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Grid-Favorable, Consumer-Centric, On/Off Smart Charging of Electric Vehicles in a Neighborhood

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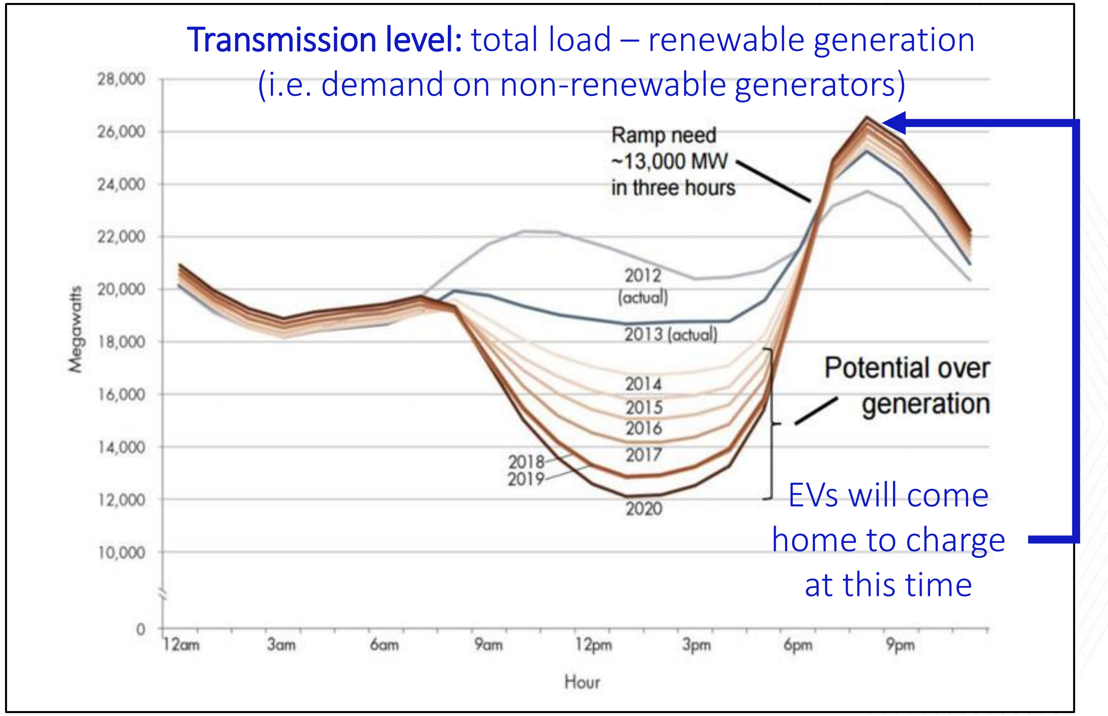
Introduction

- **Smart charging is motivated by grid-level issues**
  - Transmission level: "duck curve", see right
  - Distribution level: demand of EVs → overloading, low power quality
  - As EV adoption increases, battery 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



The "duck curve" phenomenon caused by a solar-dominated renewable portfolio, together with uncoordinated EV charging

Image Source: https://www.nuscalepower.com/environment/renewables/the-duck-curve

Scope and Contributions of Study

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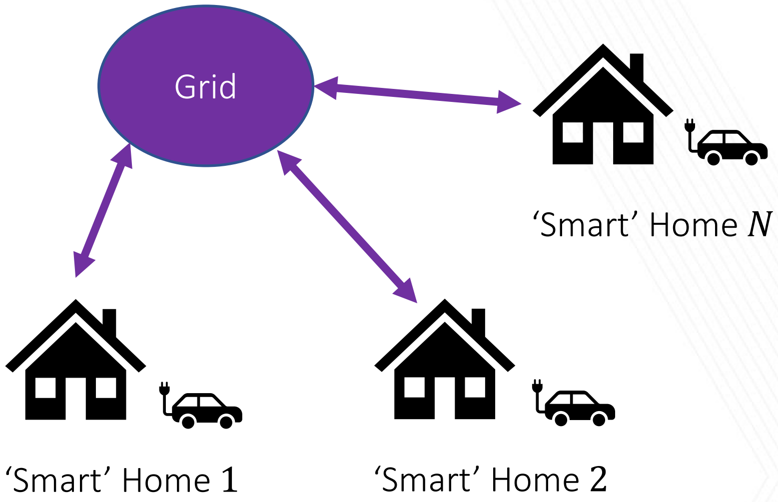
- **Setting:** Neighborhood of single-family residences, each having an EV
- **Contribution 1:** Smart EV charging algorithm
  - Uses multi-objective representation of the EV owner from [1]
    - **Contrast:** single-objective representations in smart charging literature
  - Decentralized - each home makes charging decisions independently
    - **Contrast:** centralized approaches in smart charging literature - single decision-maker dictates how each EV should charge (e.g., to maximize utility benefit); its authority to do so is simply assumed!
  - Two-stage decision process considers both consumer and grid perspectives
  - Specialized to the case of on/off charge control for near-term applicability
    - **Contrast:** variable-power control considered in smart charging literature
    - Commercially-available solutions today can only perform on/off control!
- **Contribution 2:** Grid impact assessment method for smart charging
  - Techniques from uncoordinated charging literature leveraged
  - In smart charging studies, common to run a single simulation using representative parameters - hard to make claims about generalization
  - Monte-Carlo style simulation provides more confidence in observed trends



A neighborhood of N radially-connected, independently-operating 'smart' homes, each equipped with an EV

$P^V[t] =$ **p**ower flow into **v**ehicle at time t

Variable Power: $P^V_{\min} \leq P^V[t] \leq P^V_{\max}$

On/Off: $P^V[t] \in \{P^V_{\min}, P^V_{\max}\}$

Terminology: "on/off" vs. "variable-power"

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[1] K. V. Sastry, T. F. Fuller, S. Grijalva, D. G. Taylor and M. J. Leamy, "Electric Vehicle Smart Charging to Maximize Renewable Energy Usage in a Single Residence," *IECON 2021 – 47th Annual Conference of the IEEE Industrial Electronics Society*, 2021, pp. 1-6.

Smart Charging: Stage 1

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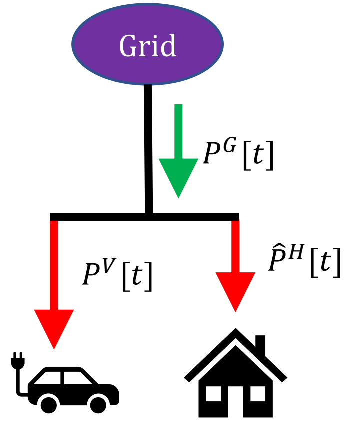
- **Consumer-centric** smart charging objective function:
  - Three terms: $J_{\{1,2,3\}}$; User-selectable weights for each term: $w_{\{1,2,3\}}$
  - $$\underset{\{P^V[t]\}_{t=1}^T}{\text{minimize}} \quad \underbrace{w_1 J_1}_{\text{\$ paid to utility}} + \underbrace{w_2 J_2}_{\text{kWh of non-renewable energy consumed}} + \underbrace{w_3 J_3}_{\text{charging time}}$$
- Constraints:
  - Power balance; EV charging power limits; Max. power draw from grid; EV battery energy limits, battery dynamics, energy boundary conditions
- Why attractive to EV owners? (see [1])
  - Comprehensive, flexible formulation; allows for human input
  - Optimization problem is a mixed-integer linear program; solvers are mature, efficient
  - Optimal substructure can be leveraged overcome uncertainty in input data
  - Tradeoffs between the objectives can be efficiently revealed to humans
- Solving yields an optimal sequence of charging commands ($\{P^V[t]\}_{t=1}^T$) from the consumer's perspective
- **Challenge:** solution may be (very) sub-optimal from grid perspective!

Source	Data
EV/Home Owner	Charging requirements Times the EV is at home
Power Utility	TOU price signal Grid mix signal
Estimator	Household demand
Battery Sensor	State of energy
Datasheets	Physical limits

Input data required for consumer-centric smart charging



Schematic representation of smart home; $P^V[t]$ = power flow into EV

Smart Charging: Stage 2

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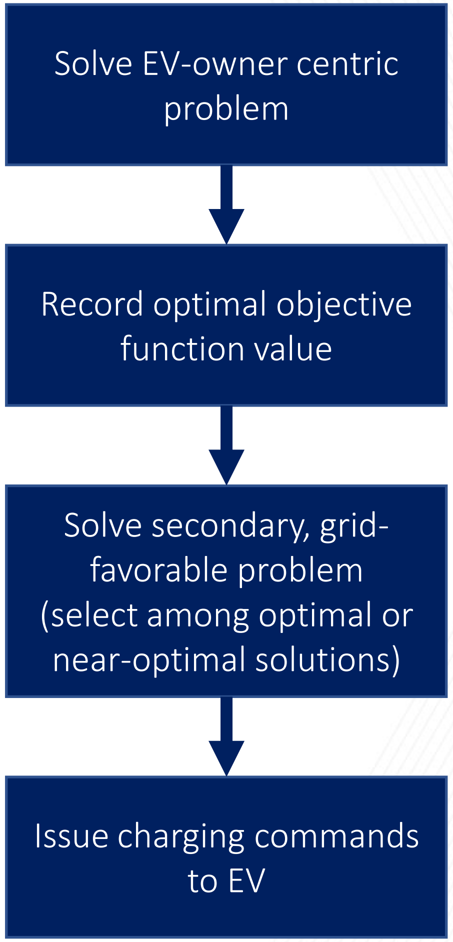
- Consider grid perspective via a **grid-favorable, secondary** objective function:
  - $\underset{\{P^V[t]\}_{t=1}^T}{\text{minimize}} \; g(\{P^V[t]\}_{t=1}^T)$ ← Design $g(\cdot)$ to be grid-favorable, e.g. flatten home's total demand profile
- Constraints
  - **Inherit from Stage 1:** Power balance; EV charging power limits; Max. power draw from grid; EV battery energy limits, battery dynamics, energy boundary conditions
  - **Add:** little (bounded) or no increase in cost to EV owner (objective value from Stage 1)
- EV owners will often seek to (i) minimize dollars paid to utility, or (ii) maximize renewable energy (RE) consumption
  - Smart EV chargers with these objectives are available on the market
- In case (i), the consumer-centric problem admits multiple optimal solutions exist. In case (ii), multiple near-optimal solutions exist
  - In these cases, **choose** the most grid-favorable optimal (or near-optimal) solution
  - Simulation results show that using this approach, significant benefits can be obtained from the grid perspective, at little to no added cost to consumers



Determination of final EV charging profile

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Grid Impact Assessment: Method

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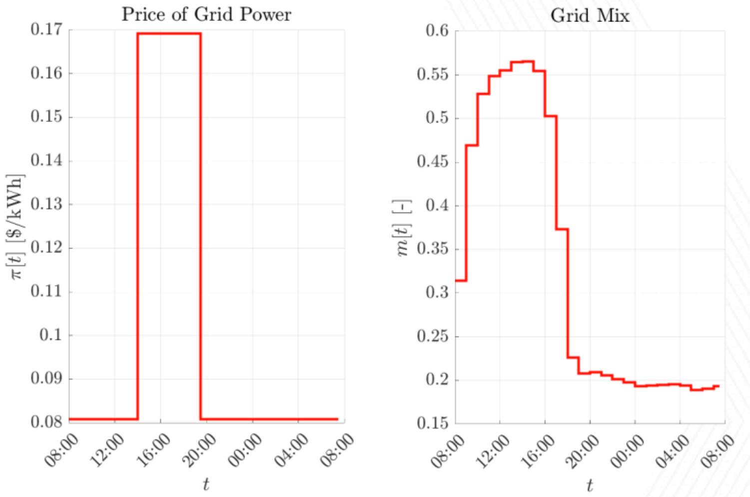
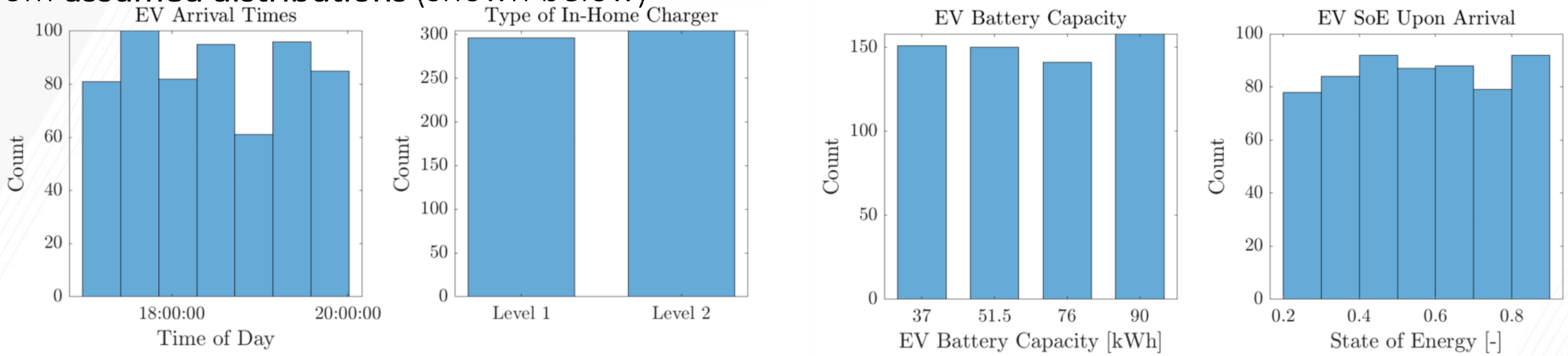
- Consider a radially-connected neighborhood of 20 homes, each with an EV
- Each home **independently** performs smart charging or rapid charging
  - Each home can define "smart" as (i) min. $ paid to utility, or (ii) max. kWh of RE consumed
  - Each such home can choose single-stage (consumer-centric) or two-stage optimization
- Evaluate impact of EV charging on **aggregate** load (sum over all homes):
  - $R = \dfrac{\text{max power drawn by all EVs and Homes}}{\text{max power drawn by all Homes only}}$
  - 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



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Grid Impact Assessment: Results

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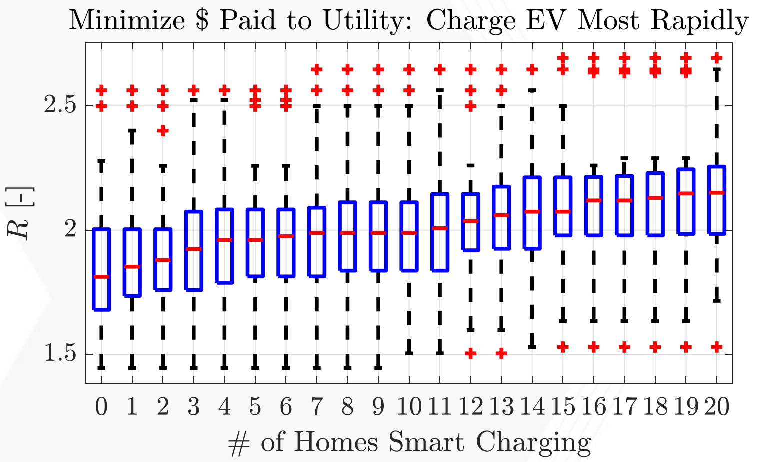
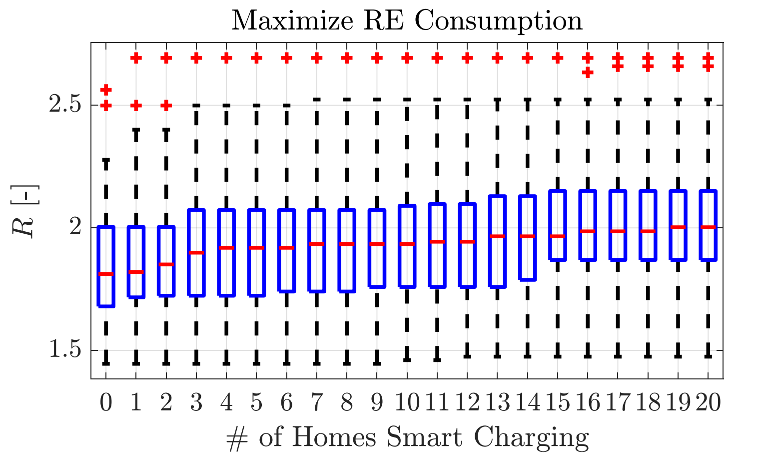
Note: EV charging power is **either** 0 **or** max. power at any time

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

Single-stage smart charging



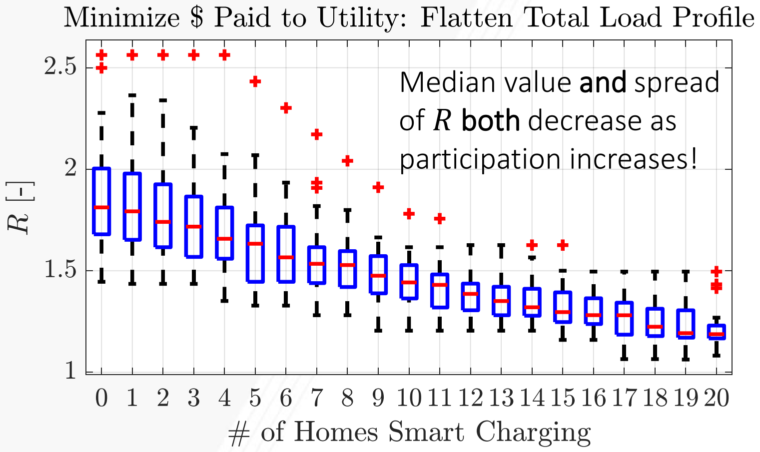
Single-stage smart charging



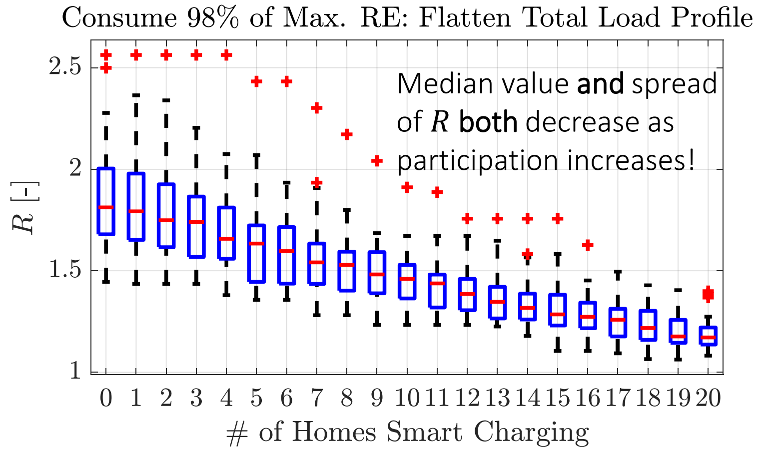
Increasing participation in smart charging

Increasing participation in smart charging

Two-stage 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

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Summary, Conclusions

- **Problem:** Simultaneous, uncoordinated, rapid charging of EVs creates demand spikes → violations of grid operational constraints, equipment damage/failure
- **Proposed remedy:** a smart charging algorithm to control EV charging in a single-family residential setting
  - EV owners represented by multiple objectives
  - Decentralized approach, no issues of control authority
  - Two-stage decision process considers both consumer and grid perspectives on smart charging
  - Specialized to the case of on/off charge control for near-term applicability; can be implemented as a software update to commercially available smart EV chargers!
    - Similar demand spikes also occur in the case of “variable-power” smart charging. Therefore, even users of “variable-power” smart chargers may avoid loss of power or high “demand charges” by adopting our approach
    - A “variable-power” version of our two-stage approach also exists, which yields similar results (to be published soon!)
- **Results:**
  - In common cases (dollar-cost minimization and renewable energy maximization), even smart charging can lead to demand spikes!
  - Remedy is to apply the two-stage approach proposed herein, rather than a single-stage, strictly consumer-centric approach
  - If deployed on a neighborhood-scale, smart charging can potentially reduce need for capital investment in line/transformer upgrades

Next Steps

- Refine grid-impact studies for residential smart charging
  - Use real data for EV arrival time, energy transfer per charging session, etc.
  - Use high-fidelity models of distribution feeders, multiple grid impact metrics
  - Same general analysis approach will be applied!
- Complete development and testing of a smart charger prototype
- Investigate smart charging for fleets; analyze associated grid impact

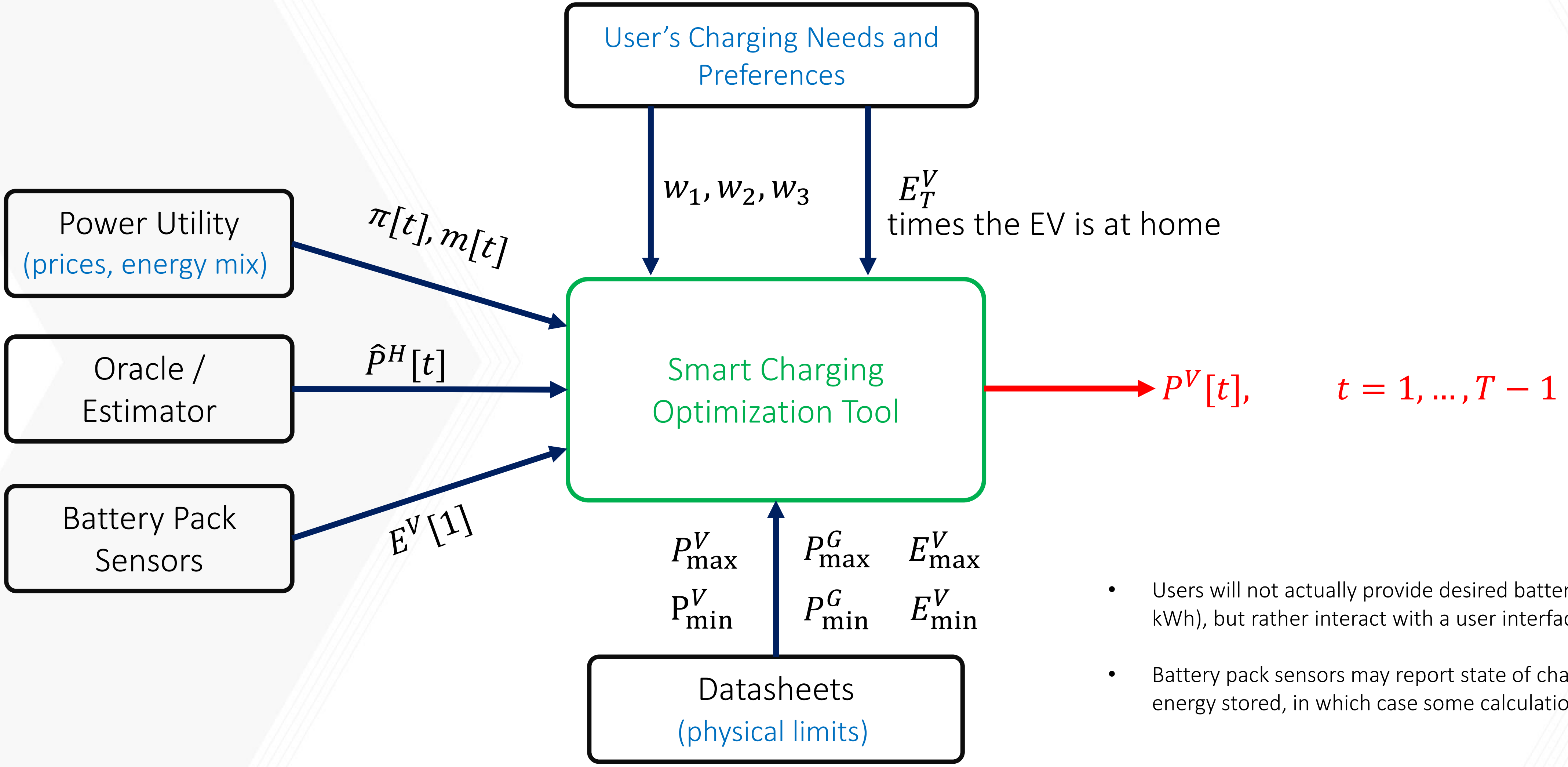
Schematic of smart charger prototype under development

EV charging cable plugs into receptacle in smart charger

Thank you for this opportunity!

Backup Slides for Questions

Data Requirements



- Users will not actually provide desired battery energy levels (in kWh), but rather interact with a user interface
- Battery pack sensors may report state of charge instead of energy stored, in which case some calculations will be needed

Stage 1: Formulation Details

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- Three terms: J_1, J_2, J_3; User-selectable weights for each term: w_1, w_2, w_3
- All terms and constraints are linear in the optimization variables

$$\text{minimize } \; w_1 J_1 + w_2 J_2 + w_3 J_3$$

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

To minimize $ paid to utility

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

To minimize kWh of **non-RE** consumed

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

To minimize charging time (units are not meaningful)

For $t = 1, \dots, T$:

$$P^G[t] = P^V[t] + \hat{P}^H[t]$$ Power balance

$$P^G_{\min} \leq P^G[t] \leq P^G_{\max}$$ Max. power draw from grid

$$P^V[t] \in \{P^V_{\min}, P^V_{\max}\}$$ EV: (dis)charging power limits

$$E^V_{\min} \leq E^V[t] \leq E^V_{\max}$$ EV: stored energy limits

For $t = 2, \dots, T$:

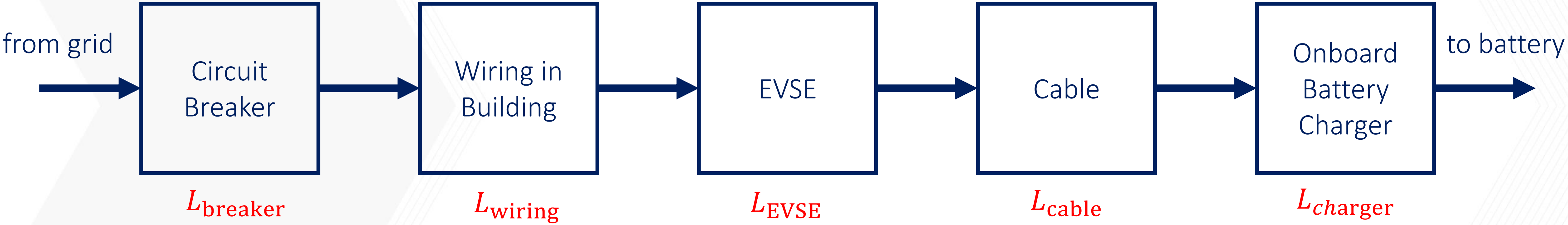
$$E^V[t] = E^V[t] + \Delta \, P^V[t-1]$$ Battery dynamics (LTI discrete-time model)

For $t = 1, T$:

$$E^V[1] \text{ and } E^V[T] \text{ specified}$$ Boundary conditions (either auto-specified, or obtained from user)

Determination of $P^V_{\max}$

Power flow path during EV charging:



Each component on the power flow path has an associated power flow limit, $L_{\text{component}}$

We must respect <u>all</u> relevant power flow limits. Therefore:

$$P^V_{\max} = \min\ \{L_{\text{breaker}}, L_{\text{wiring}}, L_{\text{EVSE}}, L_{\text{cable}}, L_{\text{charger}}\}$$