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Electric Vehicle Smart Charging to Maximize Renewable Energy Usage in a Single Residence

Kartik V. Sastry [1], Prof. Thomas F. Fuller [2], Prof. Santiago Grijalva [1], Prof. David G. Taylor [1], Prof. Michael J. Leamy [3]

[1] School of Electrical and Computer Engineering, Georgia Tech, Atlanta, Georgia, USA
[2] School of Chemical and Biomolecular Engineering, Georgia Tech, Atlanta, Georgia, USA
[3] School of Mechanical Engineering, Georgia Tech, Atlanta, Georgia, USA

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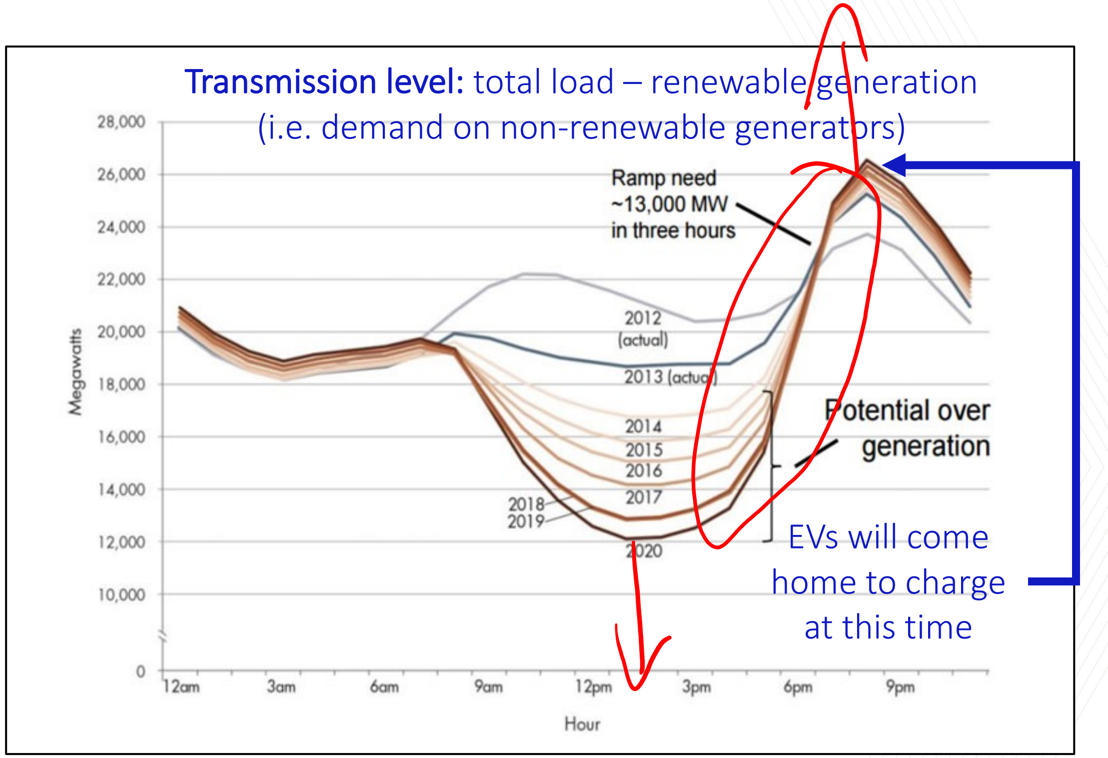
Introduction

- 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, 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

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

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Scope of our Study, Contributions

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- Literature review
  - Most studies consider a *single* objective function. Choice of objective functions varies due to multi-stakeholder nature (Kong, 2016) (Nimalsiri, 2020)
  - Few studies balance one EV owner-centric, one utility-centric objective (Das, 2020) (Das, 2021)
  - **Gap:** Interests of EV owners (and the utility) may not be represented well by a single objective function
  - **Gap:** Utilization of renewable energy is not often considered
- We adopt an EV owner-Centric viewpoint to limit scope
- Our contributions (focus of this presentation)
  - Introduced renewable energy consumption as a smart charging objective
  - Developed a framework for multi-objective smart charging in a single residence
    - How to formulate and solve the smart charging problem
    - How to reveal tradeoffs inherent to the problem
  - We believe that this is the most comprehensive treatment of EV owner-centric smart charging to date

Objective functions from the smart charging literature

Utility/Grid-Centric	EV Owner-Centric
Load profile flattening	Maximize convenience
Minimize transmission loss	Maximize fairness
Maximize utilization	Minimize battery degradation
Maximize profit	Minimize charging costs
Regulate power quality	Maximize profit from grid services

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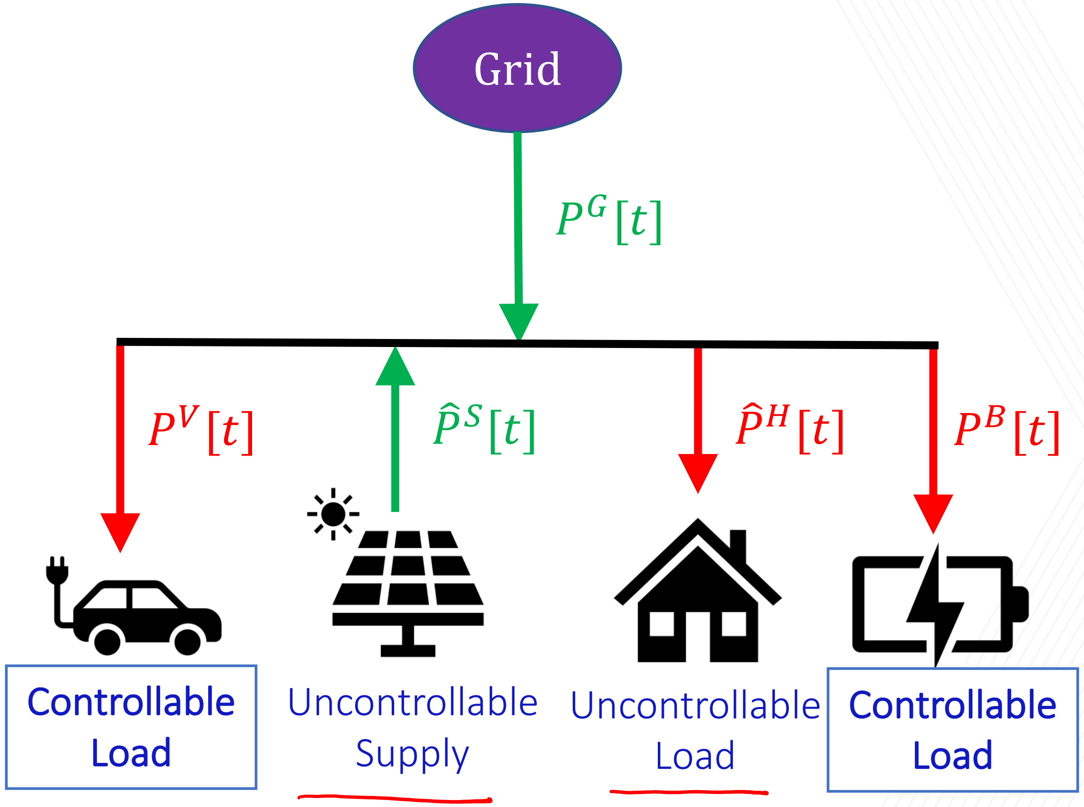
Details: Home Model

- $P^G[t]$ [kW]: Net power flow *from* grid
- $\hat{P}^H[t]$ [kW]: Estimated power flow *into* home
- $\hat{P}^S[t]$ [kW]: Estimated power flow *from* local solar
- $P^V[t]$ [kW]: Controlled power flow *into* vehicle battery
- $P^B[t]$ [kW]: Controlled power flow *into* storage battery

- Power balance (assume lossless interconnection):

$$P^G[t] + \hat{P}^S[t] = P^V[t] + P^B[t] + \hat{P}^H[t]$$

- Variations:
  - Bidirectional power flow (dis)allowed with grid
  - Bidirectional power flow (dis)allowed with EV
  - Bidirectional power flow (dis)allowed with storage battery
  - No storage battery / solar panel present



Smart charging: Determine the `best' way to (dis)charge the controllable devices over time

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Utilization of Renewable Energy

- Utilization of renewable energy should be considered as a smart charging objective
  - Environmentally-conscious EV owners may want to maximize their renewable energy consumption
  - Utilities may want to incentivize EV owners to do this. If many EV owners opt-in:
    - Less concern about over-generation around mid-day
    - Utilities can rely more on renewable sources (less on fossil sources!)
- Maximizing renewable energy consumption in a home:
  - Utilities purchase power from several generating resources, including renewable sources
    - Utilities can keep track of the "grid mix" and broadcast this information (e.g. $m[t]$)
    - Broadcast can leverage existing infrastructure used for time-of-use price signals
  - Homeowners *can never* know the origins of the electrons flowing into their home
  - *But* homeowners *can* rely more on the grid when the grid is fed by renewable sources!
- Consider the smart charging objective:

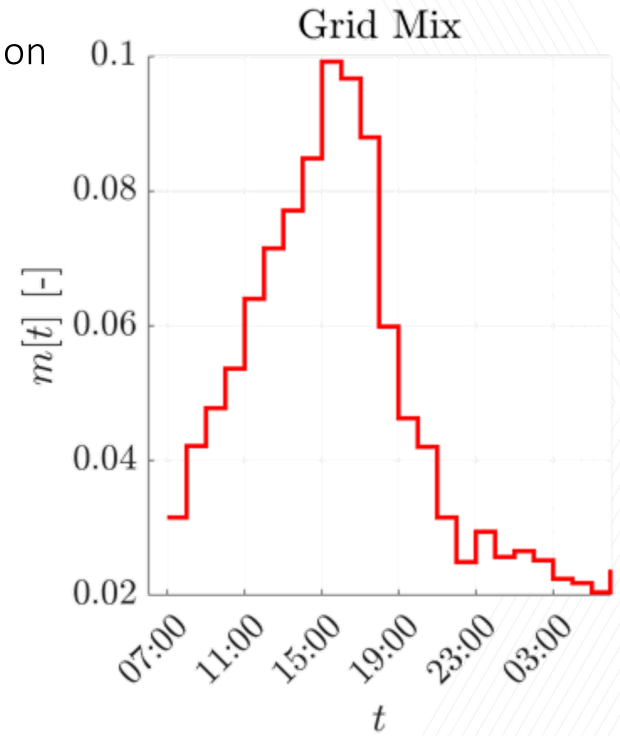
$$\underset{P^V[t],\, P^B[t]}{\text{minimize}} \sum_{t=1}^{T-1} \left[\left(m[t]P^G[t] + \hat{P}^S[t]\right) - \left(\hat{P}^H[t] + P^V[t] + P^B[t]\right)\right]^2$$

Decision variables

Easy to account for local solar (zero if none present)

renewable "supply"

Total demand (house + charging)



Example grid mix signal from electric utility in Atlanta, GA

$$\text{Grid Mix} = \frac{\text{Power output from renewable sources}}{\text{Power output from all sources}}$$

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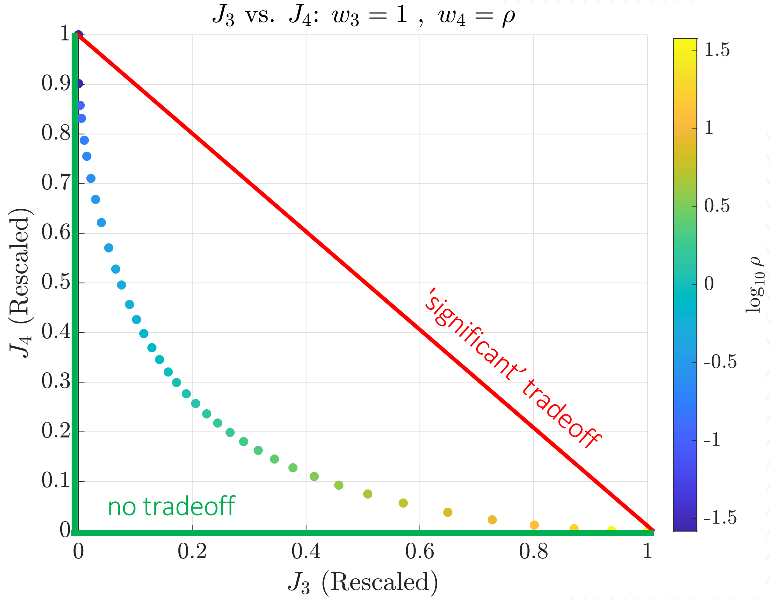
Multi-Objective Smart Charging

- EV owners probably have multiple objectives which they might expect to *simultaneously* achieve
  - **Examples:** maximize renewable energy consumption, charge as fast as possible, minimize battery degradation
  - Represent each objective with a functional (to be minimized): $J_1, \dots, J_N$
- Natural formulation:

$$\underset{P^V, P^B}{\text{minimize}} \begin{bmatrix} J_1(P^V, P^B) \\ \vdots \\ J_N(P^V, P^B) \end{bmatrix} \quad \text{subject to:} \begin{cases} \text{Power balance} \\ \text{Power/energy upper/lower bounds} \\ \text{Battery dynamics} \\ \text{Initial/final battery energy levels} \end{cases}$$

- All objectives cannot be simultaneously minimized ⇒ *Pareto optimality*
  - At a Pareto optimal solution: performance improvements in one objective can only be achieved by *sacrificing* performance in another objective
  - Inherent tradeoffs in the problem revealed by *set of all* Pareto optimal solutions
  - EV owners should be informed of these tradeoffs!
- For *any* choice of positive weights, **minimize** $\sum_{n=1}^{N} w_n J_n$ yields a Pareto optimal solution to the above problem *if* $J_1, \dots, J_N$ *are all* ***convex***
  - Revealing tradeoffs: Solve *many* instances of above problem, *vary* $w_1, \dots, w_N$
  - Convex formulation makes revealing tradeoffs computationally feasible



Visualization of a Pareto frontier in the "objective-space". Axes are rescaled using min./max. values. Here:

$$J_3 = \sum_{t=1}^{T-1} t\, P^V[t] \quad \text{(charge quickly)} \qquad J_4 = \sum_{t=1}^{T-1} (P^V[t])^2 + (P^B[t])^2 \quad \text{(charge gently)}$$

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Multi-Objective Smart Charging

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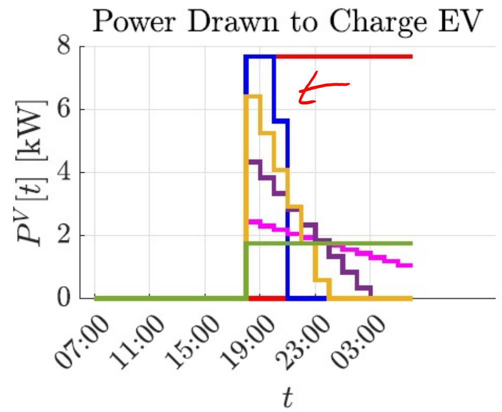
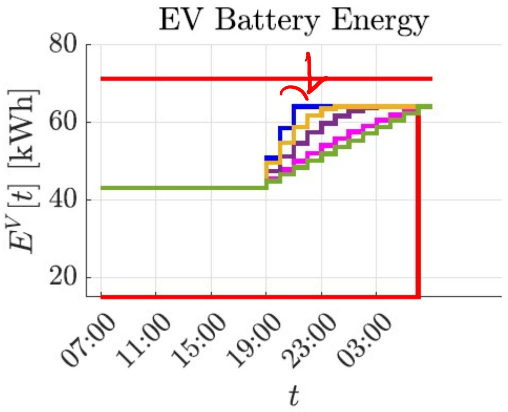
- Critical to ensure that *each* of $J_1, \ldots, J_N$ is a *convex function* of $P^V[t], P^B[t]$
  - Some design is needed. Not all desires are naturally represented by a convex function
- **Example:** Our EV-owner-centric smart charging objective function
  - Weighted sum of four convex functionals, $J_{\{1,2,3,4\}}$. Weights are user-selectable
  - $\underset{P^V[t],\,P^B[t]}{\text{minimize}} \quad w_1 J_1 + w_2 J_2 + w_3 J_3 + w_4 J_4$
    - Decision variables: $P^V[t], P^B[t]$
    - J_1: Min. $ paid to utility
    - J_2: Max. renewable energy consumption
    - J_3: Max. EV charging urgency
    - J_4: Min. battery degradation
  - **Constraints:** Power balance; EV/storage (dis)charging power limits; Max. power draw from grid; EV/storage battery energy limits, battery dynamics, energy boundary conditions
- Virtues
  - Formulation is comprehensive, flexible, allows for human input
  - Problem is *convex by design:* solvers are mature and efficient, revealing tradeoffs is easy
    - Our problem can be expressed as a quadratic program: $\underset{\boldsymbol{x}}{\text{minimize}} \ \ \boldsymbol{x}^{\mathrm{T}}\boldsymbol{H}\boldsymbol{x} + \boldsymbol{f}^{\mathrm{T}}\boldsymbol{x} \quad \text{subject to} \quad \boldsymbol{A}\boldsymbol{x} \leq \boldsymbol{b}$
    - Checking problem feasibility = solving a linear program: $\underset{\boldsymbol{x}}{\text{minimize}} \ \boldsymbol{0}^{\mathrm{T}}\boldsymbol{x} \ \text{subject to} \ \boldsymbol{A}\boldsymbol{x} \leq \boldsymbol{b}$
    - Can choose to solve problem as a *series* of optimization problems (exploiting optimal substructure). This may help overcome uncertainty / unexpected variations in input data, **see our paper!**

Charging urgency and battery degradation can be traded off by varying w_3 and w_4





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Summary, Conclusions

- Interests of EV owners may not be represented well by a single smart charging objective. EV owner-centric smart charging must therefore be viewed as a multi-objective optimization problem

- We introduced renewable energy consumption as a smart charging objective
  - And borrowed others from the literature to develop a comprehensive and flexible objective function

- We developed a *framework* for treating multi-objective smart charging problems in a single residence
  - We treated the EV owner-centric case, but the ideas apply also to the utility-centric case (see table on Slide 3)
  - We insisted on formulating the smart charging problem as a convex optimization problem
  - Our insistence on a convex problem formulation allowed us to *efficiently* reveal tradeoffs between multiple objectives
  - We also developed a post-processing method to easily present tradeoffs to a human – **see our paper!**
  - Convex problem formulation also has other benefits:
    - Checking problem feasibility is easy
    - May help overcome uncertainty / unexpected variations in input data, **see our paper!**

Next Steps

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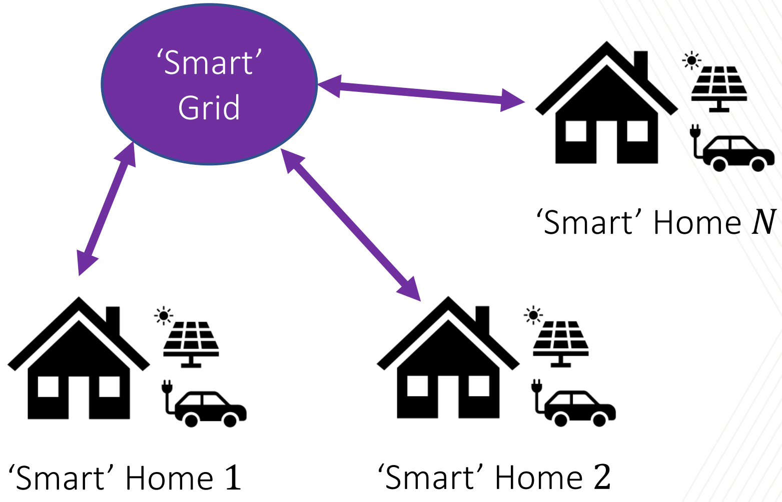
- We plan to:
  - Demonstrate that the power utility can obtain benefits by influencing selection of weights in homes operating independently using the proposed smart charging strategy
  - Assess the grid impact of multiple homes operating independently using the proposed smart charging strategy
  - Develop a hardware demonstration of smart charging featuring embedded optimization solvers
  - Study how to coordinate the charging of multiple EVs without a centralized decision maker
  - Study how EV owners and the utility (where both parties self-interested) can interact to address utility-side needs



Thank you for this opportunity!

Details: Smart Charger Integration

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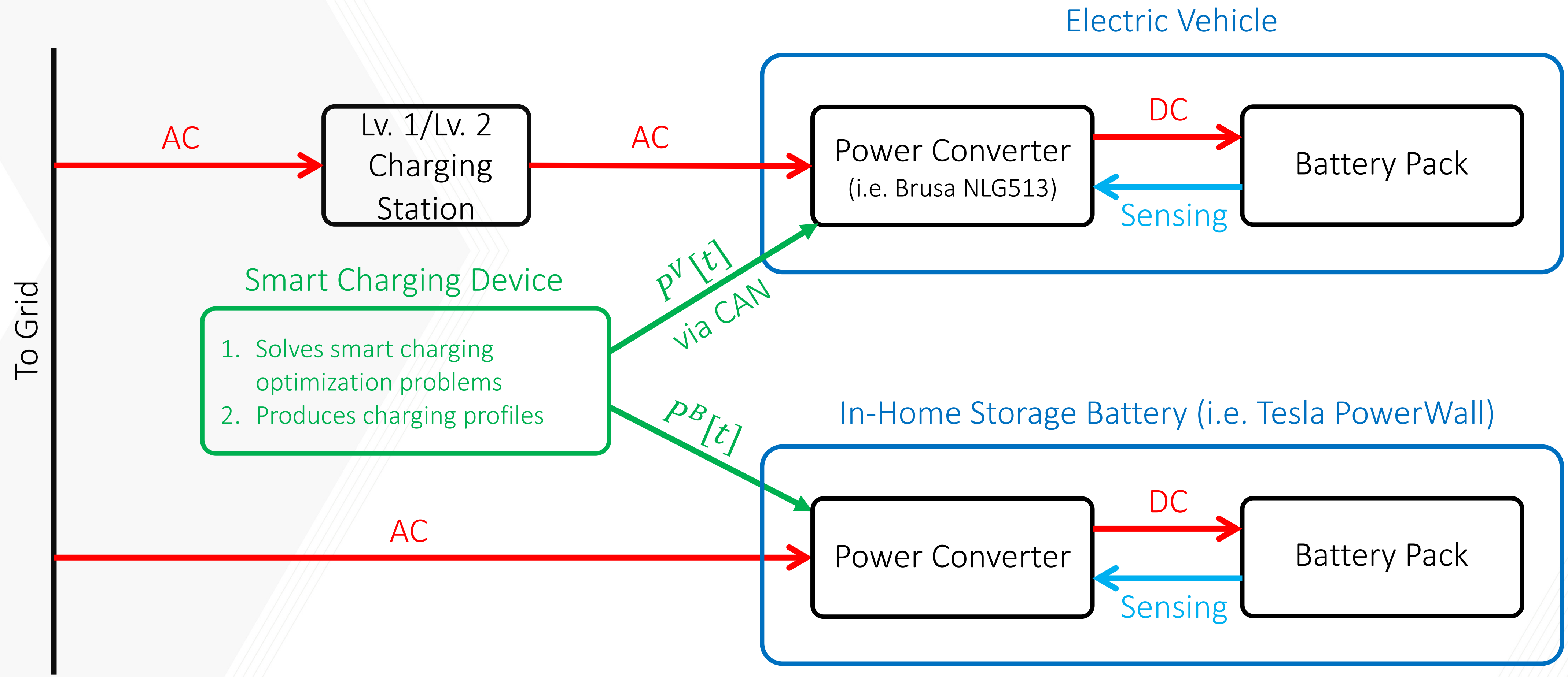
- We assume that battery power converters will relinquish authority over (dis)charging to us:



Details: Data Requirements

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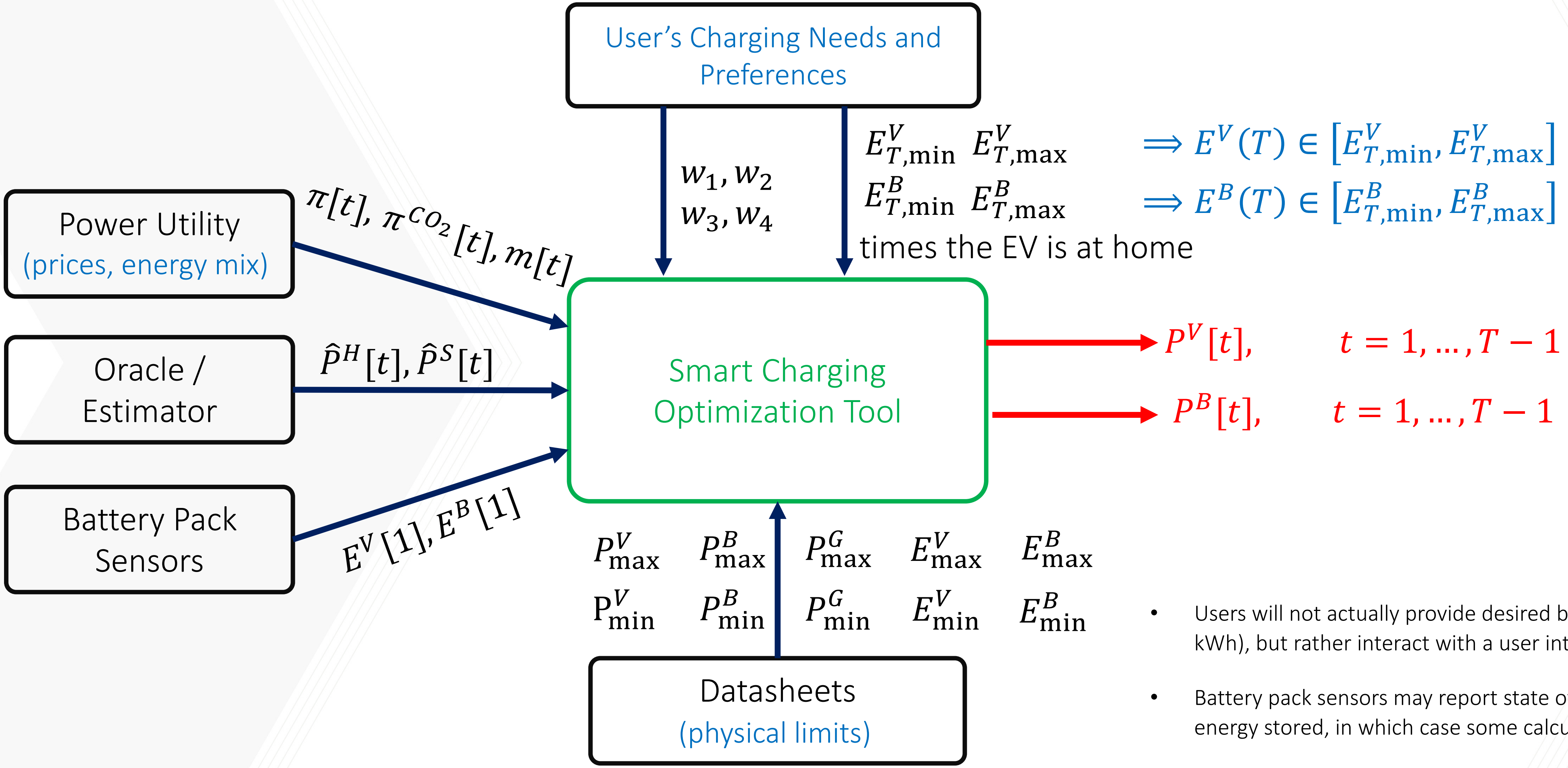

- Users will not actually provide desired battery energy levels (in kWh), but rather interact with a user interface
- Battery pack sensors may report state of charge instead of energy stored, in which case some calculations will be needed

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Details: Objective Function

- Four terms: J_1, J_2, J_3, and J_4; User-selectable weights for each term: w_1, w_2, w_3, and w_4
- All four terms are either linear or quadratic in the optimization variables

- Blue: Decision variable
- Orange: Input data

$$\text{minimize } w_1 J_1 + w_2 J_2 + w_3 J_3 + w_4 J_4$$

$$J_1 = \sum_{t=1}^{T-1} (\pi[t] + \pi^{CO_2}[t]) P^G[t]$$

Min. payments to the utility

$$J_2 = \sum_{t=1}^{T-1} \Big[\underbrace{\big(m[t]P^G[t] + \hat{P}^S[t]\big)}_{\text{renewable supply}} - \underbrace{\big(\hat{P}^H[t] + P^V[t] + P^B[t]\big)}_{\text{total demand}}\Big]^2$$

Use up renewable energy

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

Charge EV aggressively

$$J_4 = \sum_{t=1}^{T-1} (P^V[t])^2 + (P^B[t])^2$$

Min. battery degradation

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Details: Constraints

- All constraints are linear in the optimization variables.

- Blue: Decision variable
- Orange: Input data

Can be < 0 if bidirectional power flow allowed

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

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

$$P^G_{\min} \le P^G[t] \le P^G_{\max}$$ Limits on power flow to/from grid

$$P^V_{\min} \le P^V[t] \le P^{EV}_{\max}$$

$$P^B_{\max} \le P^B[t] \le P^B_{\max}$$ Limits on power flow to/from batteries

$$E^V_{\min} \le E^V[t] \le E^V_{\max}$$

$$E^B_{\min} \le E^B[t] \le E^B_{\max}$$ Limits on energy stored in batteries

For $t = 1, \ldots, T-1$:

$$E^V[t+1] = E^V[t] + \Delta P^V[t]$$

$$E^B[t+1] = E^B[t] + \Delta P^B[t]$$ Battery dynamics

For $t = 1, T$:

$$E^V[1] \text{ specified, } E^V[T] \in [E^V_{T,\min}, E^V_{T,\max}]$$

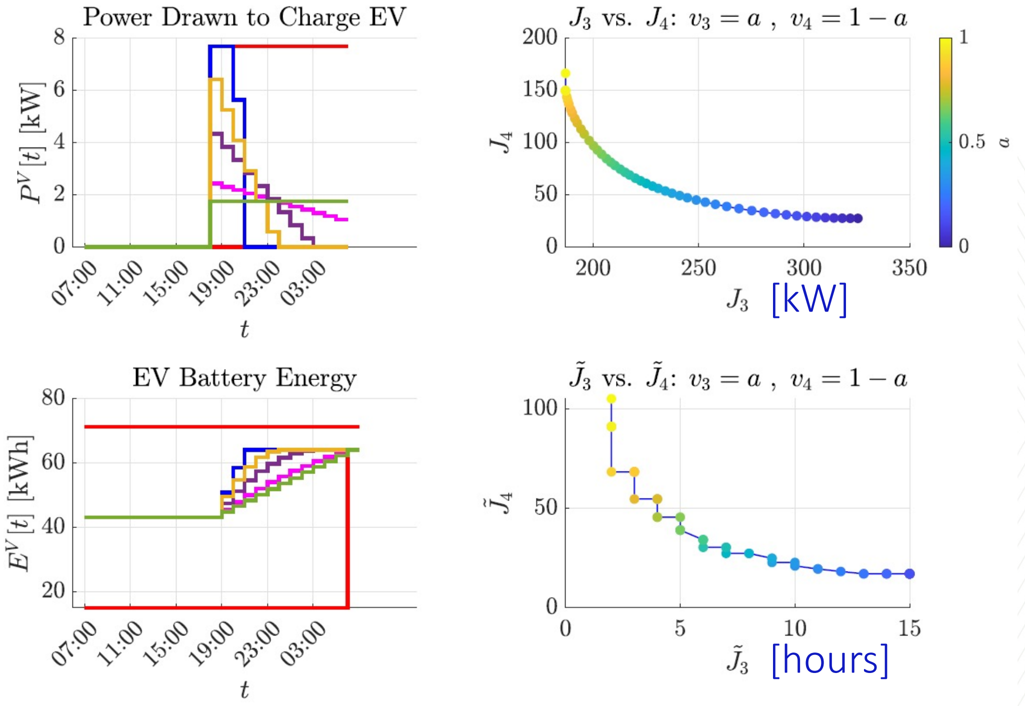
$$E^B[1] \text{ specified, } E^B[T] \in [E^B_{T,\min}, E^B_{T,\max}]$$

Boundary conditions
(either auto-specified, or obtained from user)

Details: Revealing Tradeoffs

- Objective function terms designed to be convex, not necessarily to be easily-interpretable
  - E.g. minimizing $J_3(P^V) = \sum_{t=1}^{T-1} t\, P^V[t]$ will charge the EV as fast as possible, but J_3 does not have units of time
- Change how we present the tradeoffs to a human by post-processing Pareto-optimal solutions
  - Each Pareto optimal solution corresponds to a charging schedule
  - Charging schedule can be used to evaluate more easily interpretable performance functionals (proxy functionals)
  - Create *up to two* functionals to represent a particular smart charging objective/desire

Convex Functional	Interpretable Functional
Not necessarily most interpretable	Not necessarily a convex function of decision variables
Used for solving smart charging optimization problems and revealing tradeoffs	Used to post-process solutions and reveal tradeoff curves with interpretable units



Example from paper in which charging urgency (J_3,$\tilde{J}_3$) and battery degradation (J_4,$\tilde{J}_4$) are traded off

Aside: v_3 and v_4 are related to w_3 and w_4. Some details are omitted in this presentation

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