Will EVs Break the Power Grid?

Professor Scott Moura

PATH Faculty Director | Chair of Engineering Science

Clare and Hsieh Wen Shen Endowed Distinguished Professor

University of California, Berkeley

9 May 2025


1000 kW

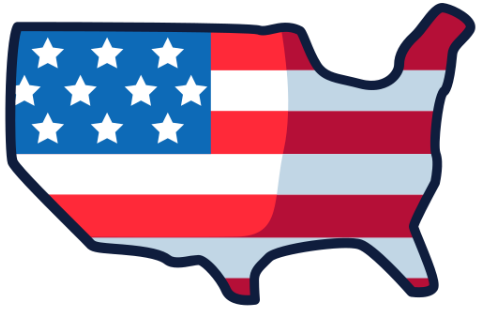
Two More Chinese Companies Announce 'Megawatt' EV Charging

The new 1.2-megawatt and 1.5-megawatt chargers from Zeekr and Huawei are absolutely nuts. But are they really needed?

1
kilowatt

1
megawatt

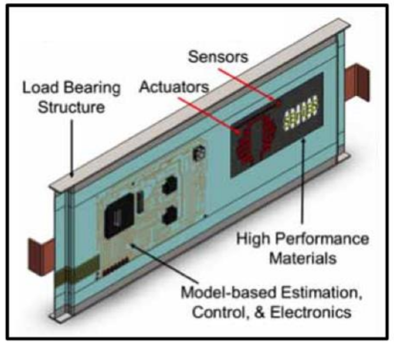
1
gigawatt



5000
gigawatts

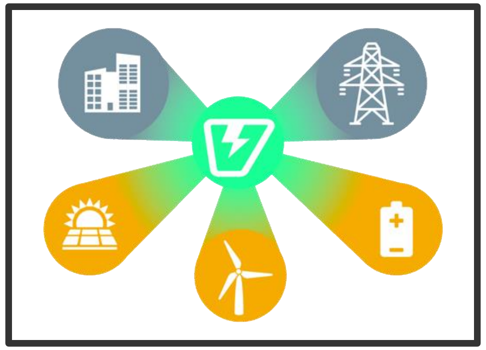

Charge EV overnight
Charge EV overnight, at home
Charge in 30 minutes
Charge as quickly as filling gas
Charge faster than a sneeze
imgflip.com

eCAL Research Areas

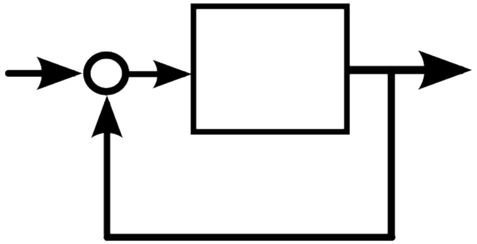


Battery Management Systems (#BATT)

Automated, Connected, & Electric Vehicles (#ACES)

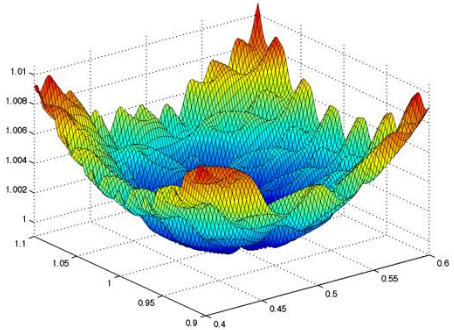


Power Systems, Grids, Markets (#GRID)



Dynamic Systems & Control

Optimization



Data Science

eCAL

energy, controls, & applications lab

Patrick
KEYANTUO

Tugba
OZTURK

Preet
GILL

Ruiting
WANG

Junzhe
SHI

Yi
JU

Shida
JIANG

Joyce
CHEN

Linda
LIM

Lejun
ZHOU

Jaewoong
LEE

Shengyu
TAO

Bhumi
TANDEL

Sam
MURTHY

Sam
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IS PEOPLE

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Dr. Caroline LE FLOCH
Storio Energy


Dr. Eric MUNSING
Tesla


Dr. Bertrand TRAVACCA
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Morphosis


Dr. Sangjae BAE
Honda Research Institute


Dr. Saehong PARK
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Dr. Mathilde BADOUAL
Storio Energy


Dr. Zach GIMA
Form Energy


Dr. Dong ZHANG
Asst Prof. at OU


Dr. Soomin WOO
Asst Prof. at Konkuk U


Dr. Teng ZENG
Tesla


Dr. Zhijia HUANG
BYD


Dr. Hassan OBEID
Attentive


Dr. Ioanna KAVVADA
PG&E


Dr. Dimitris VLACHOGIANNIS
Uber


Dr. Aaron KANDEL
Nissan USA


Dr. Dylan KATO
Form Energy


Dr. Chitra DANGWAL
Archer Aviation


Dr. Guillaume GOUJARD
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Prof. Azad GHAFFARI
Wayne State University


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Chongqing University


Prof. Satadru DEY
Penn State University


Prof. Chao SUN
Beijing Institute of Technology

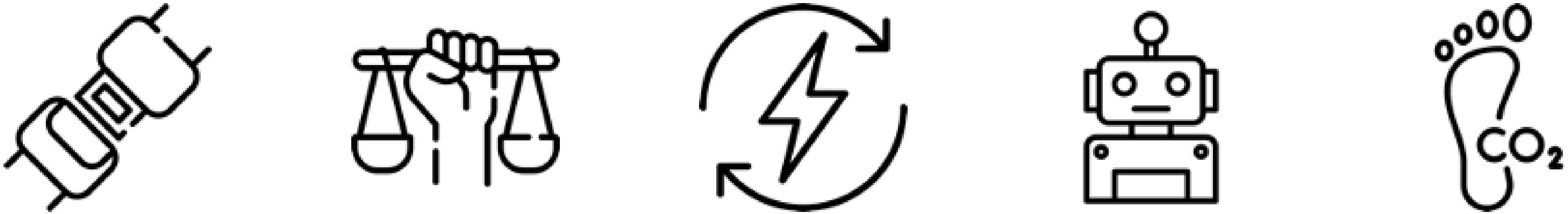

Prof. Hongcai ZHANG
University of Macau


Dr. Milad MEMARZADEH
NASA Ames

California Partners for Advanced Transportation Technology (PATH)

Mission:

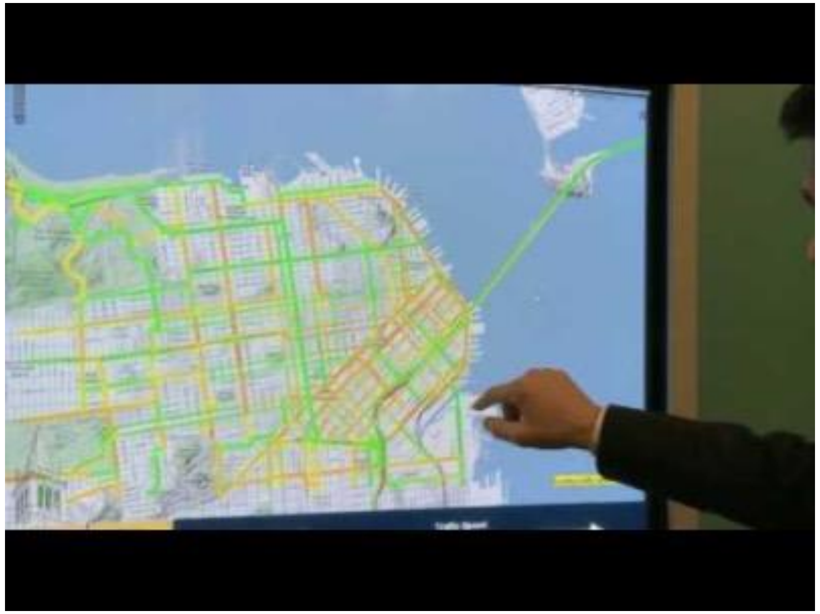
Realize a **safe, equitable, efficient, and carbon-neutral transportation system** for all, through research and development of advanced ideas and technologies.



PATH: History of Transportation Innovation

1997 Automated car platooning on I-15 near San Diego

2001 Performance Measurement System (PeMS) collects real-time data from ~40,000 road sensors



2009 Mobile Millennium tracks real-time traffic via Nokia cell phones. GMaps traffic b4 Google.

2016 Berkeley Deep Drive: Industrial/ academic research consortium on deep automotive perception technologies

PATH’s Role in Transportation Technology Ecosystem

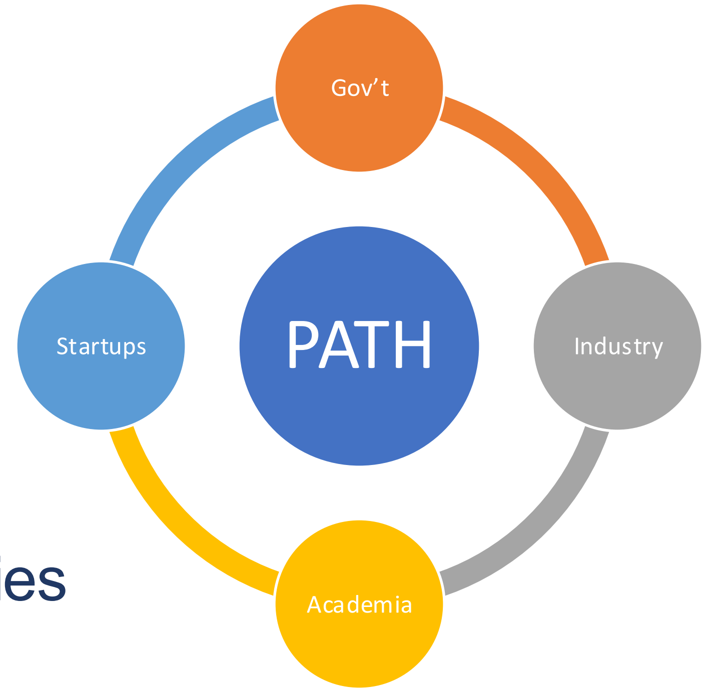
Engine of Innovation: Research → Development → Demonstration → Deployment

TRL1 → TRL2 → TRL3 → TRL4 → TRL5 → TRL6 → TRL7 → TRL8 → TRL9

Berkeley UNIVERSITY OF CALIFORNIA

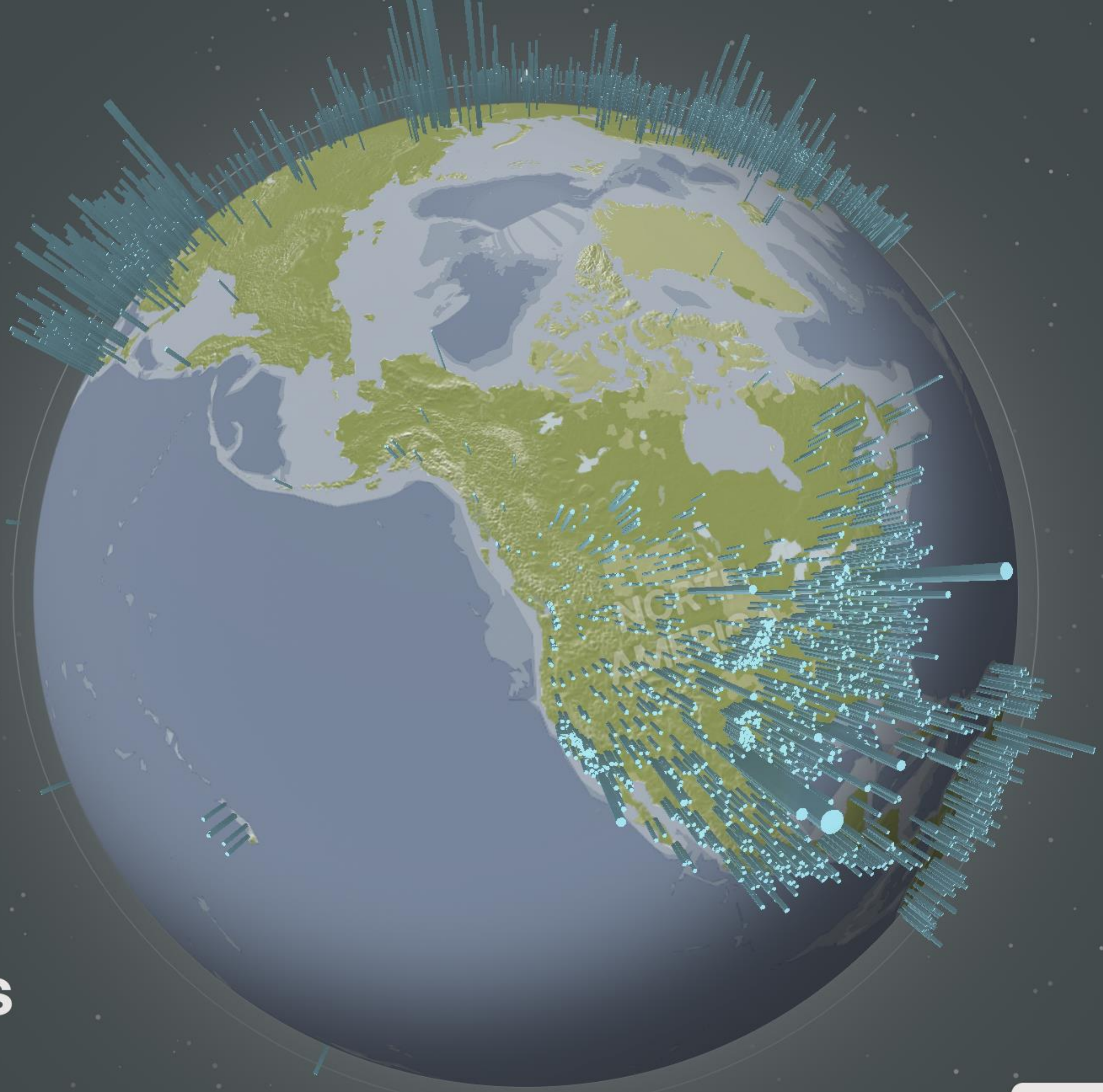
CALIFORNIA PATH

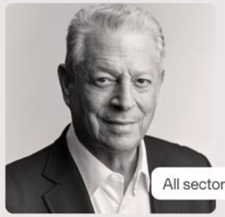
Start-ups, Big Industry, Government Agencies, etc.



Build Communities

CLIMATE TRACE





All sectors

Al Gore

STRATEGY | AL GORE

Independent Greenhouse Gas Emissions Tracking

→ Explore Map

→ Download Data

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Soccer on E... | LinkedIn | Google Scho... | CAS | Wikipedia | Transfermarkt | TeslaFi.com ... | LiveScore | erso | Add shortcut

Google Calendar

4:00pm Reception: CITRIS Retreat... In Progress
Tech Museum, Sutardja Dai Hall, 2594 Hearst Av...

6:00pm CITRIS Retreat

6:00pm Dinner: CITRIS Retreat 2025

See more

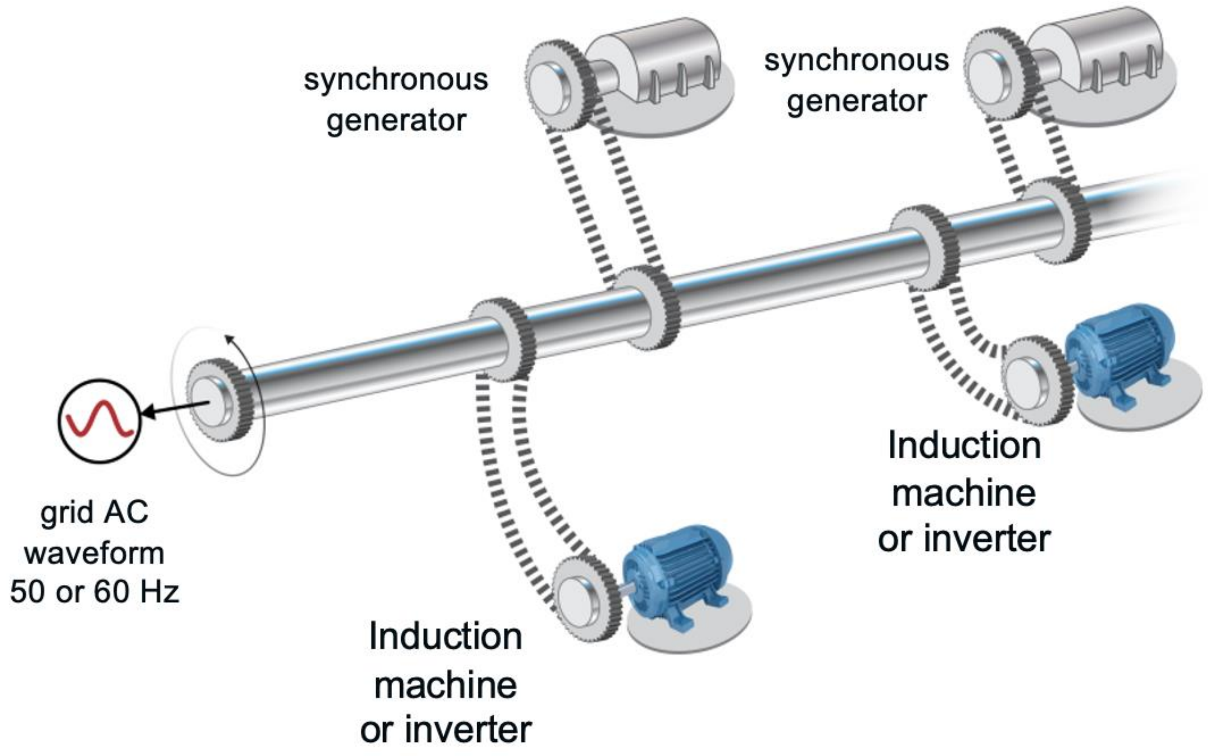
Google Drive

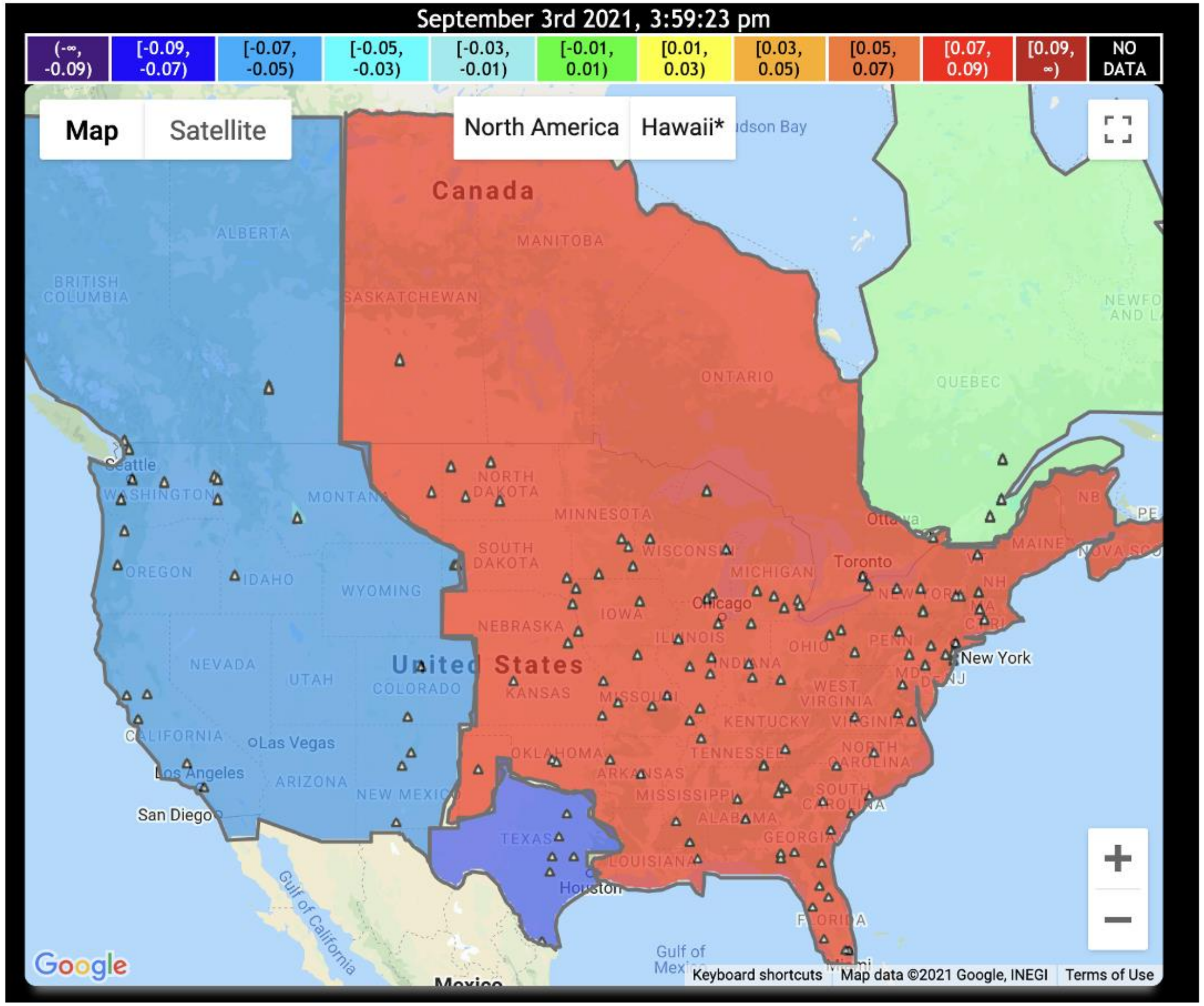
S25-CE186-JudgeInvites
You edited yesterday

DESIGN SHOWCASE May 8, 2025
You edited yesterday

Student Funding (SU2025)
You opened in the past week

Job List
You opened in the past week


synchronous generator
synchronous generator
grid AC waveform 50 or 60 Hz
Induction machine or inverter
Induction machine or inverter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[-0.07, -0.05)
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Map
Satellite
North America
Hawaii*
Canada
United States
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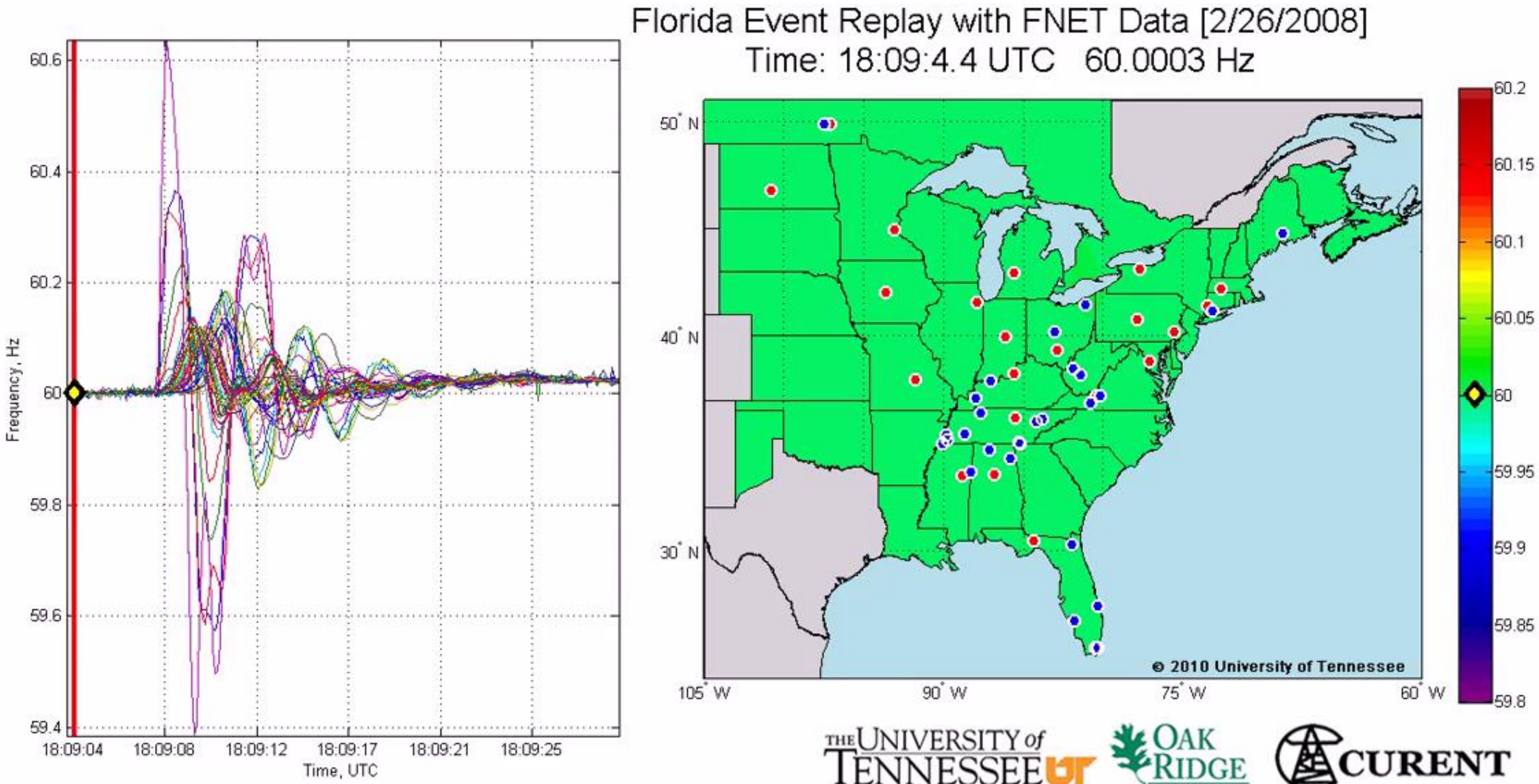

THE UNIVERSITY of TENNESSEE UT

OAK RIDGE National Laboratory

CURENT

Outline

1. Introduction
2. The Duck Curve Problem
3. Power Grid Impacts of EVs
4. Saving the Grid with SlrpEV
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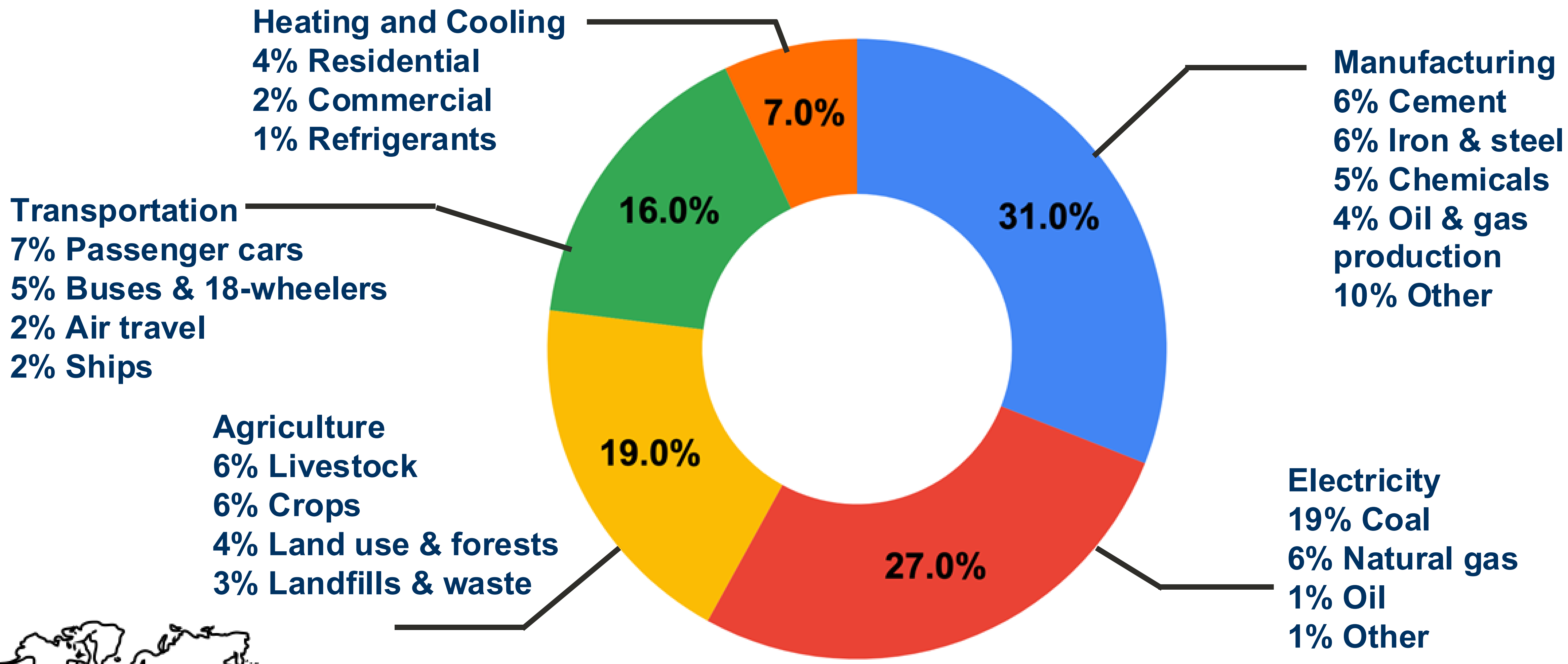
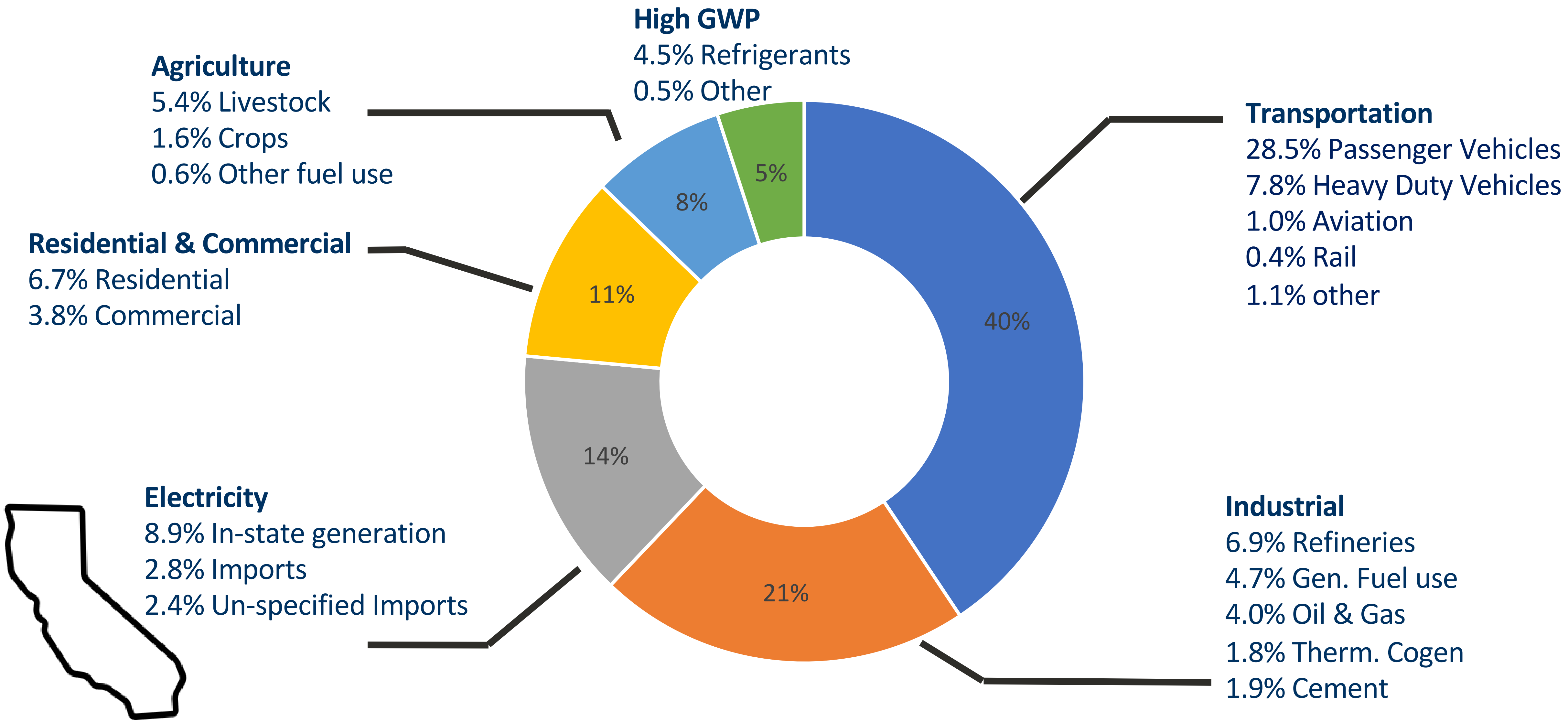
51 Billion Tons of Greenhouse Gases, Globally

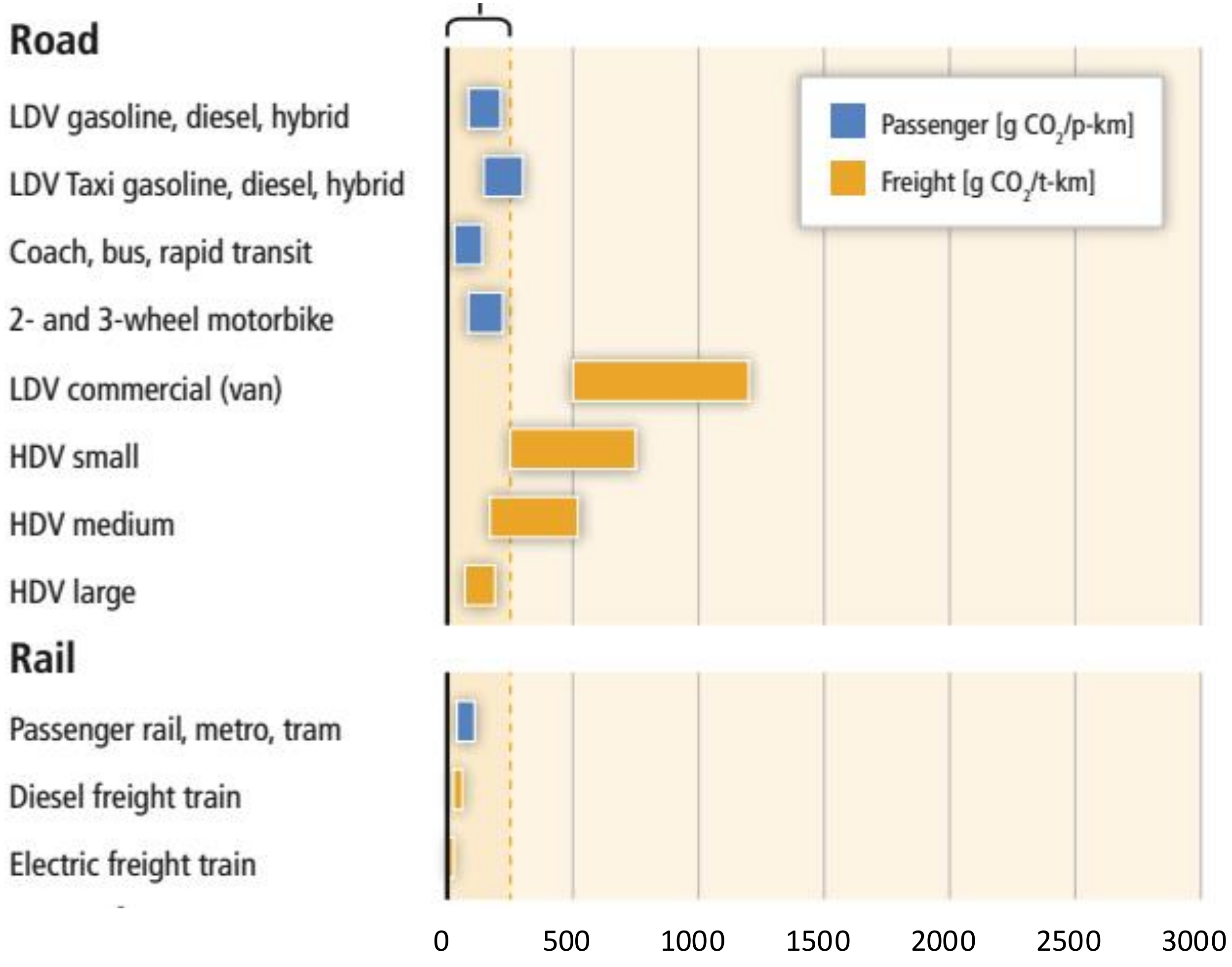


Data Source: Gates, B. (2021). How to avoid a climate disaster: The solutions we have and the breakthroughs we need. Random House.
NOTE: When thinking about these percentages, then we must consider attribution. For example, consider corn. The synthetic fertilizer is categorized under "growing things" and shipping to the grocery store is considered under "moving around."

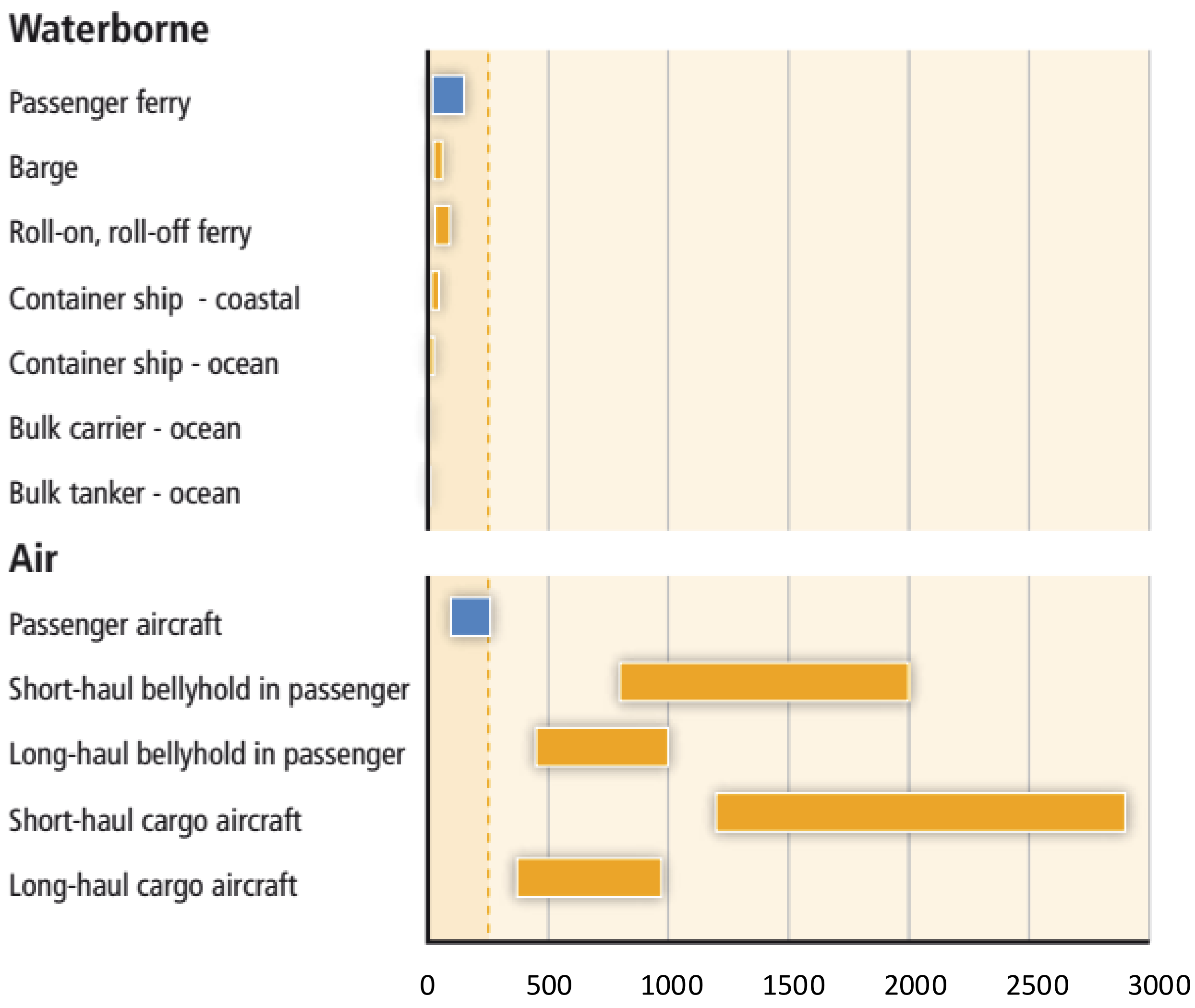
0.42 Billion Tons of Greenhouse Gases, California



Data Source: California Greenhouse Gas Emissions for 2000 to 2019 Trends of Emissions and Other Indicators
https://ww3.arb.ca.gov/cc/inventory/pubs/reports/2000_2019/ghg_inventory_trends_00-19.pdf



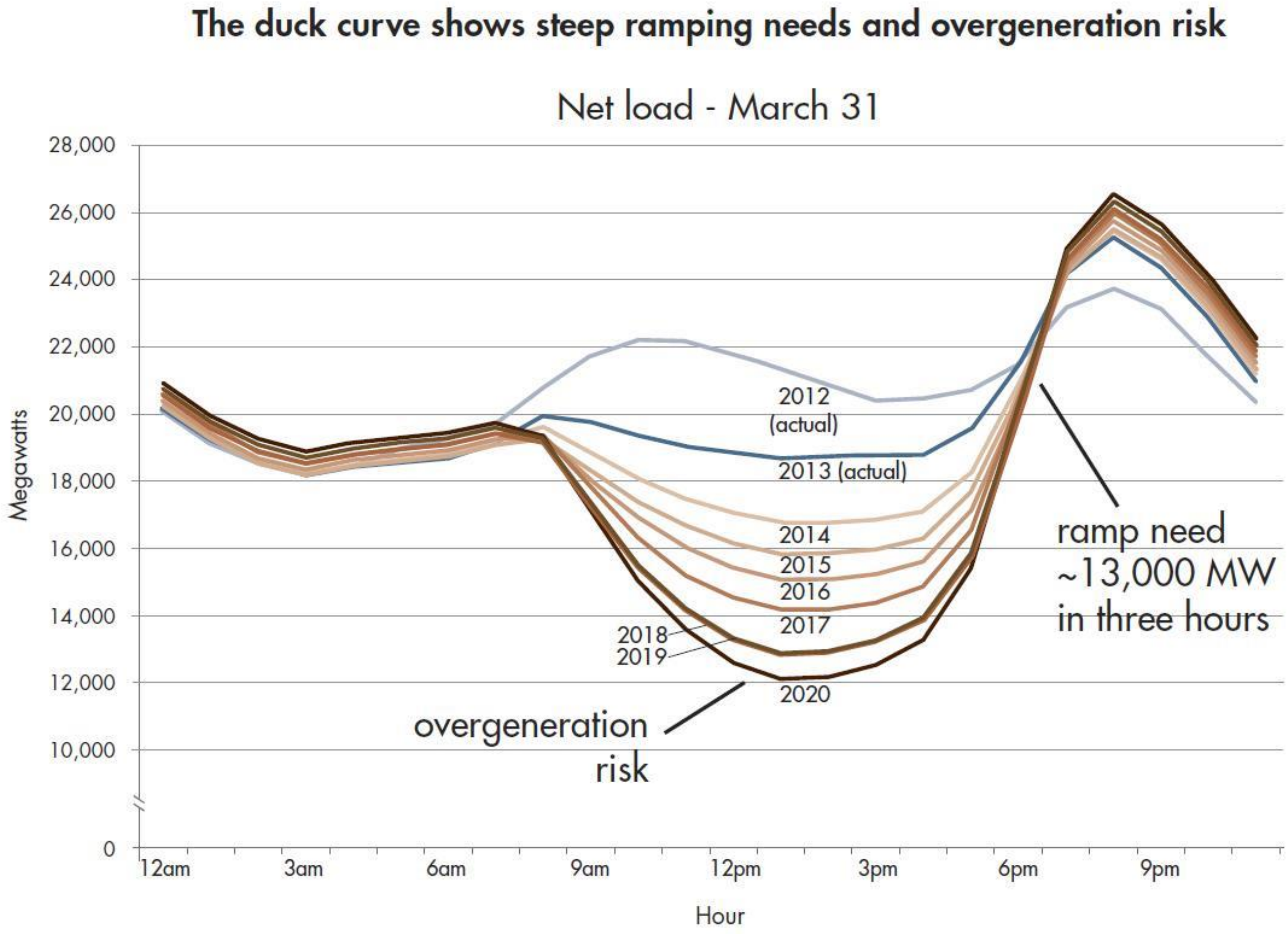
Direct CO2 Emissions per Distance [gCO_2/km]



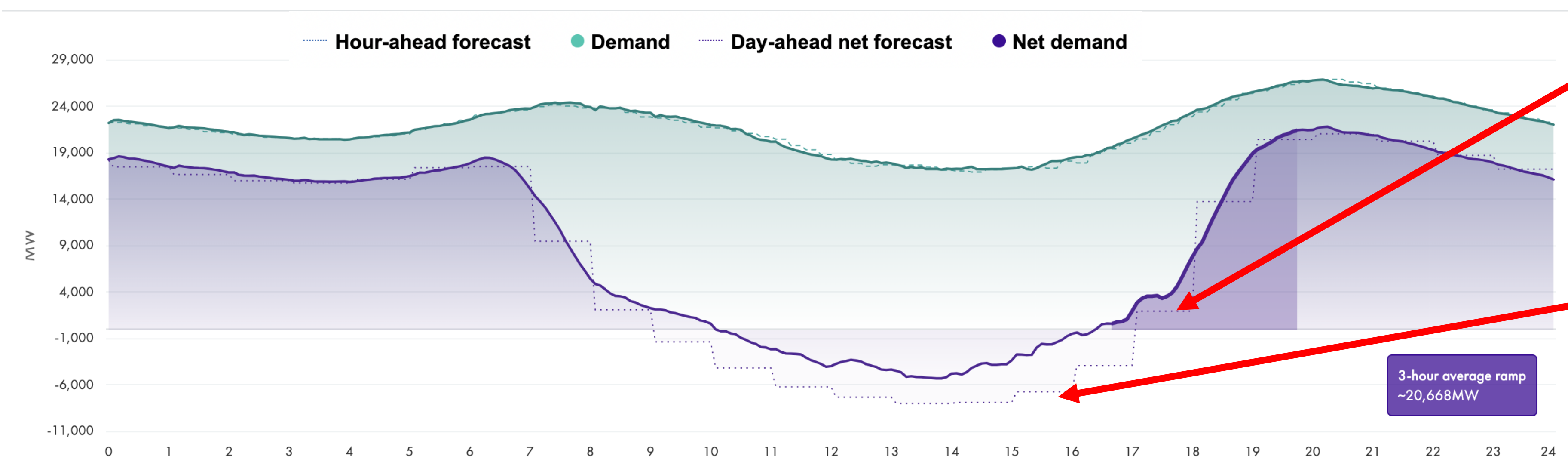
Direct CO2 Emissions per Distance [gCO_2/km]

Sims R., R. Schaeffer, F. Creutzig, X. Cruz-Núñez, M. D'Agosto, D. Dimitriu, M.J. Figueroa Meza, L. Fulton, S. Kobayashi, O. Lah, A. McKinnon, P. Newman, M. Ouyang, J.J. Schauer, D. Sperling, and G. Tiwari, 2014: Transport. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. https://www.ipcc.ch/report/ar5/wg3/

The California Example: Duck Curve



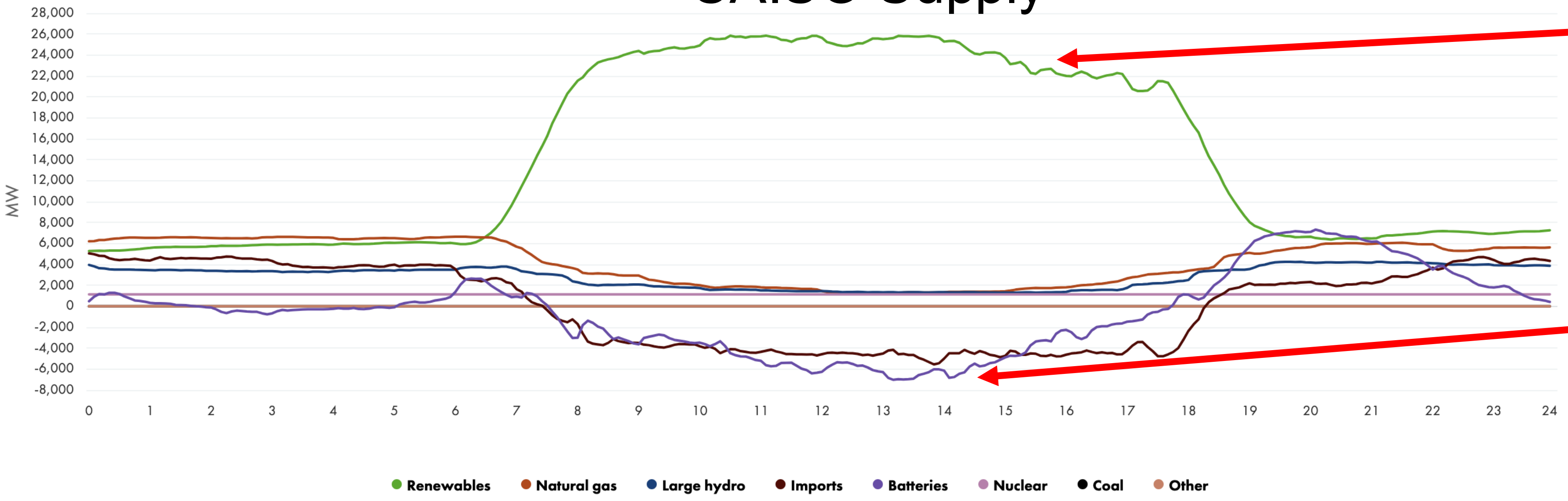
CAISO Electricity Demand



Over 20,000 MW ramp in 3 hours, net demand!

Negative net demand!

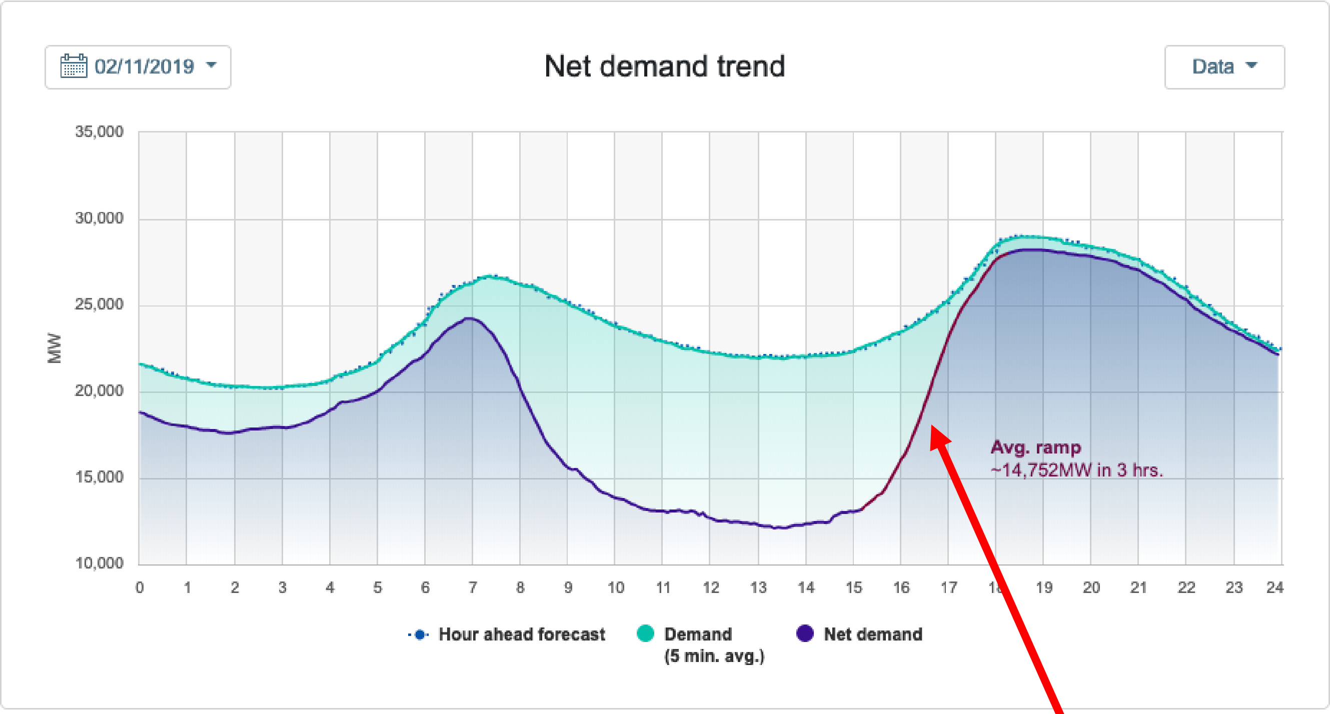
CAISO Supply

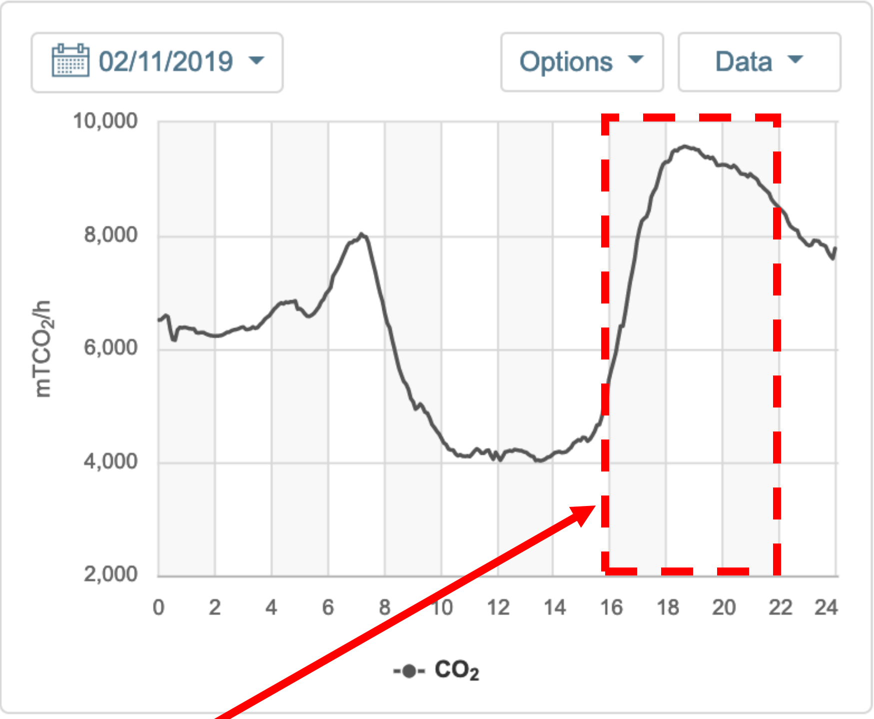


Solar curtailment

Max out energy exports, charge batteries

The Evening Charging Problem



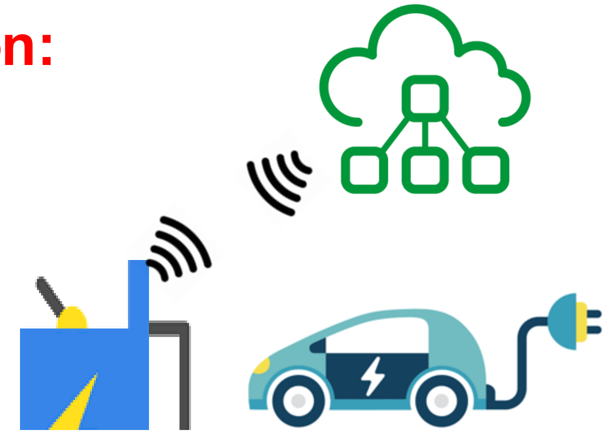


Current challenge, potentially exacerbated by EV penetration:

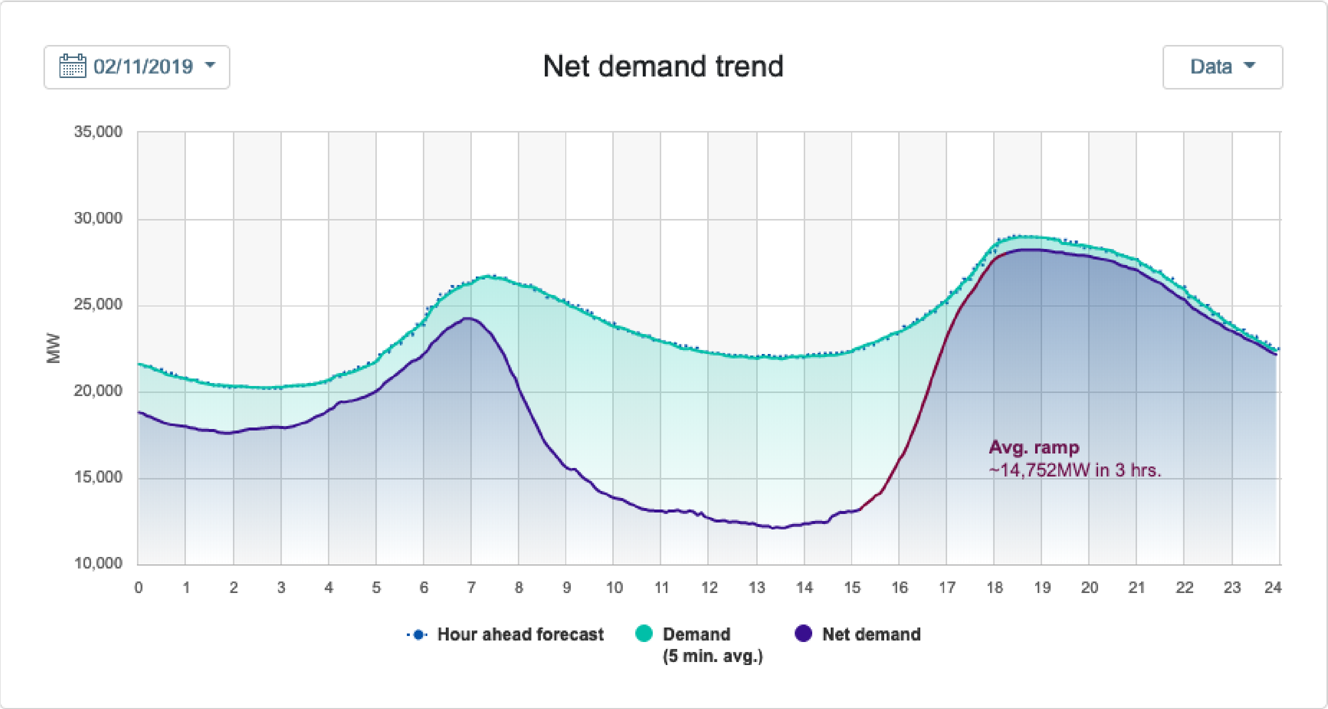
- Ramp rates increase, as folks return home and charge EVs
- CO_2 emissions are typically highest in evening

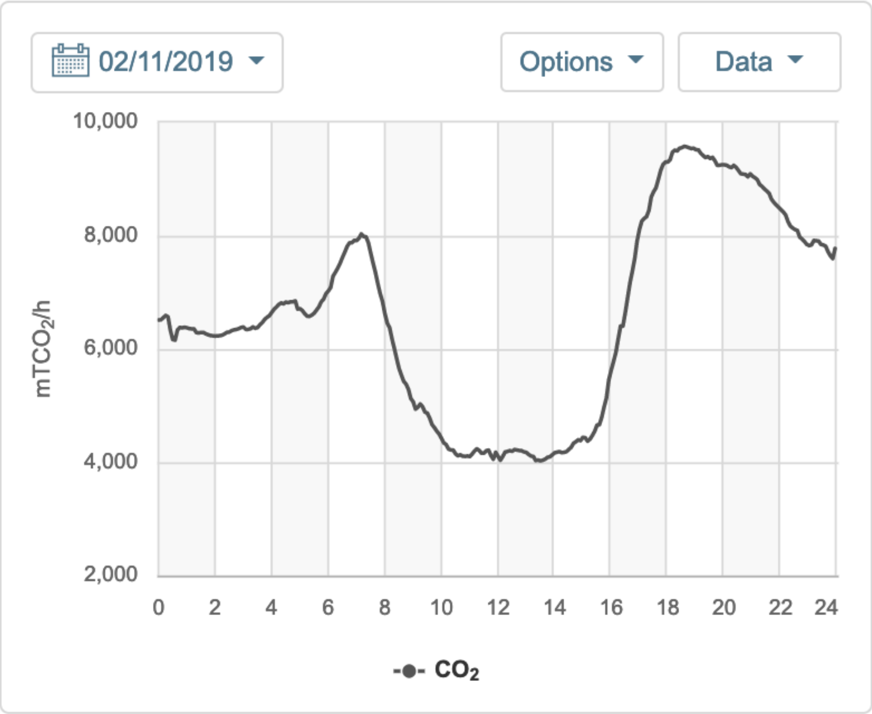
Opportunity:

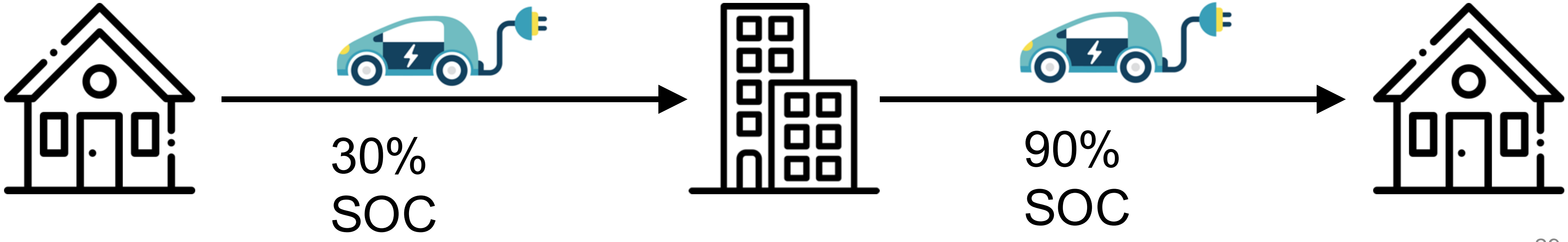
- EV charging can be controlled



The Evening Charging Problem







Outline

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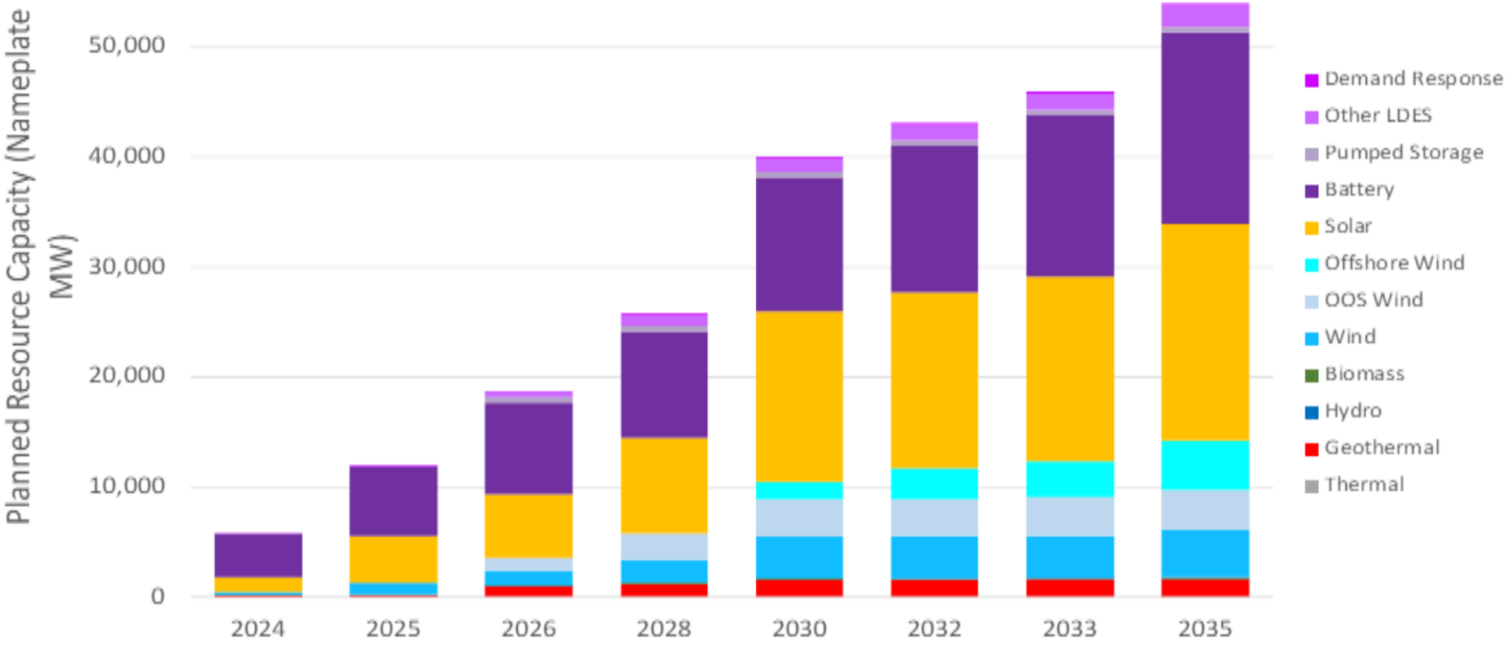
5. Summary

Increased Demand, Planned Supply

- Transportation accounts for more than 10% of projected electricity load growth.

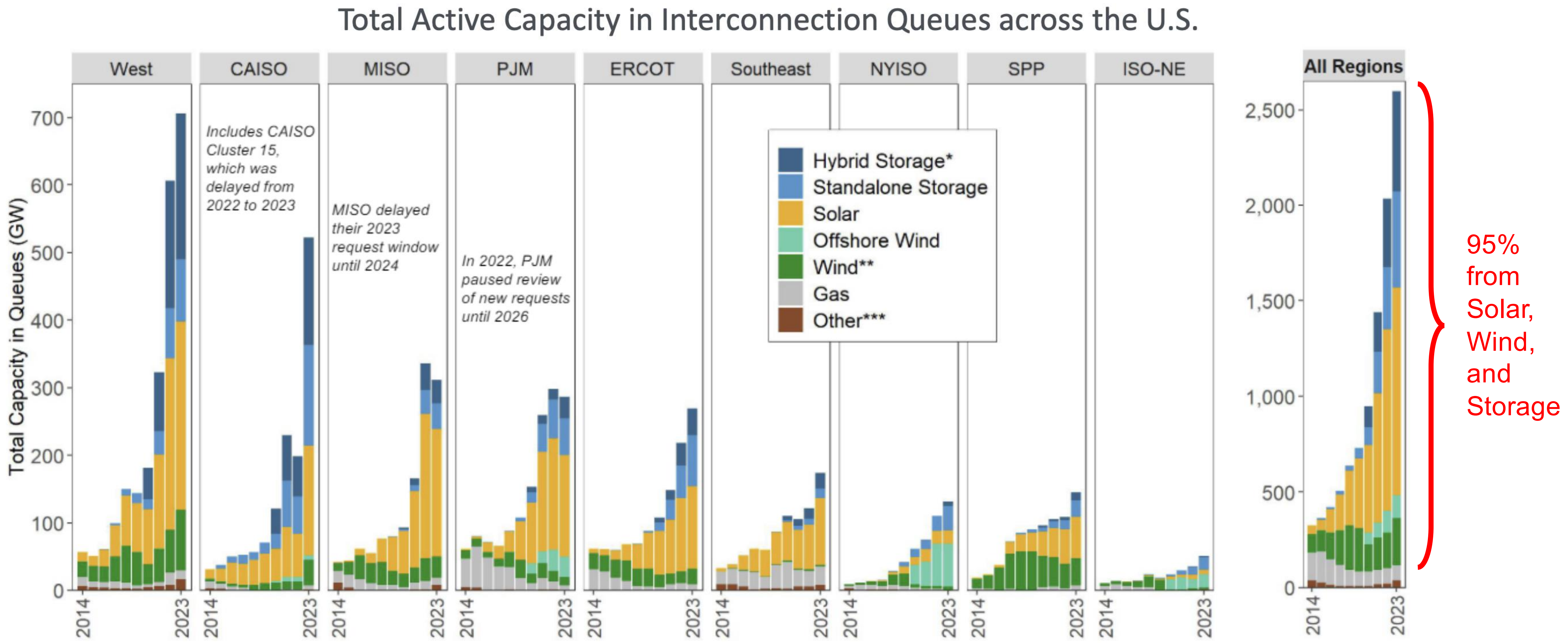
Source: The Brattle Group, Electricity Demand Growth and Forecasting in a Time of Change, May 2024

- California plans to add 52 GW of new clean energy resources through 2035, about 4.3 GW per year
- Solar & Batteries comprise over 60% of planned capacity



Source: CPUC, Integrated Resource Planning (IRP) Proposed 2023 Preferred System Plan (PSP) and 2024-2025 Transmission Planning Process Portfolios Analysis, October 2023.

Solar, Wind, & Storage Dominate the Queue of New Electricity Generation

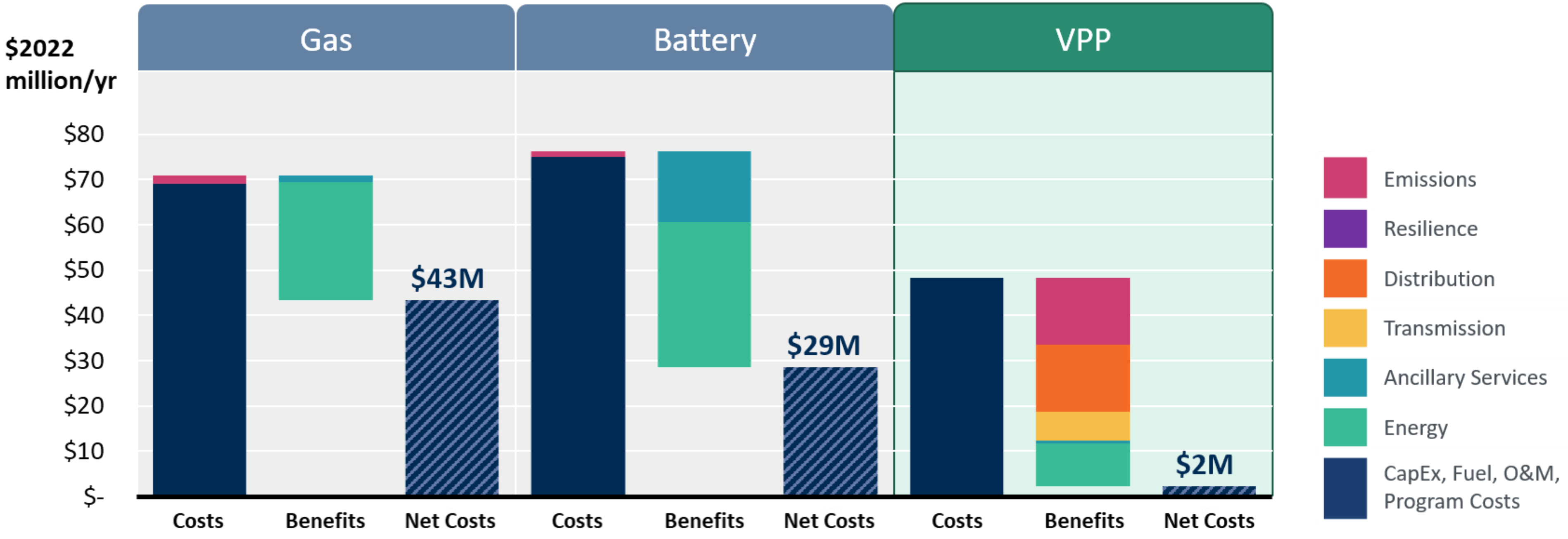


Only ~20% of projects (and 14% of capacity) requesting interconnection from 2000-2018 reached commercial operations by the end of 2023 😲😲😲

Source: LBNL, Queued Up: 2024 Edition: Characteristics of Power Plants Seeking Transmission Interconnection As of the End of 2023, April 2024

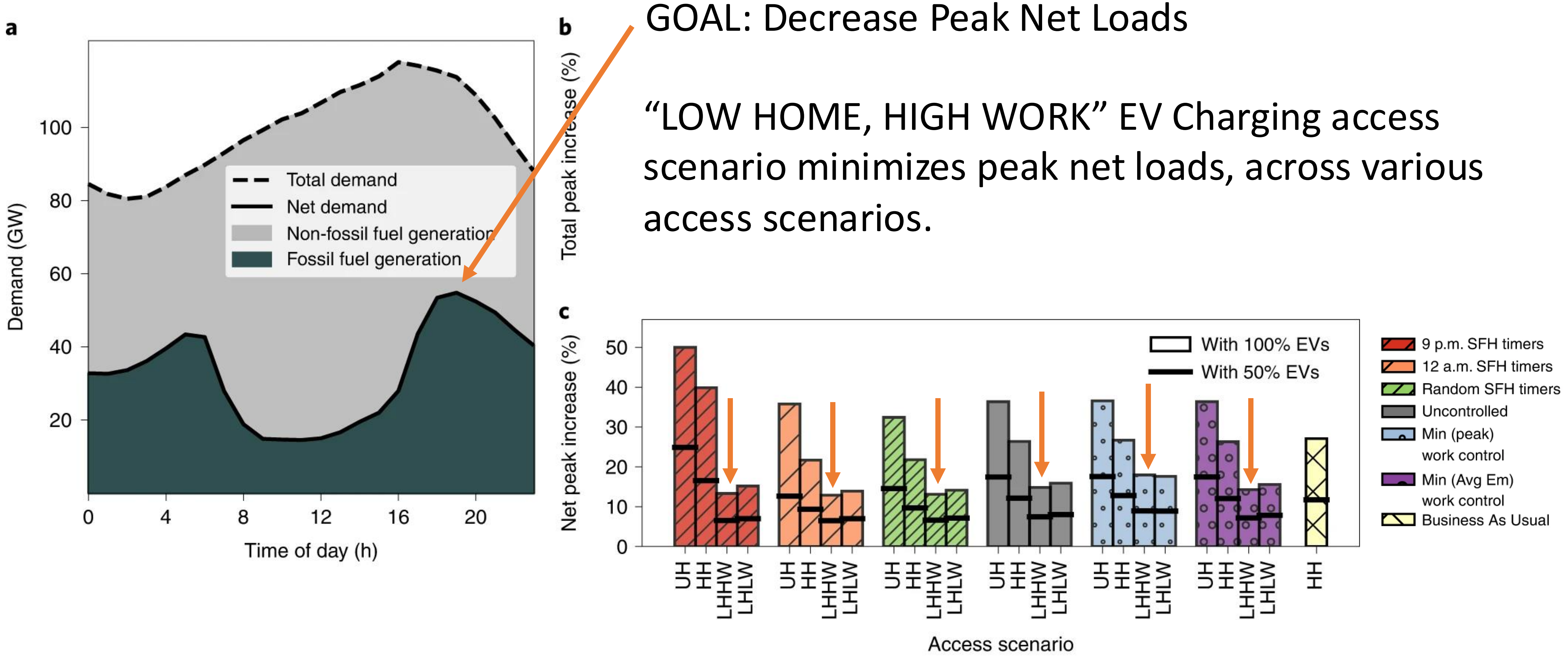
Demand Flexibility via Virtual Power Plants (VPPs)

- Many categories of electric demand are flexible: EVs, HVAC, water heaters, etc.
- Many categories of electric demand are controllable.
- VPP: A portfolio of distributed energy resources that are actively controlled to provide benefits to various stakeholders, e.g. all EVs in California.
- Avoid interconnection delay, lower cost!



Source: The Brattle Group, Real Reliability: The Value of Virtual Power, May 2023.

High Work Charging Decreases Peak Net Loads

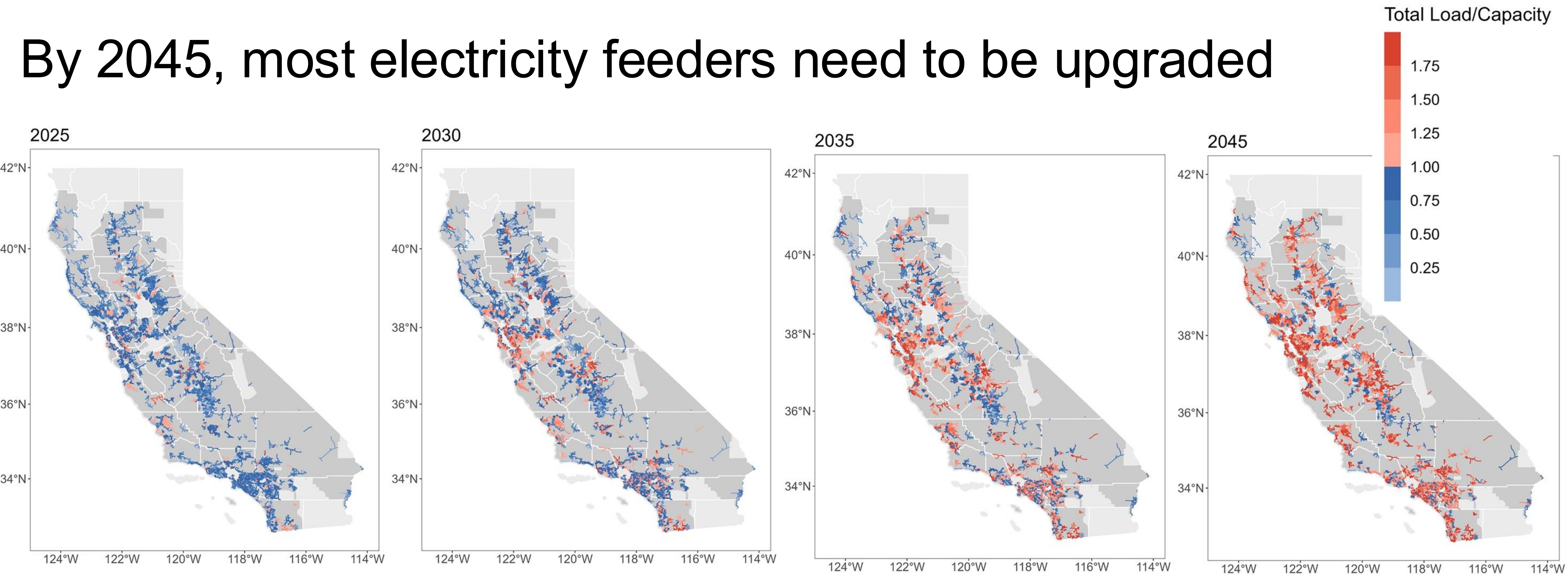


GOAL: Decrease Peak Net Loads

"LOW HOME, HIGH WORK" EV Charging access scenario minimizes peak net loads, across various access scenarios.

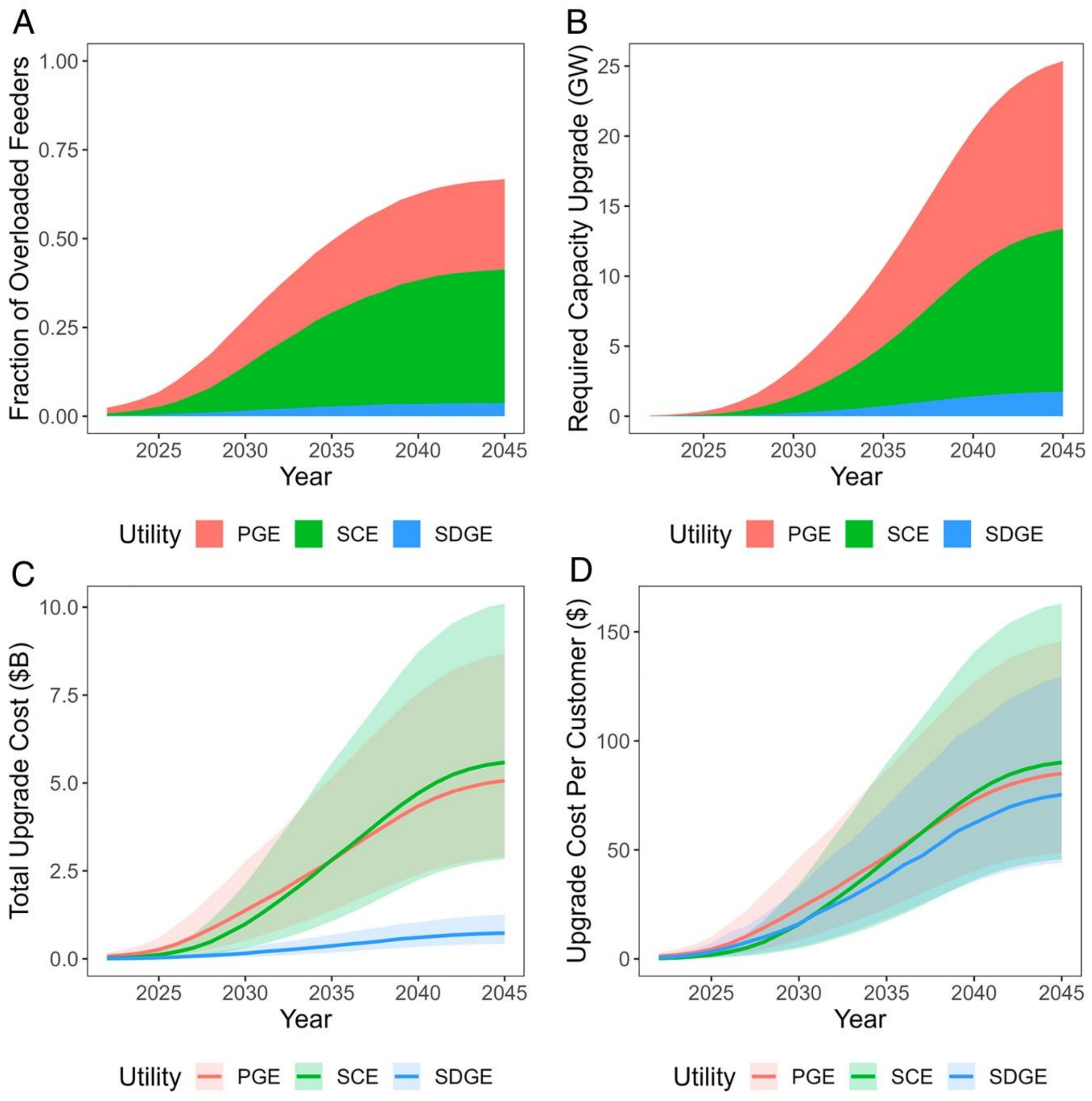
Source: S. Powell, G. V. Cezar, L. Min, et al. *Charging infrastructure access and operation to reduce the grid impacts of deep electric vehicle adoption*. Nature Energy (2022). https://doi.org/10.1038/s41560-022-01105-7

By 2045, most electricity feeders need to be upgraded



Source: Y. Li, A. Jenn, "Impact of electric vehicle charging demand on power distribution grid congestion," *Proceedings of the National Academy of Sciences,* April 2024. DOI: [10.1073/pnas.2317599121](https://doi.org/10.1073/pnas.2317599121). **Edited by SJM**.

67% of feeders are overloaded by 2045



- Southern California Edison have greater quantity of overloaded feeders, but…
- Pacific Gas & Electric has greater magnitude of overloading

- Although upgraded infrastructure puts upward pressure on price, increased load demand places downward pressure on price. Net effect? Close to zero.

Source: Y. Li, A. Jenn, "Impact of electric vehicle charging demand on power distribution grid congestion," *Proceedings of the National Academy of Sciences,* April 2024. DOI: [10.1073/pnas.2317599121](https://doi.org/10.1073/pnas.2317599121). **Edited by SJM.**

Soo… Scott…. will EVs break the grid?

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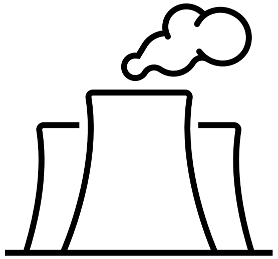
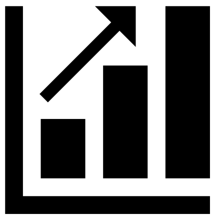
Goal & Objectives

SlrpEV Goal:

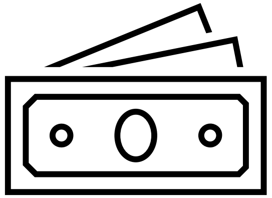
Create next generation of workplace/public EV charging that



decreases emissions



increases facility operator revenues



decreases EV owner costs

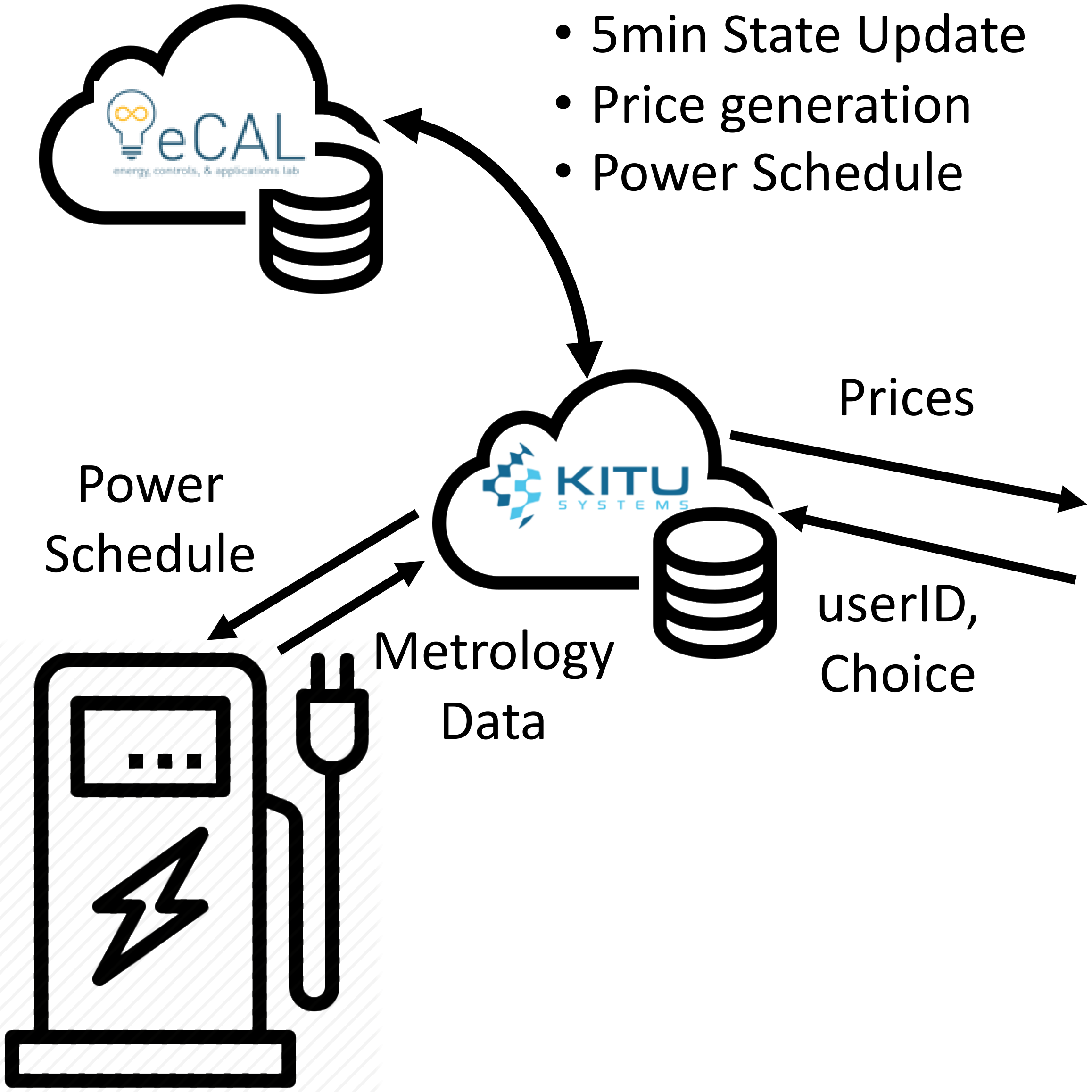
Research Objective:

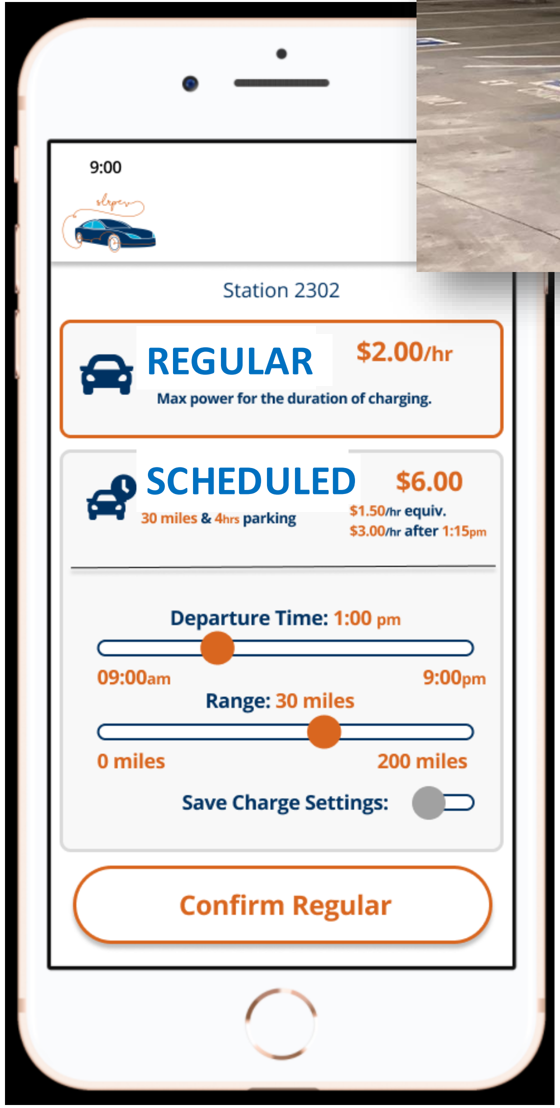
- Optimize price and charging schedule by ***learning user preferences***

Cyber-Physical & Human System

The Cyber & Physical

- 5min State Update
- Price generation
- Power Schedule





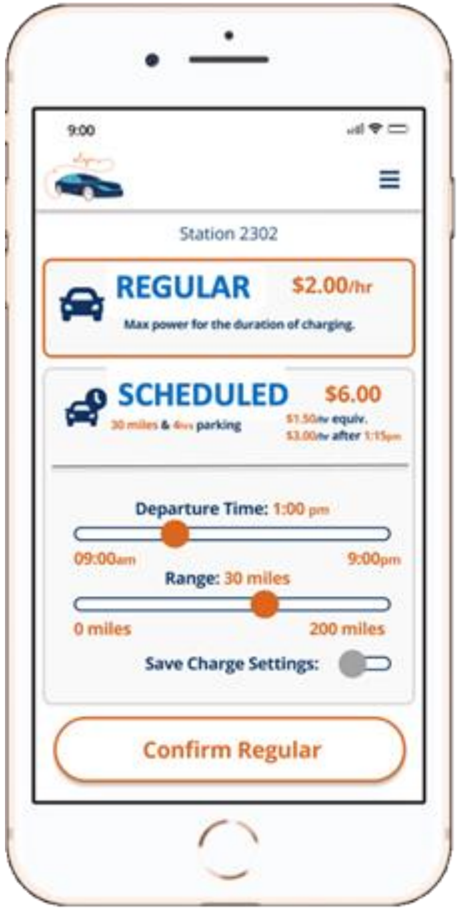
UC Berkeley

8 Level 2 chargers

(~6.6 kW)

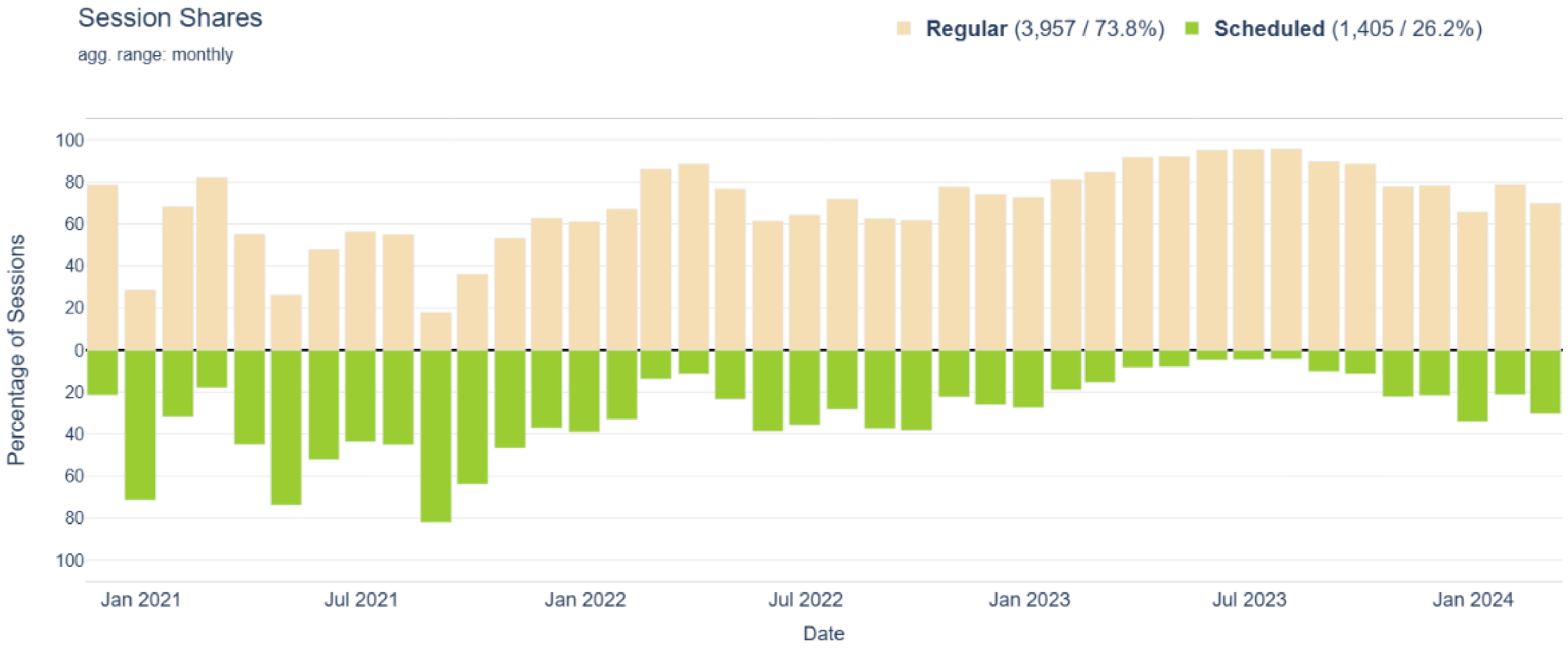
SlrpEV pilots flexible EV charging at the workplace

Smart **L**ea**R**ning **P**ilot for **E**lectric **V**ehicle Charging Stations



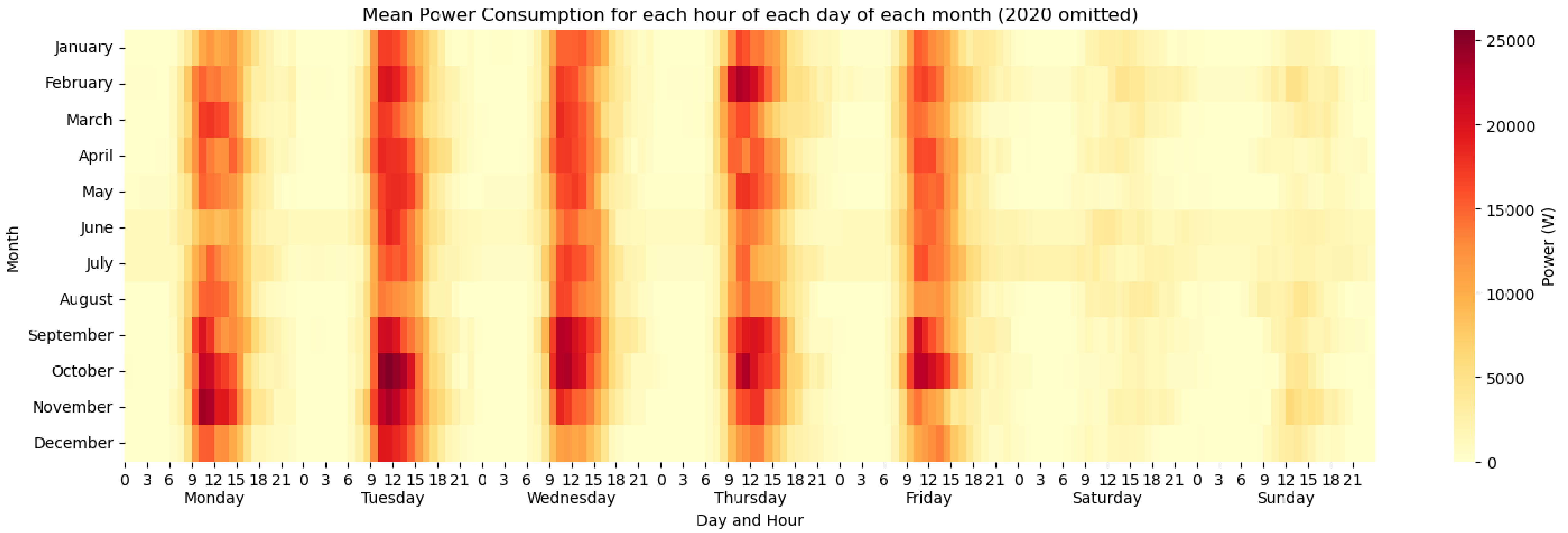
8 level-2 chargers on Berkeley campus (stats updated by 29 Dec 2023)

267 unique users, **4962** sessions, **96046** kWh delivered



Explore our *[data dashboard](http://slrpev.fun.yi-ju.me/): http://slrpev.fun.yi-ju.me/*

Seasonality of Electric Power Demand



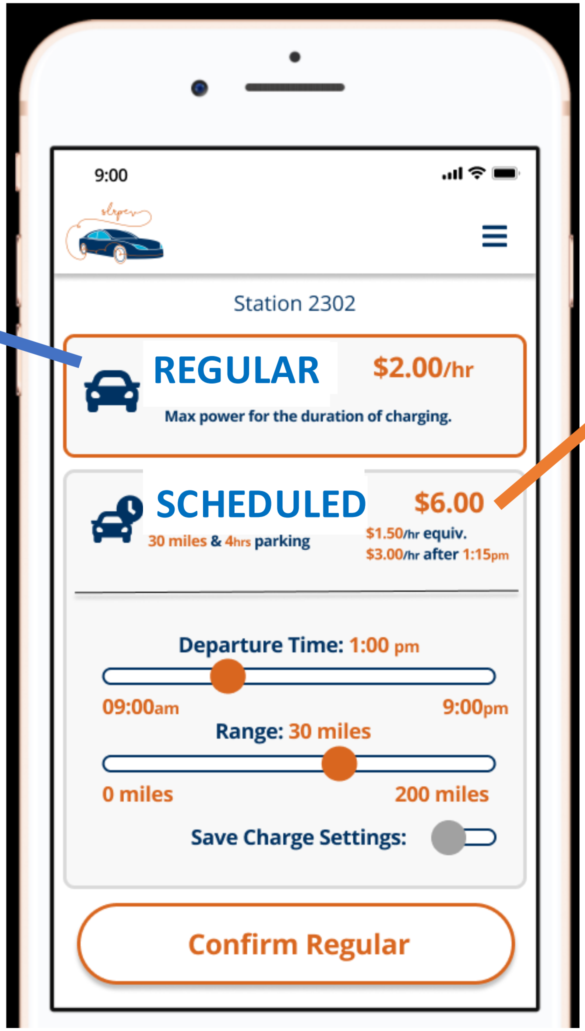
- Demand concentrated between 10a – 12n on weekdays
- Demand increases during Sept-Nov, Feb-Mar

Cyber-Physical & Human System

The Human

REGULAR

- Fixed rate in USD/hr
- Max power until unplug or top-off
- NOTE: charging power is uncontrollable load



SCHEDULED

- User provides departure time & added range
- Total cost fixed *a priori*
- NOTE: charging power is now controllable

If I want to shift load, then how much should you discount SCHEDULED to acquire flexibility?


REGULAR
SCHEDULED
SAVE MONEY AT SLRPEV!

Discrete Choice Model – How to model human behavior

Daniel McFadden
2000 Nobel Prize in
Economic Sciences

$$U_j = \beta_j^T z_j + \gamma_j^T w_j + \beta_{0j} + \varepsilon_j$$

where

U_j : Utility of j-th alternative, $j \in$ {asap, flex}

β_j: Parameters of controlled attributes

z_j: Controlled attributes (e.g. prices)

γ_j: Parameters of UN-controlled attributes

w_j: Uncontrolled attributes (e.g. arrival time)

β_{0j}: Alternative specific constant

ε_j: Undefined errors

Logit Model

Assuming "perception" errors ϵ_j have i.i.d. Extreme Value Distribution, the prob. of choosing j-th alternative is

$$\Pr(alt\ j\ chosen) = \Pr\left(\cap_{j \neq i} \left(U_j > U_i\right)\right)$$

$$= \frac{e^{V_j}}{\sum_{i=1}^{J} e^{V_i}} = sm(V)$$

where $V_j = \beta_j^T z_j + \gamma_j^T w_j + \beta_{0j}$

Optimizing Price & Power

Expected Cost Minimization Problem

$$\min_{z,u} \sum_j \Pr(J = j|z)\, h_j(z,u)$$

subject to: linear functions of (z,u)

where z is incentive control, u is direct control, and $h_j(z,u)$ is bi-convex in (z,u).

Compact Form

$$\min_{z,u} v^T h(z,u)$$

where $v_j = sm(\Theta_j z)$, $h = [h_{flex}(z,u) \quad h_{asap}(z,u)]^T$

Q: How to effectively and efficiently find solutions?
A: Re-formulate into multi-convex problem

T. Zeng, S. Bae, B. Travacca, Moura, “Inducing Human Behavior to Maximize Operation Performance at PEV Charging Station,” IEEE Transactions on Smart Grid, 2021

Optimize Price

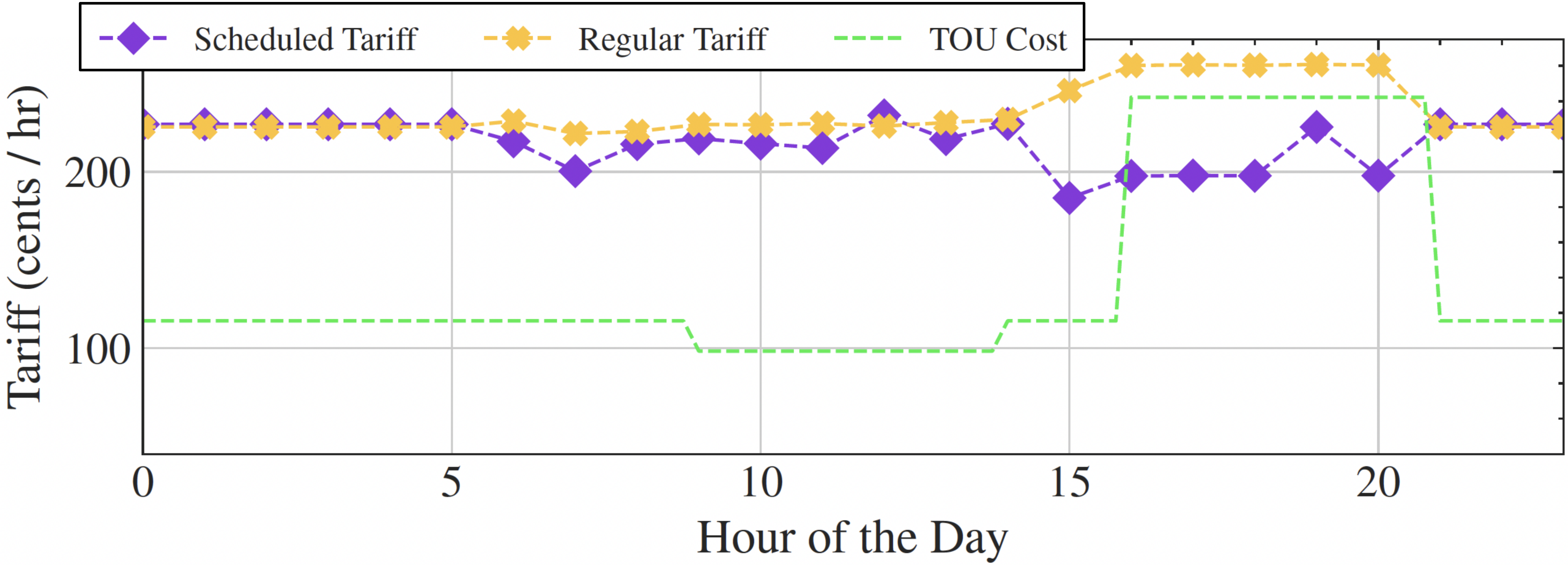
Maximize:

Net revenue

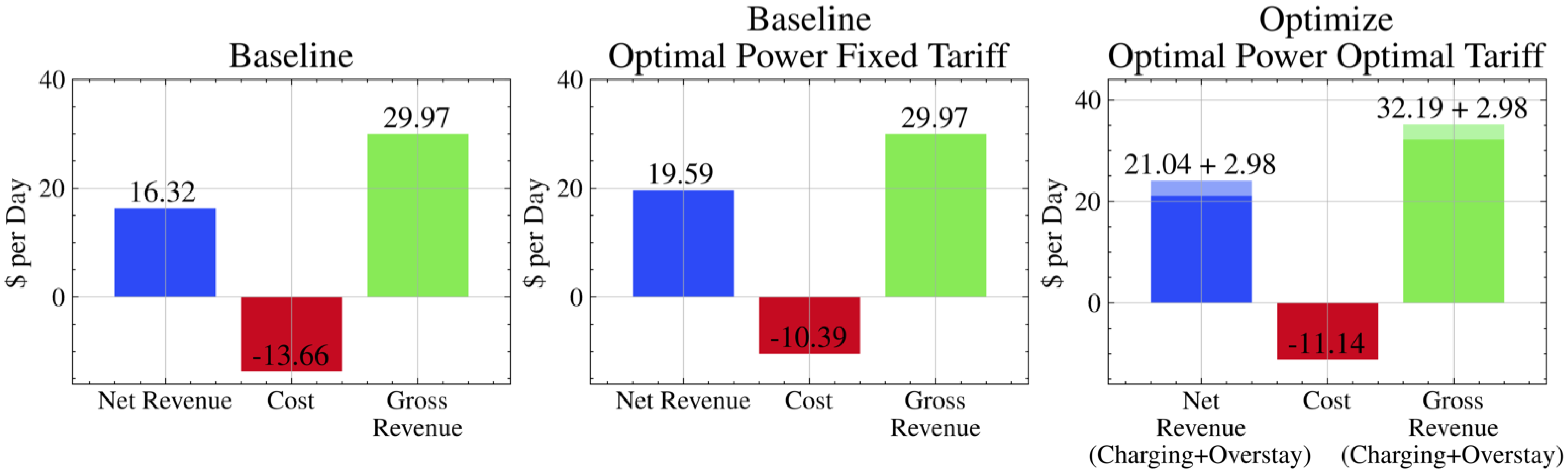
= Service Revenue – Utility Cost

Subject to:

- Discrete choice model
- Batt charging dynamics
- Departure time
- Energy Request



Net Revenue Maximization: Baseline vs. Optimize

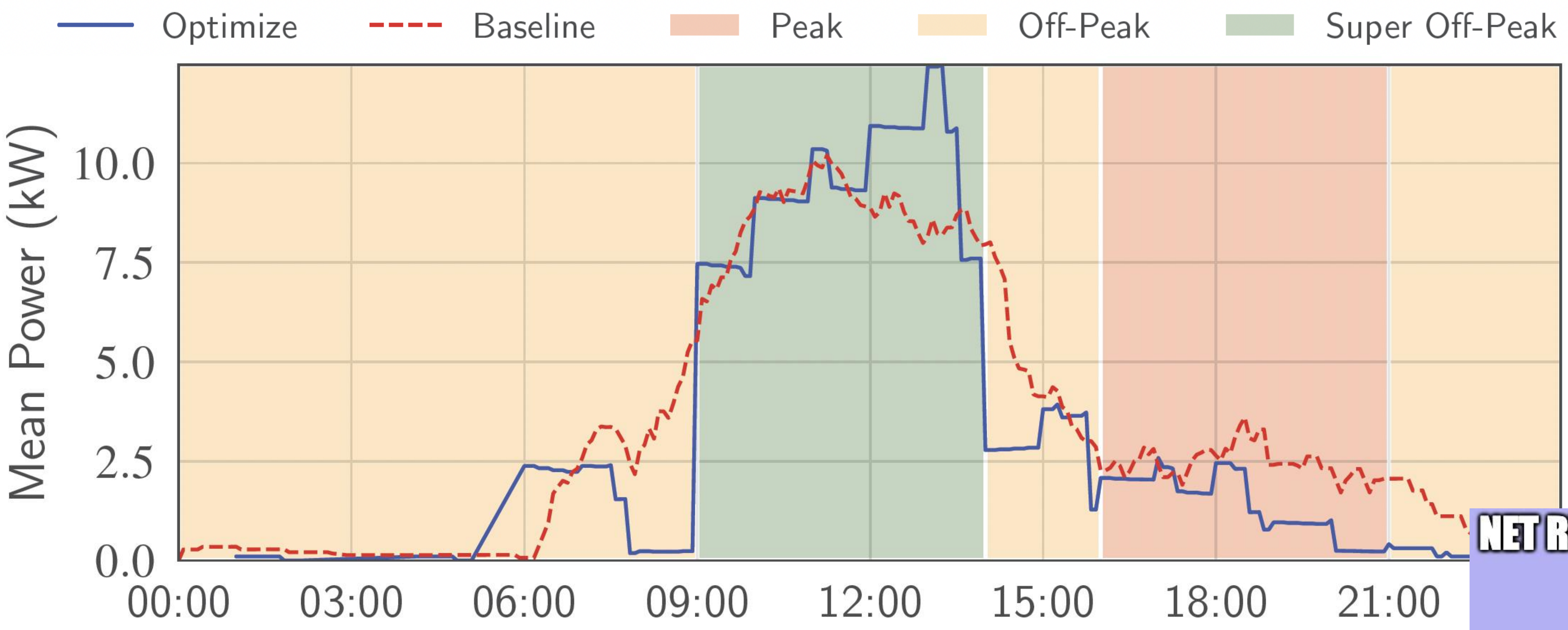


Baseline Net Revenue: $16.32 / day
Optimize Net Revenue: $24.02 / day

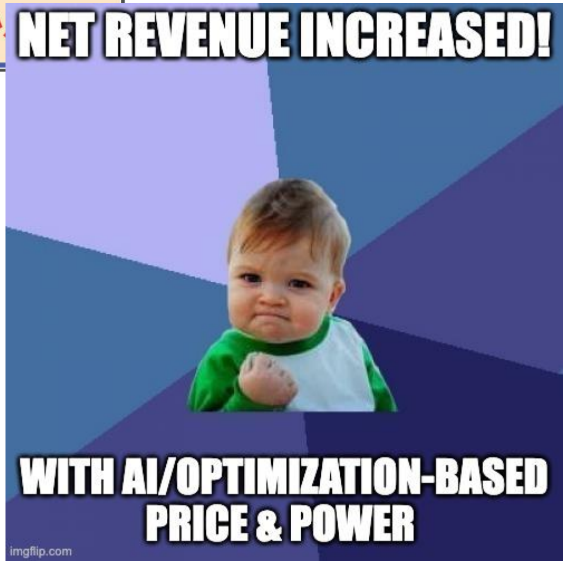
+47% increase in net revenue
+17% increase in gross revenue
-18% decrease in cost

Öztürk, Obeid, Zeng, Zeng, Moura, "Joint Price and Power Optimization Experiment for Workplace Charging Stations," *in review.*

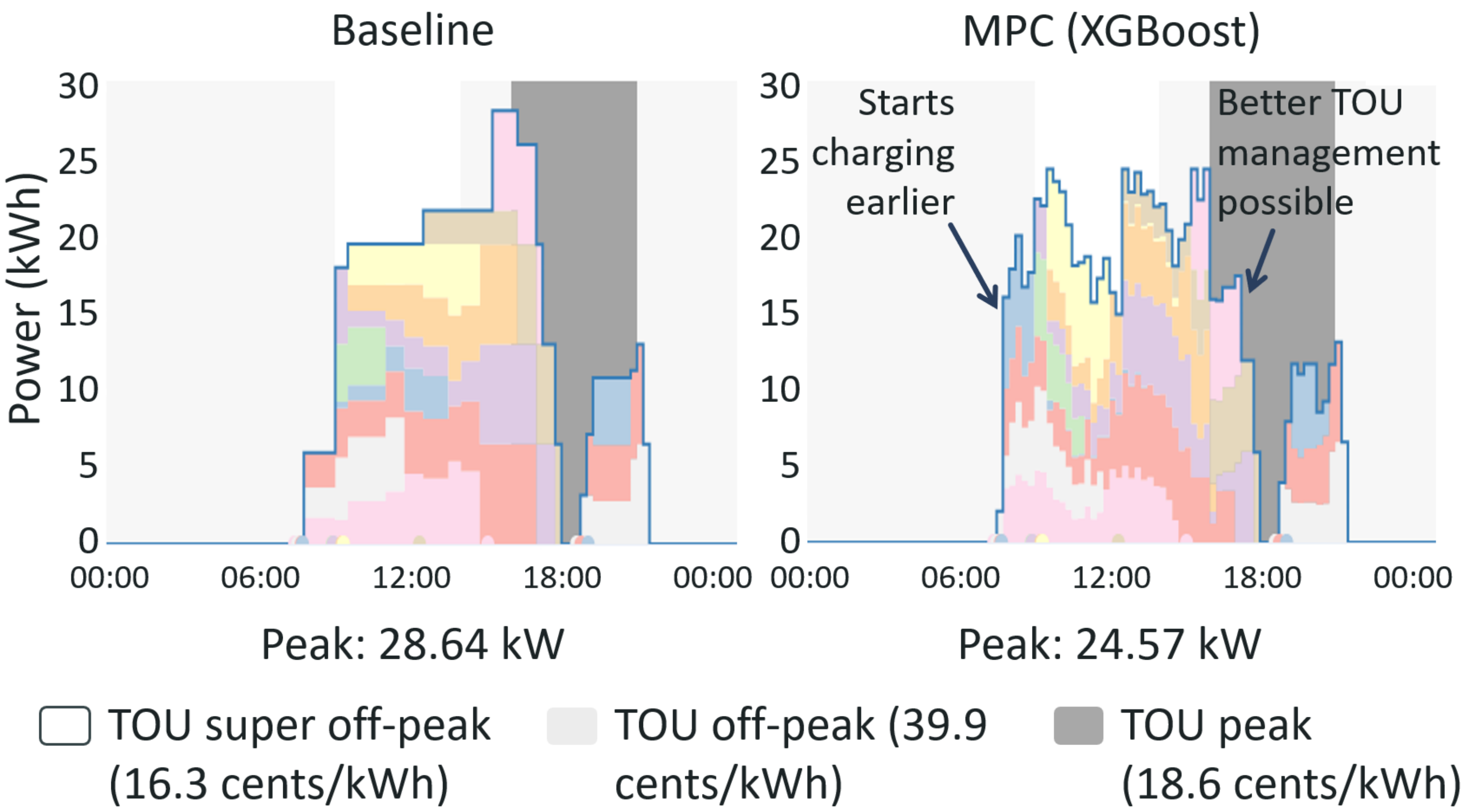
Load Shifting: Baseline vs. Optimize



Fraction of Energy Delivered	Baseline	Optimize
Super Off-peak (09:00 – 14:00)	56%	73%
Off-Peak (14:00 – 16:00, 21:00 – 09:00)	28%	17%
Peak (16:00 – 21:00)	16%	10%



Optimizing Price & Power can reduce peak power!



Peak Reduction via Price AND Power Optimization

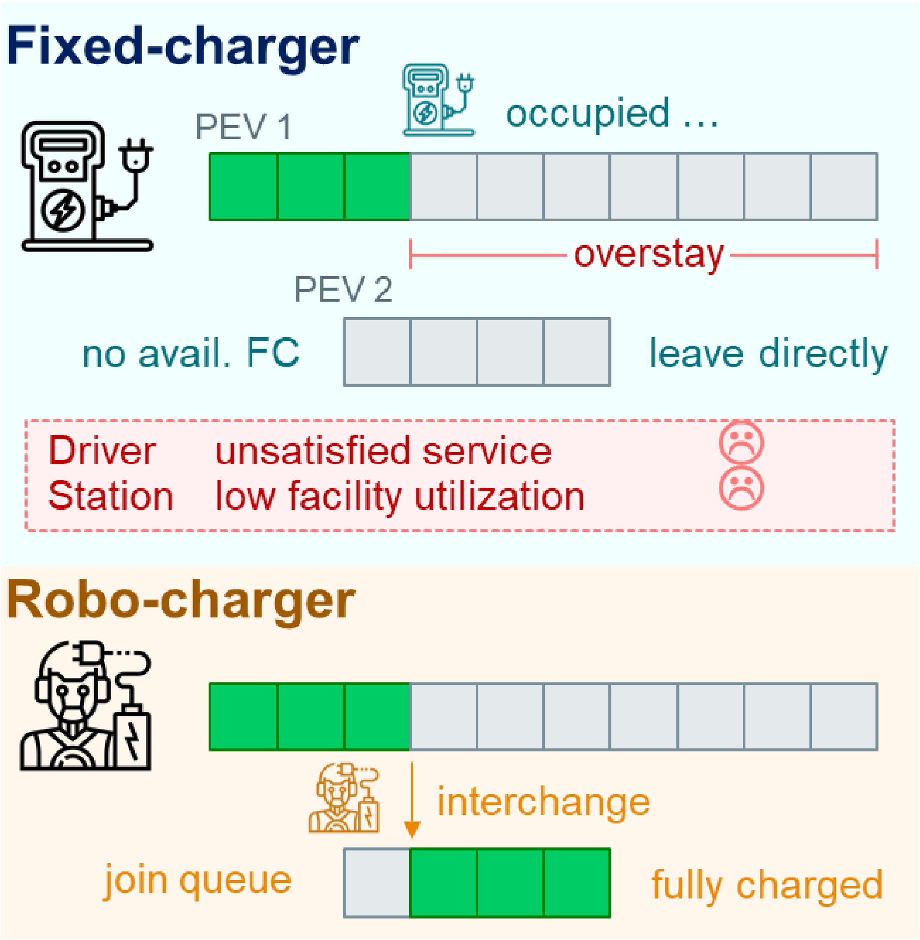
Control Scheme	Mean Cost/Revenue ($)					Change from Baseline (%)		
	Demand Charge	**TOU**	**Revenue**	**Cost**	**Profit**	**Demand Charge**	**TOU**	**Cost**
Baseline	624	1,984	4,309	2,608	1,702	0.00	0.00	0.00
Threshold	628	1,987	4,331	2,615	1,716	-0.71	0.16	+0.29
Softplus	609	2,017	**4,446**	2,626	1,819	-2.34	1.67	+0.71
MPC (Naive)	**519**	1,970	4,253	**2,488**	1,765	**-16.90**	-0.71	**-4.58**
MPC (Linear)	521	1,970	4,362	2,491	1,870	-16.50	-0.68	-4.47
MPC (XGBoost)	533	**1,956**	4,434	2,489	**1,944**	-14.57	**-1.39**	-4.55

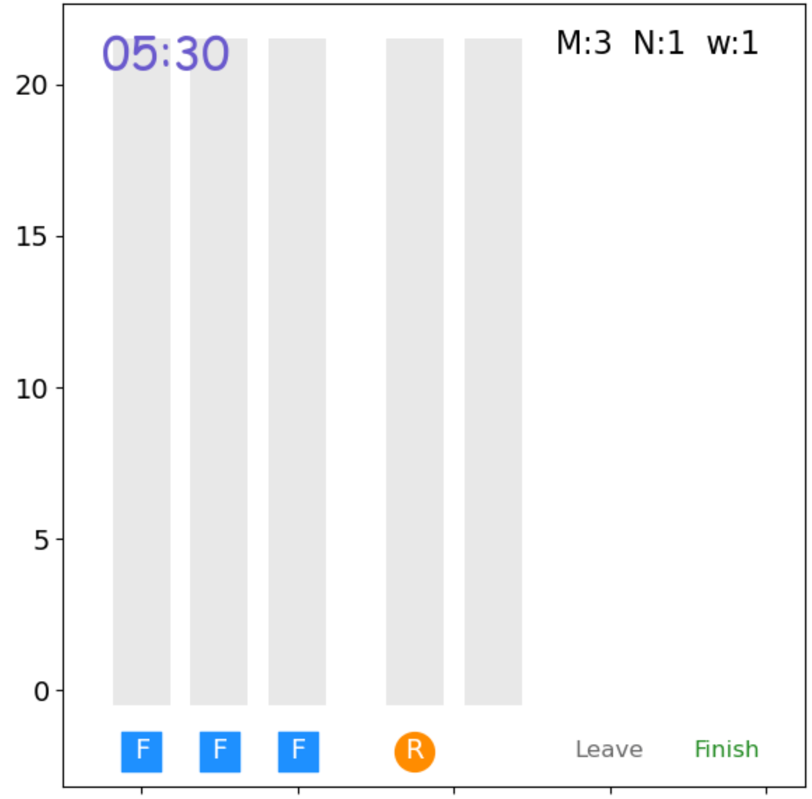
Innovative Ideas to Enable Demand Flexibility

Mobile & Robotic chargers to alleviate overstay

Optimal Operation and Planning of a Robotic Charging System to Alleviate Overstay

- Optimal scheduling, incl. charger assignment, plug-in schedules, & power profile optimization of Robo-chargers & Fixed-chargers
- Optimal combo. of Robo- & Fixed-chargers achieve minimum total cost of ownership (TCO)





Ju et al., IEEE Trans on Smart Grid (2023)

Mobile & Robotic chargers to alleviate overstay (real-world examples)

Source: Inductive Robotics

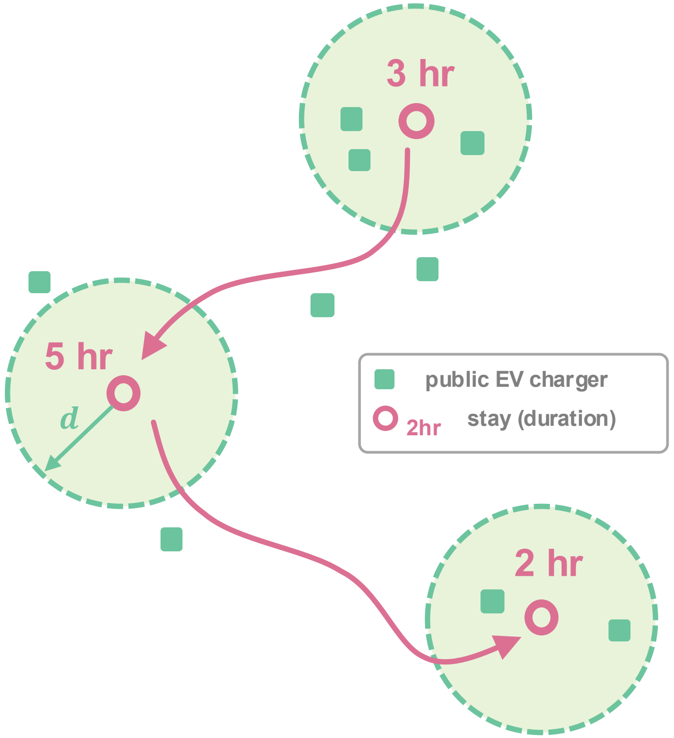
Source: ElectricFish

Note: Robo-chargers open the opportunity for demand management

(all parked EVs can be (dis)charged)

Disclaimer: we did not involve in any of above products / businesses. All resources are from the Internet.

Trajectory-Integrated accessibility -- Methodology Overview

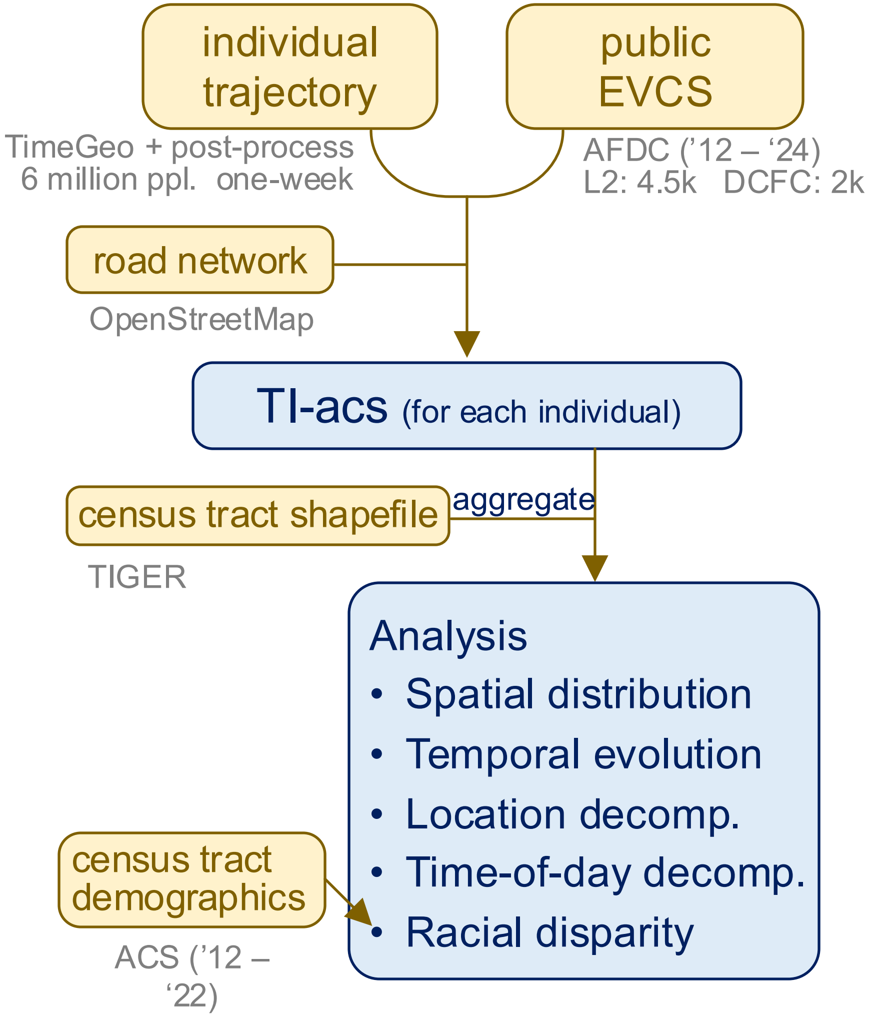


TI-acs [hours] =

$$3 \times 1 + 5 \times 0 + 2 \times 1 = 5$$

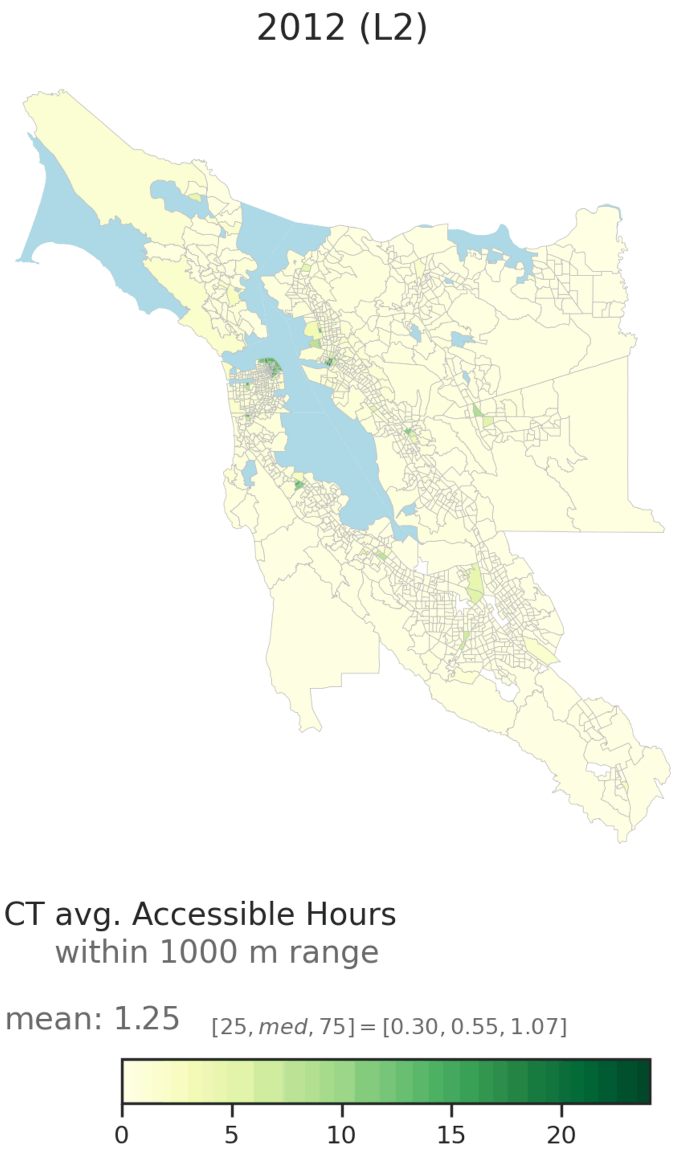
TI-acs [ports] =

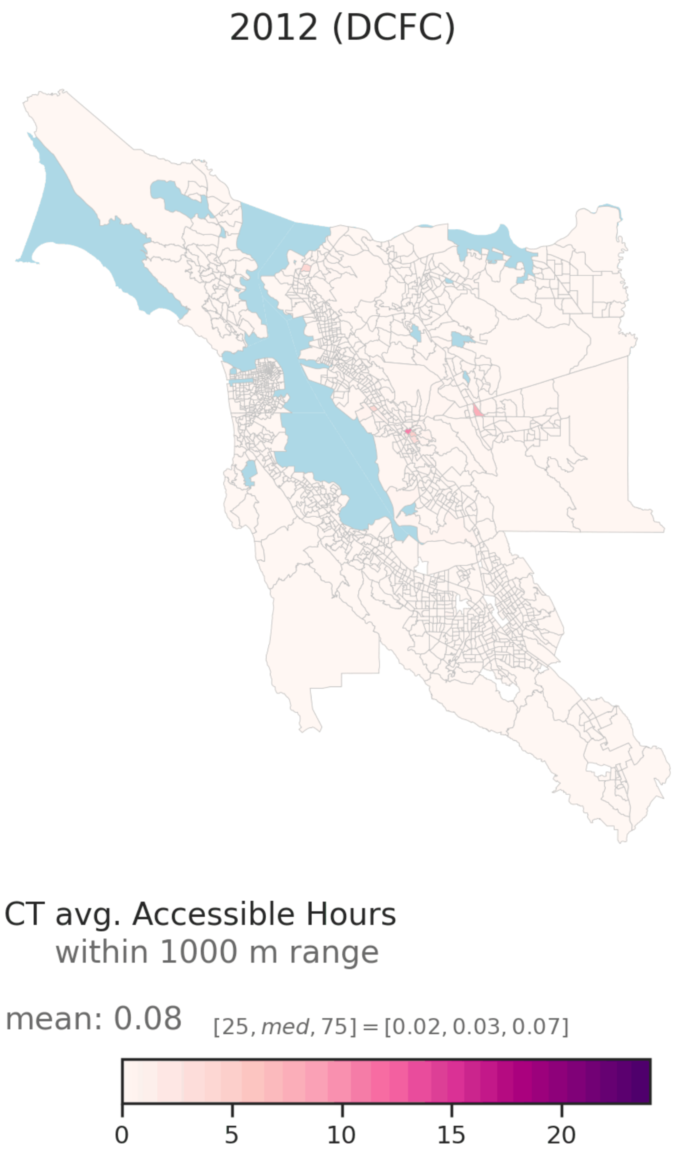
$$\frac{1}{3+5+2}(3 \times 3 + 5 \times 0 + 2 \times 2) = 1.3$$



***Ju** et al., **(2025)** manuscript in preparation*

Mobility-fulfillment market: **public charger accessibility improved over time**





As of **Aug. 2024**, on average, **SF Bay area** residents have

- **L2: 7.5** hrs / day
- **DCFC: 5.2** hrs / day

when there is at least 1 public charger within 1 km of their stays

five years ago (2019):

- L2: 4.7 hrs / day
- DCFC: 2.2 hrs / day

***Ju et al., (2025)** manuscript in preparation*

Motivation: Battery Swapping Opportunity

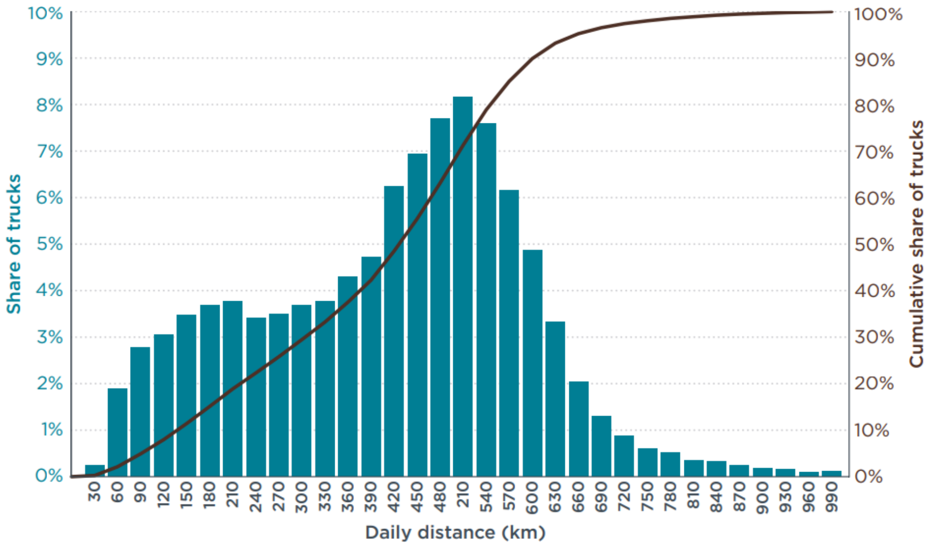
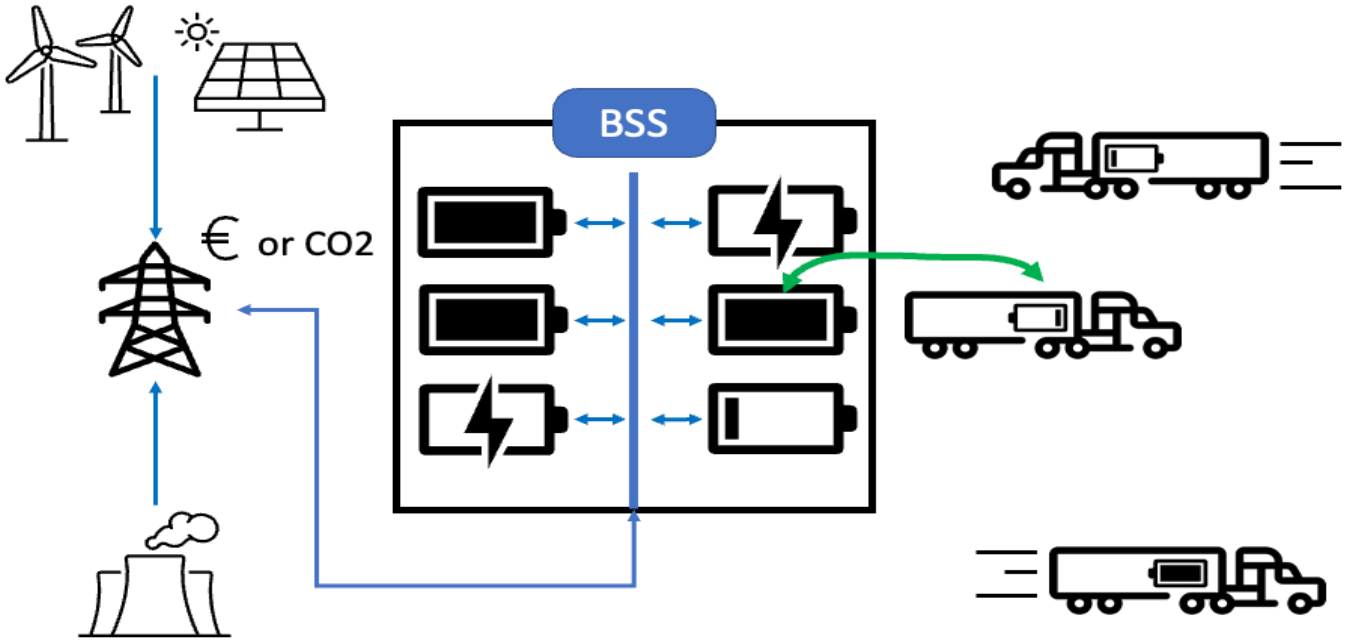


Figure 1. Average truck daily distance from a representative fleet, adapted from Wentzel (2020).

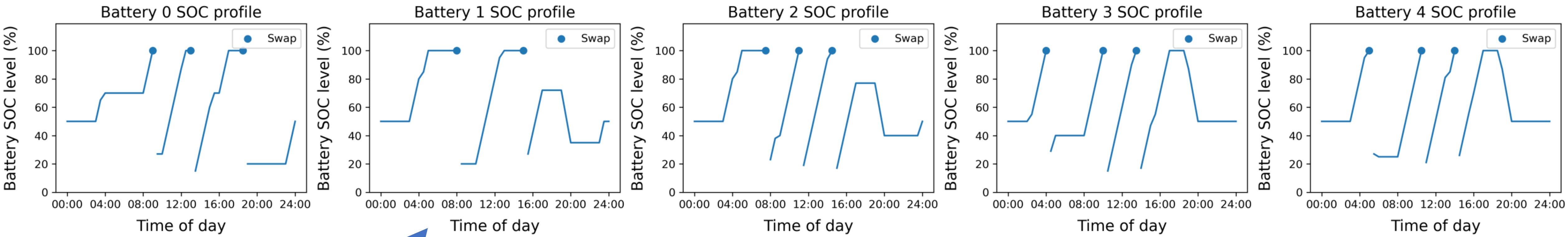


- 90% of trucks drive a daily distance shorter than 600 km / 373 mi (Basma et al., 2021)

Battery range ~ 300 km / 186 mi
With one swap ~ 600 km / 373 mi

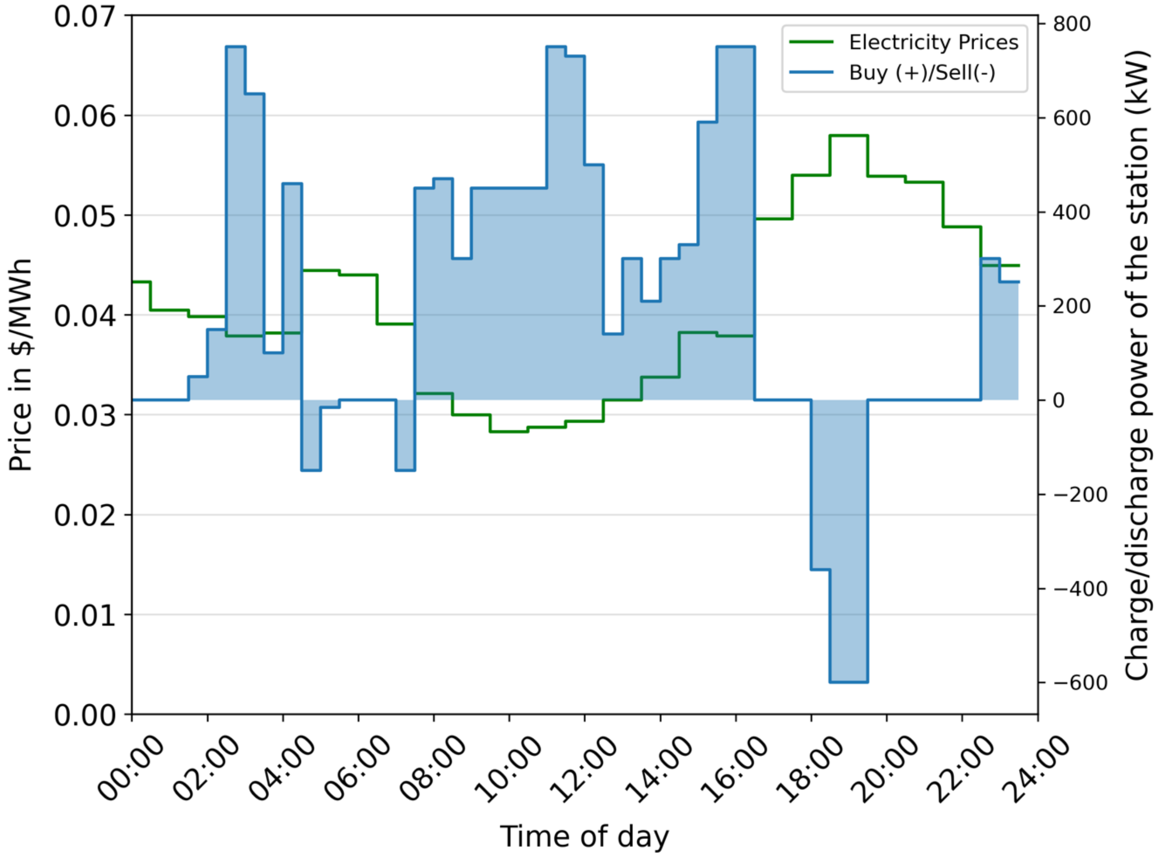
Volvo FM electric, 540kWh of battery for 300km – Solutrans 2021

Stack Services
1. Sell e-mobility service, as a fueling station
2. Sell grid services, as a battery storage system



- Charged batts are swapped out for discharged batts

- Discharge around 18h00



- Station purchases power at low prices, sells at high prices

R. Wang, Y. Ju, Z. Allybokus, W. Zeng, N. Obrecht, S. J. Moura, "Optimal sizing, operation, and efficiency evaluation of battery swapping station for electric heavy-duty trucks," *2024 American Control Conference.*

Outline

1. Introduction
2. The Duck Curve Problem
3. Power Grid Impacts of EVs
4. Saving the Grid with SlrpEV
5. Summary

Summary

Will EVs Break the Power Grid?

- Transportation contributes ~45% of CA GHG emissions
- Trajectory towards 100% ZEVs will require significant power grid infrastructure upgrades
- Queue of clean energy is huge, but interconnection is slow
- <u>Massive</u> need and opportunity to create demand flexibility from EV Charging
  - SlrpEV, robo/mobile chargers, battery swapping, behavioral nudging along mobility trajectories

eCAL energy, controls, & applications lab

CALIFORNIA PATH

Collaborate with us to…

- Reduce transportation CO2e via electrification
- Creative innovations in e-mobility

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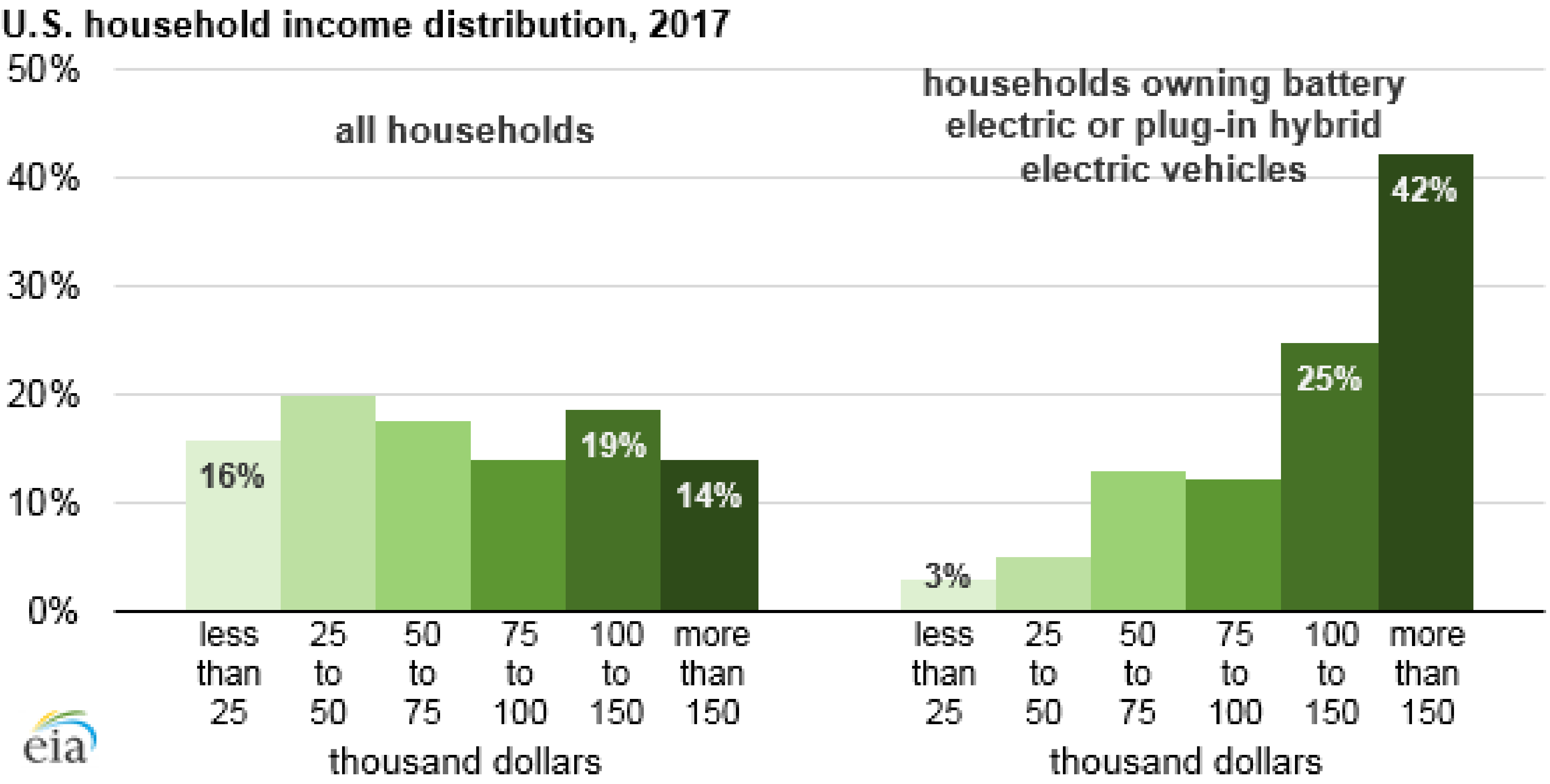
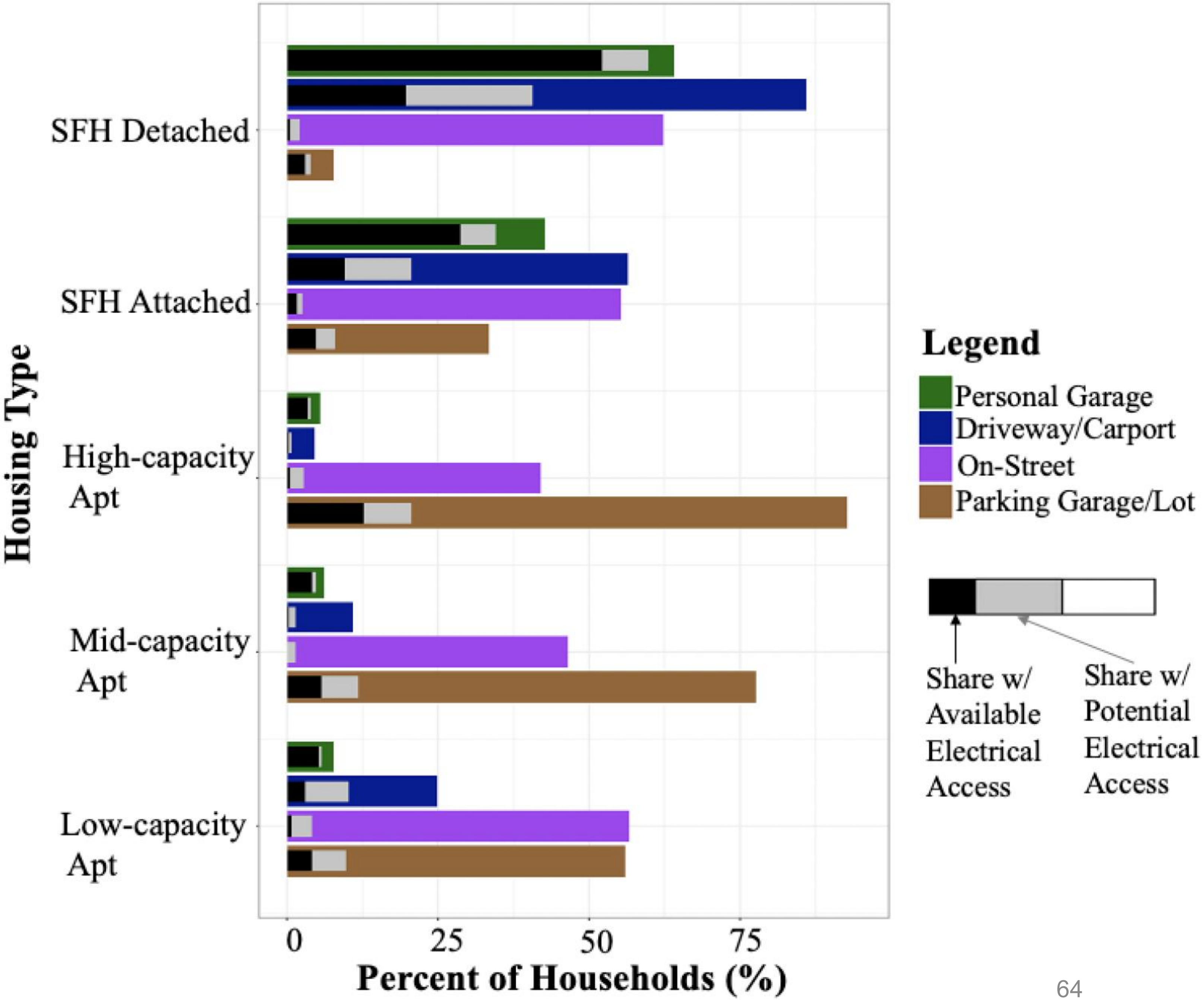
Access to ZEVs by INCOME



Equitable Access to ZEVs by HOUSING

At home, do you have an electrical plug near your car?

Apartment dwellers largely LACK electrical access for charging

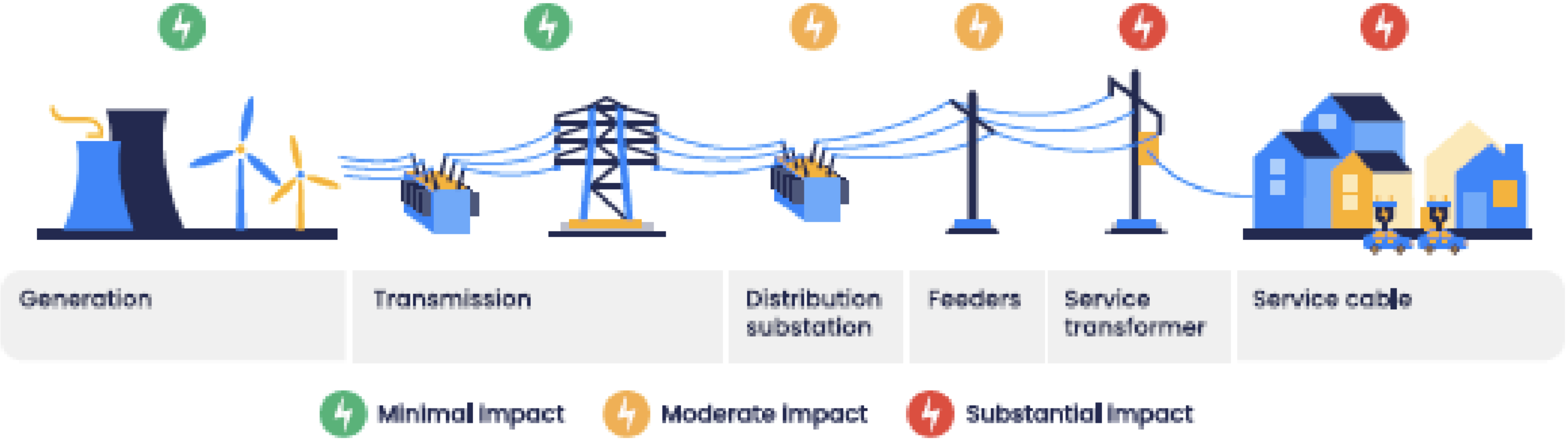


Impact of electric vehicle charging demand on power distribution grid congestion

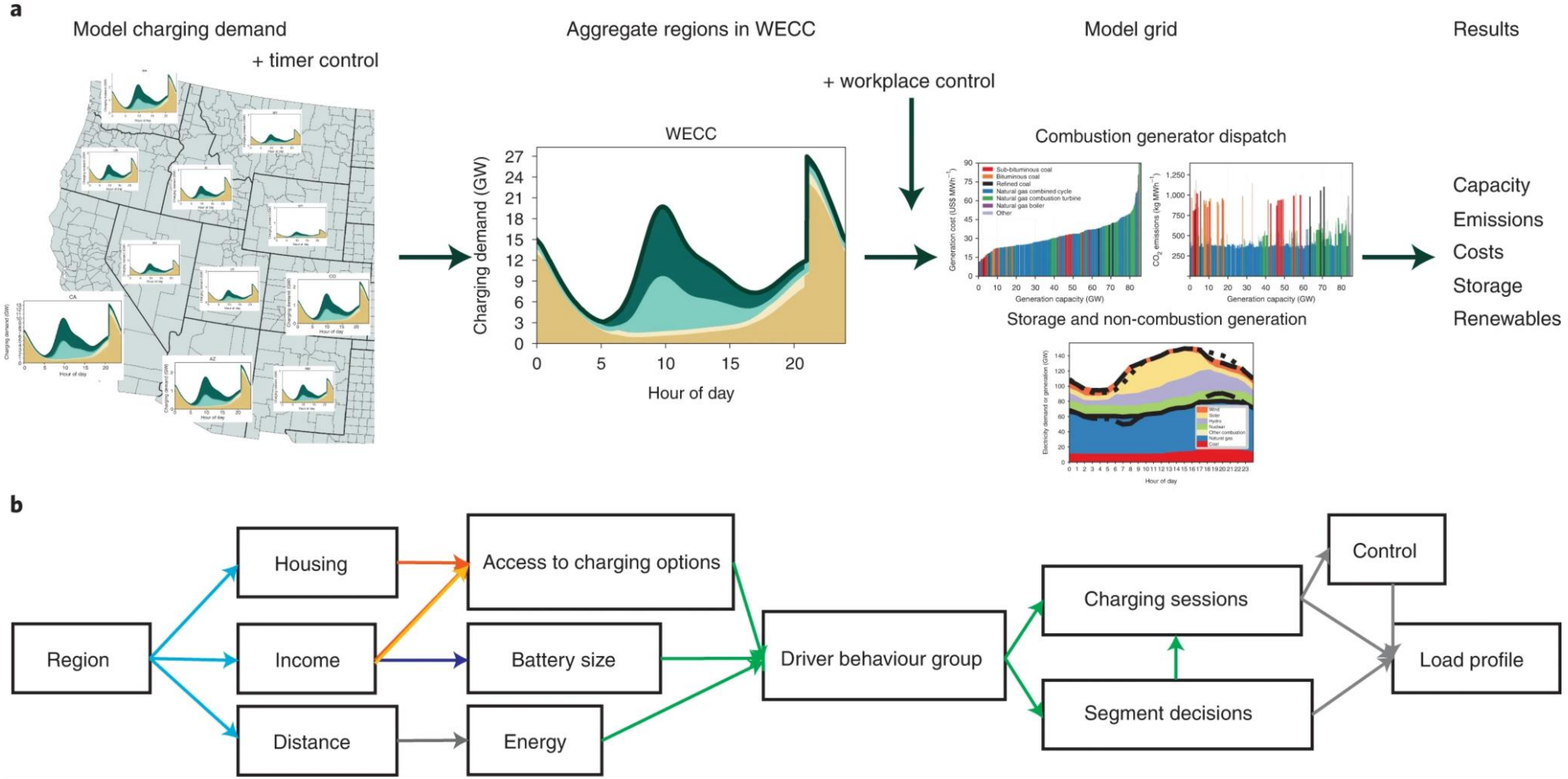
Y. Li, A. Jenn, "Impact of electric vehicle charging demand on power distribution grid congestion," *Proceedings of the National Academy of Sciences,* April 2024. DOI: 10.1073/pnas.2317599121. Edited by SJM.



Yanning Li	Alan Jenn	Edited by Scott Moura



How does Large-Scale EV Adoption Impact Peak Demand



Source: S. Powell, G. V. Cezar, L. Min, et al. *Charging infrastructure access and operation to reduce the grid impacts of deep electric vehicle adoption*. Nature Energy (2022). https://doi.org/10.1038/s41560-022-01105-7