Large-Scale Adaptive Electric Vehicle Charging

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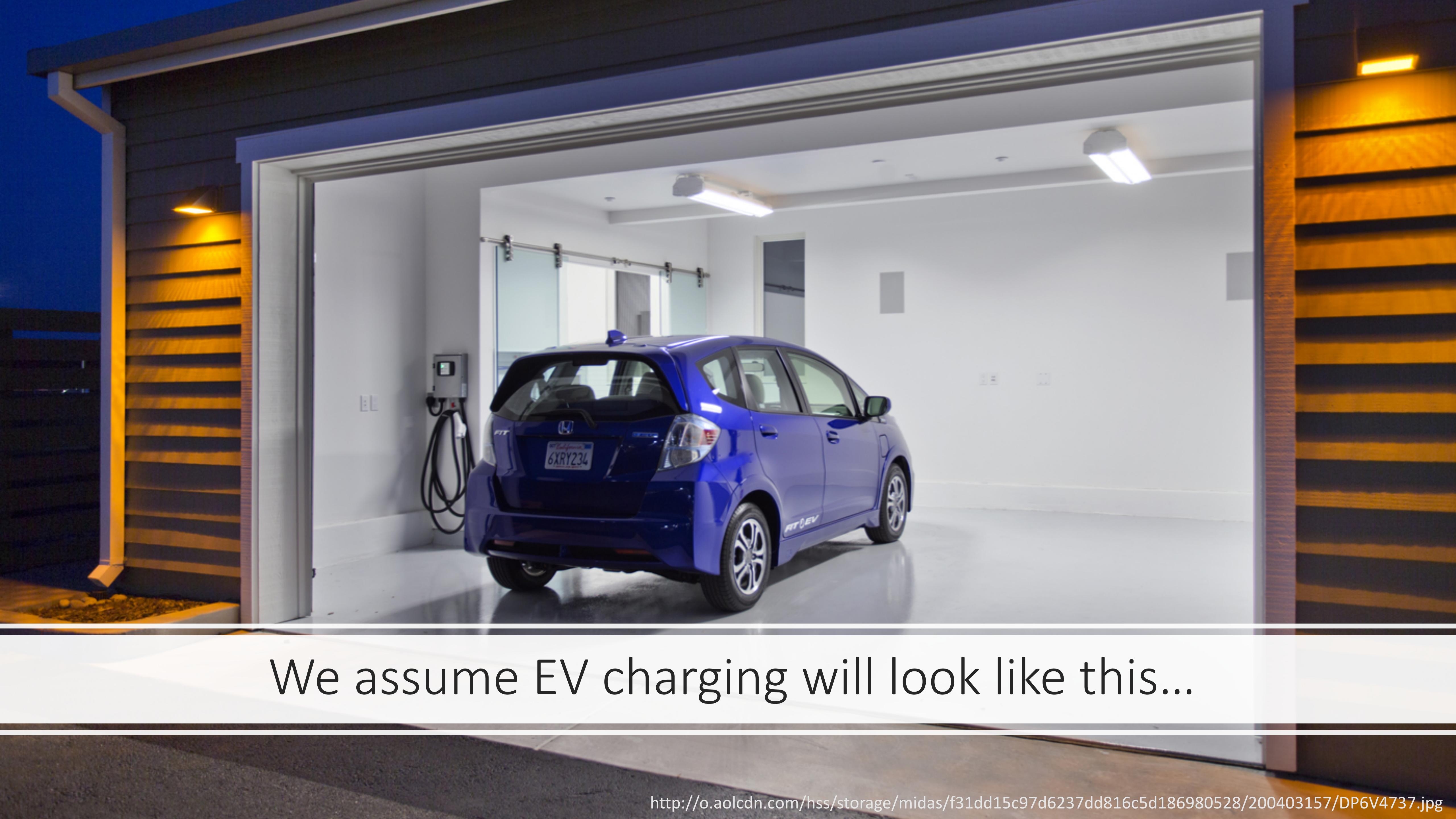
Caltech

I don’t have to convince you EV are coming…

https://i.ytimg.com/vi/tj6B489H_zg/maxresdefault.jpg



We assume EV charging will look like this…

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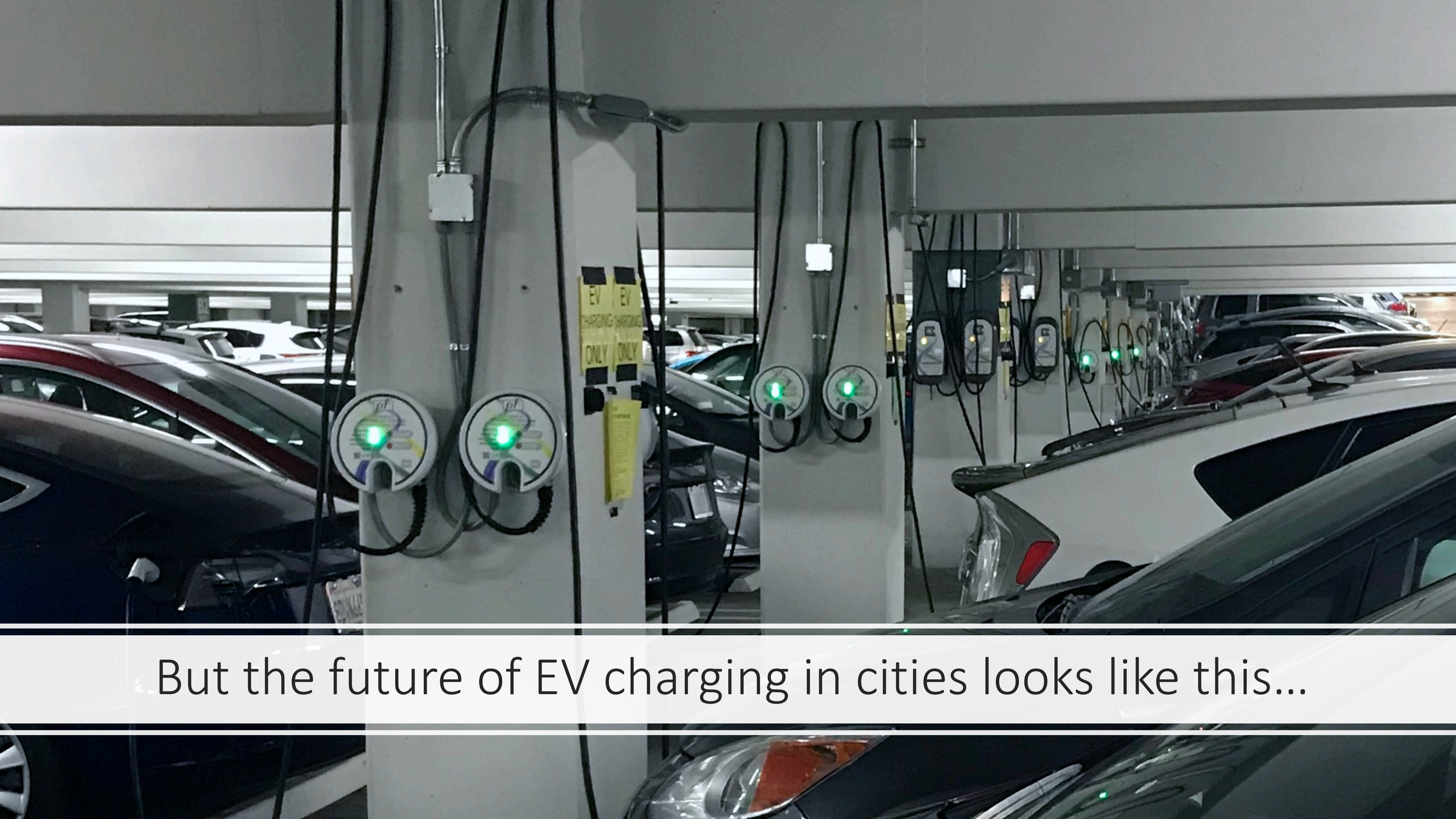
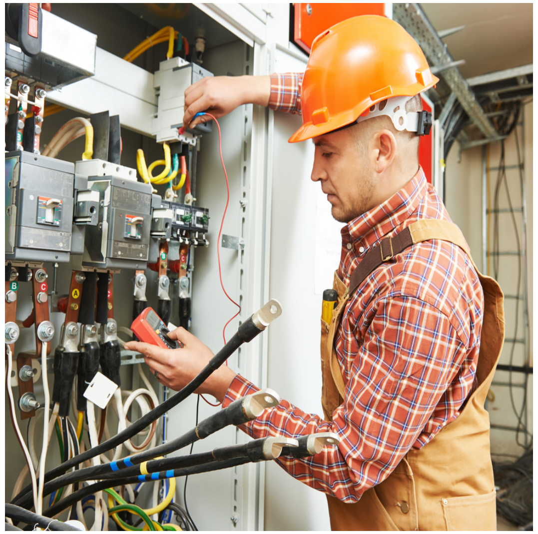
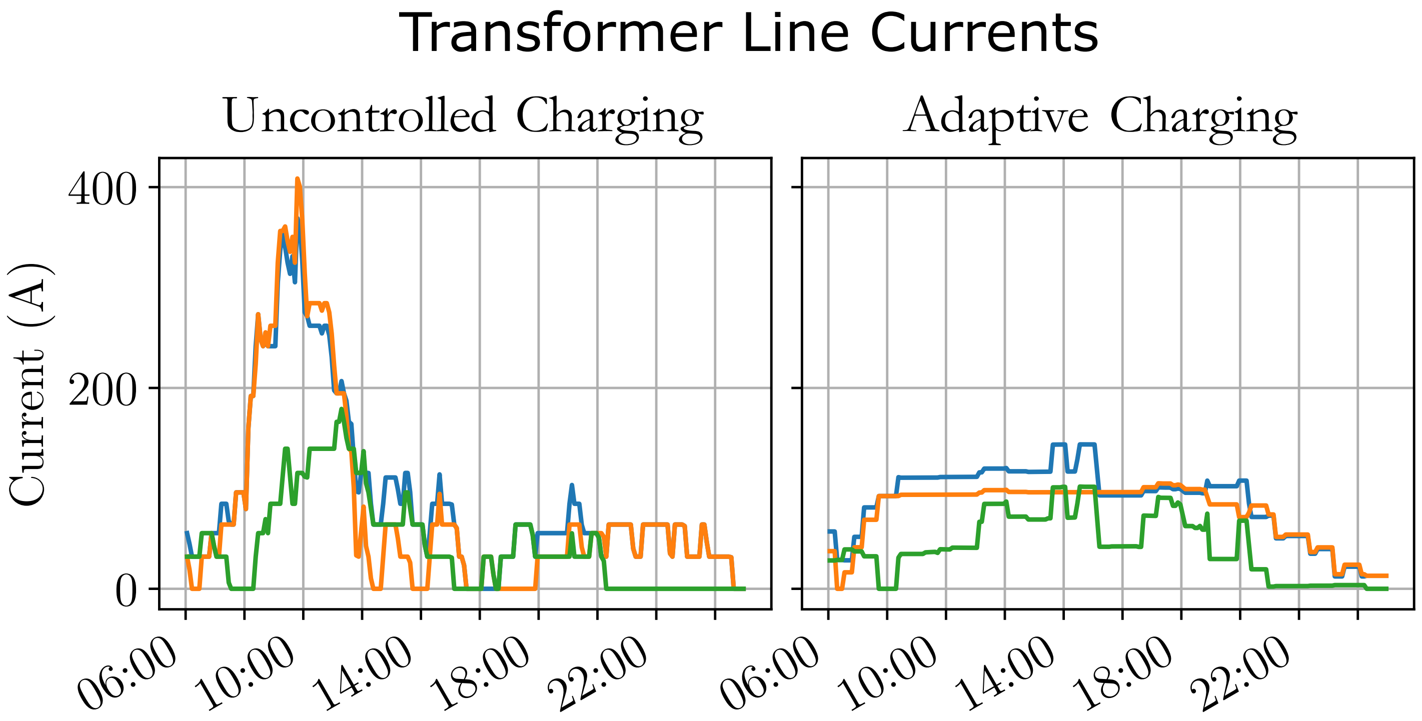


But the future of EV charging in cities looks like this…

Capital Costs Prohibitively Expensive



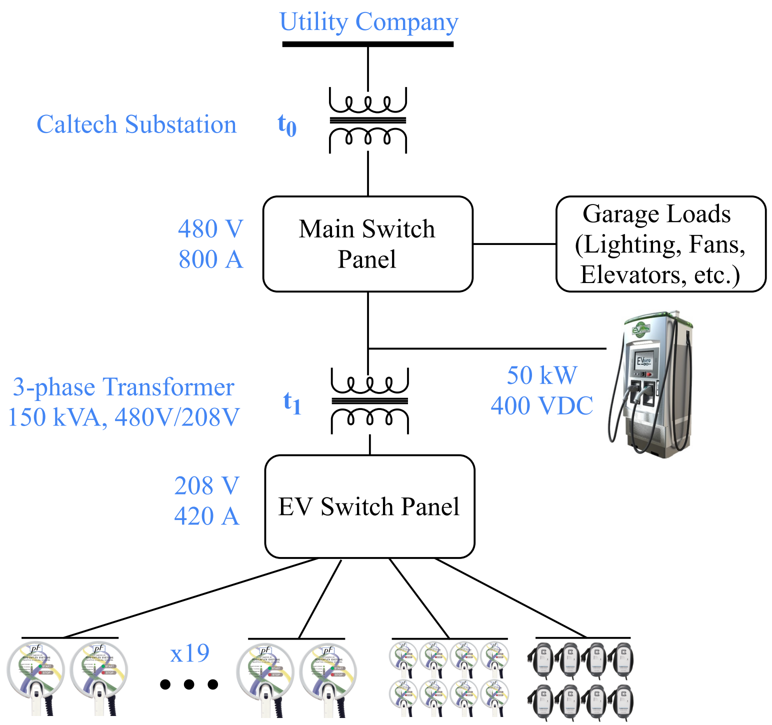
The Need for Adaptive Charging



Physical Charging Testbed

What good is a real testbed?

- Working with real systems allow us to understand their limitations.
- Without a proper understanding of these limitations our algorithms may look great on paper but be practically useless.



The Adaptive Charging Network

- 54 controllable level-2 EVSEs
- 50 kW DC Fast Charger.
- Oversubscription of transformers, cables and breakers.
- Demonstration environment for demand response, pricing schemes, and renewables integration.

54+

charging stations

150

kW of Capacity

585

MWh of energy delivered

1.8

million mile equivalent

610

tons of CO_2^{eq} avoided

What can we do with this system?

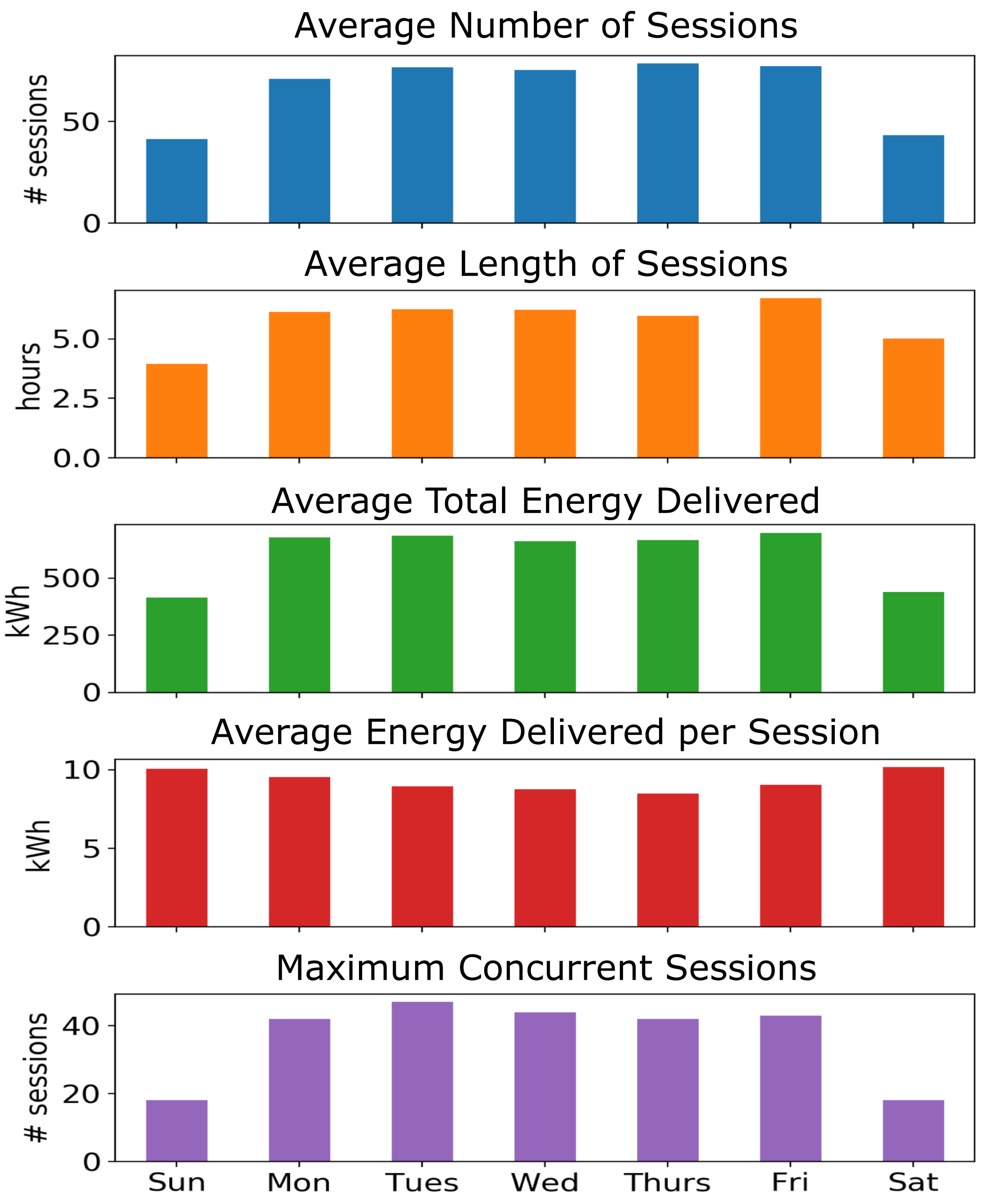
Data Collection

11,000

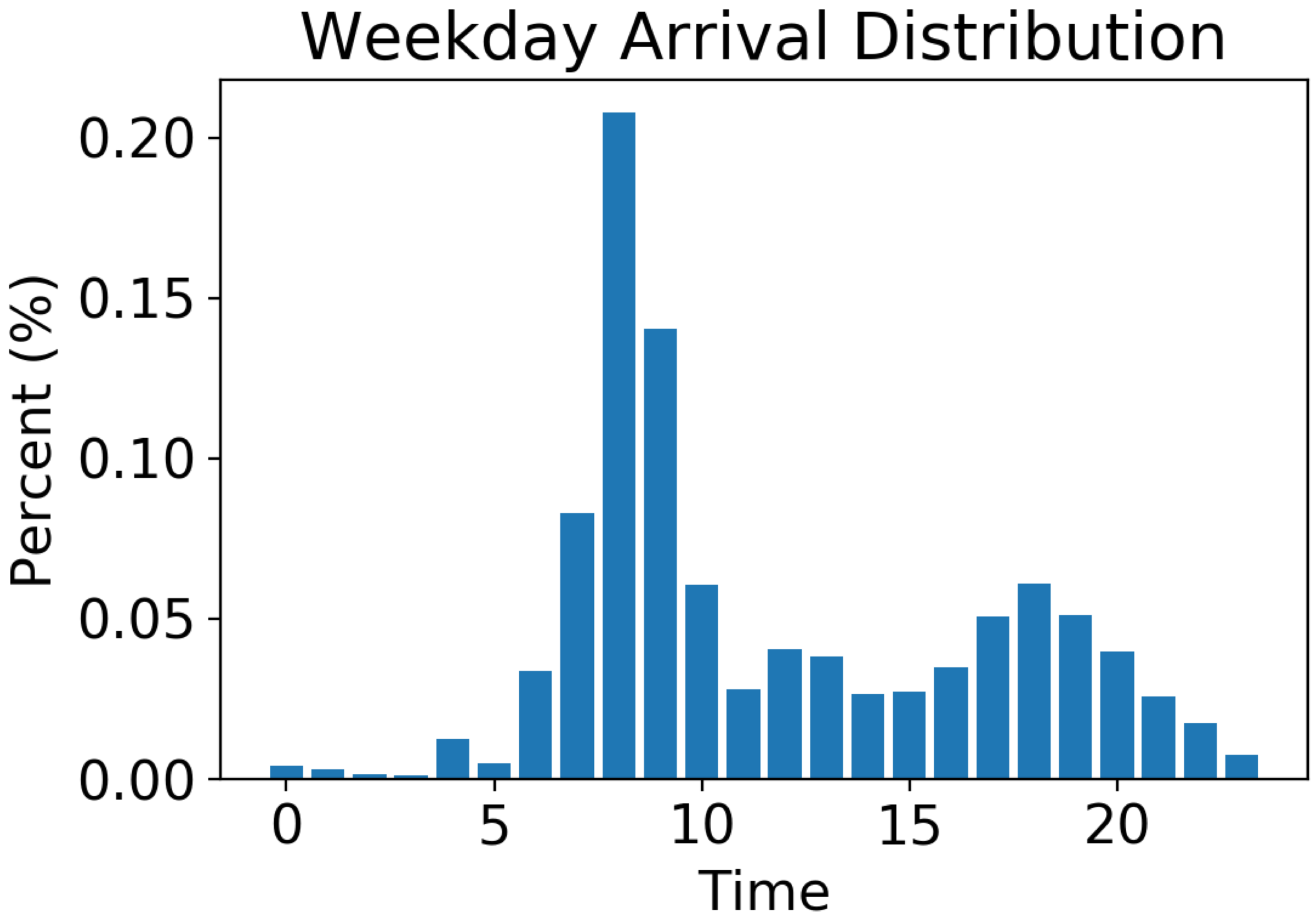
Charging Sessions since April 2018

_id: ObjectId("5bc924c8f9af8b0dc677c3c0")
userInputs: Array
0: Object
userID: 1
milesRequested: 10
WhPerMile: 500
minutesAvailable: 150
modifiedAt: 2018-06-22 13:12:18.000
paymentRequired: true
requestedDeparture: 2018-06-22 15:41:23.000
kWhRequested: 5
sessionID: "2_39_89_439_2018-06-22 20:11:23.086482"
stationID: "2-39-89-439"
spaceID: "CA-501"
siteID: "0002"
clusterID: "0039"
connectionTime: 2018-06-22 13:11:23.000
disconnectTime: 2018-06-22 14:35:39.000
kWhDelivered: 1.659
pilotSignal: Object
chargingCurrent: Object
timestamps: Array
current: Array
doneChargingTime: 2018-06-22 14:25:51.000
timezone: "America/Los_Angeles"

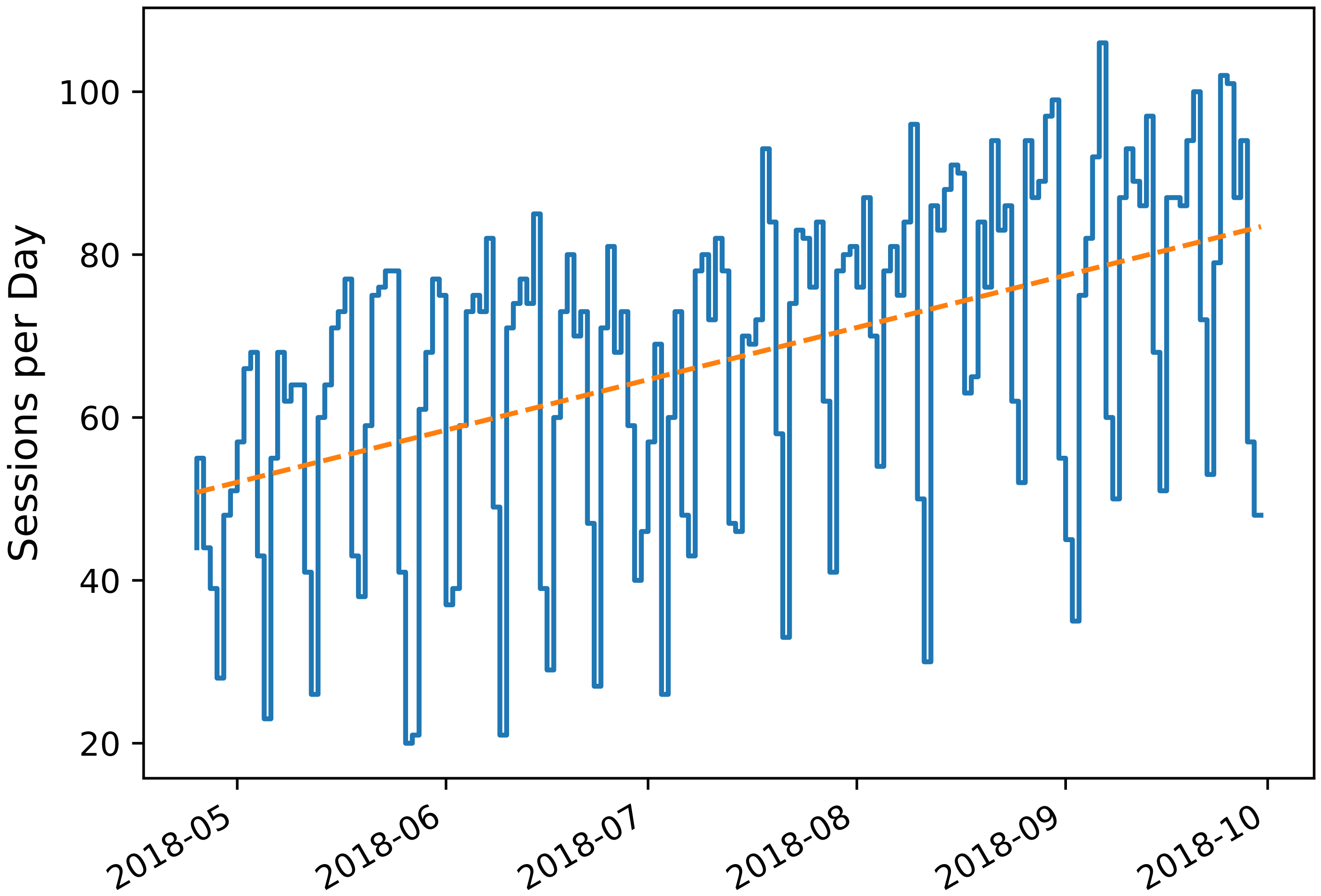
Charging Session Statistics



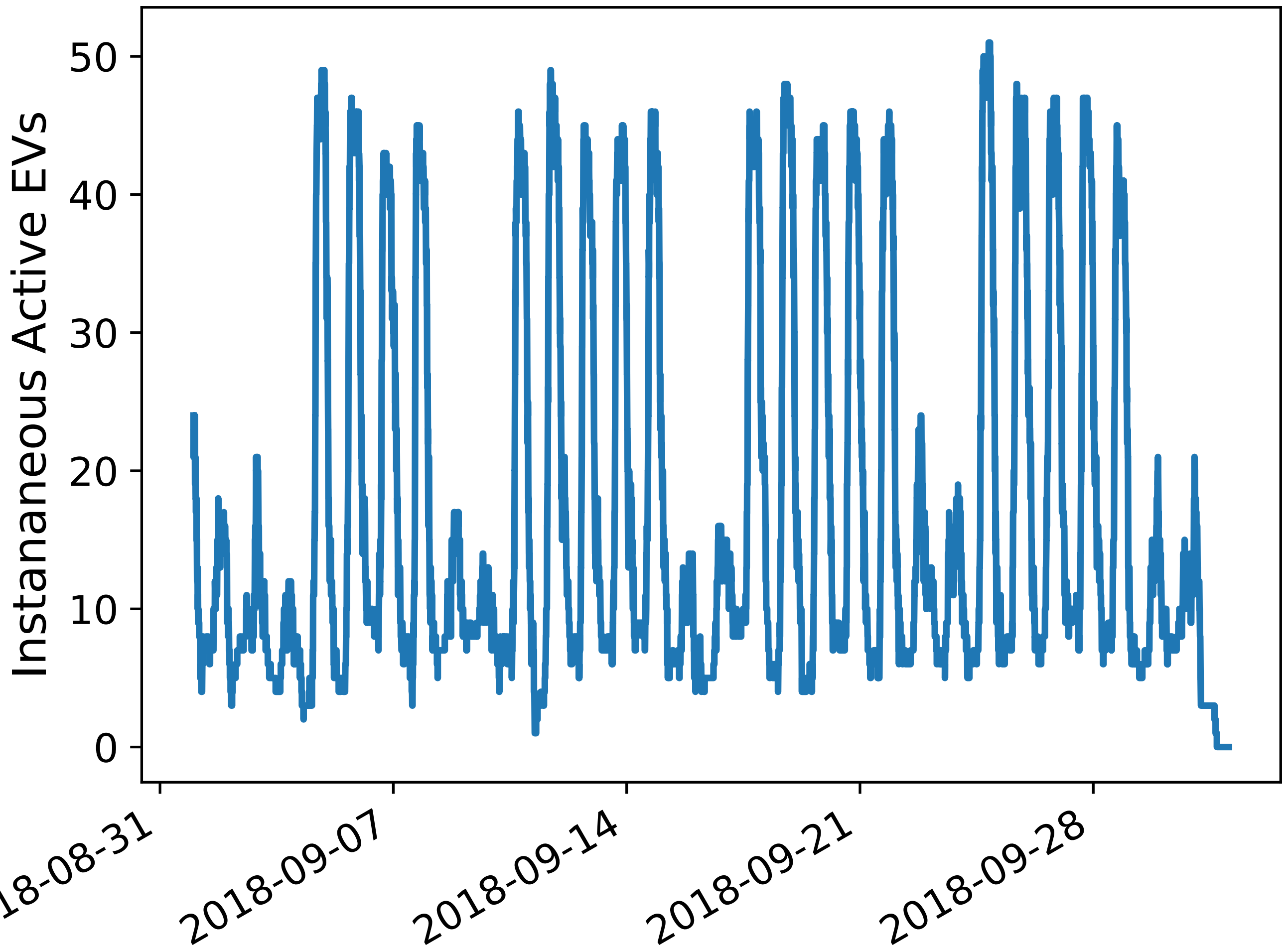
Arrival Statistics



Session per Day



Simultaneous Sessions



Online Scheduling

Scheduling Problem

SCH

$$\max_{r} \quad U_k(r)$$

$$0 \leq r_i(t) \leq \bar{r}_i(t) \qquad t < d_i$$

$$r_i(t) = 0 \qquad t \geq d_i$$

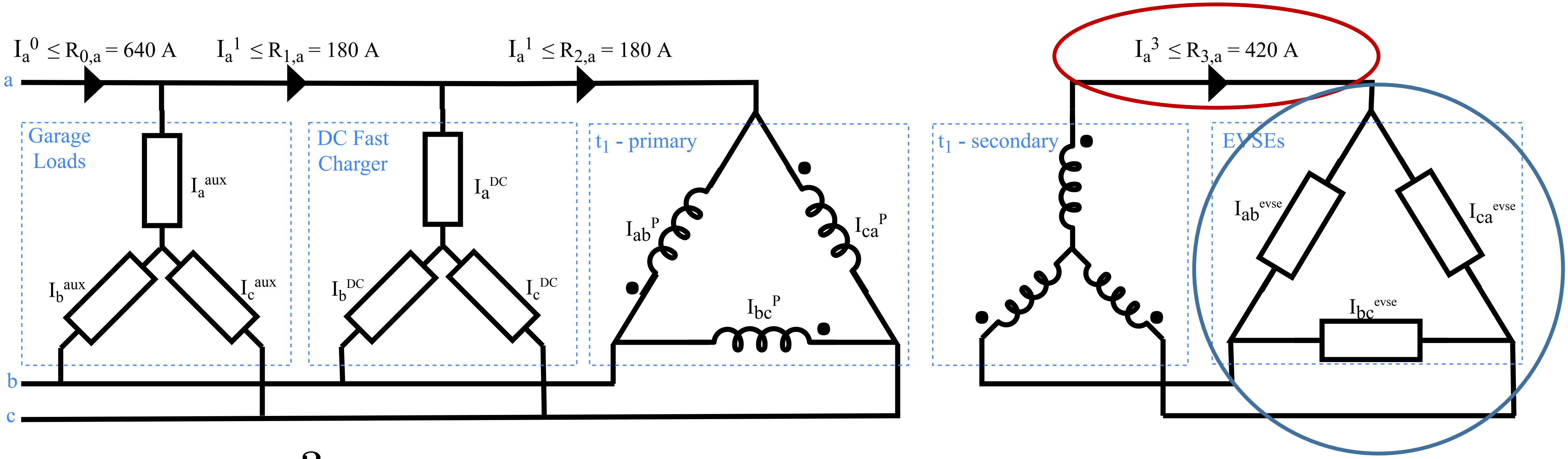
$$\sum_{t=a_i}^{d_i-1} r_i(t)\delta \leq e_i$$

$$f_j(r_1(t), ..., r_N(t)) \leq R_j(t) \qquad t \in \mathcal{T},$$

Objective $U_k(r)$:
- Maximizing profit.
- Charging quickly.
- Maximizing renewable energy use.
- Following demand response signals.

Constraints:
- No discharging. Maximum charging rate. Relaxation of allowable rate set.
- No charging after departure.
- Total energy delivered must be less than energy requested.
- Infrastructure constraints.

Unbalanced Three-Phase Constraints



$$|I_a^3| = |I_{ab}^{evse} - I_{ca}^{evse}| \leq R_{3,a}$$

Unbalanced Three-Phase Constraints

- We assume that we know/can measure the voltage phase angles at the EVSEs.
- Since EVSEs can be modeled as constant current loads with unity power factor, we thus know the phase angles of their currents.
- Since the magnitude of the current phasor is the only variable, these constraints are second-order cone constraints and the optimization problem is tractable.

$$
\begin{aligned}
|I_{3,a}|^2 &= |I_{ab}^{evse} - I_{ca}^{evse}|^2 \\
&= (|I_{ab}^{evse}| \cos\phi_{ab} - |I_{ca}^{evse}| \cos\phi_{ca})^2 \; + \; (|I_{ab}^{evse}| \sin\phi_{ab} - |I_{ca}^{evse}| \sin\phi_{ca})^2 \\
&\leq R_{3,a}^2
\end{aligned}
$$

Unbalanced Three-Phase Constraints

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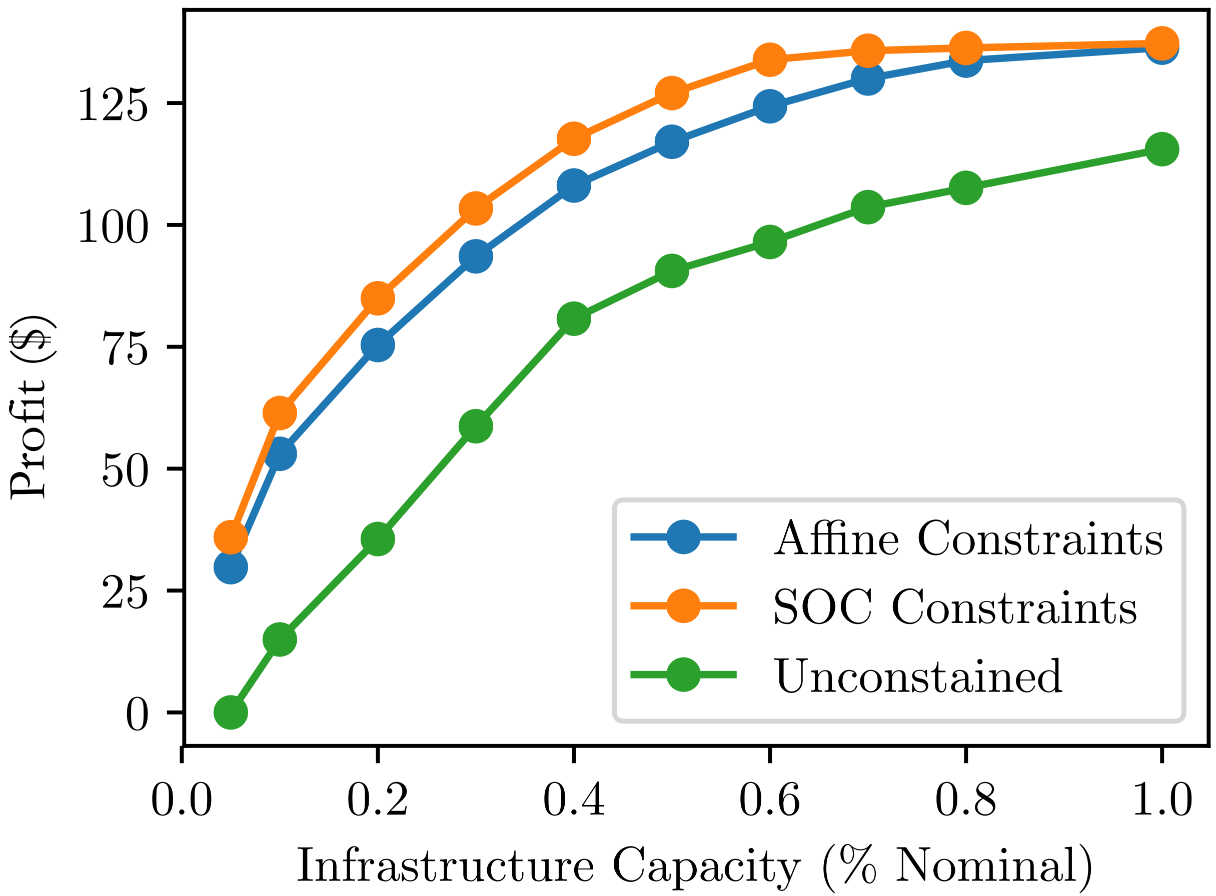
$$
\begin{aligned}
|I_{3,a}| &= |I_{ab}^{evse} - I_{ca}^{evse}| \\
&\leq |I_{ab}^{evse}| + |I_{ca}^{evse}| \\
&\leq R_{3,a}
\end{aligned}
$$

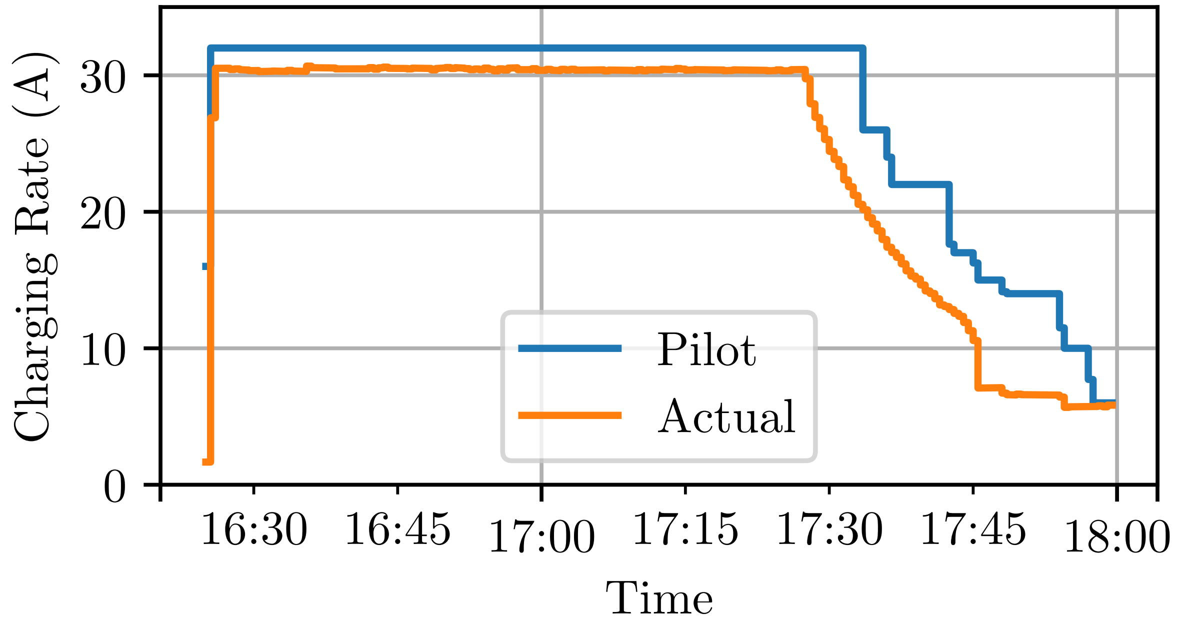
Phase Aware Constraints



$$U(r) := \sum_{\substack{t \in \mathcal{T} \\ i \in \mathcal{V}}} (p(t) - c(t)) r_i(t)$$

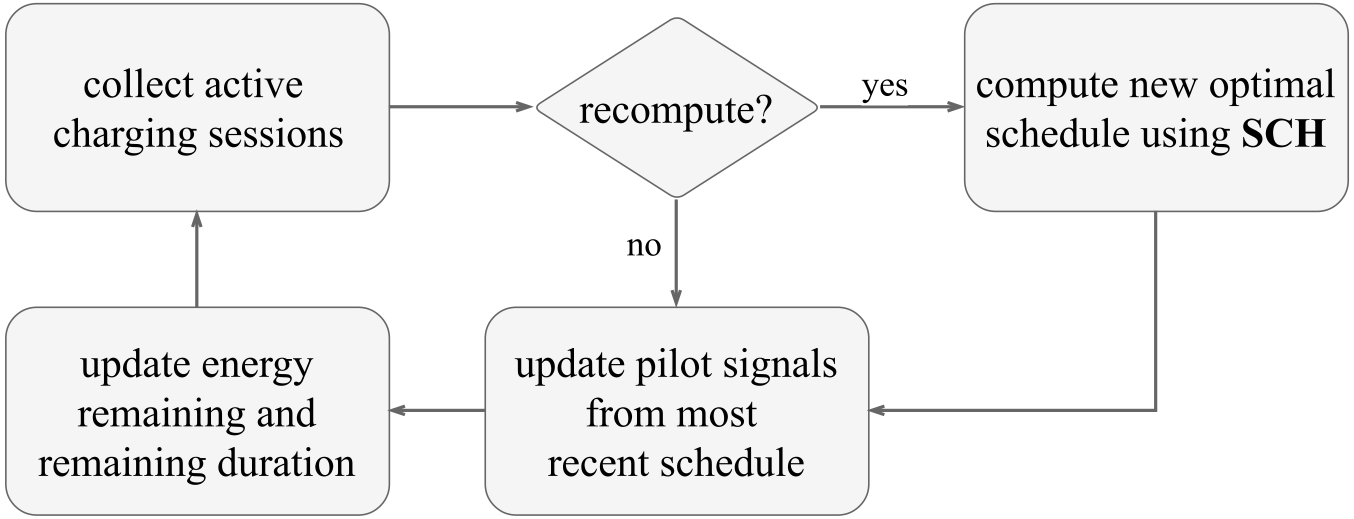
Imperfect Actuation

- Control is done via a pilot signal.
- Pilot signal is only an upper bound on charging current.
- Battery management system is free to charge at any rate lower than the pilot.



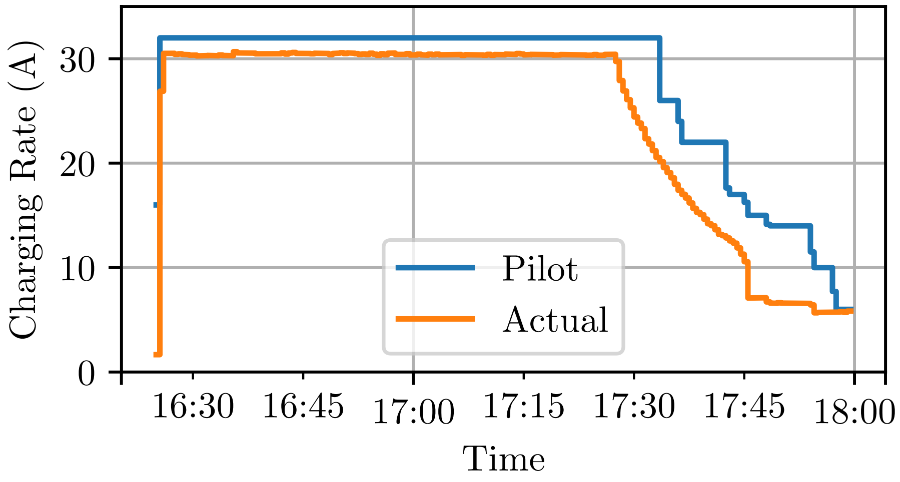
Model Predictive Control

- We use model predictive control to account for deviations.
- Schedule is recomputed periodically or when changes occur in the system.

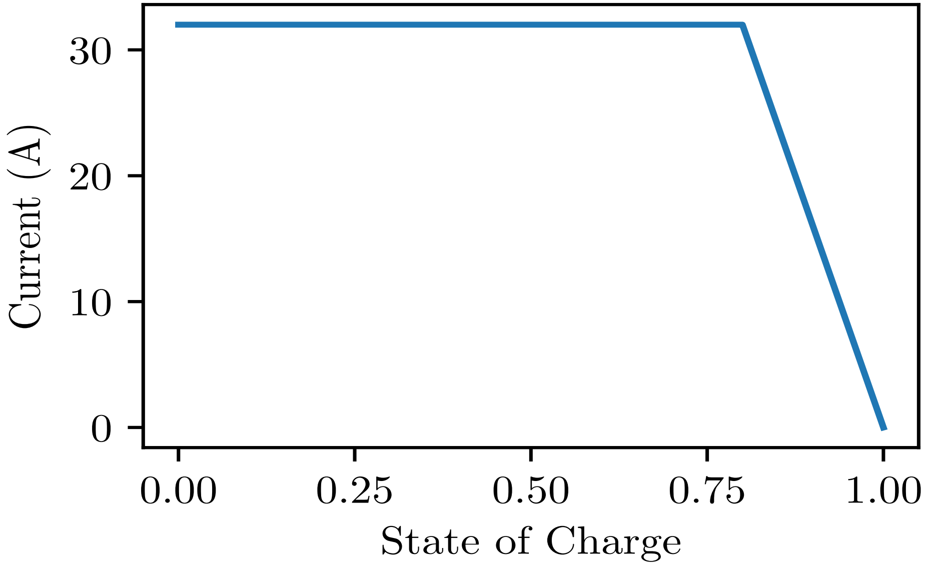


Simple Battery Model

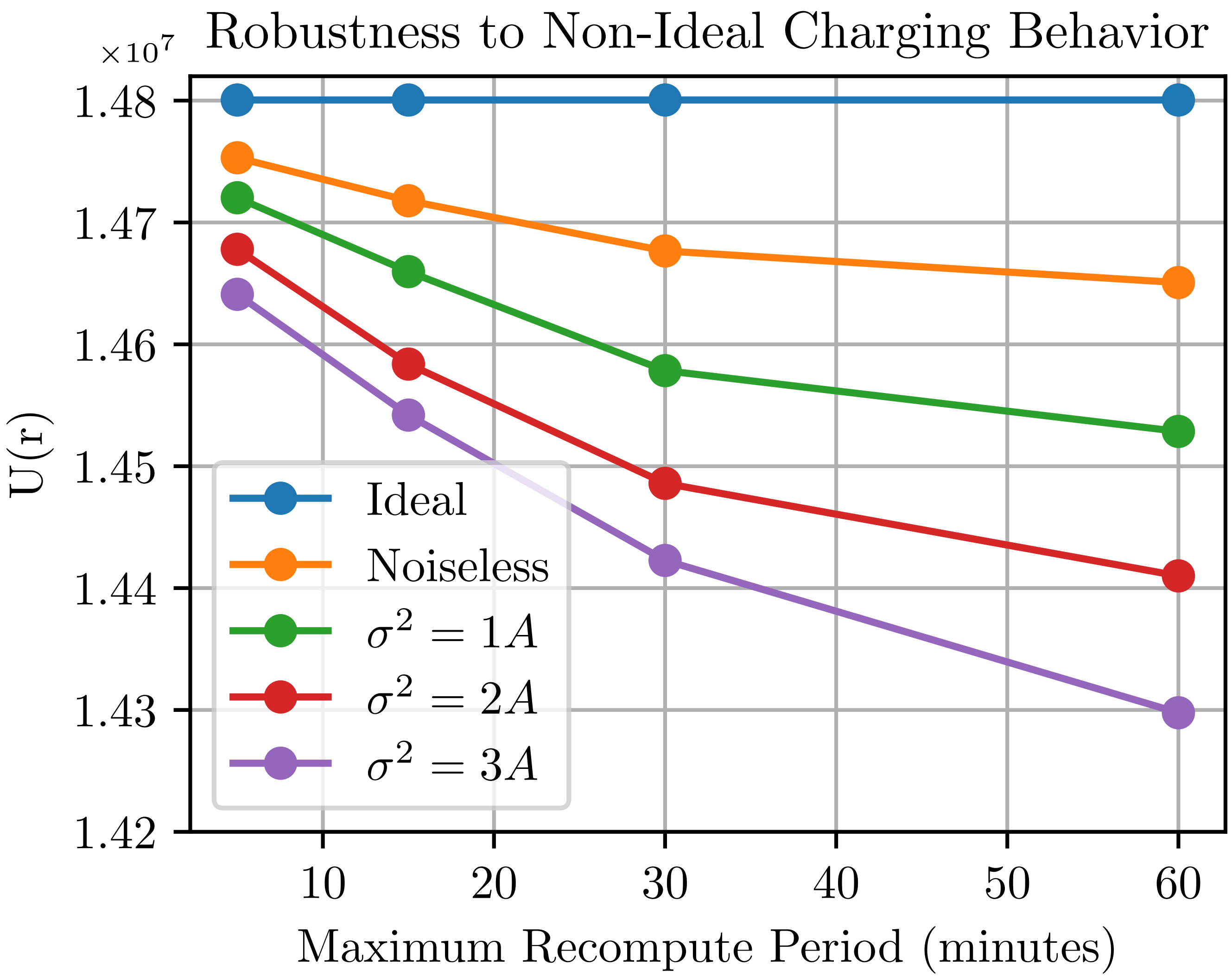
Actual Charging Behavior



Two-Stage Battery Model



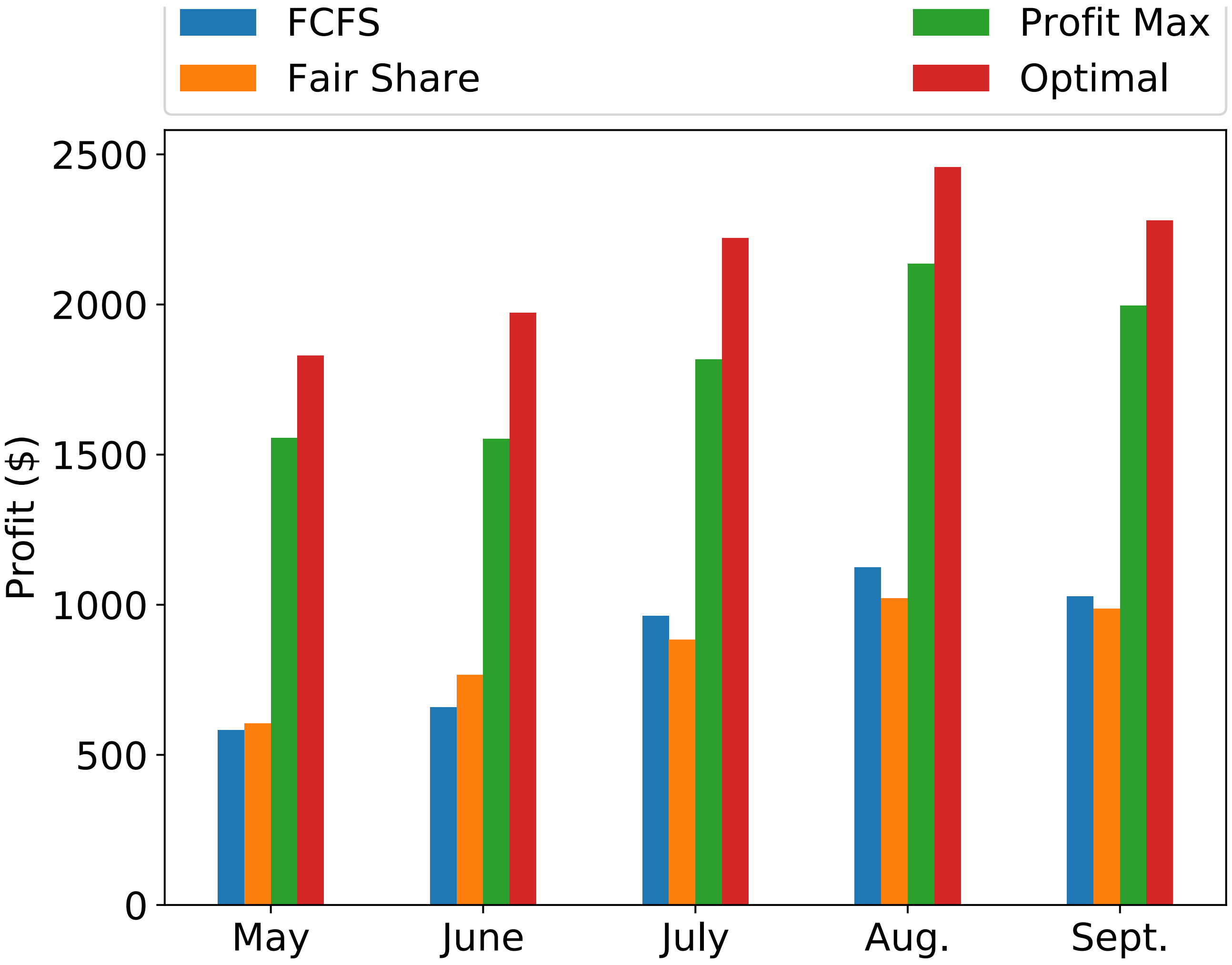
Robustness



$$U(r) := \sum_{t \in \mathcal{T}} (T - t) \sum_{i \in \mathcal{V}} r_i(t)$$

Results

Profit Maximization



$$U(r) := \sum_{\substack{t \in \mathcal{T} \\ i \in \mathcal{V}}} (p(t) - c(t)) r_i(t) \; - \; \Delta \cdot \max\left(\max_{t \in \mathcal{T}} \left(\sum_{i \in \mathcal{V}} r_i(t) + L^{aux}(t) \right), \, L_0^{max} \right)$$

Conclusions

- We should consider the unique challenges of large-scale charging infrastructure.
- Adaptive scheduling can significantly reduce the capital and operating costs of large-scale charging systems.
- Experience with real systems can inform how we design practical algorithms.
- Real time data from our testbed can be found at caltech.powerflex.com.

Future Work

- Demonstrating how large-scale EV charging can be used to flatten the “duck curve”
- Demonstrating the viability of large-scale EV charging in demand response markets
- Analyzing user behavior to design predictive scheduling algorithms

Releasing
Dataset and Simulator

email zlee@caltech.edu

to be notified of the release

Caltech

Questions