Design and Demonstration of a Smart Charging System for Plug-in Electric Vehicles

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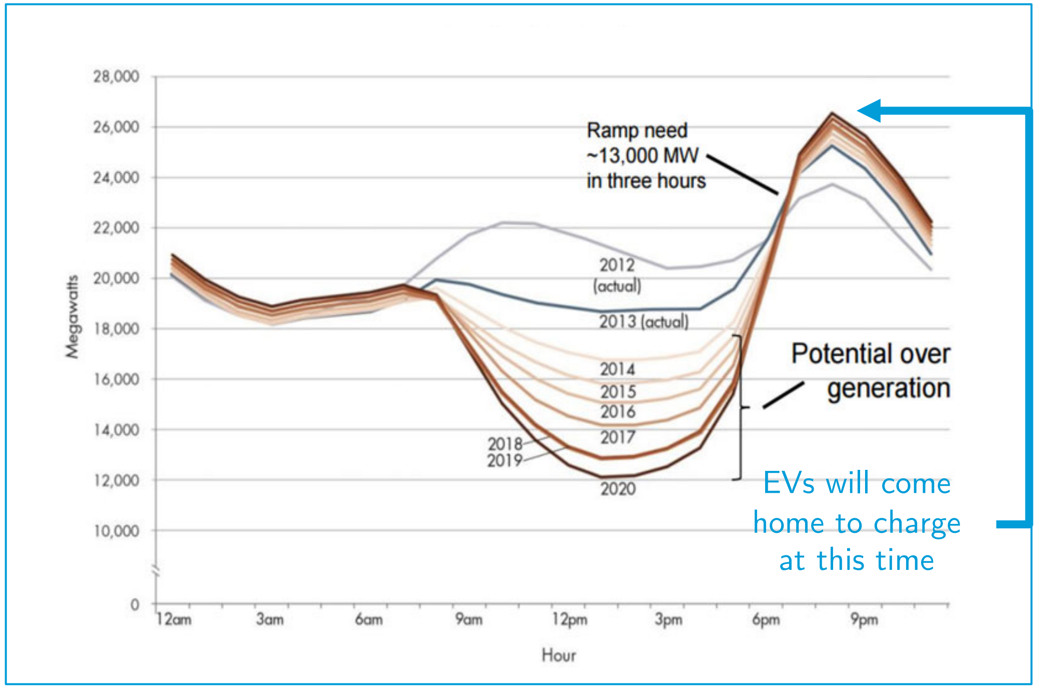
Introduction

- **Smart charging is motivated by grid-level issues**
  - Transmission level: duck curve
  - Distribution level: demand of EVs → overloading, low power quality
  - As EV adoption increases, charging load becomes significant
  - Smart charging: *control* battery charging load over time

- **Stakeholders**
  - **EV owners** should see benefits in exchange for their participation
  - **Power utility** should have operational constraints met, plan for capital investments
  - **Policy makers** should understand what technologies to invest in

- **Decentralized smart charging is attractive - will scale well**
  - EVs / homes and the power utility exchange information
  - EVs / homes make *their own* charging decisions
  - Centralized: utility dictates how and when *all* EVs charge

Transmission level: total load – renewable generation (i.e. demand on non-renewable generators)



The Duck Curve

If time permits, I have two slides on grid impact assessment of a smart charging strategy that can be realized using the prototype system discussed today!

Contributions

- **Review of Academic Literature + Commercial Solutions**
  - Academic Solutions ([1]-[12]): controllable AC/DC power converters
    - (+) **Controllable:** accept reference commands from a smart charging algorithm
    - (--) **Time to market:** If on-board type, OEMs need to license and implement
    - (--) **Accessibility:** If off-board type, not all EVs have DC charging pins (most do)
    - (--) **Not suitable for residential use:** DC charging is typically fast / high power, but most people charge at home, overnight (slow / lower power)
  - Commercial Solutions: charge scheduling "smart" EVSE's or EVs
    - (+) **Time to market:** on-board solutions already implemented by OEMs
    - (+) **Accessibility:** Every EV has AC charging pins
    - (+) **Suitable for residential use:** off-board solutions provide AC power to EVs
    - (--) **Not controllable:** Some products have heuristic scheduling features at best
- **Our Solution**
  - Controllable, off-board, optimization-based, AC smart charging system ☺
    - Compatible with 99 EV models across 25 makes, limited only by a (replaceable) third-party telematics API used for rapid implementation [13]
  - Supports wider class of TOU price signals (e.g., real-time price signals issued to manage grid impact) than commercial solutions, as well as other objectives, like maximization of renewable energy consumption

EVSE Manufacturers		EV Manufacturers
AMPROAD	Lectron	Audi
Anderson	Mustart	Chrysler Group
BougeRV	Myenergi	Ford
ChargePoint	Ocular	General Motors
Emporia	Smappee	Honda
Enel-x	Splitvolt	Hyundai
EO	Wallbox	Toyota
Fimer	ZJ Beny	Tesla
Grizzel-E		Volvo

EVs and EVSEs with Charge Scheduling Features

Enel-x JuiceBox: A "Smart" EVSE

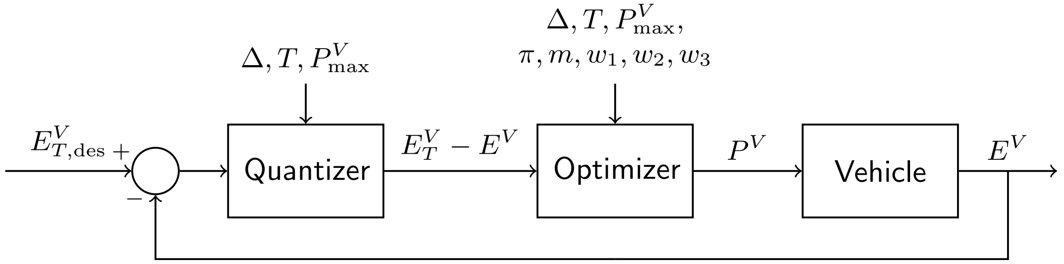
Smart Charging Algorithm

Optimization-Based Feedback Control

- **Objective**
  - Given starting energy level at $t = \tau$, $E^V[\tau]$, determine optimal charging command sequence $P^V[\tau], \ldots, P^V[T-1]$ subject to $E^V[T]$ being as close to $E^V_{T,\text{des}}$ as possible
  - (Re-)solve at $\tau = 1, 2, \ldots, T-1$ to overcome imperfect modeling, handle unexpected changes (e.g., power outage, price changes)
- **Quantizer:** Updates the goal $(E^V_{T,\text{des}} \to E^V_T[t])$
  - Ensure **Optimizer** solves feasible problems at each time step
  - Necessary because energy is delivered in packets of $\Delta \cdot P^V_{\max}$ kWh
  - $E^V_T[t] - E^V[t] = \text{quantize}(E^V_{T,\text{des}} - E^V[t])$
- **Optimizer:** Plans to reach the goal
  - Terms: J_1, J_2, J_3; user-selectable weights: w_1, w_2, w_3
  - <u>At each of</u> $t = 1, 2, \ldots, T-1$: minimize $w_1 J_1 + w_2 J_2 + w_3 J_3$
  - Problem is an integer linear program – mature and fast solvers exist

Symbol(s)	Units	Interpretation
T	-	length of time horizon
t	-	time index: $t = 1, 2, \ldots, T$
Δ	hour	time step
$\pi[t]$	\$/kWh	price of electricity at time t
$m[t]$	-	grid energy mix at time t
$P^V[t]$	kW	power flow into EV at time t
$P^V_{\max}$	kW	max power flow into EV
$E^V[t]$	kWh	energy stored in EV at time t
$E^V_{T,\text{des}}$	kWh	desired value of $E^V[T]$

Nomenclature



Block Diagram

$$J_1 = \Delta \sum_{\tau=t}^{T-1} \pi[\tau]\, P^V[\tau]$$

To minimize \$ paid to utility

$$J_2 = \Delta \sum_{\tau=t}^{T-1} (1 - m[\tau])\, P^V[\tau]$$

To minimize kWh of **non-renewable energy** consumed

$$J_3 = \sum_{\tau=t}^{T-1} t\, P^V[\tau]$$

To minimize charging time (units are not meaningful)

$$\Delta \sum_{\tau=t}^{T-1} P^V[\tau] = E^V_T[t] - E^V[t]$$

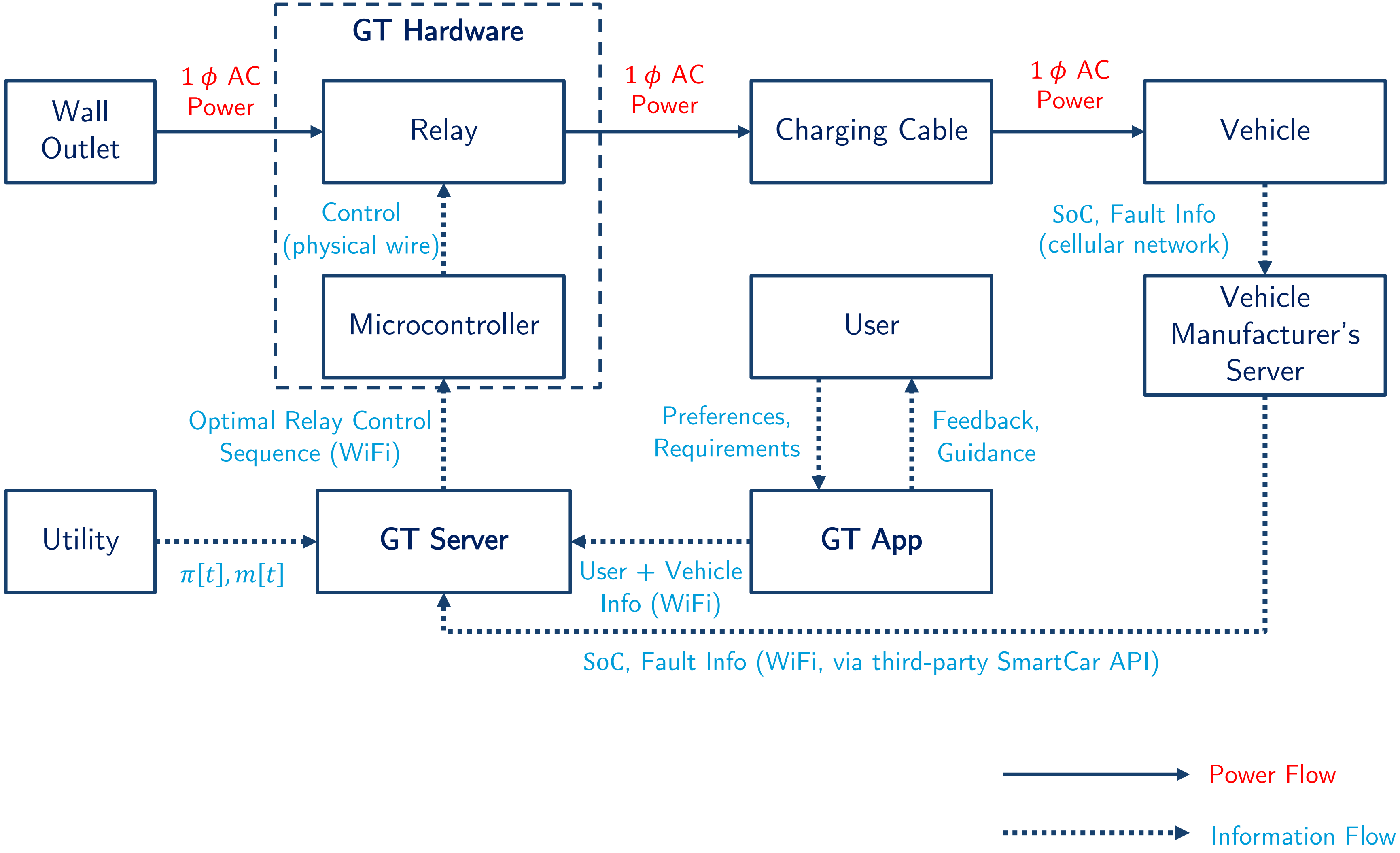
Charging requirement

$$P^V[t] \in \{0, P^V_{\max}\}$$

Charging power limits (on or off)

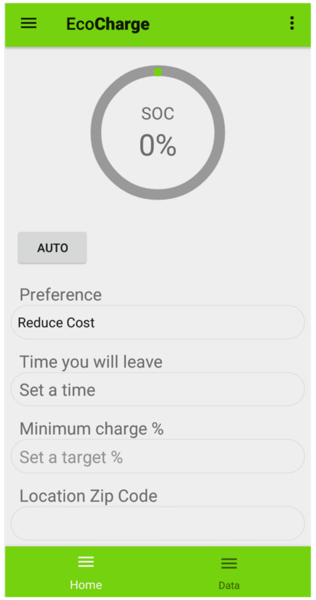
Hardware/Software Architecture

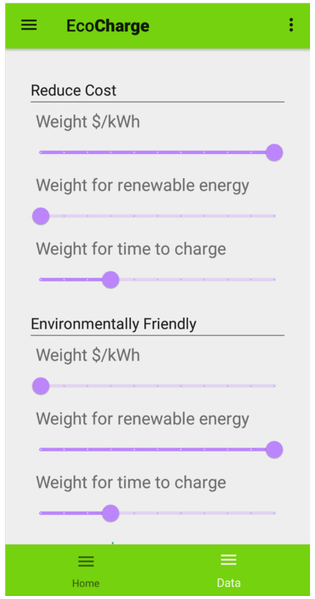
- **GT Hardware**
  - Regulates power flow
- **GT App**
  - Interfaces with user
  - Provides user preferences, requirements to **GT Server**
- **GT Server**
  - Interfaces with vehicle, utility, and **GT App**
  - Implements Smart Charging Algorithm
  - Sends relay open/close commands to **GT Hardware**

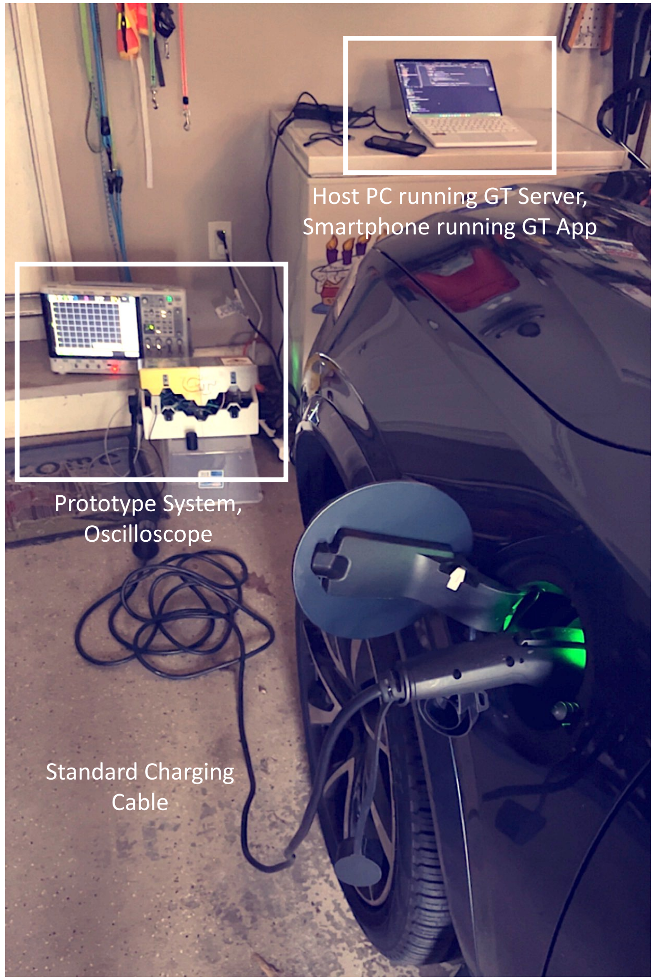


Photos

- **Enclosure**
  - 3D printed using PLA, ESD-safe resin
  - Houses MCU, relays
  - Lv. 1: NEMA 5-15
  - Lv. 2: NEMA 14-30
- **Mobile App**
  - User enters charging requirements in familiar units (wall-clock time, battery %)
  - Preset modes for preferences, informed users can tune weights





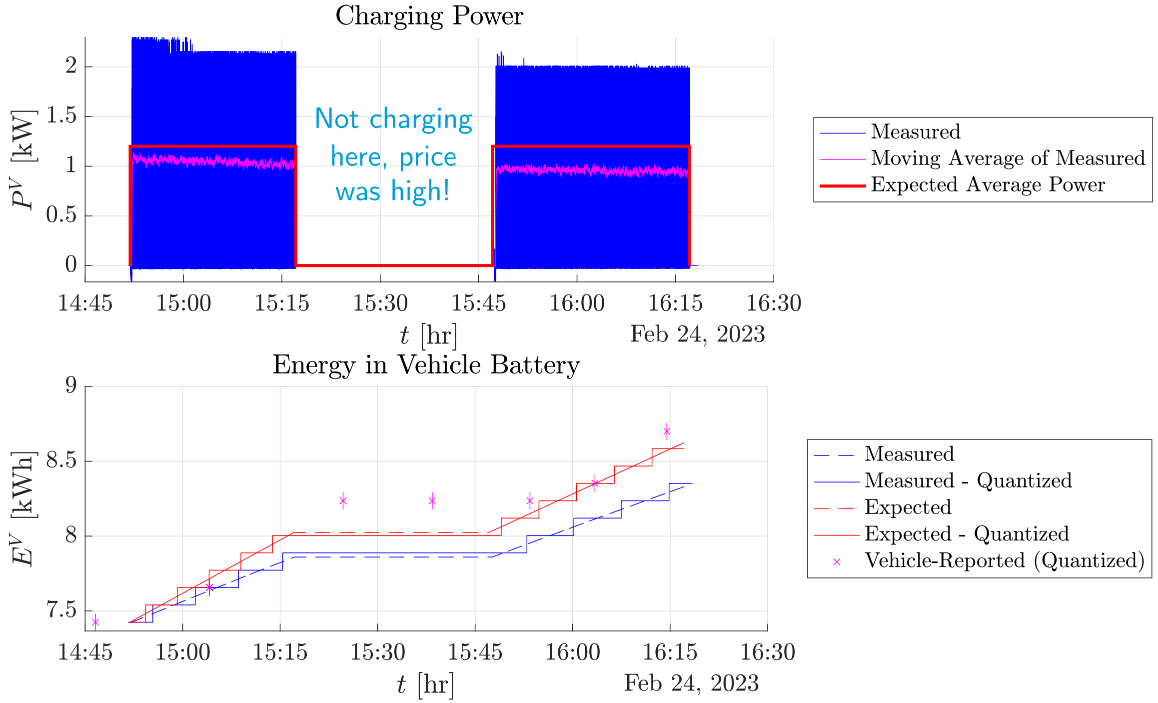


Experimental Setup

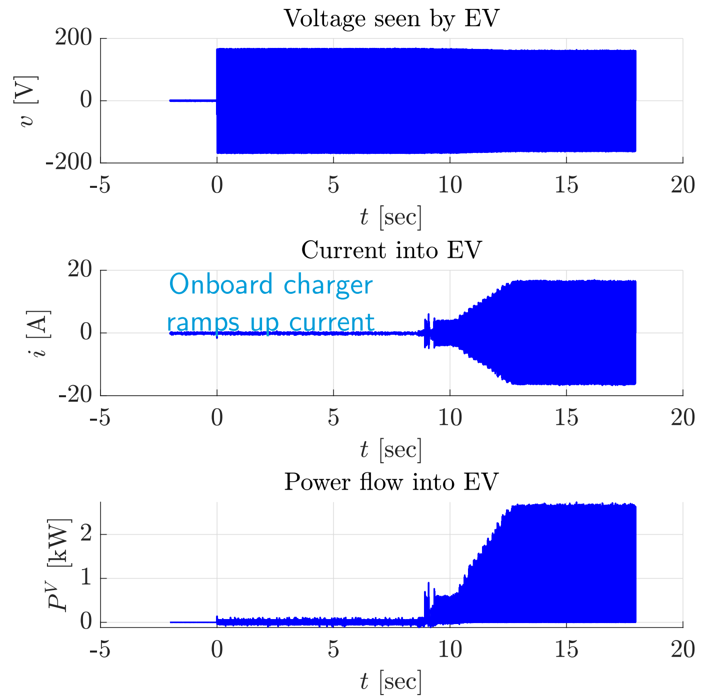
Experimental Validation

- **Equipment:** Vehicle + Charging Cable, Prototyped Smart Charging System, Oscilloscope
  - **Vehicle:** 2021 Volvo XC90 Recharge – battery pack capacity: 11.6 kWh; max. charging power at 120V: 1.2 kW
- **Response-Time Test:** Vehicle-imposed transient between relay-close command and full power flow: ≈ 13 sec
- **Command-Following Test:** Successful demonstration of minimum-cost charging, even under non-idealities
  - Average power flow during charging is not constant - possibly due to non-charging load and/or constant-voltage charging
  - Vehicle-reported energy values are higher than expected (2-3% SoC), likely due to error in state-of-charge estimation

Error shown is expected and mitigated by the combination of feedback and re-computation



Command-Following Test Results



Response Time Test Results

Summary, Conclusions

- Smart charging of electric vehicles can help manage grid impacts:
  - Our smart charging solution is suitable for near-term residential deployment (where most charging happens) because:
    - It performs comparatively low-power AC charging (rather than high-power DC charging)
    - It utilizes optimization techniques (rather than heuristic methods) to determine charging behavior
    - It is vehicle-external (rather than on-board), and readily interfaces with a wide range of vehicles (99 models across 25 makes)
- Implementation details are presented for a system that:
  - Supports charging Levels 1 and 2 defined in the SAE J1772 standard
  - Interfaces with an EV through (i) a standard charging cable, and (ii) a third-party telematics API (compatible with a wide range of EV manufacturers)
  - Uses an optimization-based feedback control algorithm determines an optimal set of time intervals during which to charge the EV at a pre-defined, constant power level
- Experimental results demonstrate minimum-cost charging of a 2021 Volvo XC90 Recharge using our prototype smart charging system
  - Even in the presence of mild, unmodeled non-idealities.

Next Steps

- **Prototype Refinement and Testing**
  - Test Level 2 charging capabilities
  - Conduct longer-duration tests with vehicle
  - Add current and voltage measurement capabilities to prototype
    - Can potentially eliminate the need for a third-party API
  - Upgrade smart charging algorithm to include grid impact management (developed in our prior work)

- **Grid Impact Assessment**
  - Higher fidelity assessment of grid impact of aforementioned smart charging algorithm, including:
    - Physics-based model of distribution feeder
    - Monte-Carlo simulation techniques to capture randomness in human behavior
    - Modeling of significant nonidealities observed in experimental work

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Thank you for this opportunity! Any questions?

Backup Slides on Grid Impact

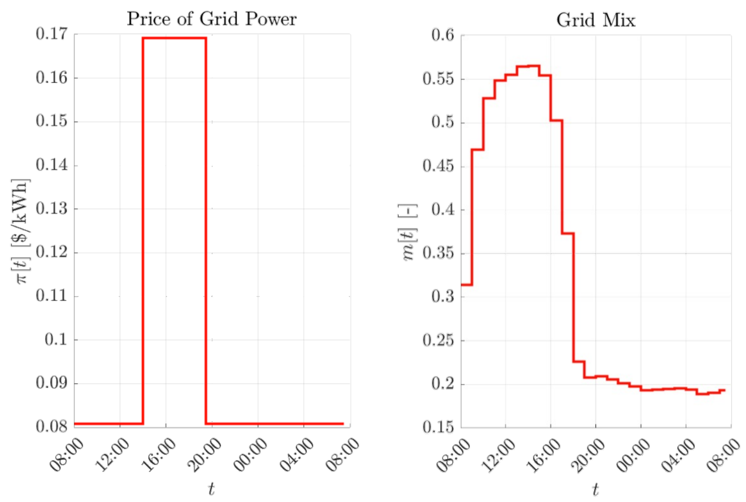
Content taken from our own prior work in [14]

Definitions:

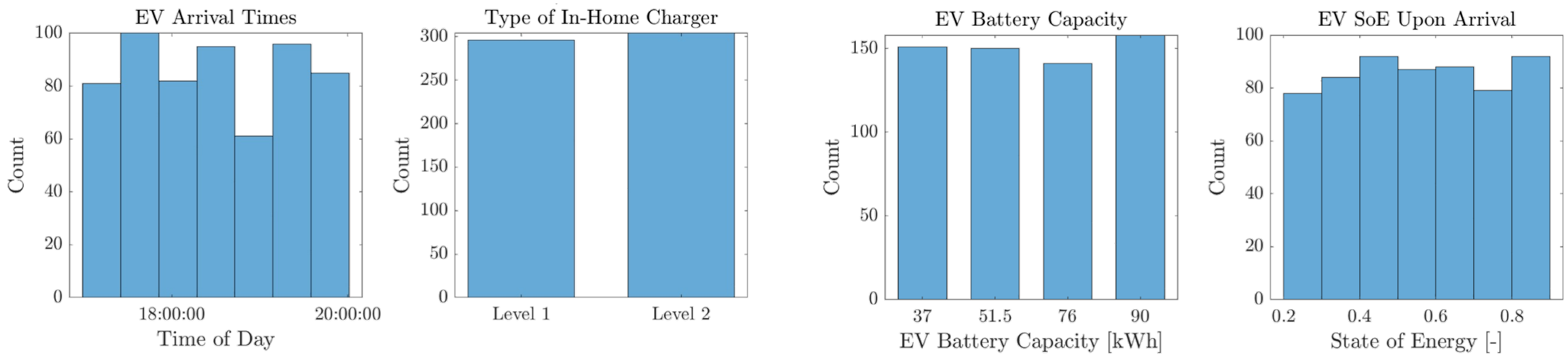
- **Rapid charging -** standard home charging behavior; EVs charge at the maximum-available power, as soon as they plug in
- **Single-stage smart charging –** naïve approach in which a smart charging objective function is directly minimized; the best that can be expected from a \`smart' EVSE (i.e., one that has charge scheduling features) in a price minimization setting
- **Two-stage smart charging –** novel method proposed in above work, in which non-uniqueness in the set of optimal (or near-optimal) solutions to a smart charging problem is leveraged to mitigate grid impact

Grid Impact Assessment: Method

- Consider a radially-connected neighborhood of 20 homes, each with an EV
- Each home **independently** performs smart charging or rapid charging
  - Each home can define "smart" as (i) min. $ paid to utility, or (ii) max. kWh of RE consumed
  - Each such home can choose single-stage (consumer-centric) or two-stage optimization
- Evaluate impact of EV charging on **aggregate** load (sum over all homes):
  - $R = \frac{\text{max power drawn by all EVs and Homes}}{\text{max power drawn by all Homes only}}$
  - Ex: $R = 1.2 \implies$ expect 1.2x more power flow into neighborhood **due to EV charging**
  - $R = 1$ is best possible scenario if EVs cannot be discharged to serve household load
- Study effect of smart charging participation on R
  - Examine trends in **statistics over multiple random trials,** in which key input parameters are randomly from **assumed distributions** (shown below)



Time-of-use price and grid mix signals used by all homes performing smart charging



Grid Impact Assessment: Simulation Result

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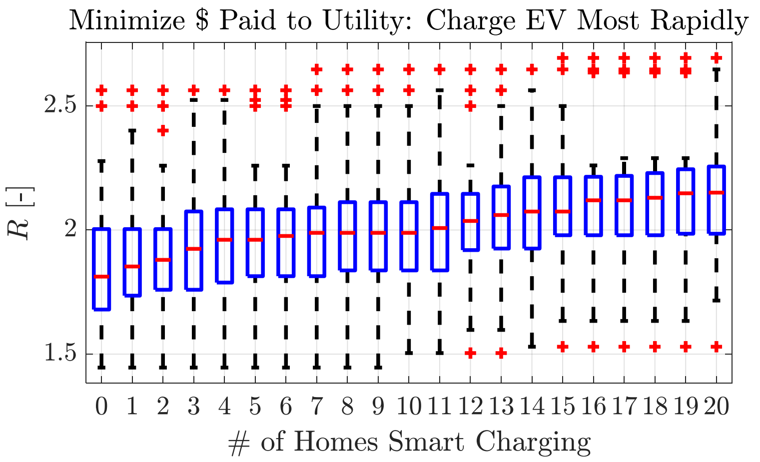
Note: EV charging power is **either** 0 **or** max. power at any time

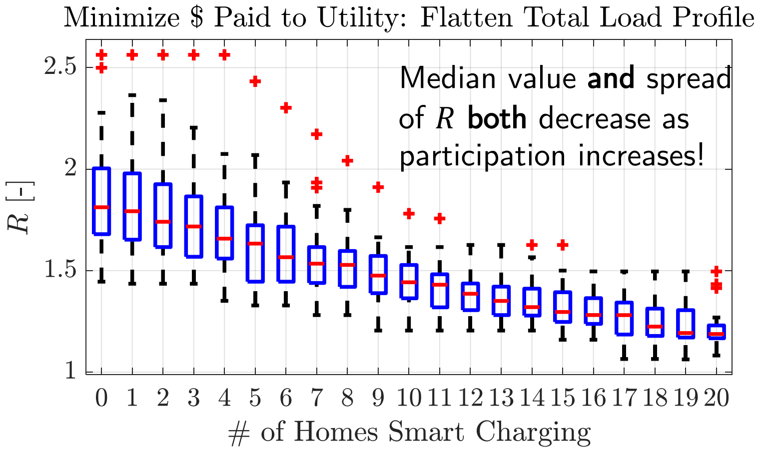
Commercially-available EV smart chargers **have this capability today**

Single-stage smart charging

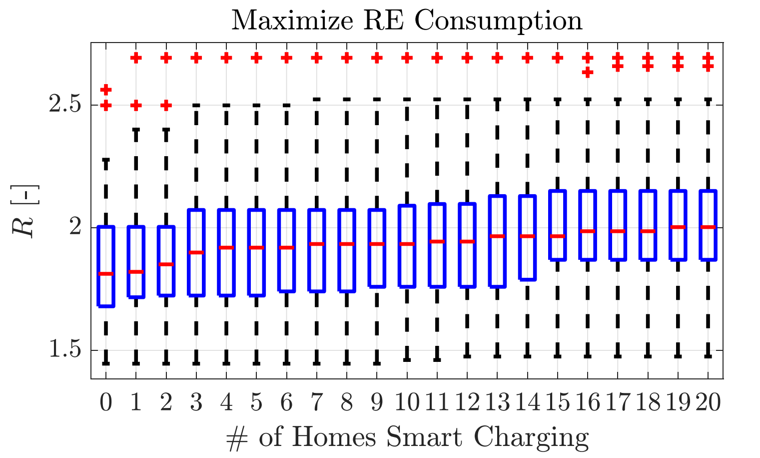


Increasing participation in smart charging

Two-stage smart charging

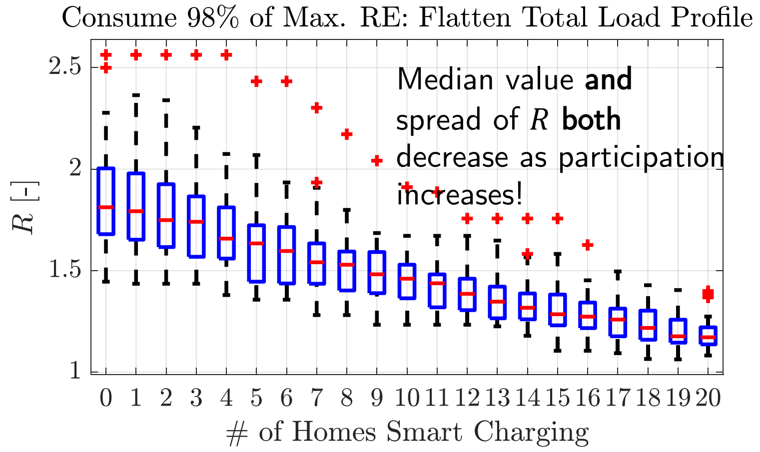


Single-stage smart charging



Increasing participation in smart charging

Two-stage smart charging



- Each box plot represents the *distribution* of R values that arises due to random selection of EV arrival time, charging needs, etc.
  - Red line = median
  - Blue box = interquartile range
- TOU pricing alone may not be effective in curtailing peak demand. Smart chargers should respond to TOU pricing in a grid-favorable way!
- Smart chargers should impose *slight* concessions on customers who wish to maximize RE consumption!
- In both cases, smart charging can potentially reduce need for capital investment in line/transformer upgrades