A RELIABILITY-AWARE DISTRIBUTED FRAMEWORK TO SCHEDULE RESIDENTIAL CHARGING OF ELECTRIC VEHICLES

Presented by Rounak Meyur

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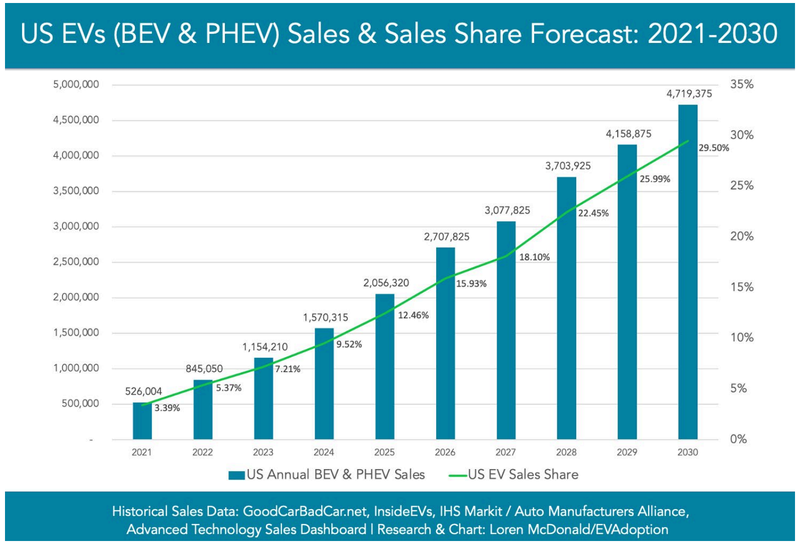
MOTIVATION



EV home charging startups on the rise

The number of startup companies offering residential charging services for electric vehicles has risen to more than 100 in Europe and more than 50 in the United States.

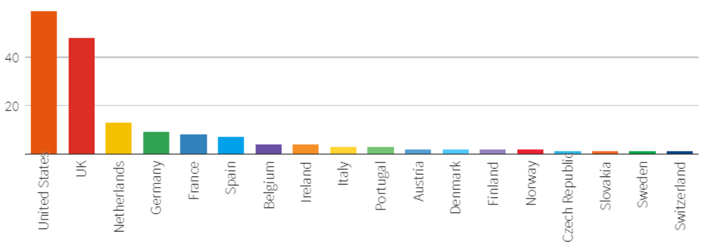
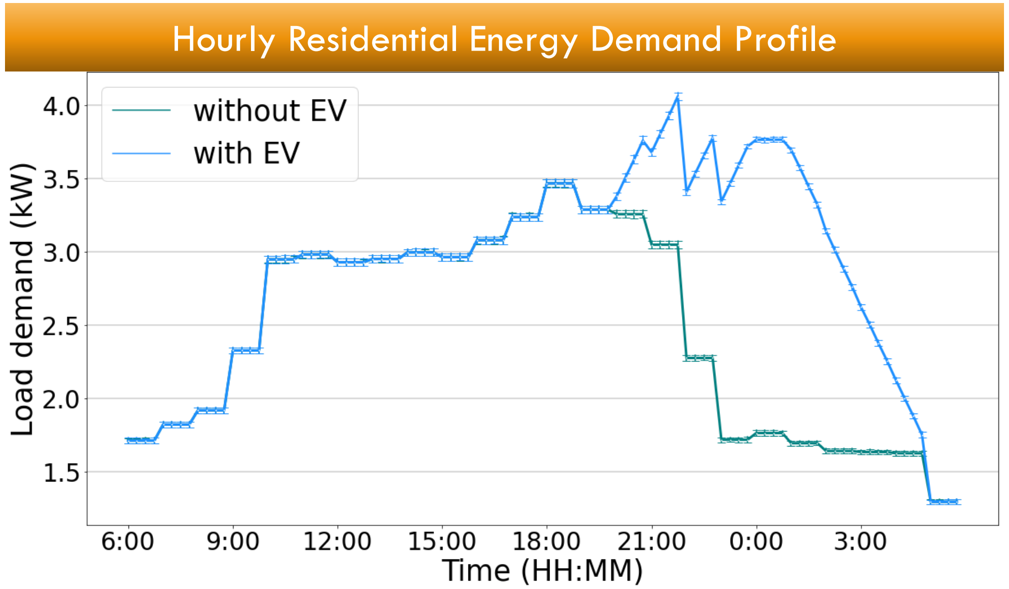


Image source: Reuters



Residential EV charging accounts for a significant amount of increase in average household energy consumption

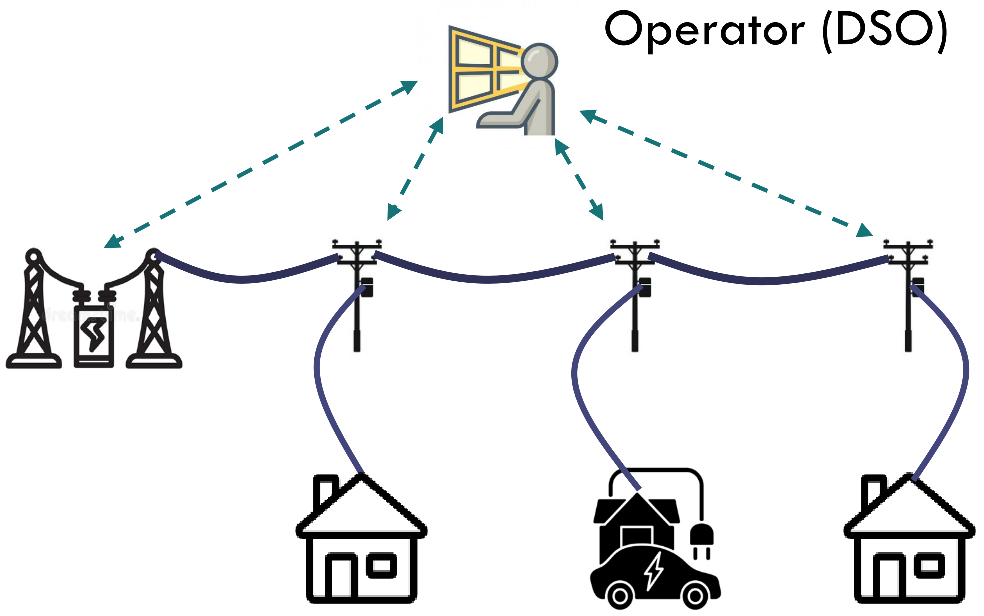
PROBLEM STATEMENT

Find out the best schedule for residential EV charging which

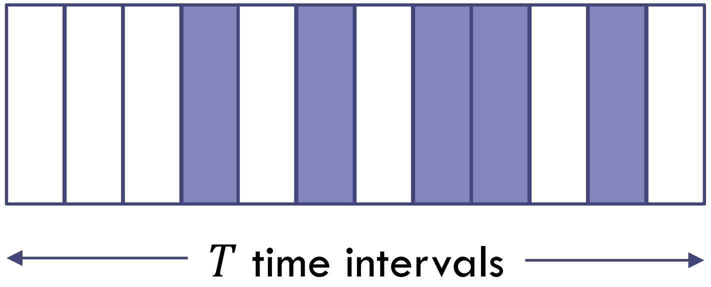
- accommodates consumer preferences.
- maintains network reliability.

Reliable network

- Node voltages within acceptable limits (0.95 – 1.05 p.u.).
- Line power flows less than line capacities.



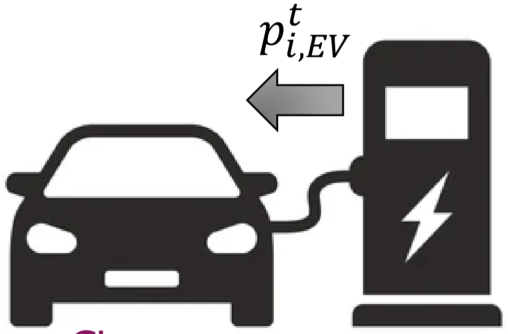
PROBLEM FORMULATION: A SINGLE RESIDENTIAL CONSUMER



$z_i^t = 0$: No EV charging
$z_i^t = 1$: EV charging

$$p_{i,EV}^t = z_i^t P_{i,EV}$$

Power consumed only for selected intervals



Charge capacity $Q_{i,EV}$

Charger power rating $P_{i,EV}$

Find optimal time intervals to charge EV at minimum cost.

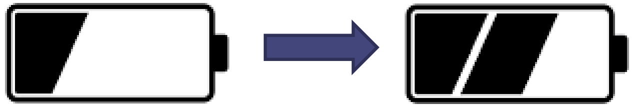
- c_i^t: tariff rate
- p_i^t: power consumption

$$p_i^t = p_{i,EV}^t + p_{i,0}^t$$

- Goal:

$$\min \sum_{t=1}^{T} c_i^t p_i^t$$

Evolution of state of charge

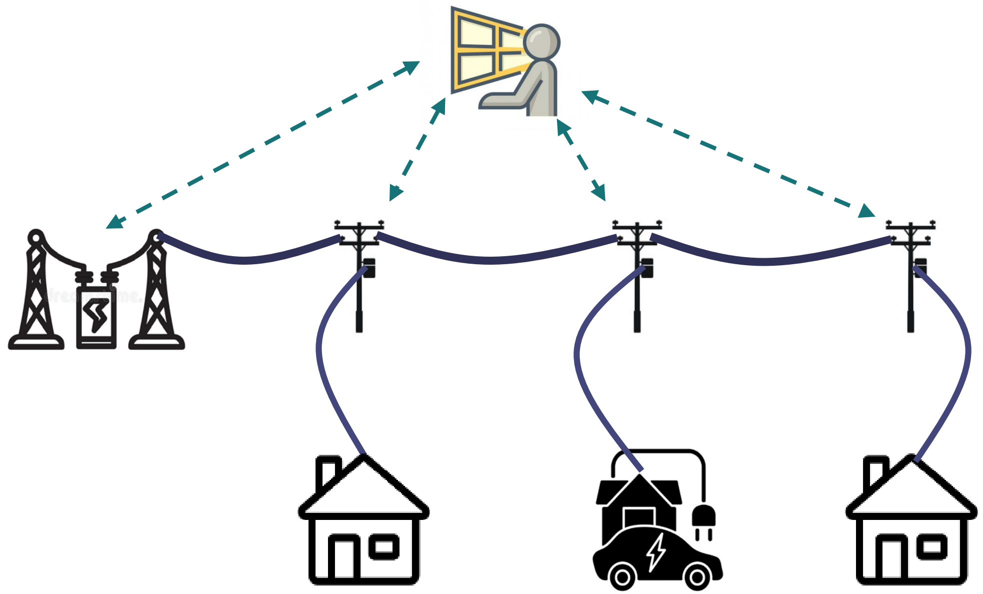


s_i^{t-1} s_i^t

$$s_i^t = s_i^{t-1} + \frac{p_{i,EV}^t}{Q_{i,EV}}$$

PROBLEM FORMULATION: DISTRIBUTION SYSTEM OPERATOR

- DSO reliability objectives:
  - Edge power flows within line ratings.
  - Node voltages within engineering standards.
- ANSI standard for distribution network voltages[1].
  - Lower limit: $\alpha = 0.95$ pu
  - Upper limit: $\beta = 1.05$ pu.
  - $\alpha\mathbf{1} \leq \mathbf{v} \leq \beta\mathbf{1}$
- DSO personal objectives:
  - Minimize losses.
  - Minimize voltage deviation.



[1] American National Standards Institute ANSI. ANSI C84.1-2020: Electric Power Systems Voltage Ratings (60 Hz), 2020

REVS: RELIABILITY AWARE EV CHARGE SCHEDULING

$$
\begin{aligned}
\min \quad & \sum_{t=1}^{T} c_i^t p_i^t \\
\text{over} \quad & p_i^t, s_i^t, z_i^t && \forall t \\
\text{s.t.} \quad & p_i^t = p_{i,0}^t + p_{i,\text{EV}}^t && \forall t \\
& p_{i,\text{EV}}^t = z_i^t P_{i,\text{EV}} && \forall t \\
& s_i^t = s_i^{t-1} + \frac{p_{i,\text{EV}}^t}{Q_{i,\text{EV}}} && \forall t \\
& z_i^t \in \{0,1\} && \forall t \\
& z_i^t = 0 \quad \forall t \le t_{\text{start}}, \ \forall t \ge t_{\text{end}} \\
& s_i^{t_{\text{start}}} = s_{i,\text{init}}, \ s_i^{t_{\text{end}}} \ge s_{i,\text{final}}
\end{aligned}
$$

Consumer optimization (MILP)

+

$$
\begin{aligned}
\min \quad & \sum_{t=1}^{T} C\left(\mathbf{p}^t\right) \\
\text{over} \quad & \mathbf{p}^t \\
\text{s.t.} \quad & \alpha \mathbf{1} \le -2\mathbf{R}\mathbf{p}^t + \mathbf{1} \le \beta \mathbf{1} && \forall t \\
& -\bar{\mathbf{f}} \le \mathbf{A}^{-1}\mathbf{p} \le \bar{\mathbf{f}} && \forall t
\end{aligned}
$$

DSO optimization (LP or QP)

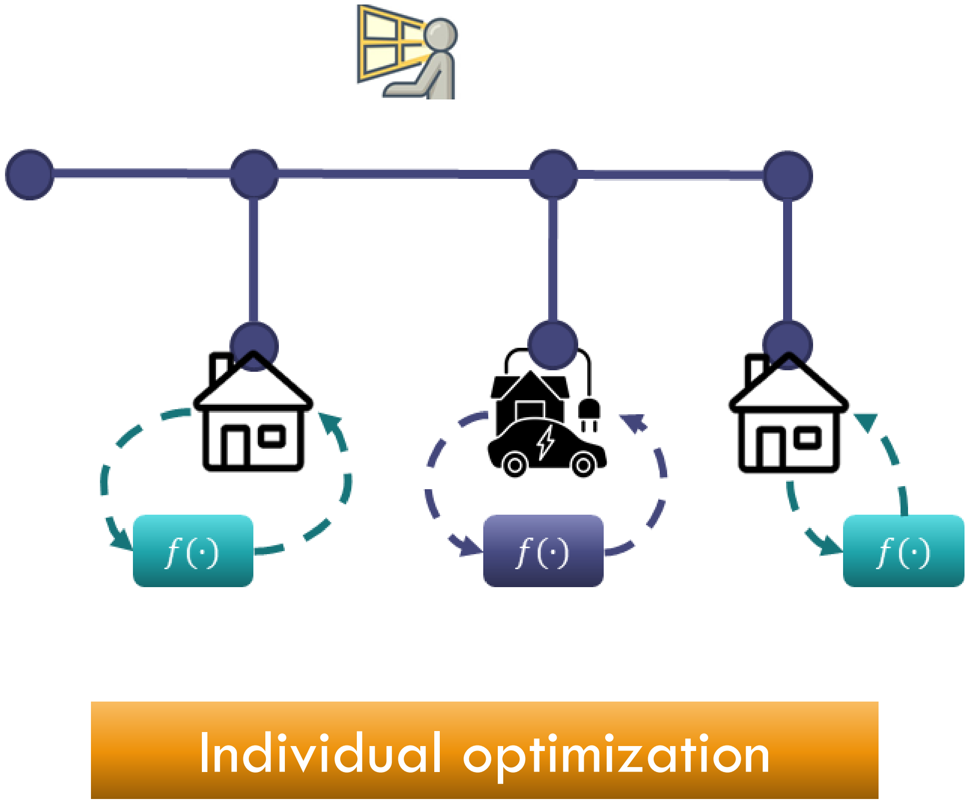
→

$$
\begin{aligned}
\min \quad & \sum_{t=1}^{T} C\left(\mathbf{p}^t\right) + \sum_{i\in\mathcal{H}} \sum_{t=1}^{T} c_i^t p_i^t \\
\text{over} \quad & p_i^t, s_i^t, z_i^t && \forall t, \forall i \in \mathcal{H} \\
\text{s.t.} \quad & p_i^t = p_{i,0}^t + p_{i,\text{EV}}^t && \forall t, \forall i \in \mathcal{H} \\
& p_{i,\text{EV}}^t = z_i^t P_{i,\text{EV}} && \forall t, \forall i \in \mathcal{H} \\
& s_i^t = s_i^{t-1} + \frac{p_{i,\text{EV}}^t}{Q_{i,\text{EV}}} && \forall t, \forall i \in \mathcal{H} \\
& z_i^t \in \{0,1\} && \forall t, \forall i \in \mathcal{H} \\
& z_i^t = 0 && \forall t \le t_{\text{start}}, \forall i \in \mathcal{H} \\
& z_i^t = 0 && \forall t \ge t_{\text{end}}, \forall i \in \mathcal{H} \\
& s_i^{t_{\text{start}}} = s_{i,\text{init}} && \forall i \in \mathcal{H} \\
& s_i^{t_{\text{end}}} = s_{i,\text{final}} && \forall i \in \mathcal{H} \\
& p_i^t = 0 && \forall t, \forall i \notin \mathcal{H} \\
& \alpha \le 1 - 2\sum_j R_{ij} p_j^t \le \beta && \forall t, \forall i \\
& -\overline{f_k} \le \sum_j \left[\mathbf{A}^{-1}\right]_{kj} p_j^t \le \overline{f_k} && \forall t, \forall k \in \mathcal{E}
\end{aligned}
$$

Overall optimization (MILP or MIQP)

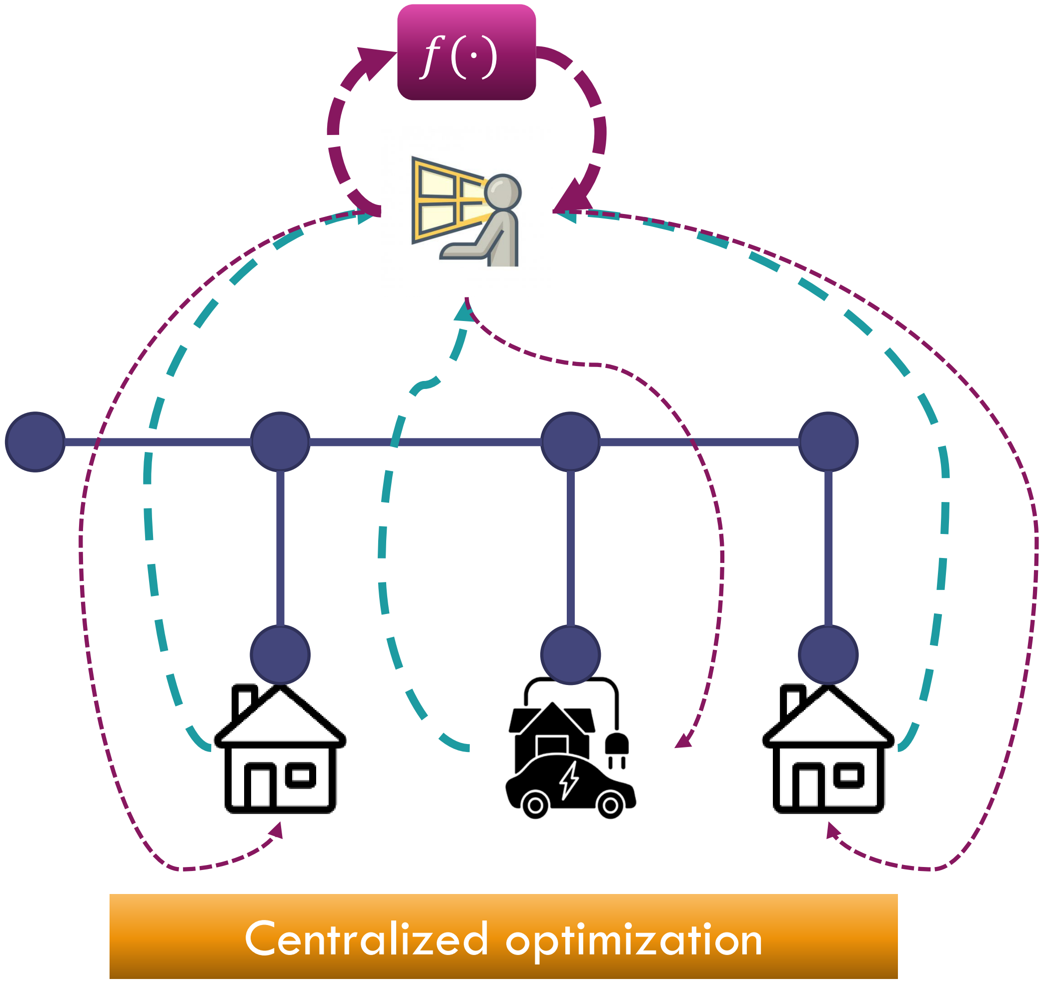
INDIVIDUAL APPROACH

- ❑ Each consumer solves own problem.
- ❑ No private information shared.
- ❑ No communication requirement.
- ❑ Optimal solution for individual consumer.
- ❑ Suboptimal or infeasible solution for DSO.



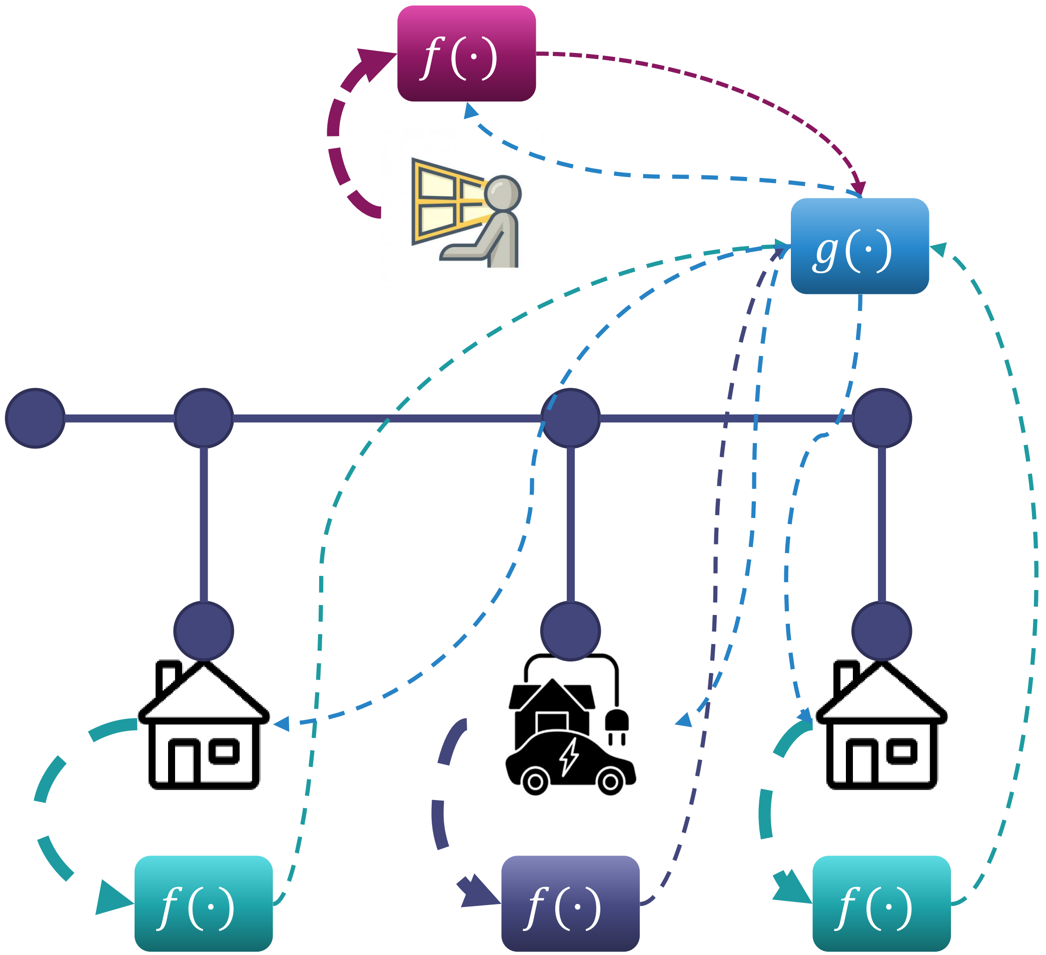
CENTRALIZED APPROACH

- ❑ All consumers share personal information with DSO.
- ❑ High bandwidth for communication required.
- ❑ Optimal solution guaranteed for consumers and DSO.



OUR APPROACH

- ❑ All consumers solve their own problem.
- ❑ DSO solves reliability problem.
- ❑ Optimal solutions are exchanged to reach consensus.
- ❑ Limited communication requirement.
- ❑ Limited exchange of information.
- ❑ Sub-optimal solution for consumers and DSO.



Distributed optimization

PROPOSED DISTRIBUTED APPROACH

DSO

Step 1: Update $\left\{\tilde{p}_i^t[l+1]\right\}_{t=1}^T \ \forall i$

$$\left\{\tilde{p}_i^t[l+1]\right\} = \min \sum_{i\in\mathcal{H}}\sum_{t=1}^{T} \frac{\kappa}{2}\left(\tilde{p}_i^t\right)^2 + \sum_{i\in\mathcal{H}}\sum_{t=1}^{T} \tilde{p}_i^t\left(\gamma_i^t[l] - \frac{\kappa}{2}\tilde{p}_i^t[l] - \frac{\kappa}{2}p_i^t[l]\right)$$
$$\text{s.t.}\quad \alpha \le 1 - 2\sum_j R_{ij}\tilde{p}_j^t \le \beta \quad \forall t, \forall i$$
$$-\overline{f}_k \le \sum_j \left[\mathbf{A}^{-1}\right]_{kj}\tilde{p}_j^t \le \overline{f}_k \quad \forall t, \forall k\in\mathcal{E}$$

Proprietary data
$\mathbf{A}, R, \alpha, \beta$

Step 2: Send $\left\{\tilde{p}_i^t[l+1]\right\}_{t=1}^T$ and receive $\left\{p_i^t\,[l+1]\right\}_{t=1}^T \ \forall i$

$\left\{\tilde{p}_i^t[l+1]\right\}_{t=1}^T$

$\left\{p_i^t\,[l+1]\right\}_{t=1}^T$

Step 3: Update $\left\{\gamma_i^t\,[l+1]\right\}_{t=1}^T \ \forall i$

$$\gamma_i^t[l+1] = \gamma_i^t[l] + \frac{\kappa}{2}\left(\tilde{p}_i^t[l+1] - p_i^t[l+1]\right)$$

Step 4: Check convergence

Consumer i

Step 1: Update $\left\{p_i^t\,[l+1]\right\}_{t=1}^T$

$$p_i^t[l+1] = \min \sum_{t=1}^{T} c_i^t p_i^t + \sum_{t=1}^{T}\frac{\kappa}{2}\left(p_i^t\right)^2 - \sum_{t=1}^{T} p_i^t\left(\gamma_i^t[l] + \frac{\kappa}{2}\tilde{p}_i^t[l] + \frac{\kappa}{2}p_i^t[l]\right)$$
$$\begin{aligned}\text{s.t.}\quad & p_i^t = p_{i,0}^t + p_{i,\mathrm{EV}}^t && \forall t\\ & p_{i,\mathrm{EV}}^t = z_i^t P_{i,\mathrm{EV}} && \forall t\\ & s_i^t = s_i^{t-1} + \frac{p_{i,\mathrm{EV}}^t}{Q_{i,\mathrm{EV}}} && \forall t\\ & z_i^t \in \{0,1\} && \forall t\\ & z_i^t = 0 && \forall t \le t_{\mathrm{start}}, \forall t \ge t_{\mathrm{end}}\\ & s_i^{t_{\mathrm{start}}} = s_{i,\mathrm{init}},\quad s_i^{t_{\mathrm{end}}} \ge s_{i,\mathrm{final}} \end{aligned}$$

Personal data
$\left\{p_{i,0}^t\right\}, P_{i,\mathrm{EV}}, Q_{i,\mathrm{EV}}, s_{\mathrm{init}}, s_{\mathrm{final}}, t_{\mathrm{start}}, t_{\mathrm{end}}$

Step 2: Receive $\left\{\tilde{p}_i^t[l+1]\right\}_{t=1}^T$ and send $\left\{p_i^t\,[l+1]\right\}_{t=1}^T$

$\left\{p_i^t\,[l+1]\right\}_{t=1}^T$

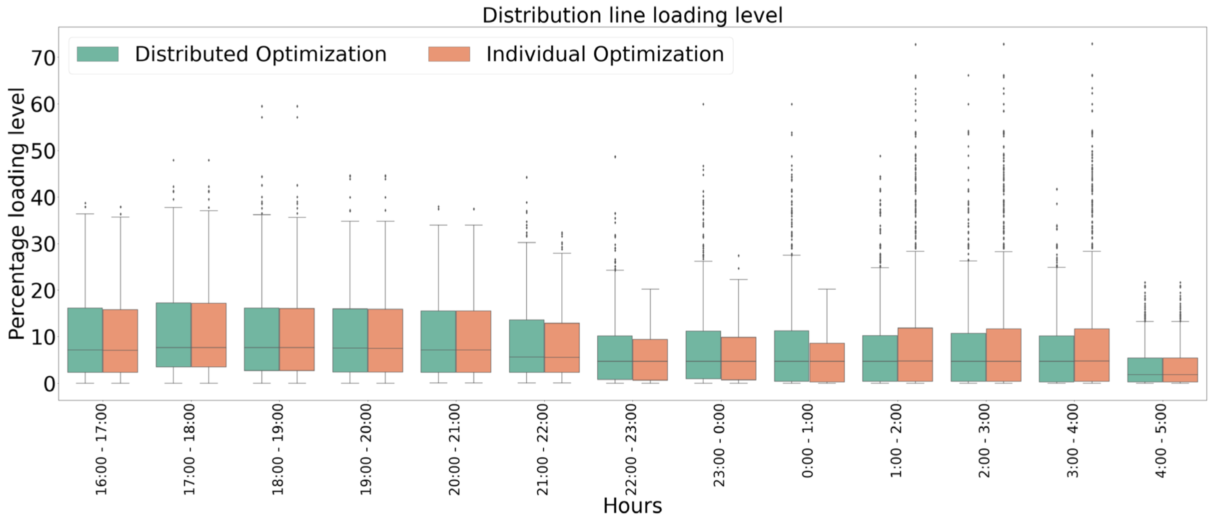
$\left\{\tilde{p}_i^t[l+1]\right\}_{t=1}^T$

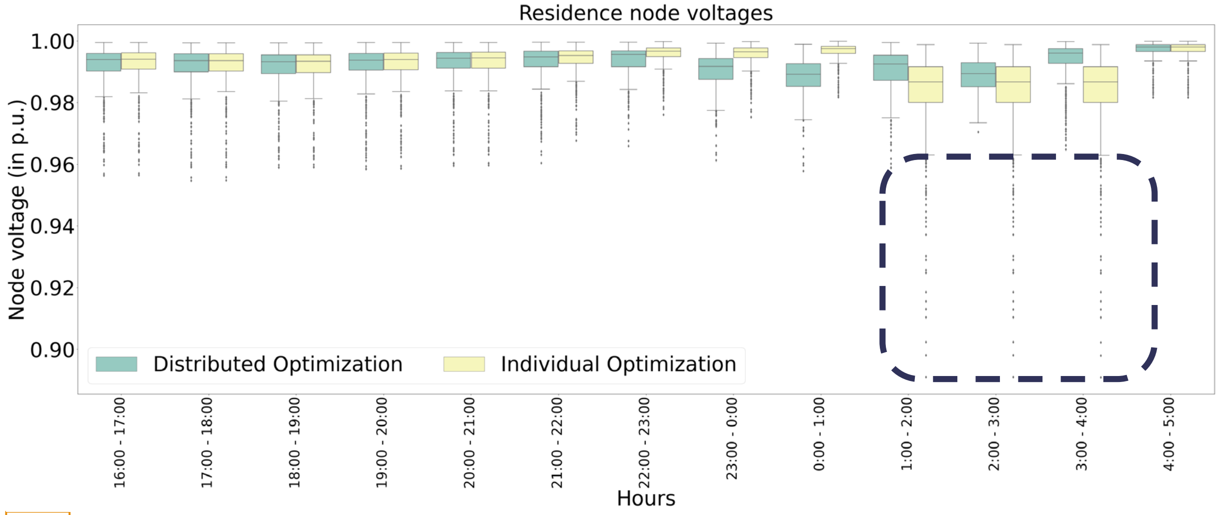
Step 3: Update $\left\{\gamma_i^t\,[l+1]\right\}_{t=1}^T$

$$\gamma_i^t[l+1] = \gamma_i^t[l] + \frac{\kappa}{2}\left(\tilde{p}_i^t[l+1] - p_i^t[l+1]\right)$$

Step 4: Check convergence

RESULTS





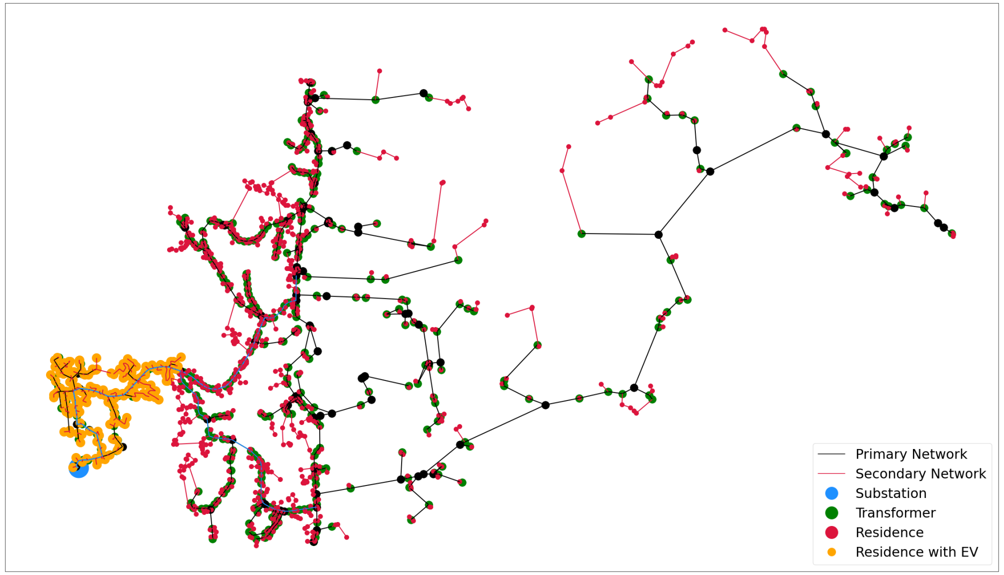
Electricity hourly tariff rates

Time Interval (HH:MM)	00:00 – 05:00	05:00 – 15:00	15:00 – 18:00	18:00 – 00:00
Tariff ($/kWh)	0.07866	0.09511	0.21436	0.09511

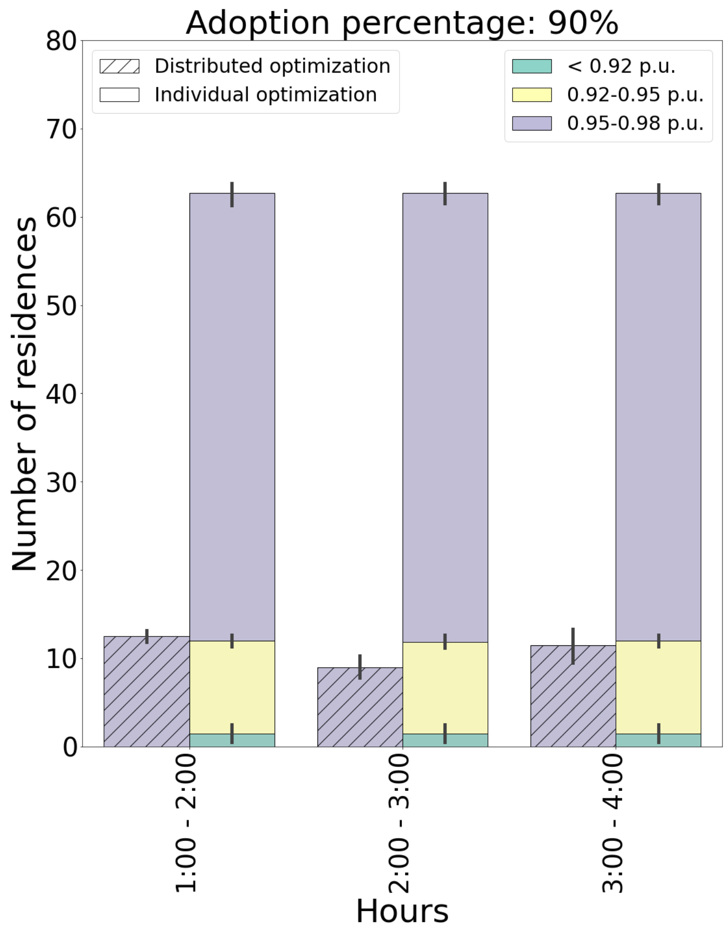
Key observations

- Line limits are not violated even at high EV adoption levels.
- Voltage limits are violated when EV charging is done in an uncoordinated way.

RESULTS



- We study impact of 90% EV adoption in a residential community.
- Individual optimization is compared to the proposed distributed approach.



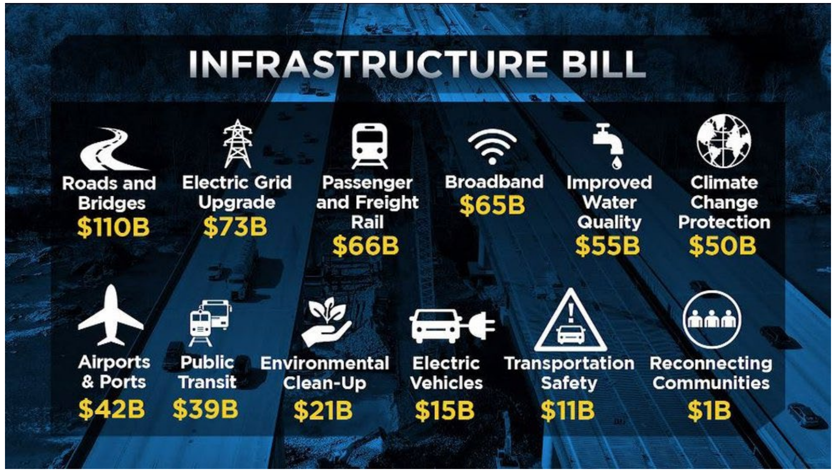
Higher level of reliability attained if consumers coordinate with the DSO

1. Thorve et.al, “High Resolution Synthetic Residential Energy Use Profiles for the United States”, Nature Scientific Data, 2022 (accepted for publication).
2. Meyur et.al, “Realistic Ensembles of Power Distribution Networks”, Proceedings of the National Academy of Sciences (PNAS), 2022 (provisionally accepted for publication).

CONCLUSIONS AND FUTURE WORK

Biden signs $1.2 trillion infrastructure bill with funding for EVs, transmission, hydrogen

Published Nov. 8, 2021 • Updated Nov. 16, 2021



Source: The Associated Press, Nov 7, 2021

Biden's $1.2 trillion infrastructure bill could take years to transform U.S.

By Jeff Stein and Michael Laris
August 10, 2021 at 12:43 p.m. EDT

Powering Smart Transportation

Smart Charging Infrastructure Pilot Program

The Smart Charging Infrastructure Pilot (or "SCIP") Program supports electric vehicle (EV) adoption in Virginia and will inform the design of managed charging programs and other EV customer offerings in the future.

The SCIP Program provides rebates for qualifying EV charging stations, charging infrastructure and installation, commonly referred to as "make-ready," and network fees. See rebate amounts in the table below.

March 23, 2021 Update: *The DCFC and Multi-family rebate segments are fully subscribed.*

June 20, 2022 Update: *The SCIP Program will end December 31, 2022. All applications must be submitted by November 30, 2022. All charging stations must be installed, active and communicating data by December 31, 2022 to receive rebate payments.*

Source: Dominion Energy Smart Charger Rebate Plan

OUR TEAM

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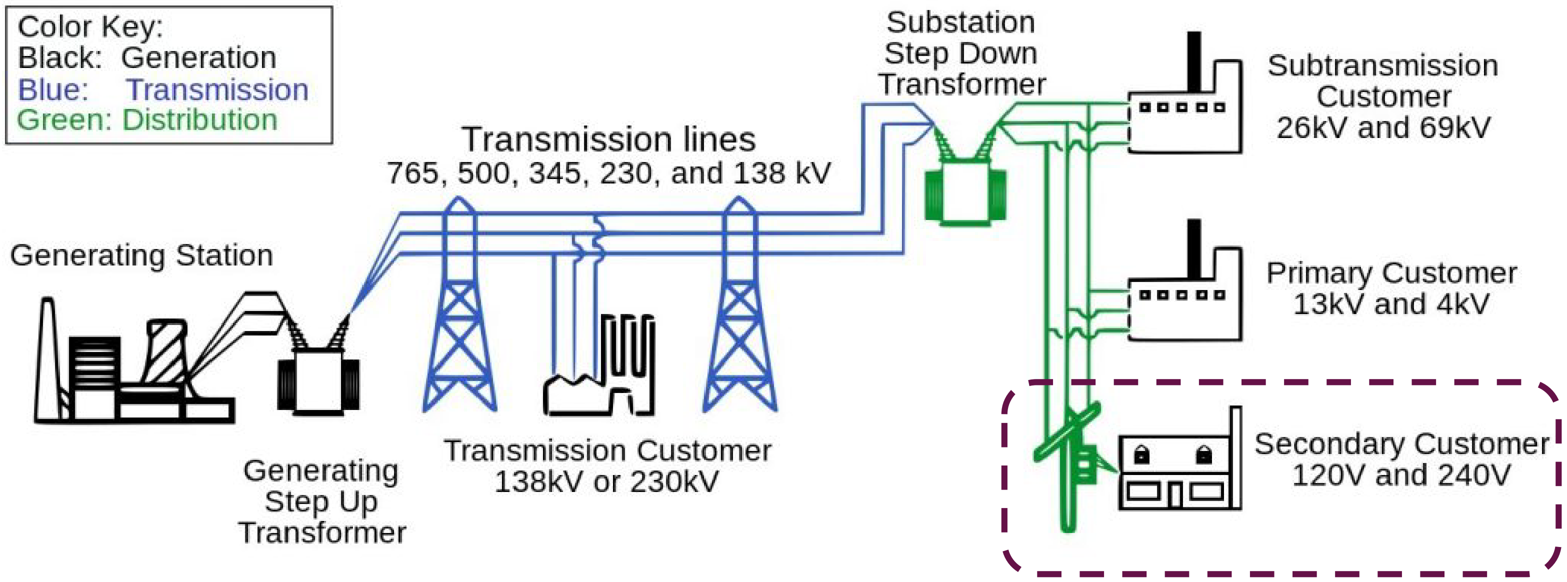
QUESTIONS

APPENDIX

THE POWER GRID

Power grid consists of

- Generation
- Transmission system
- Distribution system



DISTRIBUTION SYSTEM

- The distribution network has a tree structure.
  - Power flows in one direction.
- Voltage drop along each edge $e := (i, j)$

$$V_i - V_j = i_e r_e$$

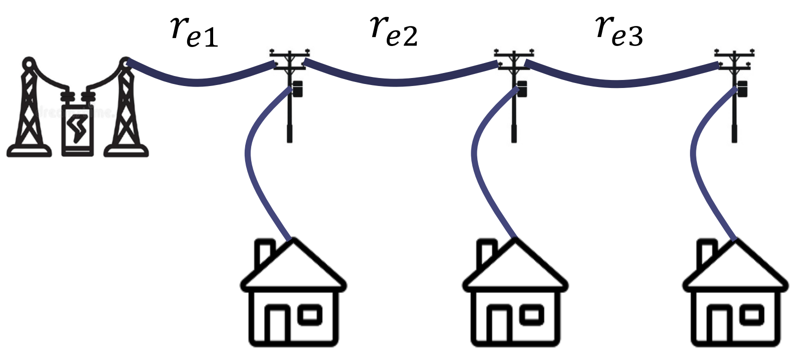
- Maximum voltage drop for nodes far away from root.
- Linearized Distribution Flow (LDF) Model [1].

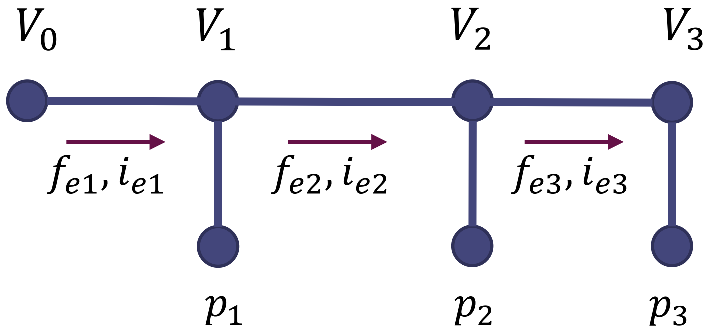
$$v_i - v_j = 2r_e f_e$$

- Linearizes the relation between voltage and power flow.

$$V_i - V_j = r_e i_e \xrightarrow{\text{LDF}} v_i - v_j = 2r_e f_e$$

$$v_i = V_i^2$$





[1] S. Bolognani and F. Dorfler. "Fast power system analysis via implicit linearization of the power flow manifold. In 53rd Annual Allerton Conference on Communication, Control, and Computing (Allerton), pages 402–409, Sep 2015.

POWER FLOW PROBLEM

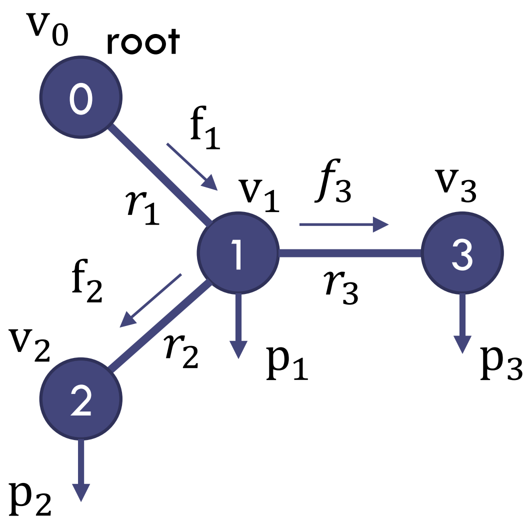
Given power consumption at nodes in the network find the node voltages and edge power flows.

- How to find edge flows from power consumption?
  - $\mathbf{p} = \mathbf{A}_{\text{red}}^{\text{T}}\mathbf{f}$
- How to infer voltages from power consumption?
  - $\mathbf{R} = \mathbf{A}_{\text{red}}^{-1}\mathbf{D}_{\text{R}}\left(\mathbf{A}_{\text{red}}^{-1}\right)^{\text{T}}$
  - $\mathbf{v} = \mathrm{v}_0\mathbf{1} - 2\mathbf{R}\mathbf{p}$

$$\mathbf{A} = \begin{bmatrix} -1 & 1 & 0 & 0 \\ 0 & -1 & 1 & 0 \\ 0 & -1 & 0 & 1 \end{bmatrix}$$

$$\mathbf{A}_{\text{red}} = \begin{bmatrix} 1 & 0 & 0 \\ -1 & 1 & 0 \\ -1 & 0 & 1 \end{bmatrix}$$

$$\mathbf{D}_R = \begin{bmatrix} r_1 & 0 & 0 \\ 0 & r_2 & 0 \\ 0 & 0 & r_3 \end{bmatrix}$$



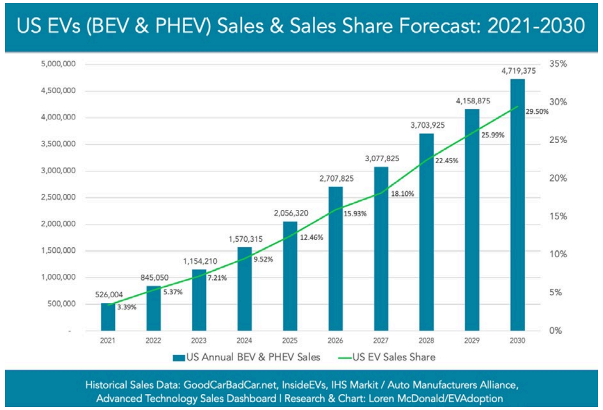
Sanity check

$p_1 = f_1 - f_2 - f_3$

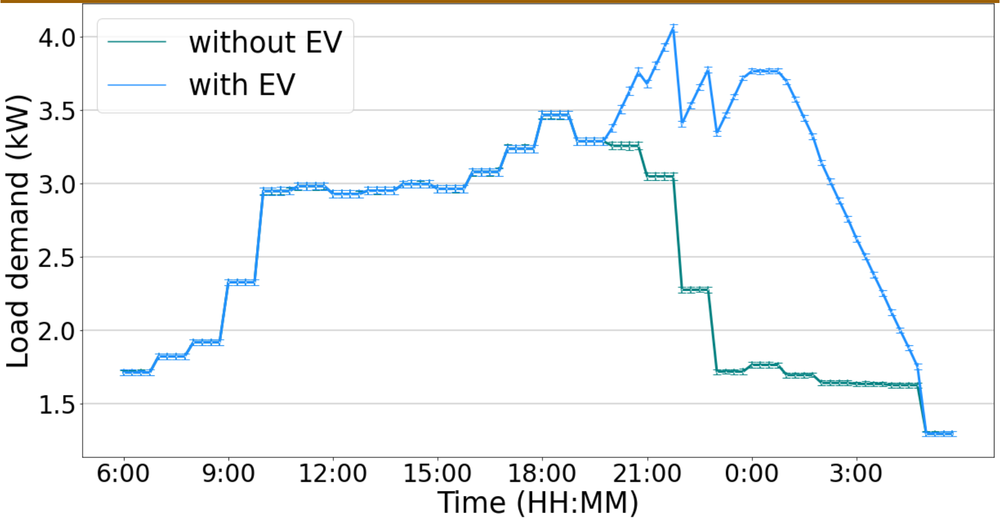
$$\mathbf{p} = \begin{bmatrix} p_1 \\ p_2 \\ p_3 \end{bmatrix} = \begin{bmatrix} 1 & -1 & -1 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} f_1 \\ f_2 \\ f_3 \end{bmatrix} = \mathbf{A}_{\text{red}}^T\mathbf{f}$$

MOTIVATION

- ❑ Electrification of vehicles.
  - ❑ EV sales projected to go up 10 times by 2030.
  - ❑ EV charging outlets at residences.
- ❑ Residential charging of EVs alters the average residential energy demand profile.



Hourly Residential Energy Demand Profile



PRIOR WORKS

- Optimization techniques are a popular choice for the scheduling problem [1,2].
- Reinforcement learning and other neural networks-based frameworks [3,4].
- Centralized approaches require exchange of private information.
- Alternating Direction Method of Multipliers (ADMM) based distributed approach for inverter control proposed in [5].

[1] Yijia Cao, Shengwei Tang, Canbing Li, Peng Zhang, Yi Tan, Zhikun Zhang, and Junxiong Li. An optimized EV charging model considering TOU price and SOC curve. IEEE Transactions on Smart Grid, 3(1):388–393, 2012.
[2] Yue Zhao, Yan Chen, and Brian Keel. Optimal scheduling of home energy management system with plug-in electric vehicles using model predictive control, Sep 2018.
[3] Yongsheng Cao, Hao Wang, Demin Li, and Guanglin Zhang. Smart online charging algorithm for electric vehicles via customized actor–critic learning. IEEE Internet of Things Journal, 9(1):684–694, 2022..
[4] Salman Sadiq Shuvo and Yasin Yilmaz. Cibecs: Consumer input based electric vehicle charge scheduling for a residential home. In 2021 North American Power Symposium (NAPS), pages 1–6, 2021.
[5] Emiliano Dall'Anese, Sairaj V. Dhople, Brian B. Johnson, and Georgios B. Giannakis. Decentralized optimal dispatch of photovoltaic inverters in residential distribution systems. IEEE Transactions on Energy Conversion, 29(4):957–967, 2014.

PROBLEM FORMULATION: DISTRIBUTION SYSTEM OPERATOR

- DSO reliability objectives:
  - Edge power flows within line ratings.
  - Node voltages within engineering standards.
- ANSI standard for distribution network voltages[1].
  - Lower limit: $\alpha = 0.95$ pu
  - Upper limit: $\beta = 1.05$ pu.
  - $\alpha\mathbf{1} \leq \mathbf{v} \leq \beta\mathbf{1}$
- DSO personal objectives:
  - Minimize losses.
  - Minimize voltage deviation.

$$
\begin{array}{lll}
\min & \sum_{t=1}^{T} C\left(\mathbf{p}^t\right) & \\
\text{over} & \mathbf{p}^t & \\
\text{s.t.} & \alpha\mathbf{1} \leq -2\mathbf{R}\mathbf{p}^t + \mathbf{1} \leq \beta\mathbf{1} & \forall t \\
 & -\overline{\mathbf{f}} \leq \mathbf{A}^{-1}\mathbf{p} \leq \overline{\mathbf{f}} & \forall t
\end{array}
$$

If ensuring reliability is the sole objective

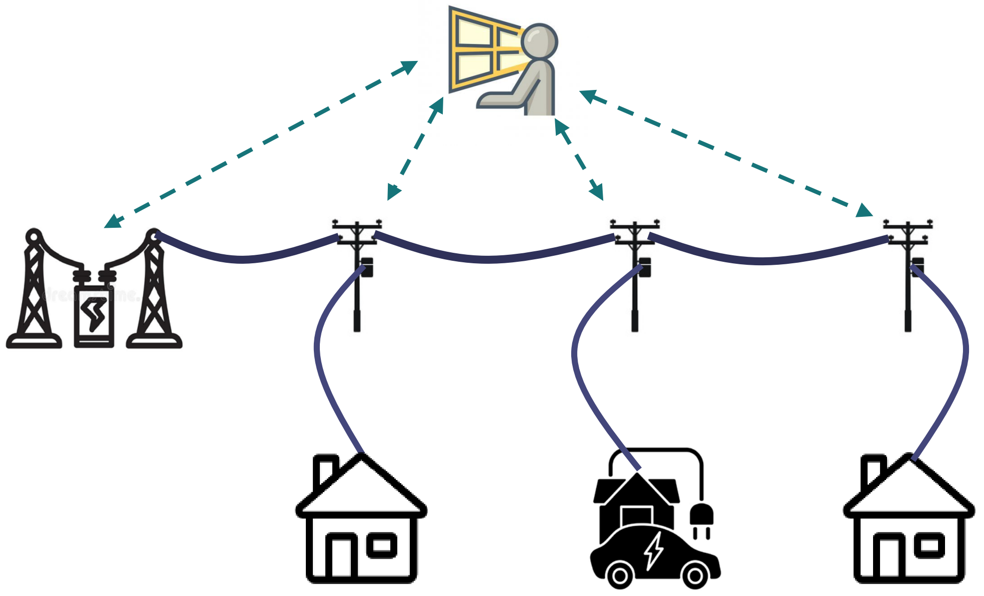
$$
\begin{array}{lll}
\text{find} & \mathbf{p}^t & \\
\text{s.t.} & \alpha\mathbf{1} \leq -2\mathbf{R}\mathbf{p}^t + \mathbf{1} \leq \beta\mathbf{1} & \forall t \\
 & -\overline{\mathbf{f}} \leq \mathbf{A}^{-1}\mathbf{p} \leq \overline{\mathbf{f}} & \forall t
\end{array}
$$

[1] American National Standards Institute ANSI. ANSI C84.1-2020: Electric Power Systems Voltage Ratings (60 Hz), 2020

MOTIVATION

- ❑ Impact on network
  - Increased edge power flow.
  - Drop in node voltages.

- ❑ Distribution system operator (DSO) needs a framework to
  - accommodate residential EV charging according to consumer personal preferences
  - maintain network reliability



When can you charge your EVs?

PROPOSED DISTRIBUTED APPROACH

- Introduce new variable $\tilde{p}_i^t$ for each residence.
- ADMM[1] based iterative solution.

$$
\begin{aligned}
\min \quad & \sum_{t=1}^{T} C\left(\mathbf{p}^t\right) + \sum_{i\in\mathcal{H}}\sum_{t=1}^{T} c_i^t p_i^t \\
\text{over} \quad & p_i^t, s_i^t, z_i^t, \boxed{\tilde{p}_i^t} && \forall t, \forall i \in \mathcal{H} \\
\text{s.t.} \quad & p_i^t = p_{i,0}^t + p_{i,\mathrm{EV}}^t && \forall t, \forall i \in \mathcal{H} \\
& p_{i,\mathrm{EV}}^t = z_i^t P_{i,\mathrm{EV}} && \forall t, \forall i \in \mathcal{H} \\
& s_i^t = s_i^{t-1} + \frac{p_{i,\mathrm{EV}}^t}{Q_{i,\mathrm{EV}}} && \forall t, \forall i \in \mathcal{H} \\
& z_i^t \in \{0,1\} && \forall t, \forall i \in \mathcal{H} \\
& z_i^t = 0 && \forall t \le t_{\mathrm{start}}, \forall i \in \mathcal{H} \\
& z_i^t = 0 && \forall t \ge t_{\mathrm{end}}, \forall i \in \mathcal{H} \\
& s_i^{t_{\mathrm{start}}} = s_{i,\mathrm{init}} && \forall i \in \mathcal{H} \\
& s_i^{t_{\mathrm{end}}} = s_{i,\mathrm{final}} && \forall i \in \mathcal{H} \\
& \alpha \le 1 - 2\sum_j R_{ij}\tilde{p}_j^t \le \beta && \forall t, \forall i \\
& -\overline{f_k} \le \sum_j \left[\mathbf{A}^{-1}\right]_{kj} \tilde{p}_j^t \le \overline{f_k} && \forall t, \forall k \in \mathcal{E} \\
& p_i^t = \tilde{p}_i^t && \forall t, \forall i \in \mathcal{H}
\end{aligned}
$$

DSO problem (QP)

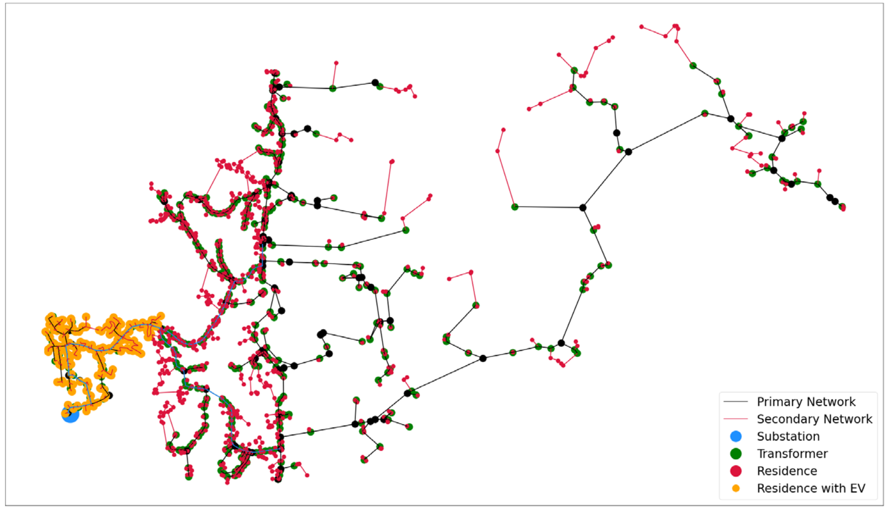
$$
\begin{aligned}
\{\tilde{p}_i^t[l+1]\} = \min \quad & \sum_{i\in\mathcal{H}}\sum_{t=1}^{T} \frac{\kappa}{2}\left(\tilde{p}_i^t\right)^2 \\
+ \quad & \sum_{i\in\mathcal{H}}\sum_{t=1}^{T} \tilde{p}_i^t \left(\gamma_i^t[l] - \frac{\kappa}{2}\tilde{p}_i^t[l] - \frac{\kappa}{2}p_i^t[l]\right) \\
\text{s.t.} \quad & \alpha \le 1 - 2\sum_j R_{ij}\tilde{p}_j^t \le \beta \quad \forall t, \forall i \\
& -\overline{f_k} \le \sum_j \left[\mathbf{A}^{-1}\right]_{kj} \tilde{p}_j^t \le \overline{f_k} \quad \forall t, \forall k \in \mathcal{E}
\end{aligned}
$$

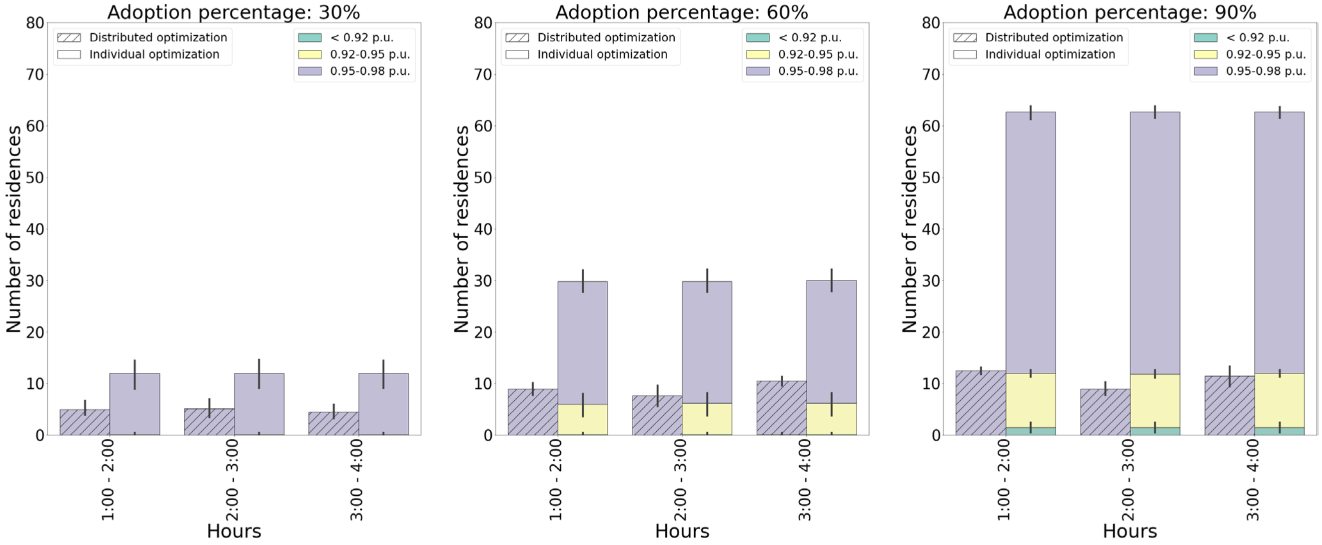
Consumer i problem (MIQP)

$$
\begin{aligned}
p_i^t[l+1] = \min \quad & \sum_{t=1}^{T} c_i^t p_i^t + \sum_{t=1}^{T} \frac{\kappa}{2}\left(p_i^t\right)^2 \\
- \quad & \sum_{t=1}^{T} p_i^t \left(\gamma_i^t[l] + \frac{\kappa}{2}\tilde{p}_i^t[l] + \frac{\kappa}{2}p_i^t[l]\right) \\
\text{s.t.} \quad & p_i^t = p_{i,0}^t + p_{i,\mathrm{EV}}^t \quad \forall t \\
& p_{i,\mathrm{EV}}^t = z_i^t P_{i,\mathrm{EV}} \quad \forall t \\
& s_i^t = s_i^{t-1} + \frac{p_{i,\mathrm{EV}}^t}{Q_{i,\mathrm{EV}}} \quad \forall t \\
& z_i^t \in \{0,1\} \quad \forall t \\
& z_i^t = 0 \quad \forall t \le t_{\mathrm{start}}, \forall t \ge t_{\mathrm{end}} \\
& s_i^{t_{\mathrm{start}}} = s_{i,\mathrm{init}}, \quad s_i^{t_{\mathrm{end}}} \ge s_{i,\mathrm{final}}
\end{aligned}
$$

[1] Stephen Boyd, Neal Parikh, Eric Chu, Borja Peleato, and Jonathan Eckstein. Distributed optimization and statistical learning via the alternating direction method of multipliers. Found. Trends Mach. Learn.,3(1):1–122, Jan 2011

RESULTS





- Different EV adoption percentages in a residential community.
- Individual optimization is compared to the proposed distributed approach.

Higher level of reliability attained through the distributed approach