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Projecting Electric Vehicle Electricity Demands and Charging Loads

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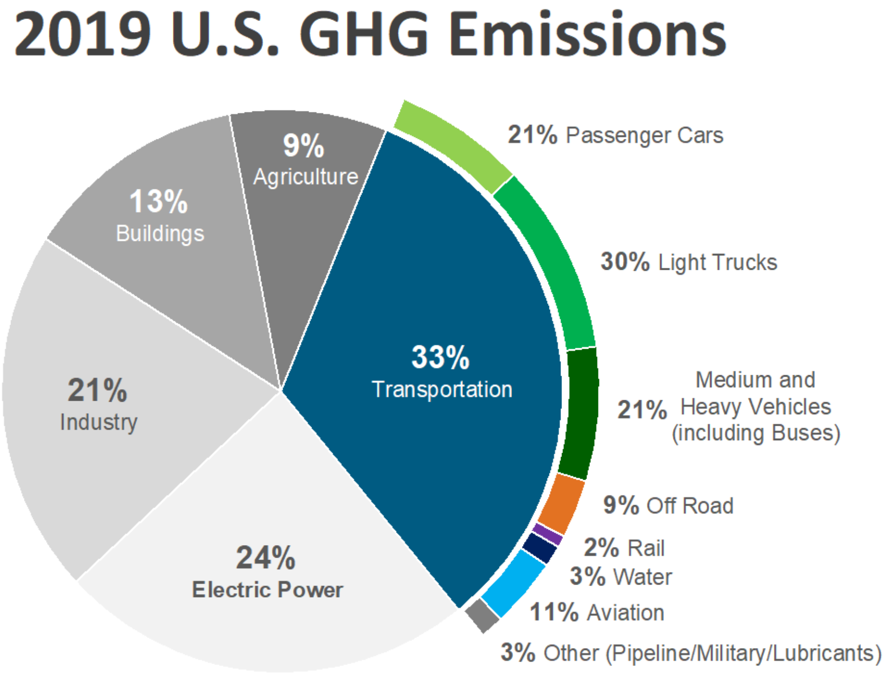
NREL/PR-5400-89775

Transportation is the Least-Diversified Energy Sector (90% Petroleum)



Source: US National Blueprint for Transportation Decarbonization

Transportation is the **largest source of U.S. greenhouse gas (GHG)** emissions

1. Responsible for **poor air quality** (disproportionate impacts)
2. The **second largest household expenditure**
3. Main driver of **global petroleum demand**

To address the climate crisis, we must **eliminate nearly all transport emissions by 2050**.

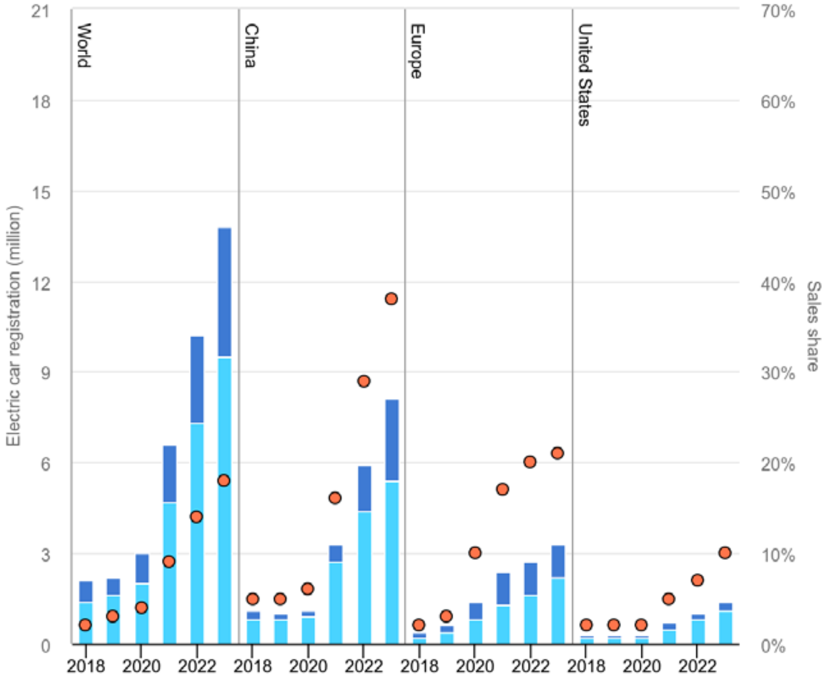
Battery Electric Vehicles: a Success Story

Source: IEA

- EVs offer a pathway to decarbonize on-road transportation when coupled to **clean electricity**.
- **Electric vehicles (EVs)** are experiencing a rapid rise in popularity and adoption:
  - Technology has matured and **costs have declined**
  - **Support for clean transportation** has incentivized adoption and promoted awareness
  - Increased **charging opportunities** enabled adoption
- Expected **rapid growth in EV adoption** for passenger vehicles as well as buses and medium- and heavy-duty trucks and other applications (off -road, planes, ships, etc.).

EV sales grew to capture 18% of the global market in 2023, 14 million EV sold!

2018-2023 Electric Car Registrations and Sales Share



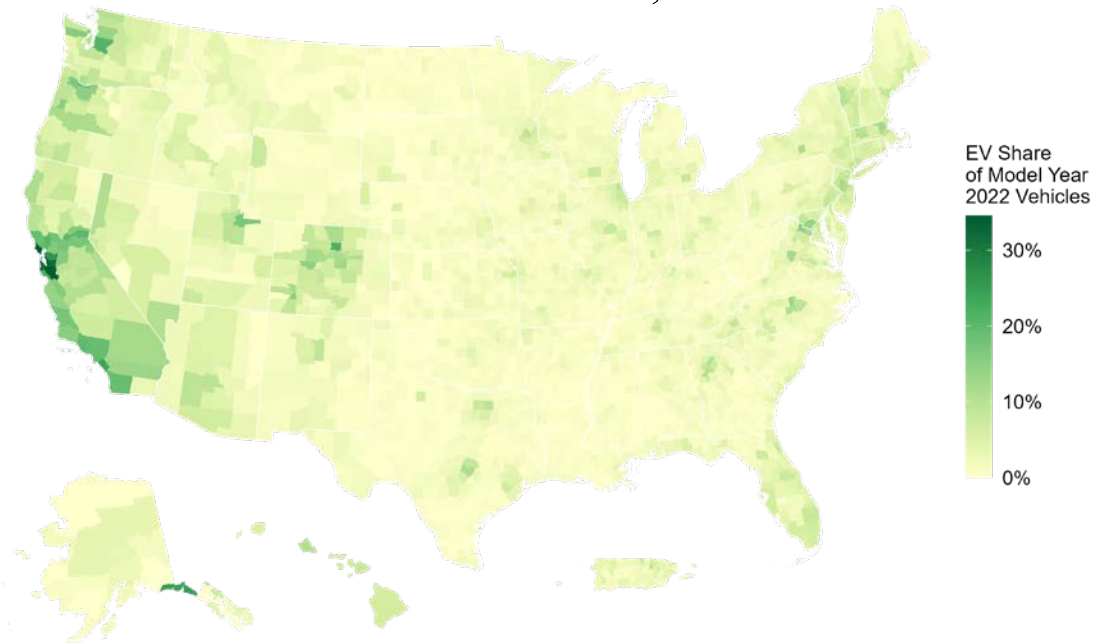
Source: IEA Electric Vehicles

- In 2023, investments in EVs surpassed renewables to become the largest in clean energy, with $634 billion invested.
- Electrification of road transport is rapidly moving beyond cars.
- One in ten vehicles sold in the U.S. in 2023 was electric (over 1.4M EVs sold in 2023)!

"The future is already here; it's just not very evenly distributed."

- William Gibson

EV Market Share, 2022



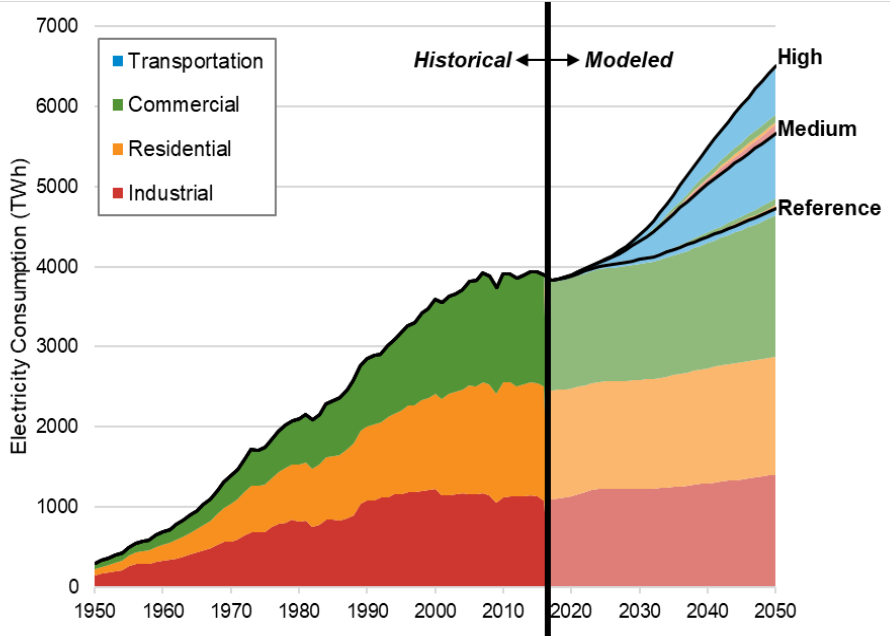
Note: EV includes BEV and PHEV.
Source: NREL analysis of 2022 Experian vehicle registration data,
from Yip et al. (2023) Highly Resolved Projections of Passenger Electric Vehicle Charging Loads for the Contiguous United States
https://www.nrel.gov/docs/fy23osti/83916.pdf

Impact on Electricity Demand

EVs are expected to be the **largest source of electricity demand growth**, and will require investments in generation, transmission, and distribution systems.

EVs are also expected to be the **largest source of demand-side flexibility**, much needed in the future electricity system dominated by renewables.

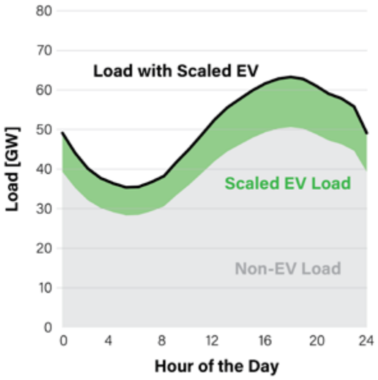
Smart integration of EVs can **strengthen the grid by providing flexibility that reduces electricity costs and increases resiliency**.

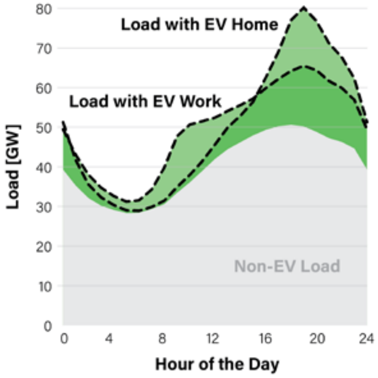


Source: NREL's Electrification Futures Study

When and *Where* EV Charging Occurs Will Be as Critical as *How Much* Electricity is Needed

a) ASSUMPTION:
EV charging is often assumed to simply scale up electricity demand.

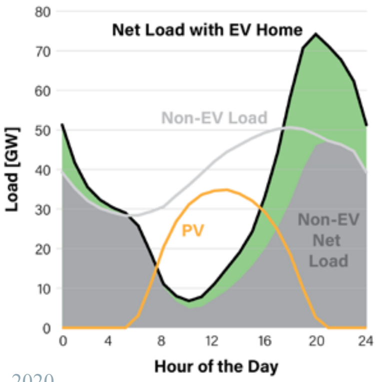


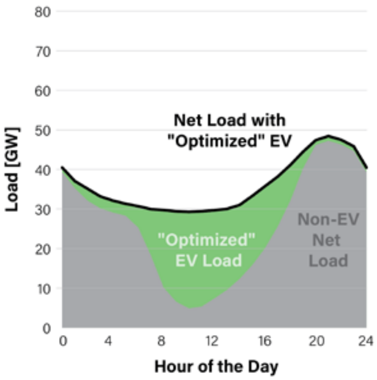


b) COMPLEXITY:
Future EV charging could change the shape of demand, depending on when and where charging occurs.

Savage, Sam L. The flaw of averages: why we underestimate risk in the face of uncertainty. John Wiley & Sons, Inc., 2012

c) INTEGRATION:
EV charging can impact power system planning and operations, particularly with high shares of variable renewable energy.





d) FLEXIBILITY:
Optimizing EV charging timing and location could add flexibility to help balance generation and demand.

Source: Muratori and Mai, 2020

NREL Produces First Ever County-Level Hourly EV Charging Data for the entire USA

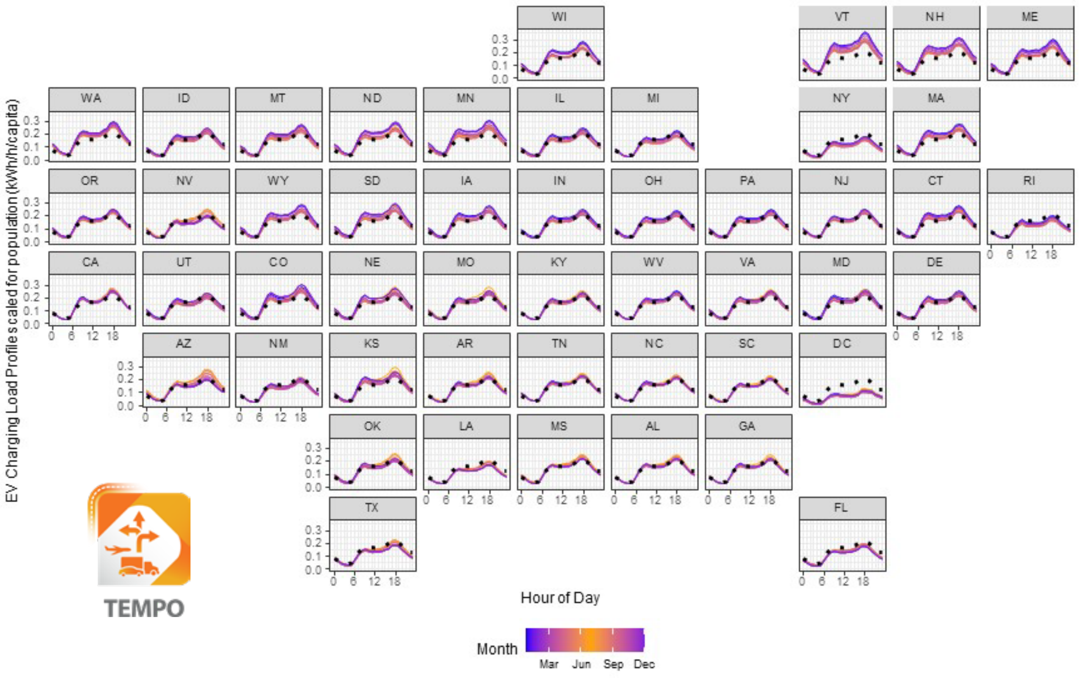


Figure ES-2. State-level per-capita EV charging load profiles for an average weekday for the All EV Sales by 2035 scenario for projected year 2035 under the immediate and ubiquitous charging strategy, for the contiguous United States, with seasonal variation shown by line color (blue for winter and orange for summer) and U.S. annual average in black dashes

Source: [Yip et al. (2023) Highly Resolved Projections of Passenger EV Charging Loads for the Contiguous United States]

Significance

- Enhanced Transportation Energy & Mobility Pathway Options™ (TEMPO) model can project spatially, demographically, and temporally resolved EV charging load profiles – from national scale to county level
- Accounting for local heterogeneity in consumers, travel behavior, vehicles, & operating conditions
- Three EV adoption scenarios for 2020 -2050 and associated data, enabling detailed power system modeling

Methods

EV Adoption

- EV adoption varies across regions and consumers
- Consumer needs are heterogenous (e.g., household location, income, vehicle ownership, vehicle class and range)

How many EVs and what kinds?

EV Use and Charging Needs

- Travel demand (VMT)
- Temperature impacts EV charging needs
- Charging options vary for different consumers

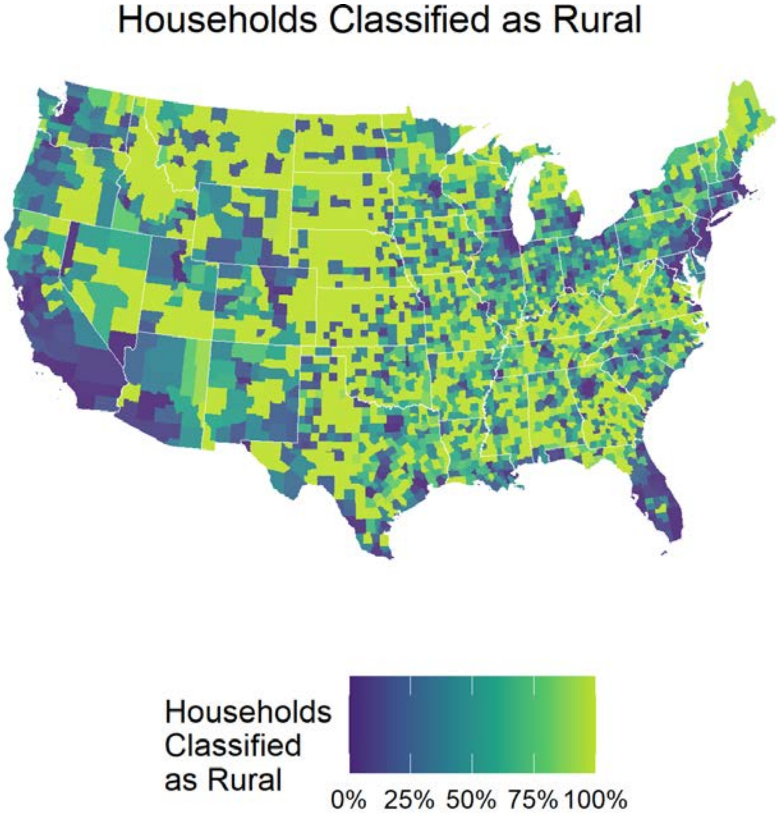
How much charging energy?

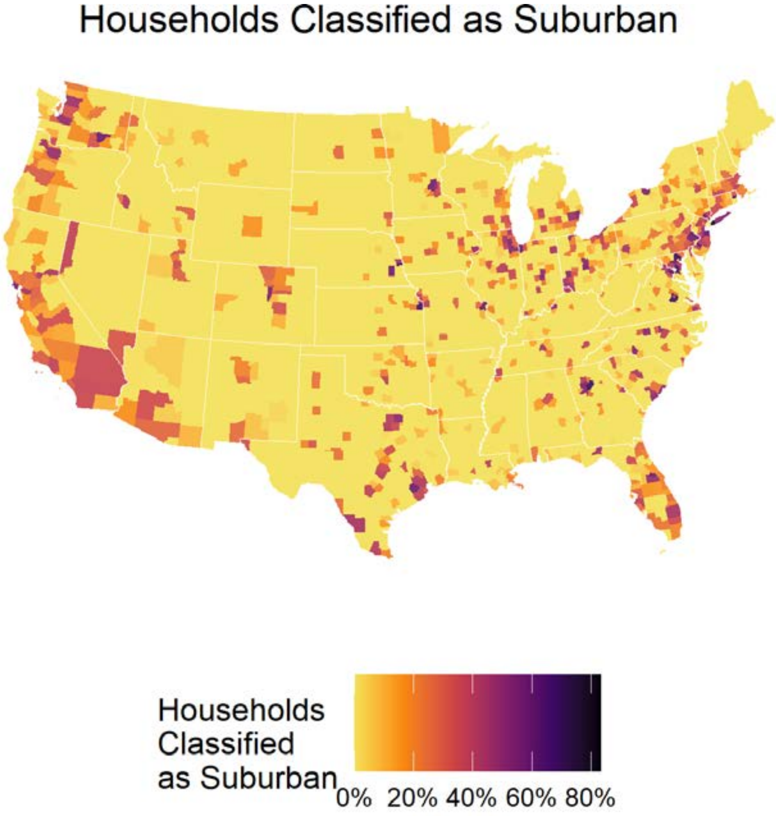
EV Charging Loads

Significant Heterogeneity in EV Charging Loads

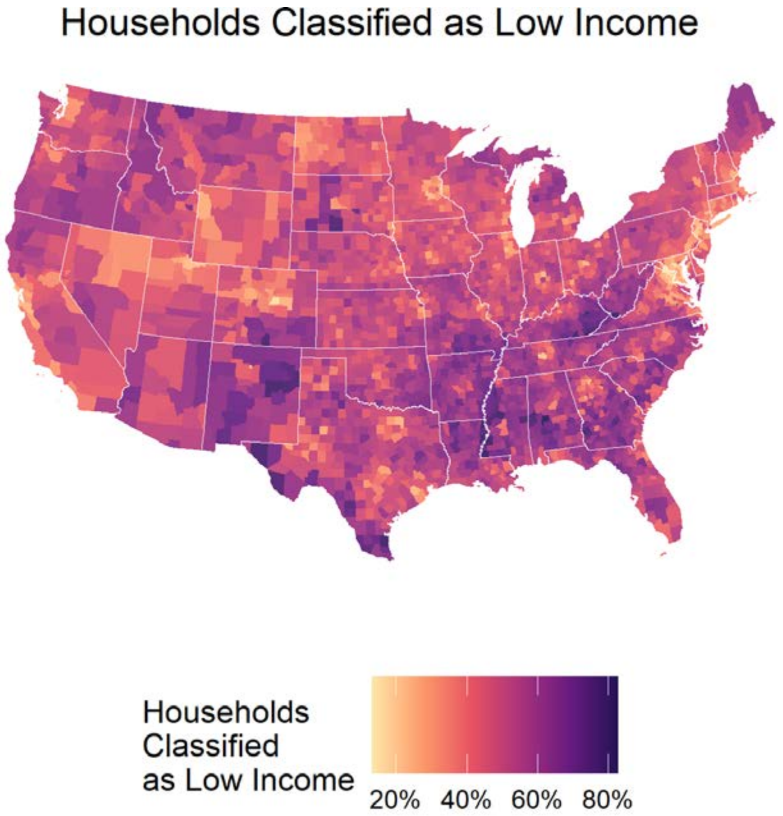
County-Level Hourly Load Shapes

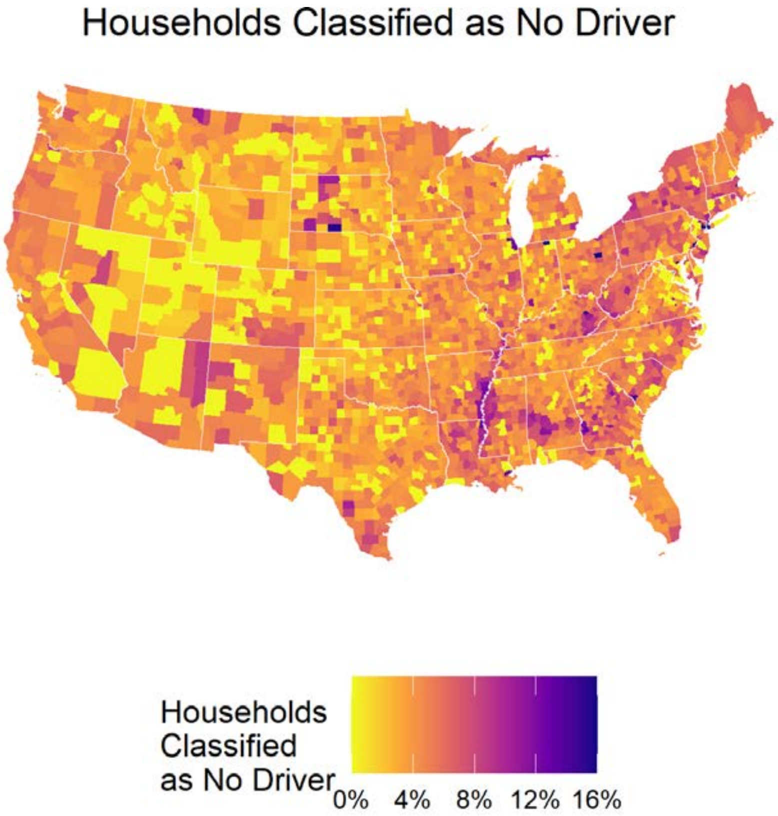
EV Adoption and Usage Depends on Household Characteristics…



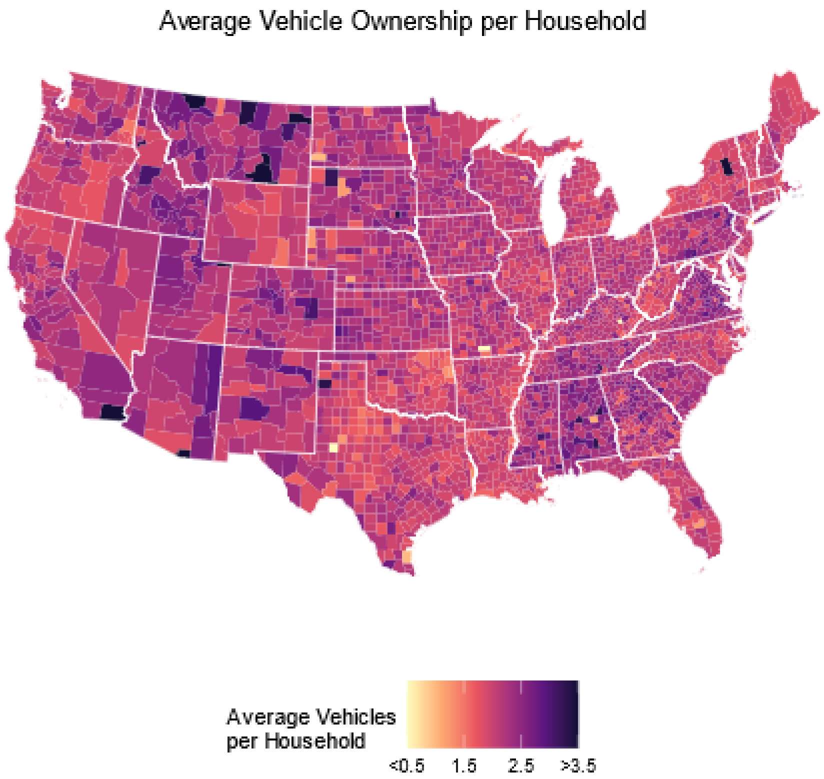


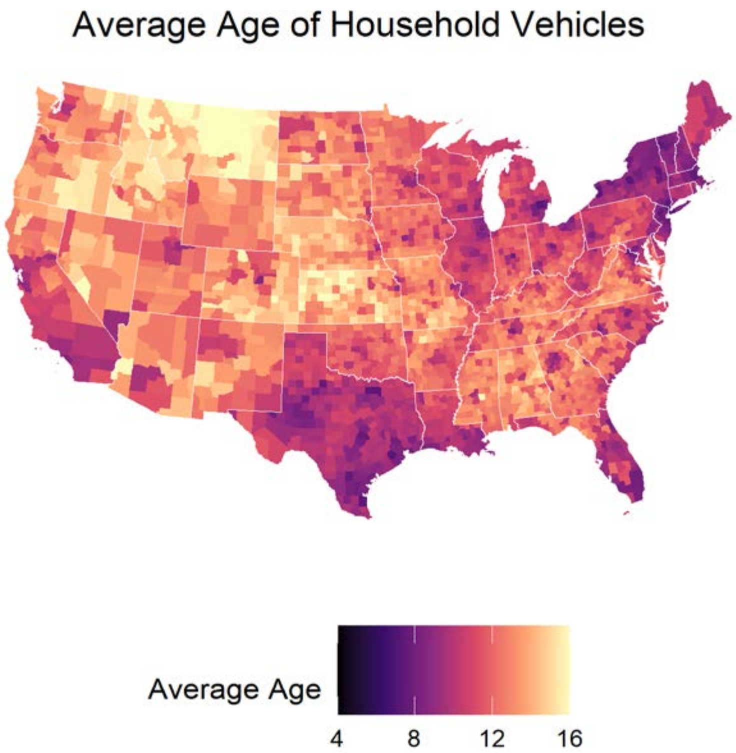
Households Are Diverse in Income, Composition, and Urbanicity





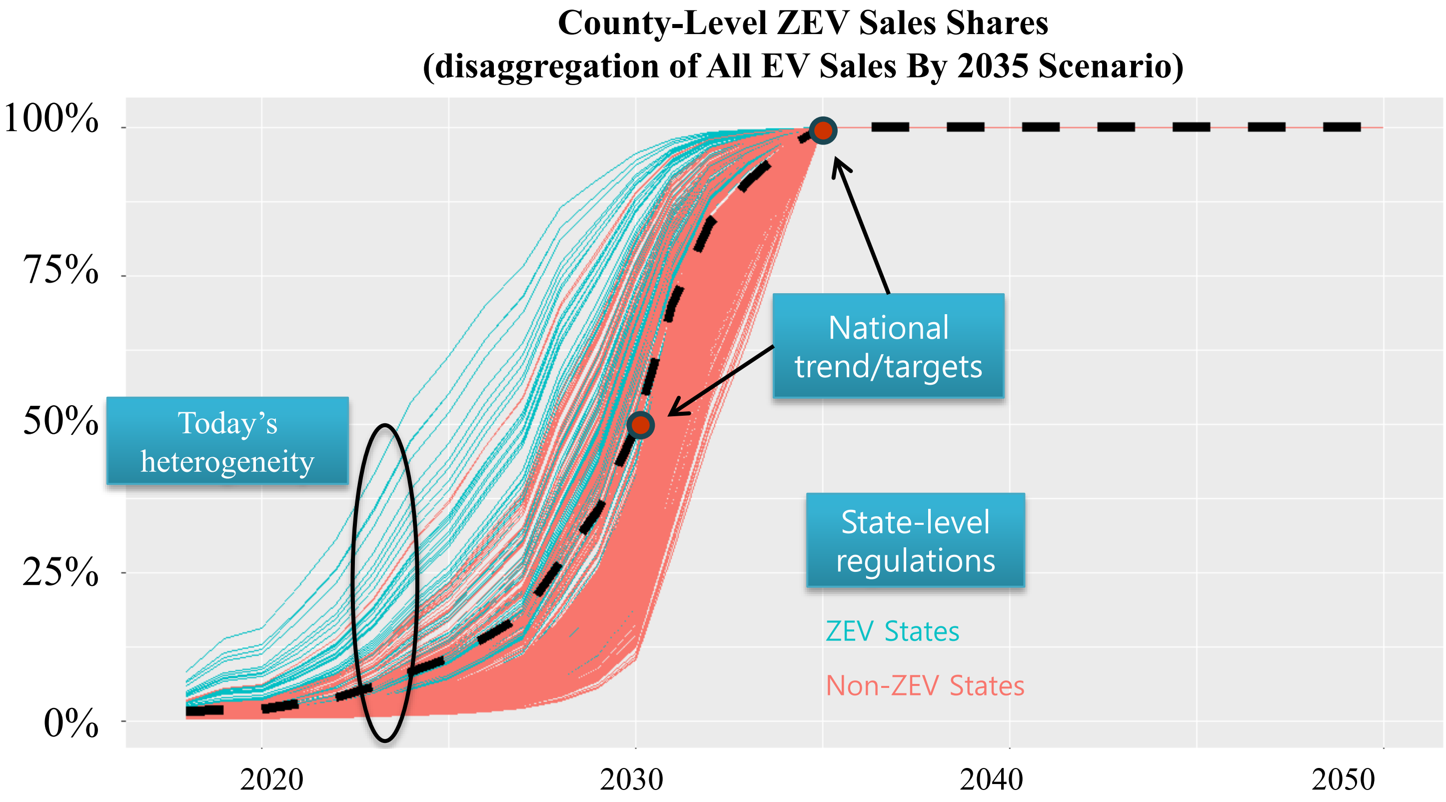
Vehicle Ownership Is Diverse





TEMPO Disaggregates National EV Sales Projections to a County-Level Spatial Resolution

TEMPO



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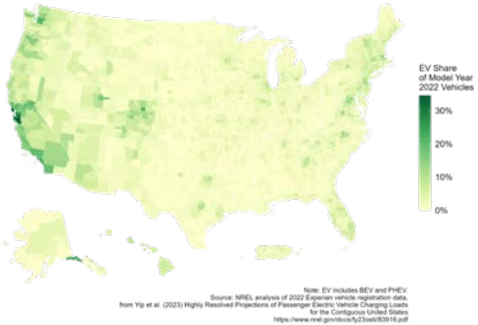
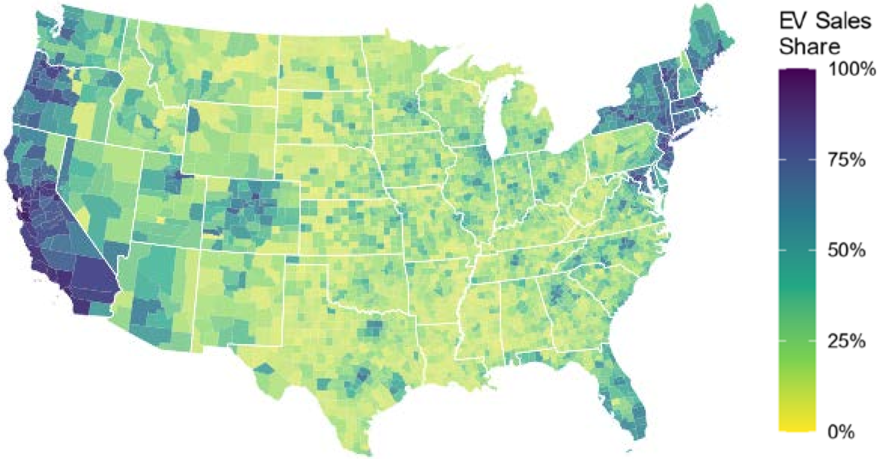
TEMPO

Today's heterogeneity



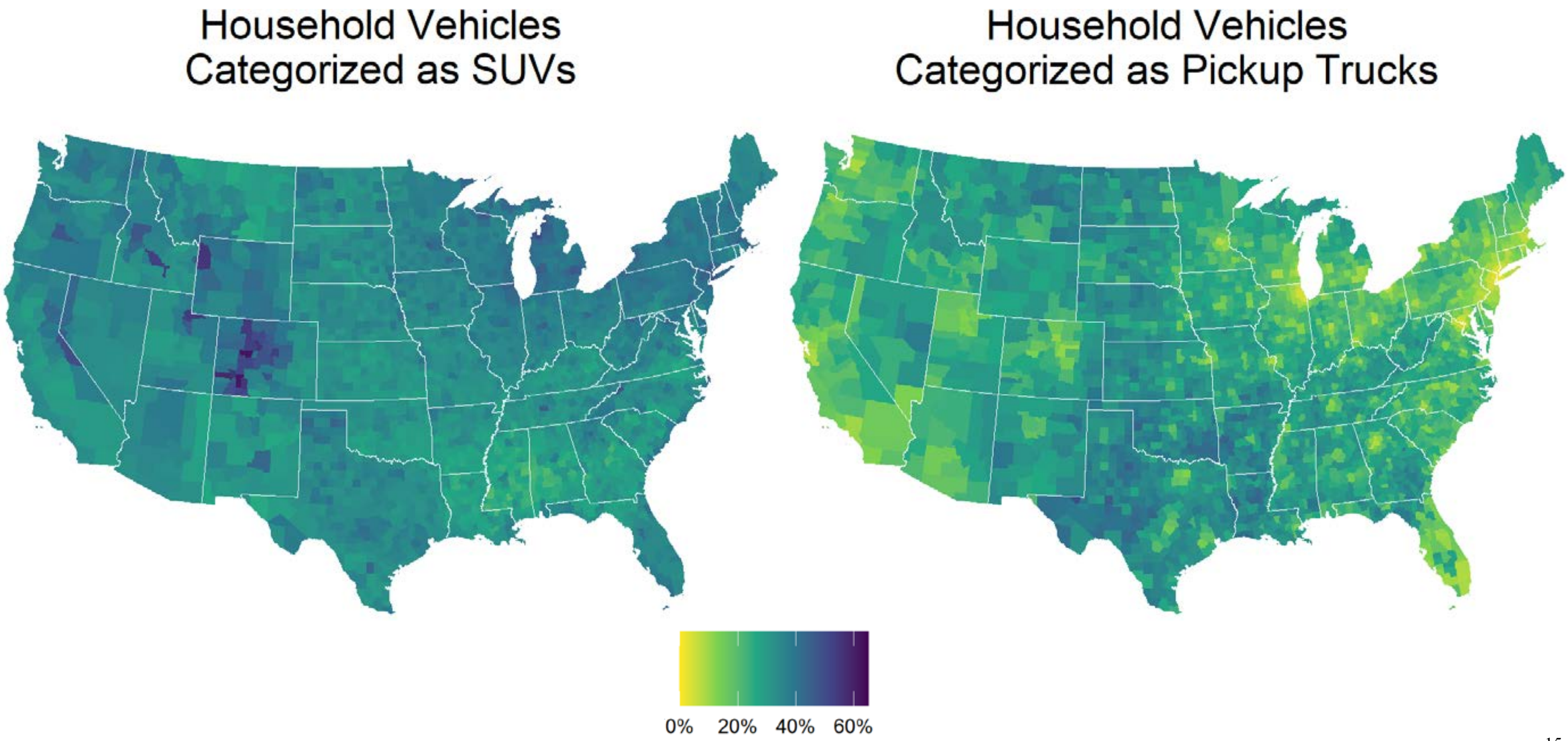
2020

2030 EV sales Projections

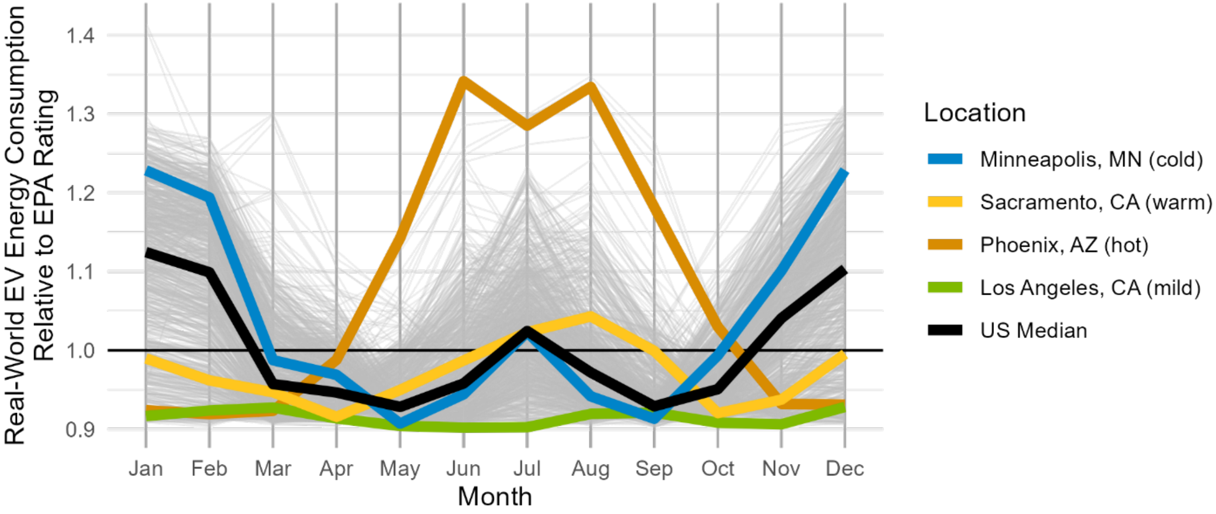


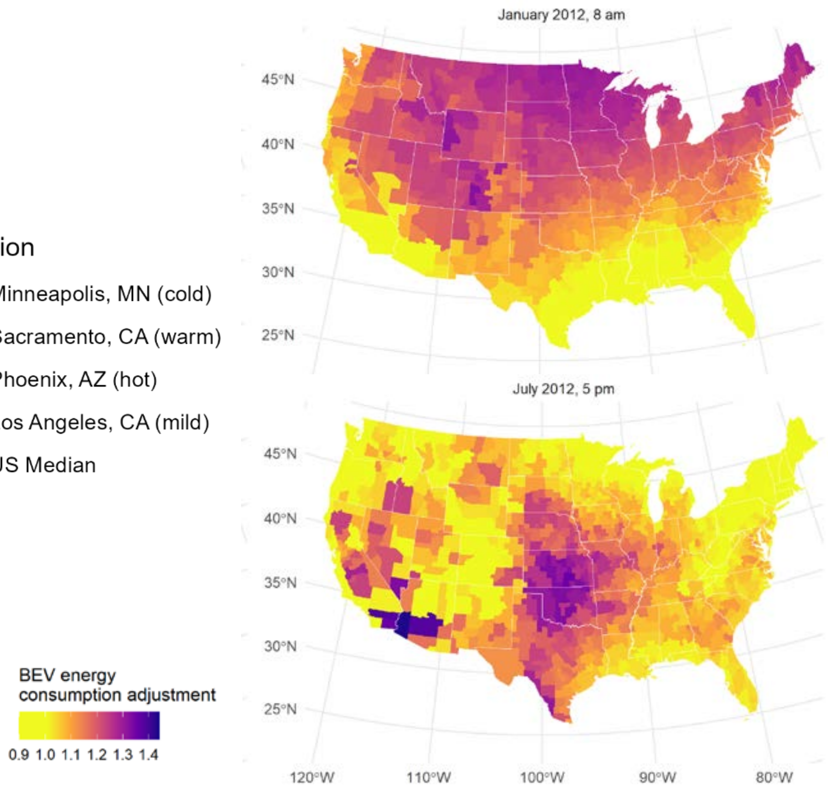
2030

Vehicle Type Affects EV Energy Use

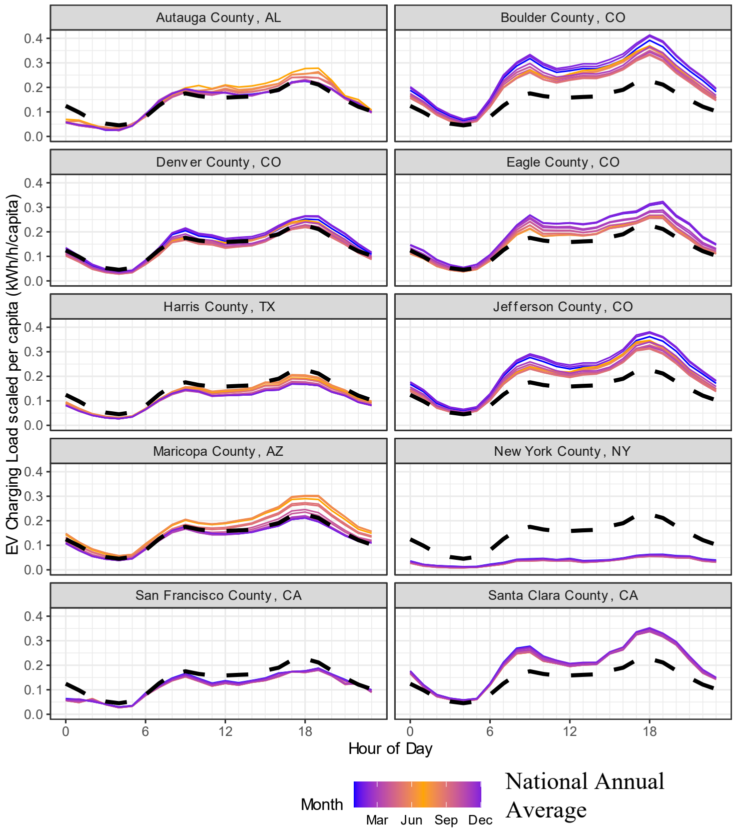


Local Operating Conditions Affect EV Energy Use



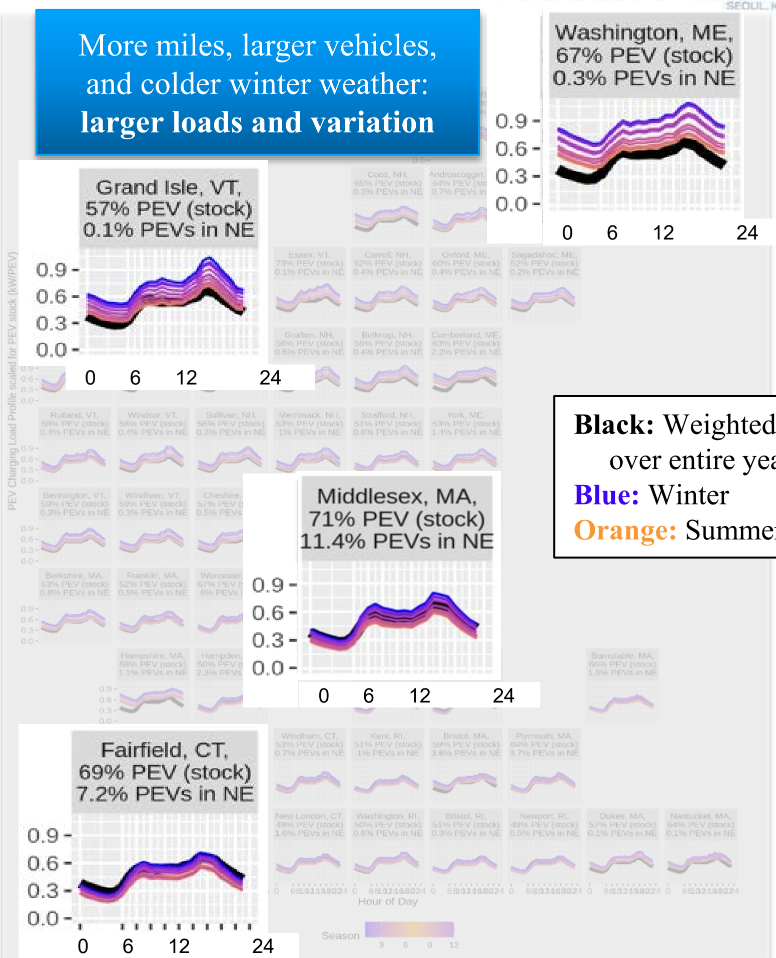


Results: Significant Heterogeneity in EV Load and Shape



National Annual Average

More miles, larger vehicles, and colder winter weather: **larger loads and variation**



Black: Weighted average over entire year
Blue: Winter
Orange: Summer

Source: [Yip et al. (2023) Highly Resolved Projections of Passenger EV Charging Loads for the Contiguous United States]()

County-Level Hourly EV Charging Data for the entire USA Through 2050

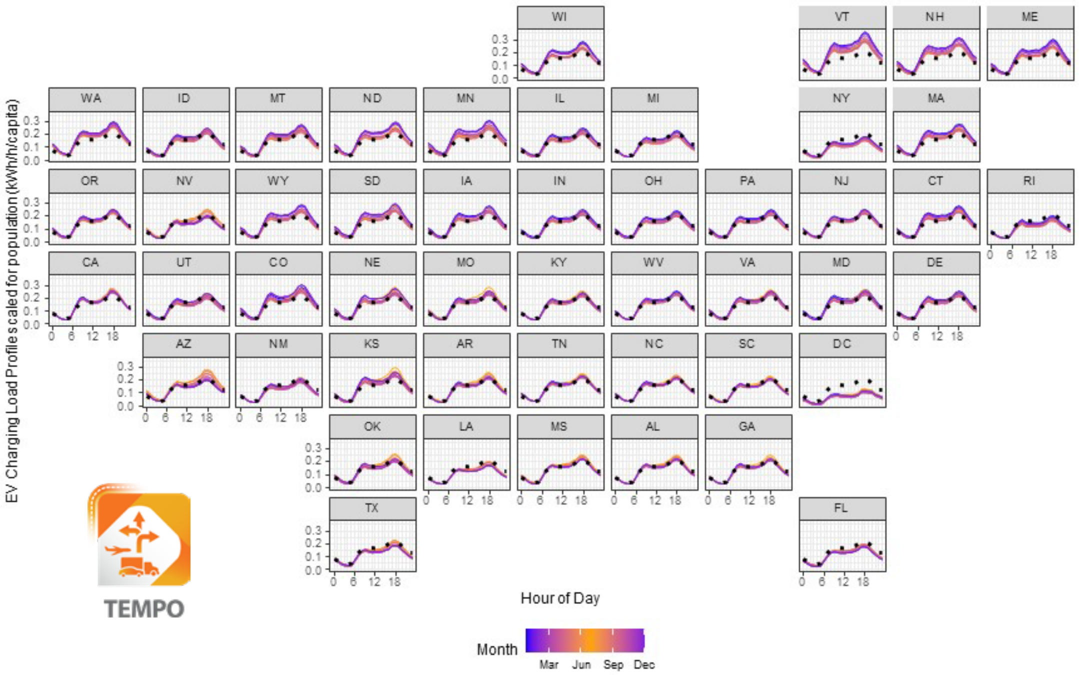


Figure ES-2. State-level per-capita EV charging load profiles for an average weekday for the All EV Sales by 2035 scenario for projected year 2035 under the immediate and ubiquitous charging strategy, for the contiguous United States, with seasonal variation shown by line color (blue for winter and orange for summer) and U.S. annual average in black dashes

TEMPO

1. Spatially disaggregating demographically resolved household and vehicle data to project **county-level EV adoption** through 2050.
2. Capturing **spatial and temporal effects of temperature**
3. Simulating week-long trip energy consumption schedules, applying charging strategies, and generating **hourly EV charging load profiles**

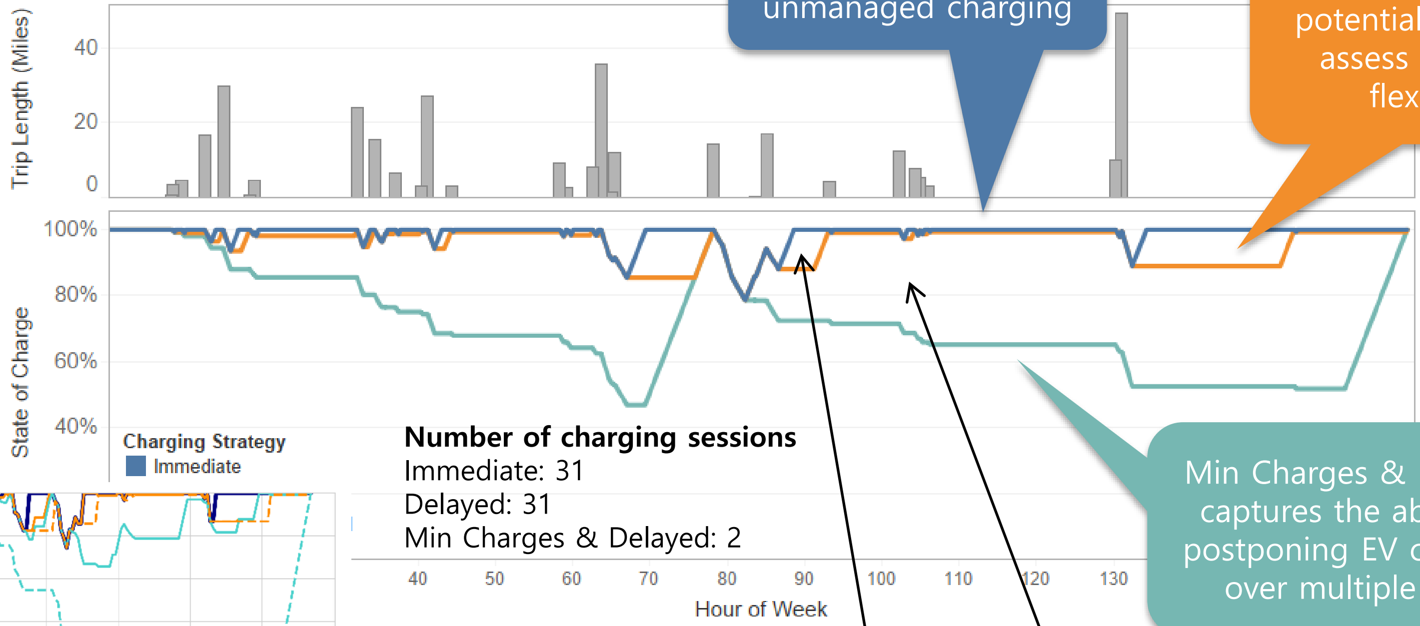
Source: Yip et al. (2023) Highly Resolved Projections of Passenger EV Charging Loads for the Contiguous United States

TEMPO simulates various charging behaviors to estimate EV charging flexibility “envelopes”

Example profiles for a single EV

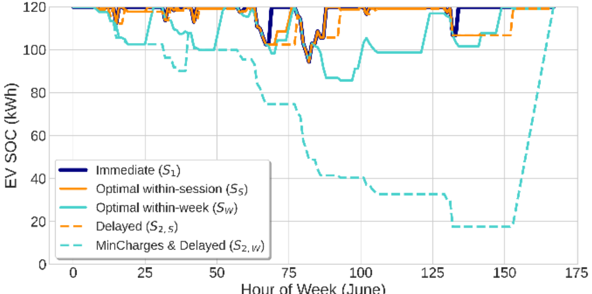
Immediate represents unmanaged charging

Delayed represents a potential bound to assess charging flexibility



Number of charging sessions
Immediate: 31
Delayed: 31
Min Charges & Delayed: 2

Min Charges & Delayed captures the ability of postponing EV charging over multiple days



Within-session flexibility envelope

Within-week flexibility envelope

How Valuable Is Electric Vehicle (EV) Managed Charging?

- **Uncoordinated** charging of EVs will lead to increased system peak load, possibly exceeding the maximum power that can be supported by distribution systems and generally **increasing power system stress**.
- Vehicles are underutilized assets parked ~96% of the time: **managed EV charging can satisfy mobility needs while also supporting the grid**:
  - We identify critical gaps and remaining challenges that need to be addressed to fully realize effective EV-grid integration.

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Assessing the value of electric vehicle managed charging: a review of methodologies and results

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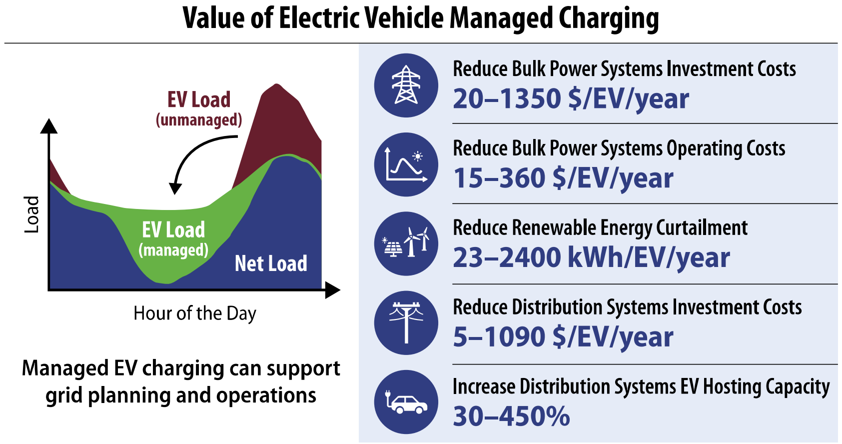

Source: Energy Environ. Sci., 2022, 15, 466-498

Transportation and Energy Systems Are at a Turning Point

- On the horizon lies a future where **affordable and abundant renewable electricity can be used to power cost-competitive battery electric vehicles (EVs) and maybe produce energy-dense low-carbon fuels** enabling to fully decarbonize transportation systems across all modes
- The **integration of EVs** presents unique opportunities for synergistic improvement of the efficiency and economics of e-mobility and the power grid
- At NREL, we're laying the scientific groundwork to get there. Among many other things, we are producing modeling capabilities and datasets representing **highly resolved EV charging loads, and their flexibility, to inform future investments and integration opportunities** (spatially and temporally: country-level hourly loads from 2020 to 2050 for the entire Nation)
  - Yip *et al.* (2023) Highly Resolved Projections of Passenger EV Charging Loads for the Contiguous United States

Challenge What Is Possible

Bring us your most complex decarbonization challenges, and together we can reimagine what comes next for powering a carbon-neutral U.S. economy by 2050.

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References

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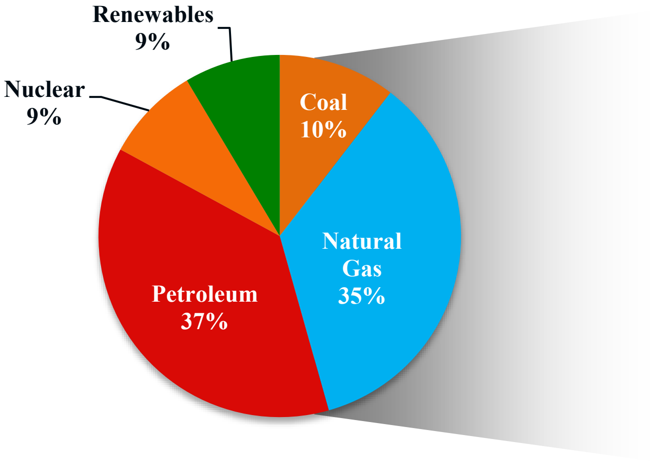
Supplemental

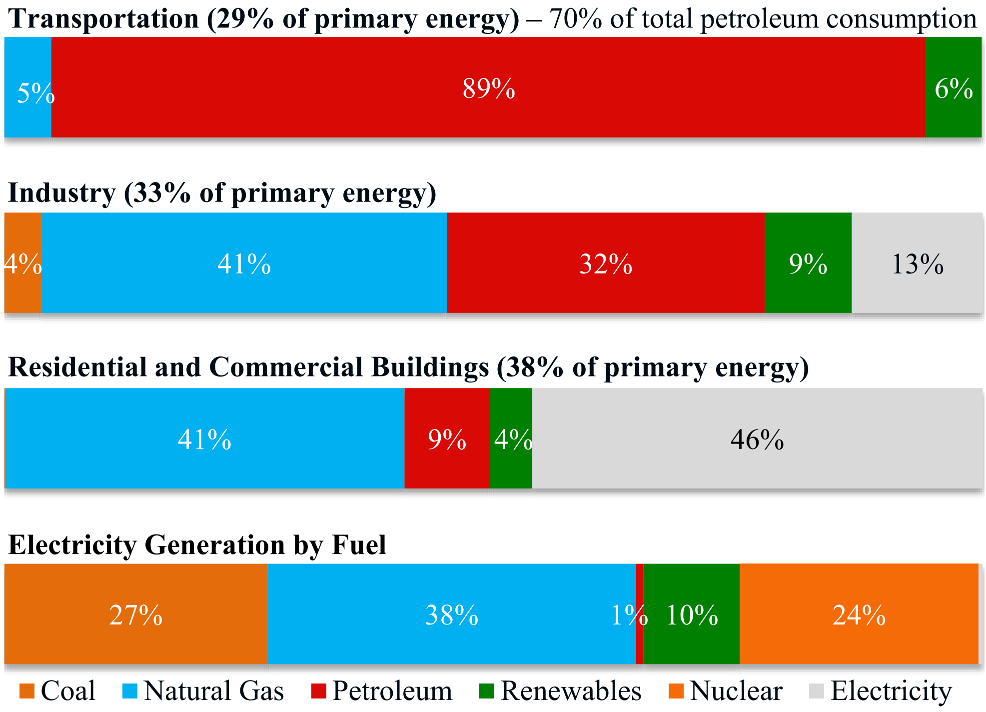
2022 Energy Snapshot: Not All Sectors Are the Same

U.S. Primary Energy By Fuel (2022)



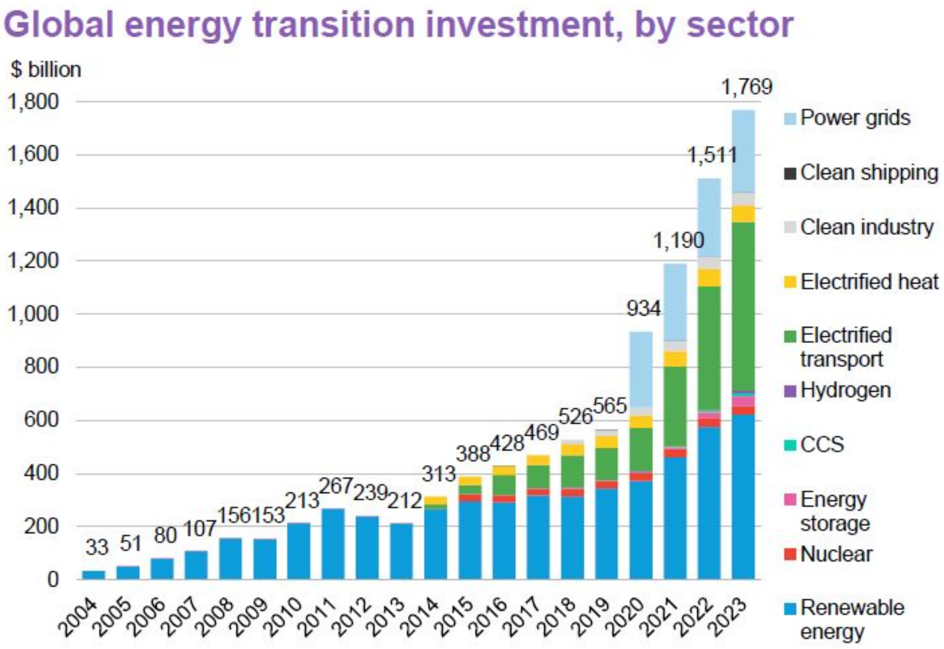
Source: Matteo Muratori (NREL).
Data from U.S. Energy Information Administration Annual Energy Review. End-use electricity consumption excludes associated electrical system energy losses. Total shares of energy use by sector allocate electrical system energy losses to end uses.

U.S. Energy Consumption by Sector and Fuel (2022)



The Landscape Is Changing Rapidly: Major Investments in Clean Mobility, Especially EVs

- **Low-carbon energy transition global investments totaled $1.8 trillion in 2023**.
- **Electrified transportation overtook renewables**, with $634 billion invested in 2023 – an impressive 36% increase from 2022!!
- Renewable energy, now the second largest sector, achieved a new record of $623 billion, up 8% from the year prior.
- Hydrogen is the sector that received the least financial commitment in 2023, but H_2 investments are tripling year on year.



Note: Start years differ by sector but all sectors are present from 2020 onwards – see Methodology for more detail. Most notably, nuclear figures start in 2015 and power grids in 2020. CCS refers to carbon capture and storage.

Source: BloombergNEF

While transport electrification is expected, load impacts are highly uncertain

- High degree of uncertainty exists in **where and when** EV loads will show up
- National-level or average assumptions will miss local impacts of particular interest to transmission and distribution planners

Example factors of uncertainty

Note **EV adoption** is a large source of uncertainty, with many factors listed here impacting adoption (e.g., costs, model availability, etc.)

Charging infrastructure
- Availability
- Speed of deployment
- Perception & preferences
- Charging behavior/ utilization

Vehicle technology
- Battery/vehicle costs
- EV performance/efficiency
- Range/battery size
- Battery degradation
- Competing technologies (ICEV & conventional fuel costs; FCEV & H2 costs)

Vehicle market
- Make & model availability
- Used vehicle market
- EV marketing
- Supply chain
- Fleet ownership/charging business model

Environment/Macro
- Temperature
- Extreme weather events
- Urban planning/design
- Household demographics

Grid
- Electricity rates/prices
- TOU rate designs
- Response to TOU rates
- Grid capacity

Managed Charging
- Cost & availability
- Reliability & flexibility
- Preferences/perception
- Operation/dispatch

Consumer choice
- Preferences/perception
- Size class preference
- Values of EVs for resiliency

Policy
- ZEV mandates
- ICEV bans
- Tax credits/rebates

Transportation system
- Telework/virtual travel
- Travel behavior
- Emerging modes & AVs
- Freight logistics
- Transit services
- Fleet makeup & locations

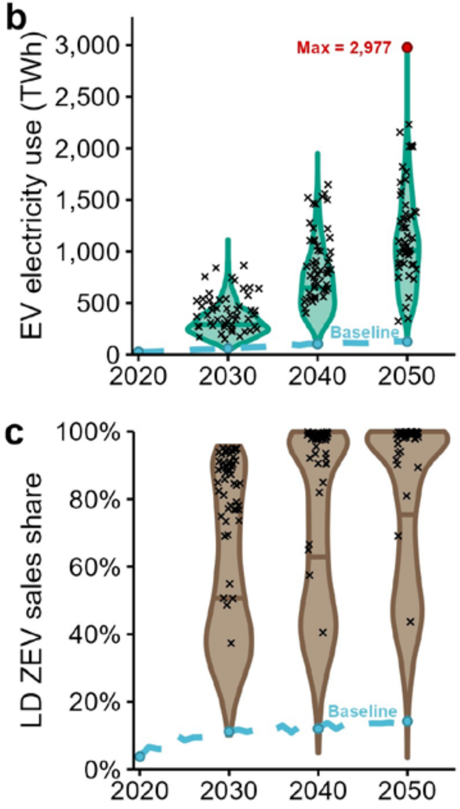
Savage, Sam L. The flaw of averages: why we underestimate risk in the face of uncertainty. John Wiley & Sons, Inc., 2012

Decarbonization Will Require Rapid Transition to EVs, Leading to Major Electricity Demand Growths

A. **<u>Rapid EV adoption</u>**: Scenarios achieving deep decarbonization without reductions in travel demand reach 100% ZEV sales by 2040 (and really high adoption already in 2030).

B. **<u>Major growth in clean electricity supply</u>**: Our results show up to 3,000 TWh needed in 20050 to charge EVs (extreme case, probably closer to 1,500). And hydrogen production for transportation couple require an extra 1,000 TWh.

C. **<u>Managing travel demand</u>**: Reducing overall travel demand is the most consistent driver of emissions reductions as it avoids emissions entirely. Rapid EV adoption alongside travel demand management will be essential to ease future needs for constrained low-carbon electricity supplies.



Source: Hoehne *et al.* Nature Comm. 2023.