehicles," **IEEE Transactions on Intelligent Transportation Systems**, vol. 21, no. 11, pp. 4725-4738, November 2020. DOI: 10.1109/TITS.2019.2946152

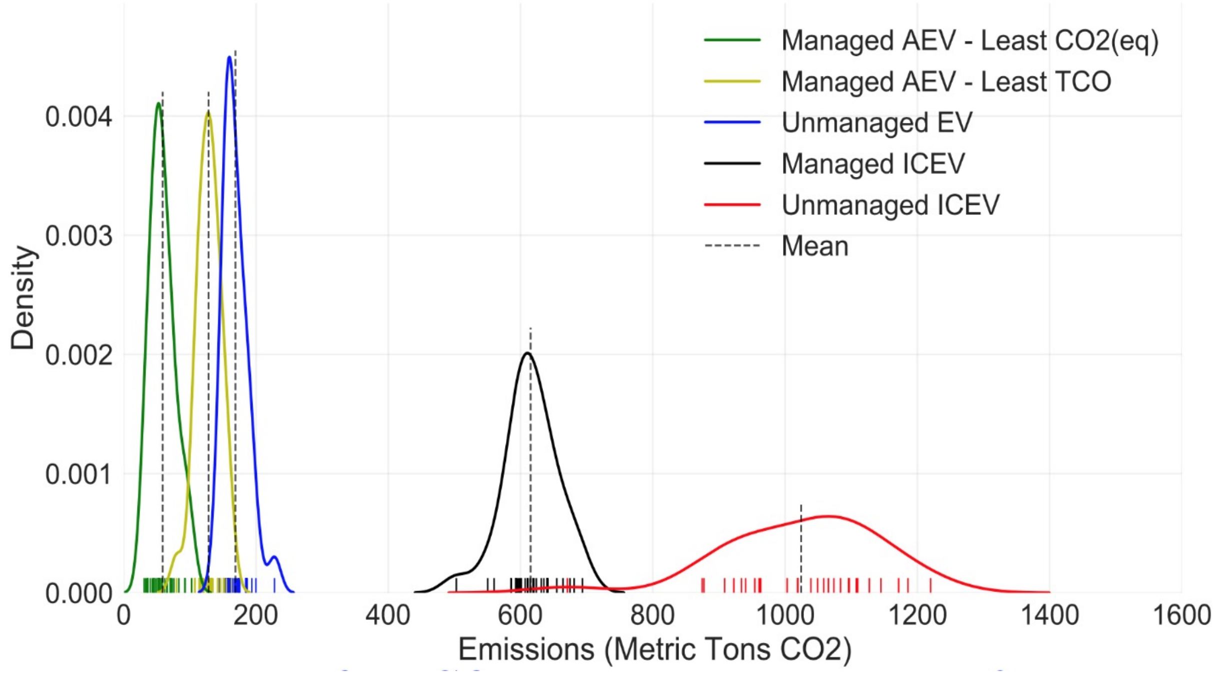
H. Zhang, Z. Hu, and Y. Song, "Power and Transport Nexus: Routing Electric Vehicles to Promote Renewable Power Integration," **IEEE Transactions on Smart Grid, vol. 11, no. 4, pp. 3291-3301, July 2020. DOI: 10.1109/TSG.2020.2967082

Experiments & insights on ride-hailing service in New York City

- Automation leads to 45% VMT reduction, and 45% reduction on CO_2 and PM2.5 emissions (managed ICEV vs unmanaged ICEV)
- Electrification leads to 84% reduction on CO_2 (EV vs ICEV)
- Electrification and automation save over 90% CO_2 emissions (AEV vs ICEV)



Carbon emissions comparing managed or unmanaged AEV and ICEV



Carbon emissions comparing managed or unmanaged AEV and ICEV

*T. Zeng, **H. Zhang**, S. J. Moura, and Z. M. Shen, "Economic and Environmental Benefits of Automated Electric Vehicle Ride-Hailing Services in New York City," **Scientific Reports**, vol. 14, p. 4180, 2024. DOI: 10.1038/s41598-024-54495-x

With vehicle-to-grid technology, EVs can provide services to power grid

- EVs, as **mobile energy storage systems**, can provide **spatiotemporal emergency power supply** to enhance **urban power system resilience** during extreme events

Battery capacities across EV types

Small

Private (50-100kWh)

Taxi (50-100kWh)

≈ **One month's** electricity consumption **for a person**

Medium

Truck (130-180kWh)

Bus (120-300kWh)

≈ **Two weeks'** electricity consumption **for a family**

Large

Dumper Truck (≥300kWh)

Emergency (≥300kWh)

≈ **One week's** electricity consumption **for a six-story apartment**

EV-powered emergency power supply

- **California Wildfire (2025):** Tesla deployed Cybertrucks & mobile Powerwalls to **restore communication base stations**

- **Changsha Flood (2024):** EVs supported flood-affected grid recovery by **powering repair equipment**

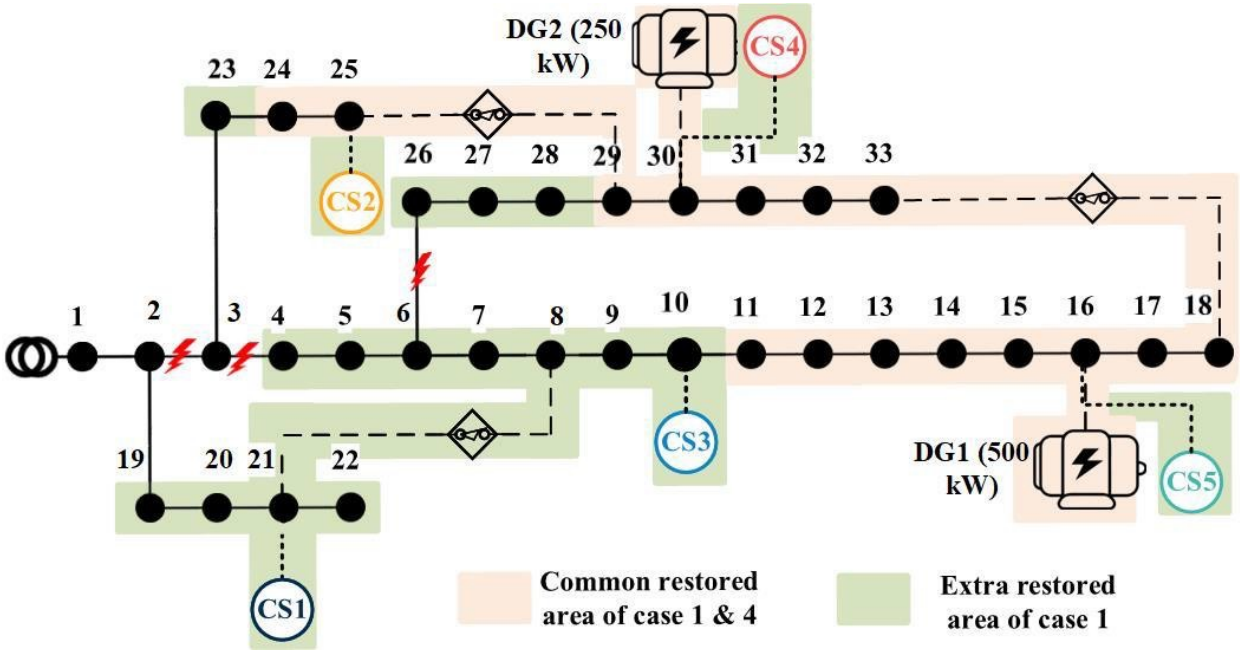
- **Hainan Typhoons (2024):** EVs contributed to **hospital load restoration** during power outage periods

*L. Kong, **H. Zhang**, D. Xie, and N. Dai, "Leveraging Electric Vehicles to Enhance Resilience of Interconnected Power-Transportation System Under Natural Hazards," **IEEE Transactions on Transportation Electrification**, vol. 11, no. 1, pp. 1126-1140, 2025. DOI: 10.1109/TTE.2024.3400289

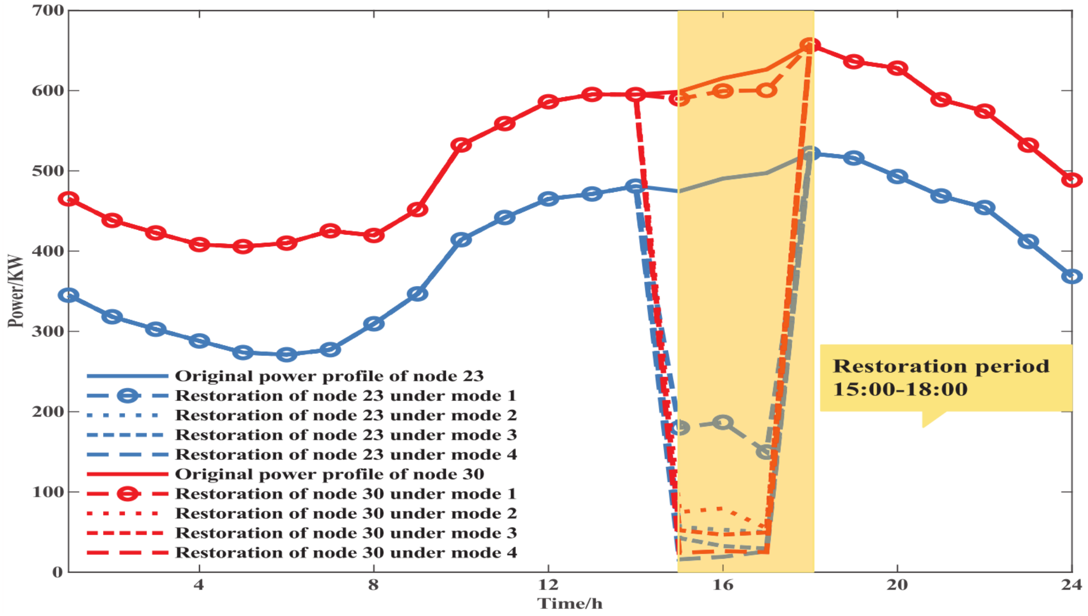
** L. Kong, **H. Zhang**, W. Li, H. Bai, and N. Dai, "Spatial-temporal Scheduling of Electric Bus Fleet in Power-Transportation Coupled Network," **IEEE Transactions on Transportation Electrification**, vol. 9, no. 2, pp. 2969-2982, 2023. DOI: 10.1109/TTE.2022.3214335

With vehicle-to-grid technology, EVs can provide services to power grid

- Utilizing autonomous EVs can significantly increase the restored area and restored power supply after hazards



Restored power network topology under case 1 (proposed) and 4 (without EVs)



Total supplied power profiles at buses 23 and 30 under different cases

*L. Kong, **H. Zhang**, D. Xie, and N. Dai, “Leveraging Electric Vehicles to Enhance Resilience of Interconnected Power-Transportation System Under Natural Hazards,” **IEEE Transactions on Transportation Electrification**, vol. 11, no. 1, pp. 1126-1140, 2025. DOI: 10.1109/TTE.2024.3400289

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Research Problems on EVs/AEVs

Grid-integration

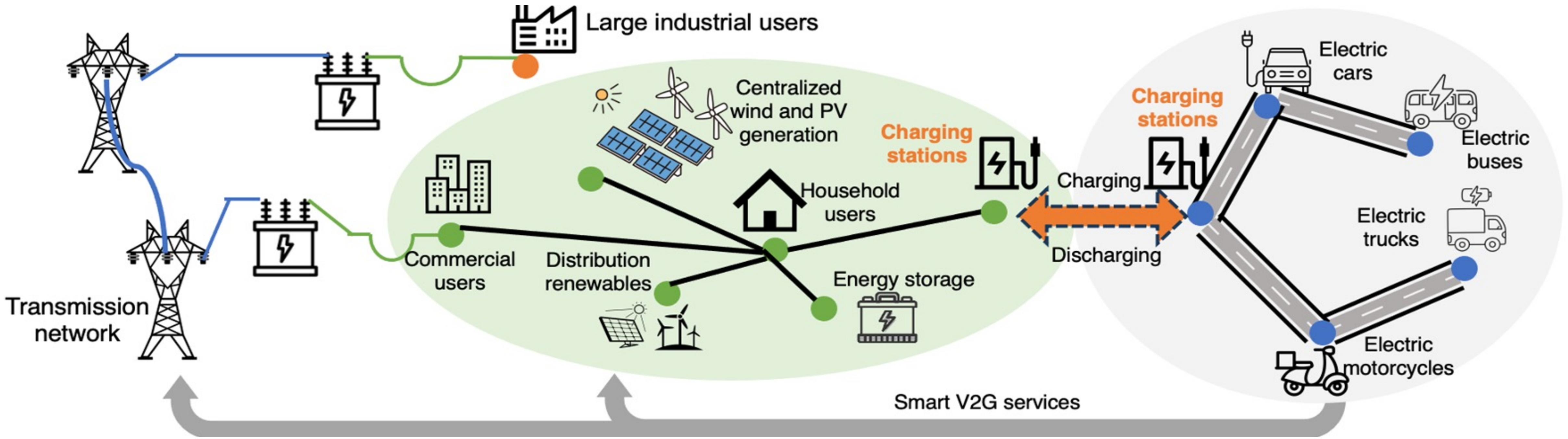
Modeling, operation & control of EVs/AEVs for power grid services

Power-transport nexus

Routing & pricing strategies for power & transport synergy

Infrastructure planning

Fleet sizing and charging systems siting & sizing



*H. Zhang, X. Hu, Z. Hu, and S. J. Moura, "Sustainable plug-in electric vehicle integration into power systems," **Nature Reviews Electrical Engineering**, vol. 1, pp. 35-52, 2024. DOI: 10.1038/s44287-023-00004-7 (Invited, cover page paper)

Content

Methodology: Markov Decision Process & Dynamic Programming

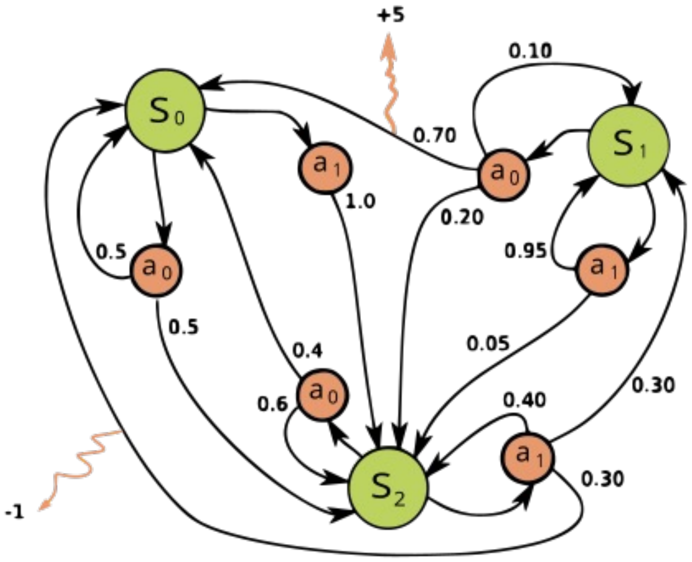
- Belleman Equation (optimality condition) for Markov Decision Process
  - Optimal decision today = best immediate payoff + best future payoff

$$U(s) = R(s) + \gamma \max_{a \in A(s)} \sum_{s'} P(s'|s,a) U(s')$$

Utility of one of the next states, s’

Choose the best action a that maximizes future expected reward

Expected future utility when takes action a at current state s



Markov Decision Process

- Optimal policy solved by classical dynamic programming
  - Can make optimal decisions when $P(s'|s,a)$ & $U(s)$ are given

$$\pi^*(s) = \operatorname*{argmax}_{a \in A(s)} \sum_{s'} P(s'|s,a) U(s')$$

Methodology: Markov Decision Process & Dynamic Programming

- Belleman Equation (optimality condition) for Markov Decision Process

$$U(s) = R(s) + \gamma \max_{a \in A(s)} \sum_{s'} P(s'|s,a)U(s')$$

- Optimal policy

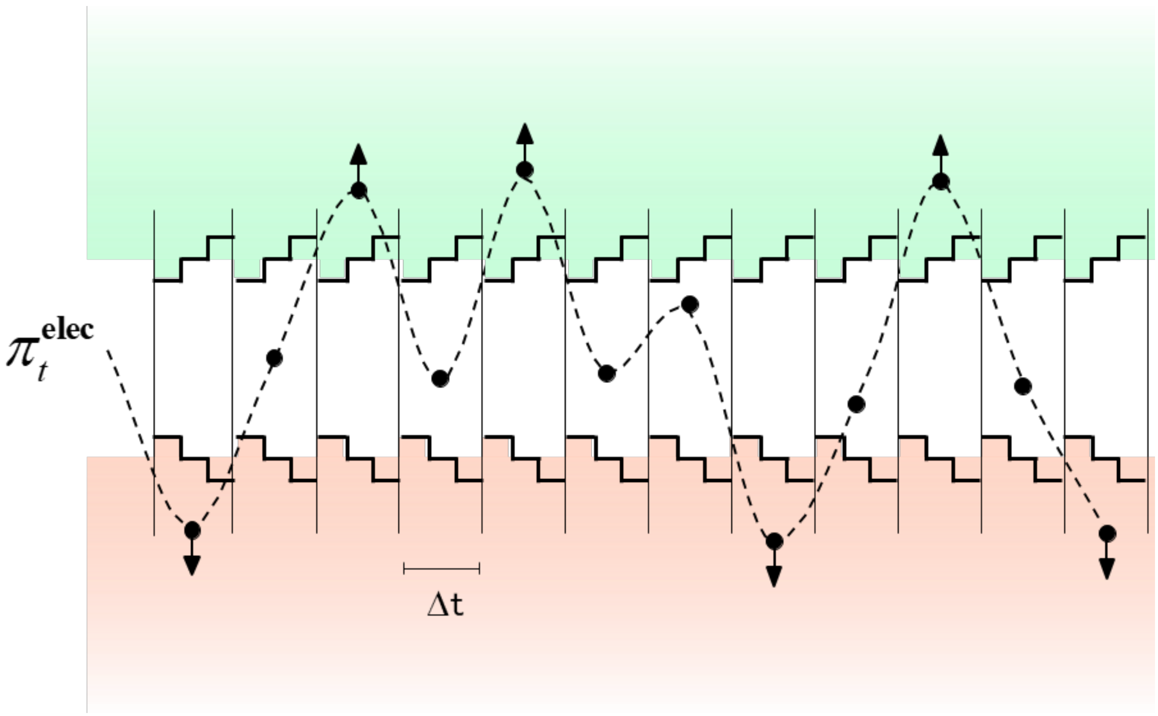
$$\pi^*(s) = \underset{a \in A(s)}{\operatorname{argmax}} \sum_{s'} P(s'|s,a)U(s')$$

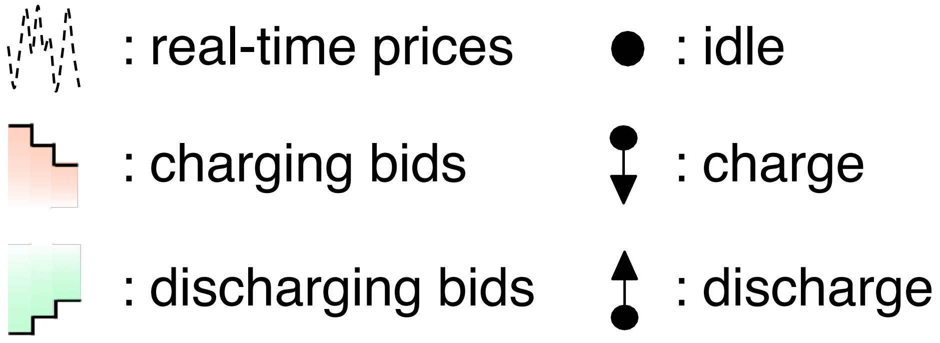
Method	Model availability	Methodology	Application scenario
Dynamic Programming	Known	Classical optimization	Simple problem with tabular state space
Approximate Dynamic P.	Partially unknown or very large	Approximate based on real data or simulation	Large-scale stochastic problem
Reinforcement Learning	Model unknown	Approximate from interactive sampling (trial & error)	Super complex real-world problem with unknown dynamics

Content

Economic bidding of aggregated EVs in power markets

- Economic viability of V2G depends on electricity price fluctuations
  - During low-price periods, EVs charge from the grid
  - During high-price periods, EVs discharge to the grid
  - Otherwise, EVs stay idle





Challenges:
- **Price-threshold:** It is nontrivial to define “low” vs. “high” prices, i.e., profitable action threshold
- **Uncertainty:** real-time prices are highly volatile and uncertain, making arbitrage decisions risky

*Z. Zhu, **H. Zhang** and Y. Song, “Economic Bidding Strategy of Electric Vehicles in Real-Time Electricity Markets based on Marginal Opportunity Value,” submitted to **IEEE Transactions on Transportation Electrification**, 2025. (major revision, arXiv: https://arxiv.org/abs/2510.00744).

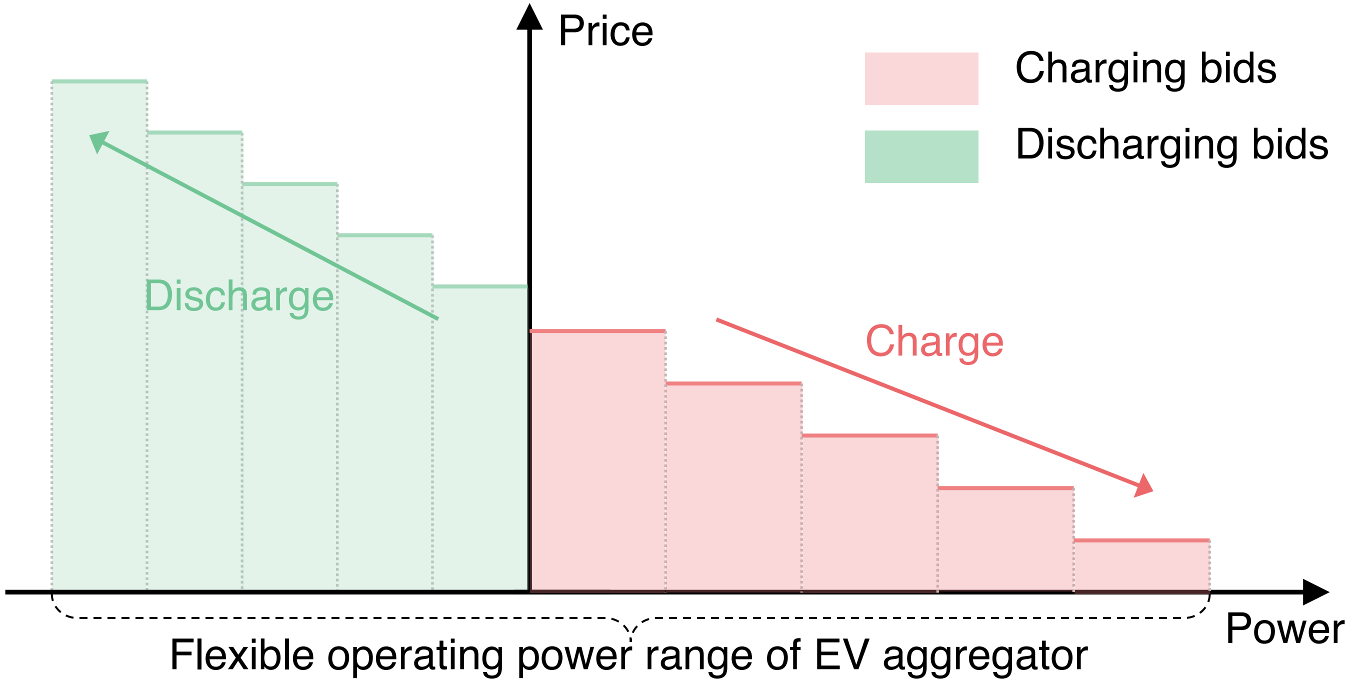
Economic bidding of aggregated EVs in power markets

- Economic bids of an EV aggregator (two-sided):
  - Charging (as a controllable load): monotonically decreasing demand curves
  - Discharging (as a distributed generator): monotonically increasing supply curves

Bidding options:

➢ Self-schedule bids (Price-accepting bids)
  - ➢ Bids fixed MW/MWh
  - ➢ Easy to implement
  - ➢ Limited profitability

➢ Economic bids (Price-making bids):
  - ➢ Bids $/MWh
  - ➢ Difficult to implement
  - ➢ Enhanced revenue



Illustrative example of EV aggregator economic bidding

*Z. Zhu, **H. Zhang** and Y. Song, "Economic Bidding Strategy of Electric Vehicles in Real-Time Electricity Markets based on Marginal Opportunity Value," submitted to **IEEE Transactions on Transportation Electrification**, 2025. (major revision, arXiv: https://arxiv.org/abs/2510.00744).

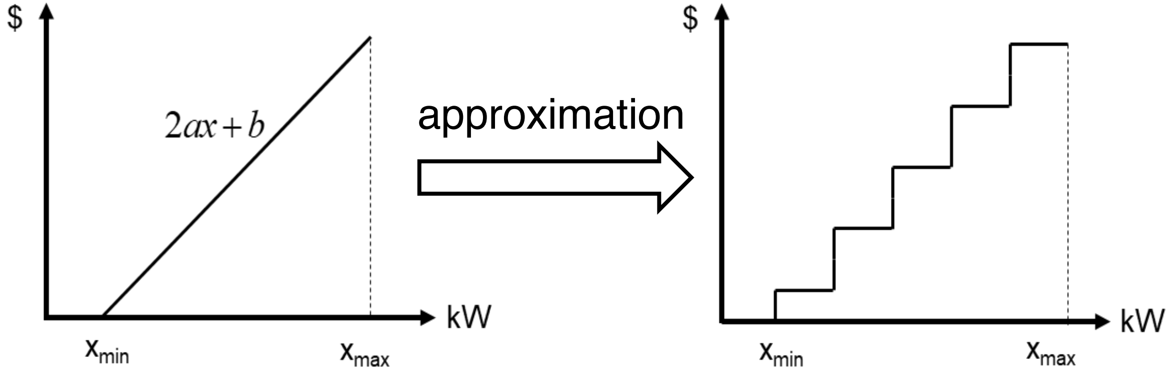
Economic bidding of aggregated EVs in power markets

- Price-quantity pairs in economic bids reflect participant's marginal cost or value

Thermal Power Plant	EV Aggregator

Thermal Power Plant

- Physical cost function: $ax^2 + bx + c$
- Marginal cost function: $2ax + b$



EV Aggregator

charging:
- Opportunity value function: $V(e_t)$
- Marginal value function: $v(e_t)\eta$

dis-charging:
- Opportunity cost function: $V(e_t)$
- Physical cost function: $\pi^{\mathbf{deg}} p_t^{\mathbf{d}}$
- Marginal cost function: $\pi^{\mathbf{deg}} + v(e_t)/\eta$

$V(e_t)$: **opportunity value of stored energy**
$v(e_t)$: **marginal opportunity value of stored energy**

Features:
- Explicit and time-invariant cost functions
- Determined by physical characteristics
- Bids only in one direction—as suppliers

Features:
- Implicit and inter-temporal opportunity costs
- Affected by uncertain prices & EV availability
- Bids as both generator and load

*Z. Zhu, **H. Zhang** and Y. Song, "Economic Bidding Strategy of Electric Vehicles in Real-Time Electricity Markets based on Marginal Opportunity Value," submitted to **IEEE Transactions on Transportation Electrification**, 2025. (major revision, arXiv: https://arxiv.org/abs/2510.00744).

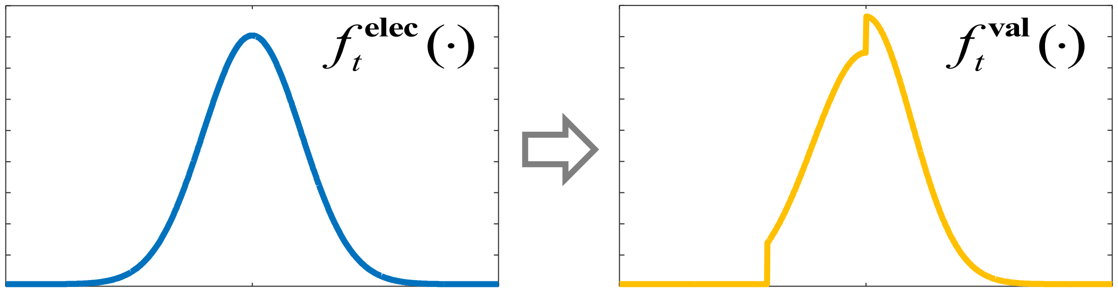
Economic bidding of aggregated EVs in power markets

- **Key idea:** Link EVs' opportunity value to its MDP's value function, & then derive its closed-form probability distribution

Bellman's equation:

$$V_t(e_t) = \max_{a_t \in \Omega} \left\{ r_t(s_t, a_t) + \mathbb{E}_{\pi_{t+1}^{\text{elec}}} \left[V_{t+1}(e_{t+1}) \right] \right\}$$

Trade-off: immediate economic gains and the preservation of flexibility for future opportunities



PDF of real-time electricity prices

PDF of marginal opportunity value

Real-time electricity prices are modeled as stage-wise stochastic variables following PDF $\pi \sim f_P$

Notes: MDP=Markov decision process; PDF = probability distribution function

a) Marginal value as a function of action $v = g(a)$

b) Optimal action as a piecewise function of price

$$a^*(\pi) = \begin{cases} y_1(\pi), & \pi \in (\alpha_1, \beta_1], \\ \vdots & \vdots \\ y_n(\pi), & \pi \in (\alpha_n, \beta_n]. \end{cases}$$

c) Marginal value as a piecewise function of price

$$v = g\left(a^*(\pi)\right) = h(\pi) = \begin{cases} h_1(\pi), & \pi \in (\alpha_1, \beta_1], \\ \vdots & \vdots \\ h_n(\pi), & \pi \in (\alpha_n, \beta_n], \end{cases}$$

d) Distribution transfer

$$f_V(x) = \begin{cases} f_P\left(h_1^{-1}(x)\right)\left|\frac{d}{dx} h_1^{-1}(x)\right|, & x \in (h_1(\alpha_1), h_1(\beta_1)], \\ \vdots & \vdots \\ f_P\left(h_n^{-1}(x)\right)\left|\frac{d}{dx} h_n^{-1}(x)\right|, & x \in (h_n(\alpha_n), h_n(\beta_n)]. \end{cases}$$

*Z. Zhu, **H. Zhang** and Y. Song, "Economic Bidding Strategy of Electric Vehicles in Real-Time Electricity Markets based on Marginal Opportunity Value," submitted to **IEEE Transactions on Transportation Electrification**, 2025. (major revision, arXiv: https://arxiv.org/abs/2510.00744).

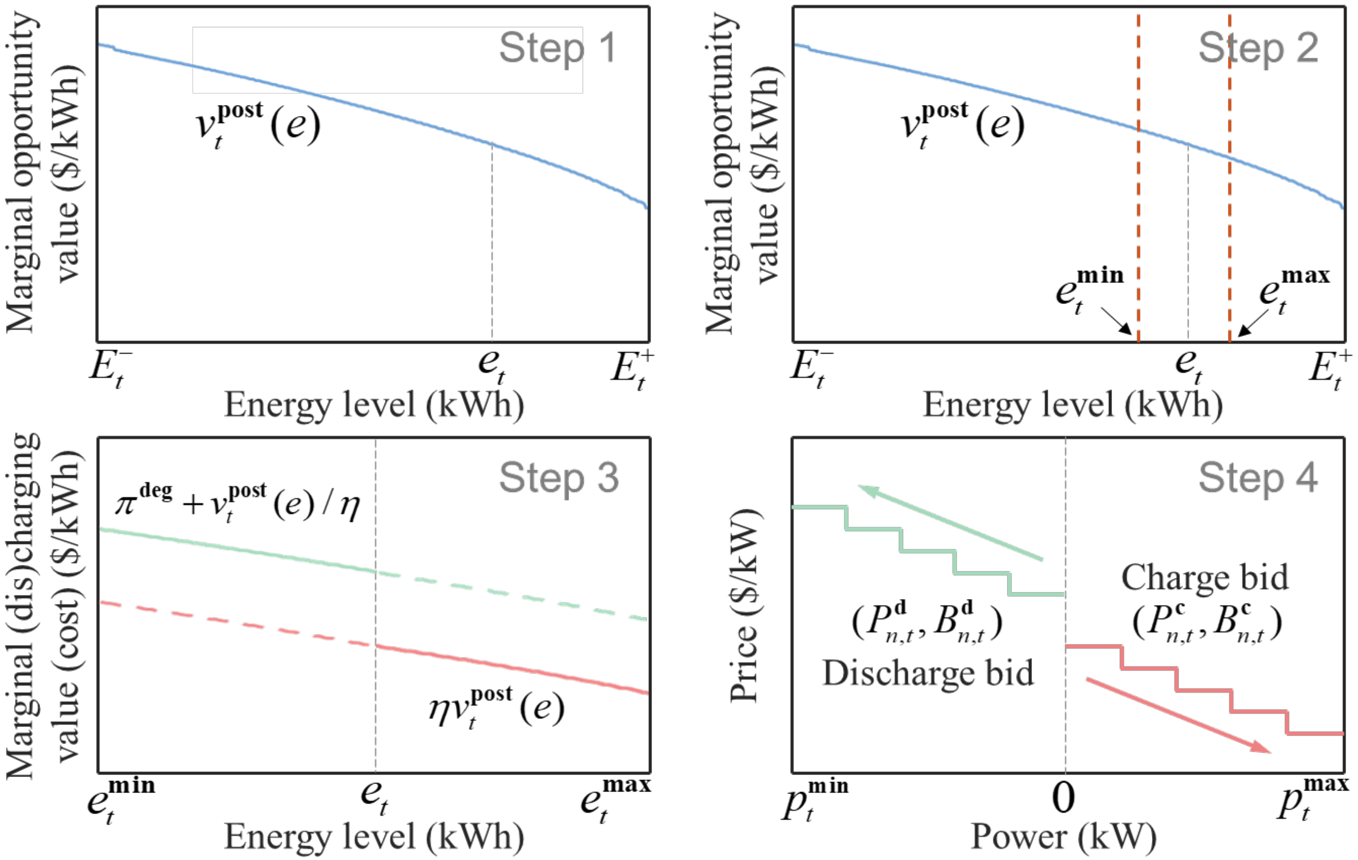
Economic bidding of aggregated EVs in power markets

Expectation Marginal Opportunity Value

$$\mathbb{E}[v_t(e)] = \int_{-\infty}^{\infty} x\Pr[v_t(e) = x]dx$$

Risk-Averse Marginal Opportunity Value

$$\rho[v_t(e)] = (1-\lambda)\int_{-\infty}^{\infty} x\mathbf{Pr}[v_t(e) = x]dx + \frac{\lambda}{1-\alpha}\int_{-\infty}^{\mathrm{VaR}_\alpha} x\mathbf{Pr}[v_t(e) = x]dx$$



Market-Compliant Bid Construction

Step 1:

Evaluate marginal opportunity values under risk-neutral or risk-averse preferences

Step 2:

Identify feasible energy range

Step 3:

Map to marginal charging value and marginal discharging cost

Step 4:

Generate stepwise bid curves

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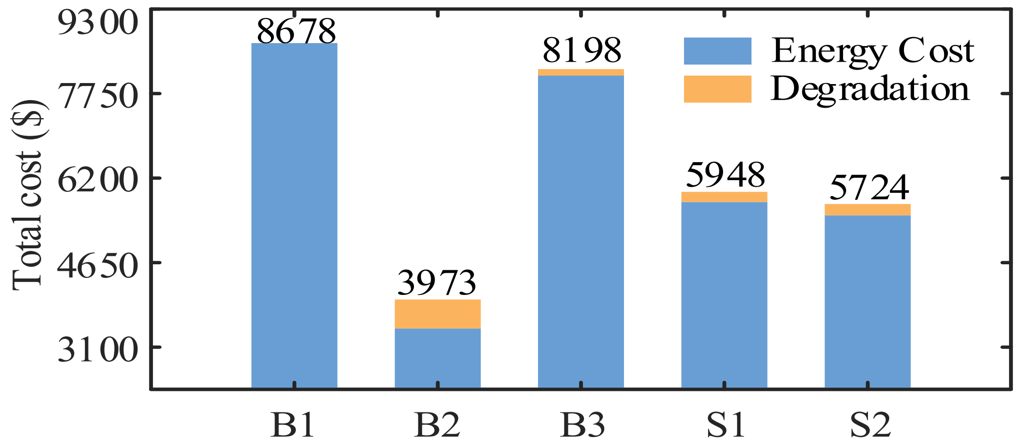
Economic bidding of aggregated EVs in power markets

- **Scenario**
  - New York ISO real-time market
- **Dataset**
  - 10,040 real EV charging records from Macau (March 2021, 5-minute resolution)
  - NYISO 2018 real-time electricity prices (5-min resolution)
- **Benchmarks**
  - B1: uncoordinated charging
  - B2: perfect foresight
  - B3: day-ahead baseline
- **Proposed strategy**
  - S1&S2: risk-neutral bidding strategy with different uncertainty modeling
  - S3: risk-averse bidding strategy

Economic performance (risk-neutral)



	Energy cost ($)	Degradation cost ($)	Total cost ($)
B1	8677.83	0	8677.83
B2	3442.86	530.41	3973.27
B3	8082.32	115.94	8198.26
S1	5763.21	184.76	5947.97
S2	5517.07	207.7	5724.77

Proposed strategy realizes 31.5% cost reduction compared to the uncoordinated baseline

*Z. Zhu, **H. Zhang** and Y. Song, "Economic Bidding Strategy of Electric Vehicles in Real-Time Electricity Markets based on Marginal Opportunity Value," submitted to **IEEE Transactions on Transportation Electrification**, 2025. (major revision, arXiv: https://arxiv.org/abs/2510.00744).

Economic bidding of aggregated EVs in power markets

- Comparative analysis of risk-neutral & risk-averse bidding strategies

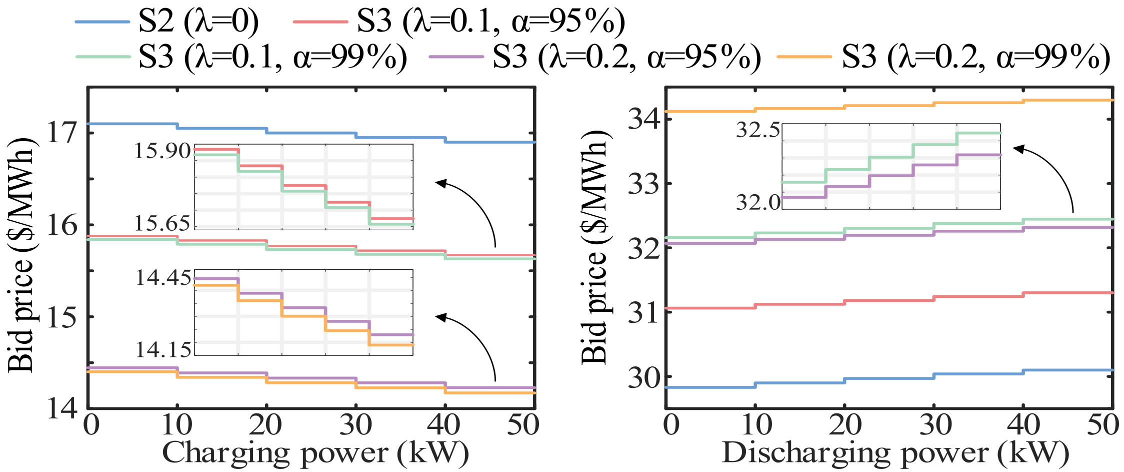
Cost comparison under different risk settings

	λ	α	Energy cost ($)	Degradation cost ($)	Total cost ($)	CPU time (s)
S2	0	-	5517.02	207.70	5724.71	462
S3	0.1	95%	5636.04	145.00	5781.04	1709
	0.1	99%	5652.89	139.58	5792.47	
	0.2	95%	5821.15	106.92	5928.07	
	0.2	99%	5840.88	99.44	5940.32	

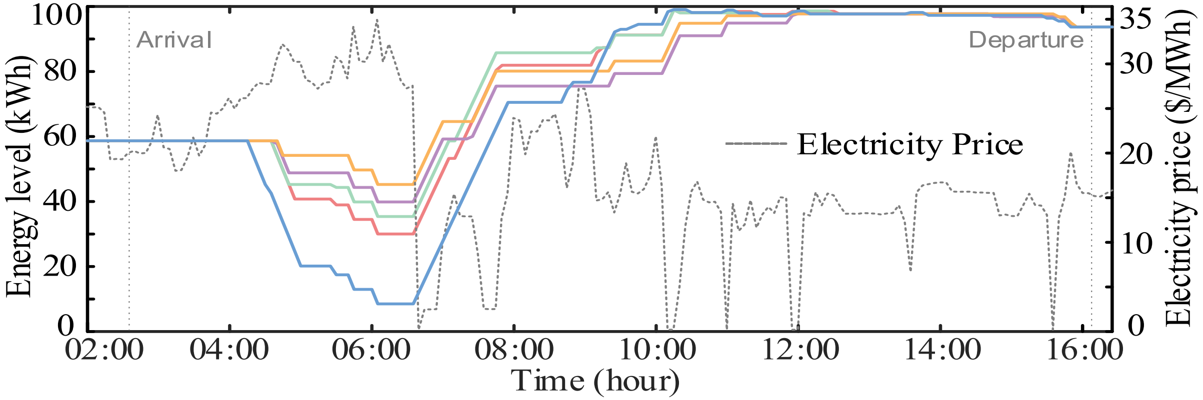
As EVs adopt lower risk preference:

- higher total costs, reduced degradation
- lower charging bid prices
- higher discharging bid prices
- smoother EV charging profile

Make more conservative decisions to mitigate financial risks!



Charge bids of EVA at t=1 **Discharge bids of EVA at t=1**



Energy trajectories for one EV and electricity price

*Z. Zhu, **H. Zhang** and Y. Song, "Economic Bidding Strategy of Electric Vehicles in Real-Time Electricity Markets based on Marginal Opportunity Value," submitted to **IEEE Transactions on Transportation Electrification**, 2025. (major revision, arXiv: https://arxiv.org/abs/2510.00744).

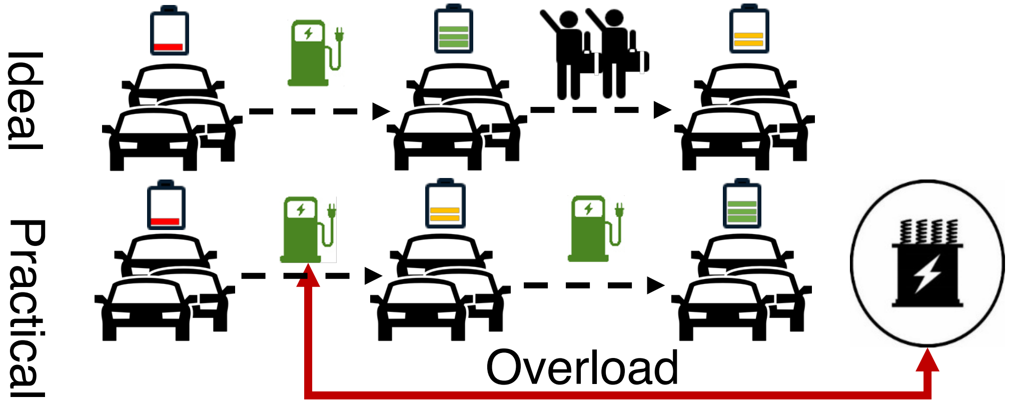
Content

- Methodology preliminaries
- Online economic V2G bidding of aggregated EVs in power markets
- Online operation of electric autonomous mobility-on-demand system subject to power constraints
- Summary

Real-time Operation of Electric Autonomous Mobility-on-Demand System

- Electric autonomous mobility-on-demand (EAMoD) systems are emerging all over the world
- Unregulated EAMoD system may lead to negative impact on power system
- Challenges of EAMoD and power system coordination
  - Computational burden in large-scale fleet dispatch
  - Real-time operation with uncertain trip requests

Global EAMoD companies

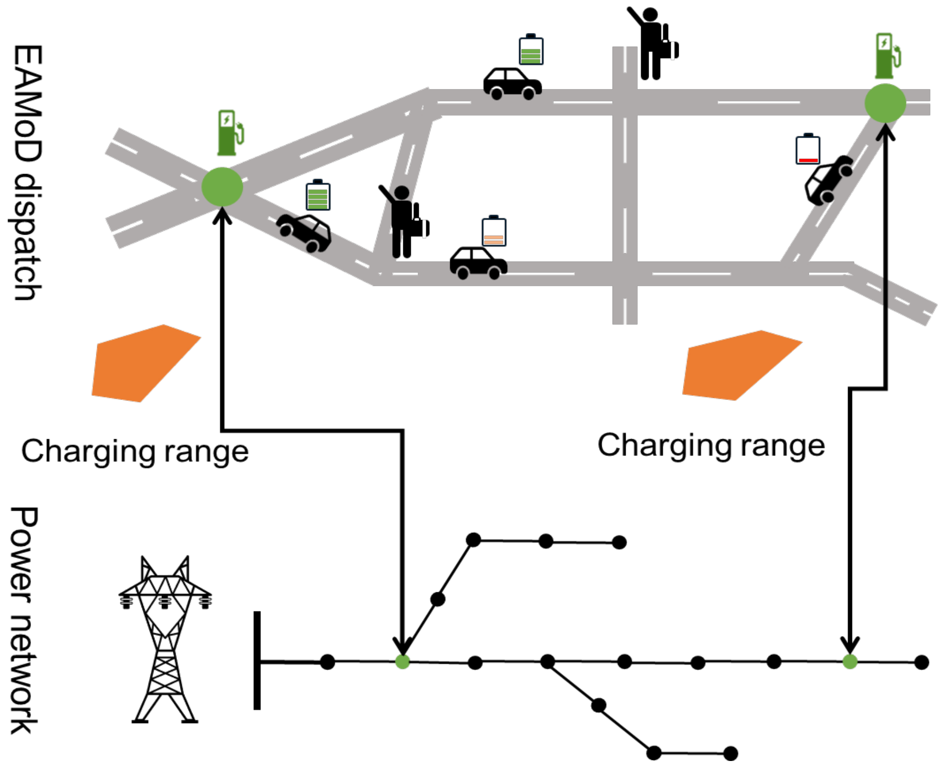


Waymo depot in San Francisco & Unregulated charging leads to overload

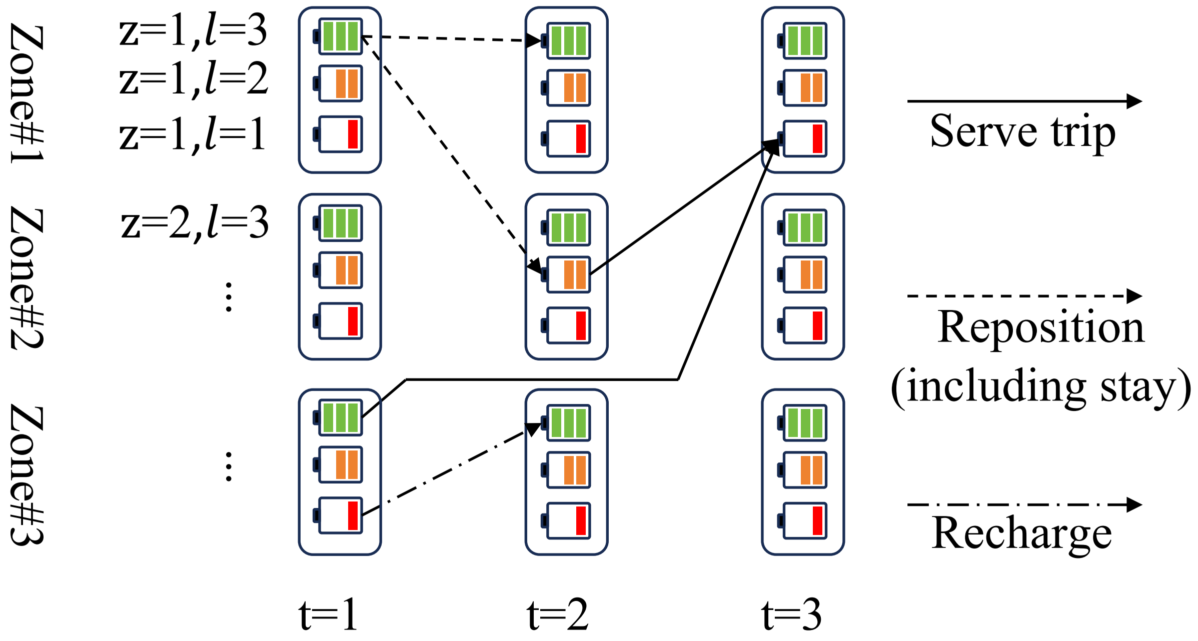
Real-time Operation of Electric Autonomous Mobility-on-Demand System

- **Problem statement:** EAMoD system makes decision (serve trips, reposition, recharge) considering vehicle driving range constraints, & power grid regulations
- **Modelling framework:** Adopt fleet-based model for urban-scale scenarios

Model framework



EAMoD fleet model

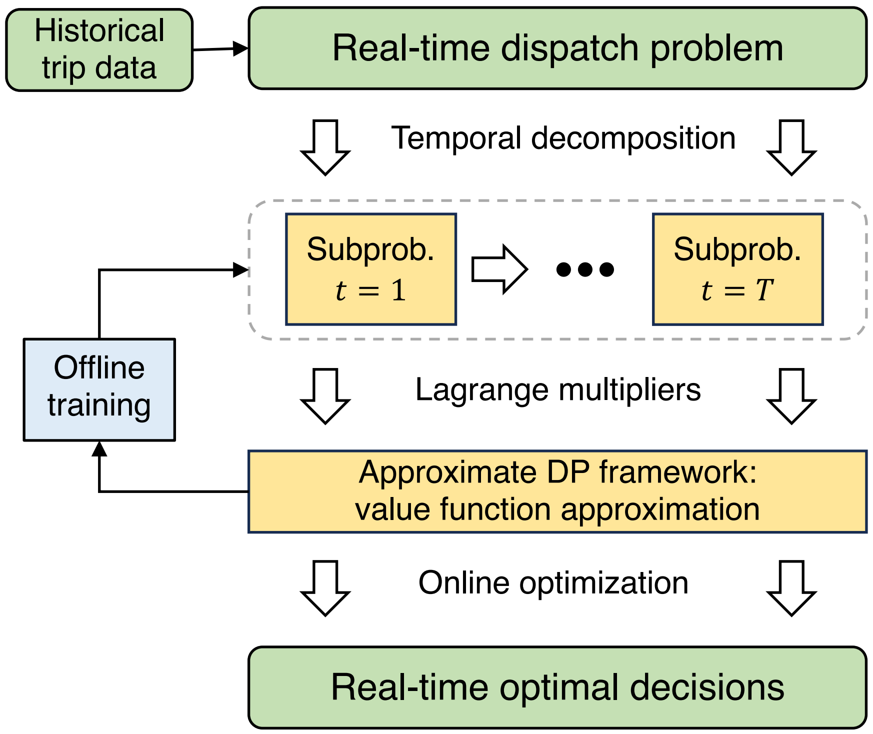


*L. Pan, **H. Zhang**, “Real-time Operation of Electric Autonomous Mobility-on-Demand System Considering Power System Regulation,” **IEEE Transactions on Smart Grid**, 2026.
DOI: 10.1109/TSG.2025.3649840

Real-time Operation of Electric Autonomous Mobility-on-Demand System

- **Key method:** Approximate dynamic programming to address real-time dispatch problem
- Approximated value function can depict the future value of current decisions

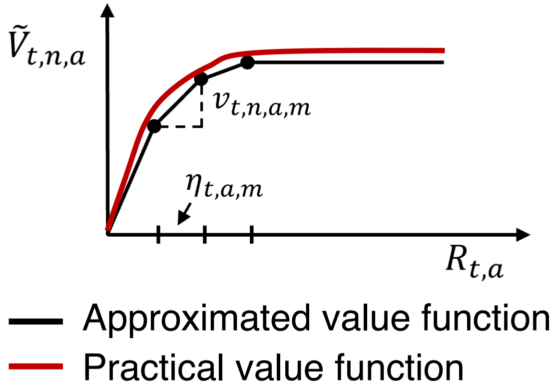
Algorithm framework



ADP: approximate dynamic programming

Single-period subproblem

- Objective function
  - $\max \boldsymbol{r}_t^T \boldsymbol{x}_t + \sum_\tau \tilde{V}_{t+\tau,n,a}(R_{t+\tau})$ — Current revenue; Future value
- Constraints
  - Traffic flow conservation: Lagrange multipliers
  - Charging range
  - Transition function
    - $R_{t+1} = R'_{t+1} + R''_{t+1},\ R'_{t+1} = \Delta \boldsymbol{x}_t$
  - Value function
    - $\tilde{V}_{t,n,a} = \sum_m v_{t,n,a,m} \eta_{t,a,m}$
    - $\sum_m \eta_{t,a,m} = R_{t,a}$
  - Reward
    - $r = \begin{cases} \text{taxi fare, if } x \text{ is serving trips} \\ 0, \text{if } x \text{ is reposition} \\ -\text{charge fare, if } x \text{ is charging} \end{cases}$



*L. Pan, **H. Zhang**, "Real-time Operation of Electric Autonomous Mobility-on-Demand System Considering Power System Regulation," **IEEE Transactions on Smart Grid**, 2026.
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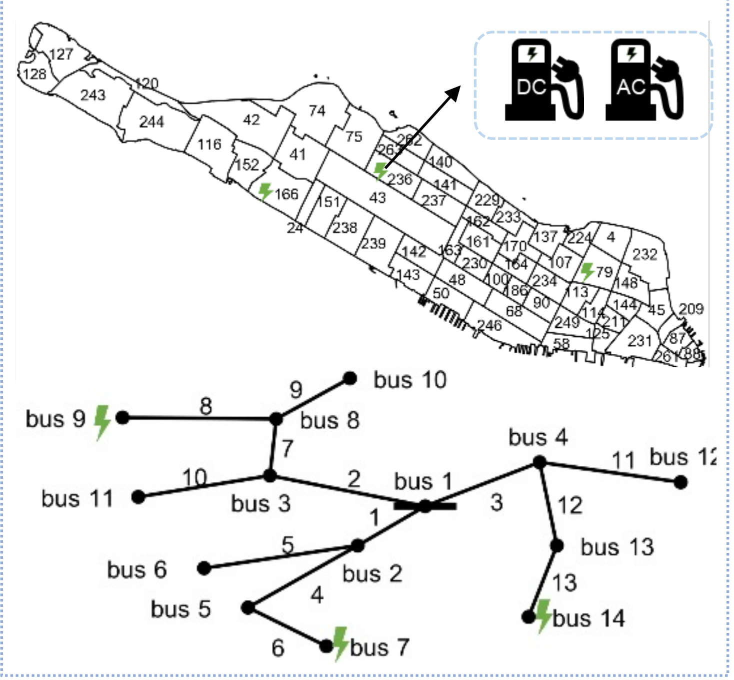
Real-time Operation of Electric Autonomous Mobility-on-Demand System

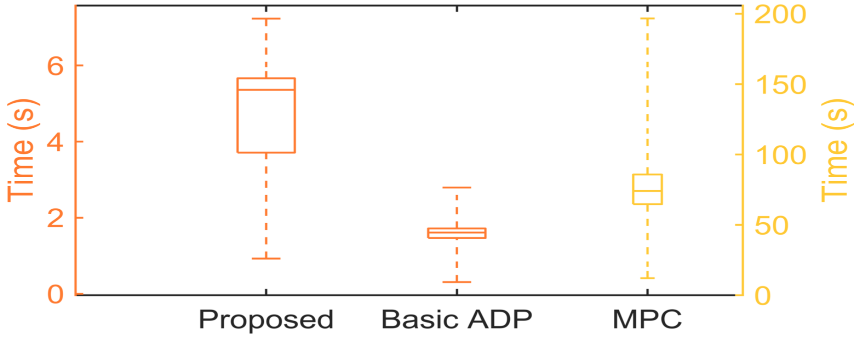
- **Case study:** Manhattan transportation network and 14-node power network
- **Key results:** Proposed method finds near-optimal solution (7.9% gap) with high computational efficiency (~5 s per decision), showing potential in large-scale real-time coordination

Case study configuration

Case setting	Value
Traffic zone	60
Power node	14
Vehicle scale	600
Battery	40 kWh
Depot	3
Rated power (DC/AC)	60/7.5 kW
Charging fare (DC/AC)	1/0.2 $/kWh
Trip fare	3+2.2 $/km



Algorithm performance



(a) Solution time for one decision (5 mins resolution)

Algorithm	Proposed	Basic ADP	MPC	Ideal
Average profit (k$)	268	239	255	291
Standard deviation (k$)	0.71	1.15	1.62	0.44
Quality of service (%)	92.3	86.4	89.5	-
Average profit per trip ($)	5.40	5.27	5.38	-

(b) Economic performance

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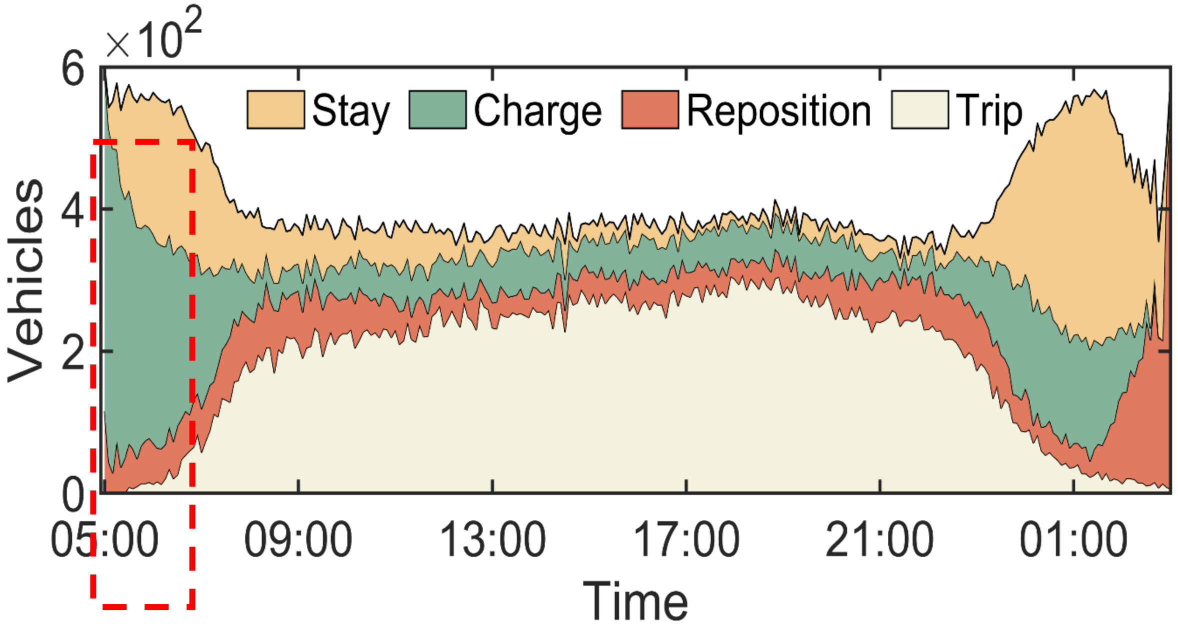
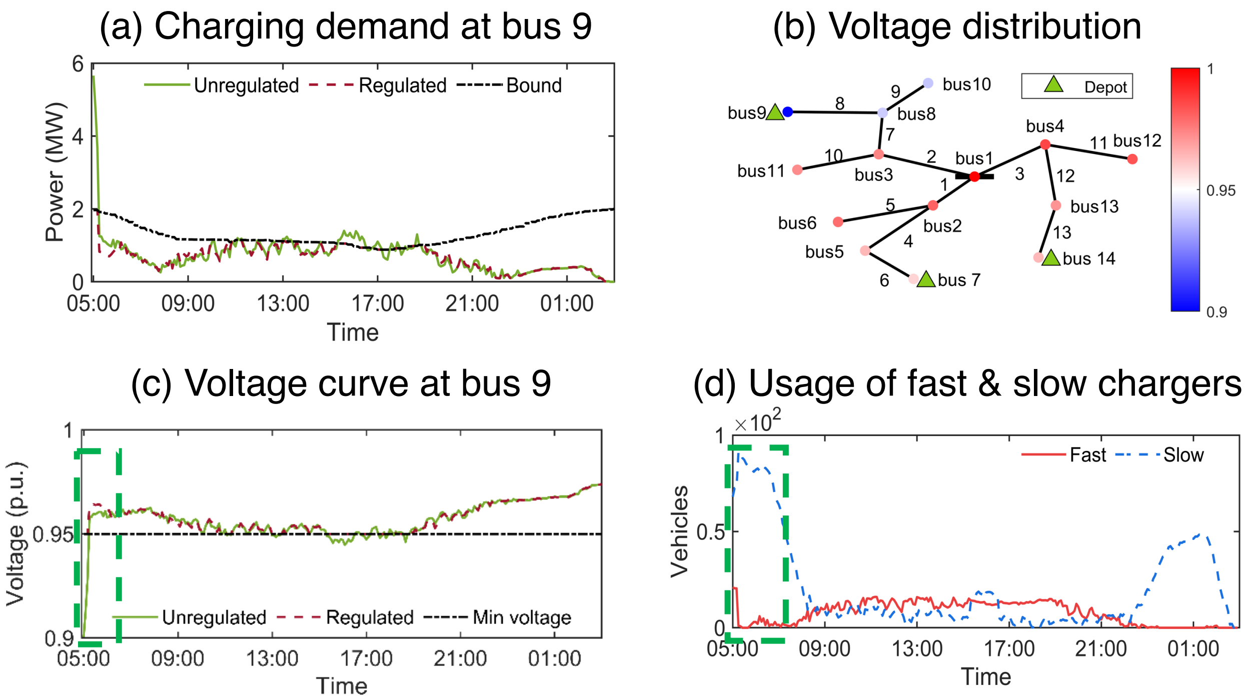
Real-time Operation of Electric Autonomous Mobility-on-Demand System

- Cluster charging behavior occurs in the optimal EAMoD system decisions (without considering power grid constraints), leading to overload
- Synergy between EAMoD and power systems can effectively avoid undervoltage by strategically using fast and slow chargers

Daily AEV behaviors



Impact of AEV charging on power grids



*L. Pan, **H. Zhang**, "Real-time Operation of Electric Autonomous Mobility-on-Demand System Considering Power System Regulation," **IEEE Transactions on Smart Grid**, 2026.
DOI: 10.1109/TSG.2025.3649840

Content

Summary

- EVs are rapidly evolving from passive loads into flexible, mobile energy resources, fundamentally reshaping power system operation
- Autonomous driving further strengthens power-transport synergy
  - Stronger motivation for cleaner and cheaper electricity
  - Enhanced spatiotemporal flexibility with relaxed human-related constraints
- **Market participation of EVs**: Economic bids grounded in the opportunity value of stored battery energy subject to uncertainties from market prices & EV behaviors
- **Autonomous electric mobility system**: Strategically routing autonomous EVs improve power system efficiency, & promote renewables integration

Relevant recent publications

- **H. Zhang**, X. Hu, Z. Hu, and S. J. Moura, “Sustainable plug-in electric vehicle integration into power systems,” **Nature Reviews Electrical Engineering**, vol. 1, pp. 35-52, 2024. DOI: 10.1038/s44287-023-00004-7 (Invited, cover page paper)
- L. Kong, **H. Zhang**, D. Xie, and N. Dai, “Leveraging Electric Vehicles to Enhance Resilience of Interconnected Power-Transportation System Under Natural Hazards,” **IEEE Transactions on Transportation Electrification**, vol. 11, no. 1, pp. 1126-1140, 2025. DOI: 10.1109/TTE.2024.3400289
- Z. Zhu, **H. Zhang** and Y. Song, “Economic Bidding Strategy of Electric Vehicles in Real-Time Electricity Markets based on Marginal Opportunity Value,” submitted to **IEEE Transactions on Transportation Electrification**, 2025. (major revision, arXiv: https://arxiv.org/abs/2510.00744)
- Z. Zhu and **H. Zhang**, "Real-Time Coordinated Operation of Electric Vehicle Fast Charging Stations With Energy Storage: An Efficient Spatiotemporal Decomposition Approach," **IEEE Transactions on Smart Grid**, vol. 16, no. 3, pp. 2464-2477, May 2025. DOI: 10.1109/TSG.2025.3525495
- Z. Zhu, **H. Zhang** and Y. Song, "A Distributed Training and Scheduling Approach for Real-Time Coordination of Electric Vehicle Fast Charging Stations With Energy Storage," **IEEE Transactions on Transportation Electrification**, vol. 11, no. 5, pp. 12197-12209, Oct. 2025. DOI: 10.1109/TTE.2025.3586742
- L. Pan, **H. Zhang**, and Y. Xu, “Optimal Pricing of Electric Vehicle Charging on Coupled Power-Transportation Network based on Generalized Sensitivity Analysis,” **IEEE Transactions on Transportation Electrification**, 2026. DOI: 10.1109/TTE.2026.3654165
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