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Energy Systems Decarbonization

Perspectives on Electric Vehicles and Grid Integration

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Feb 8th, 2024

U.S. DOE National Lab System

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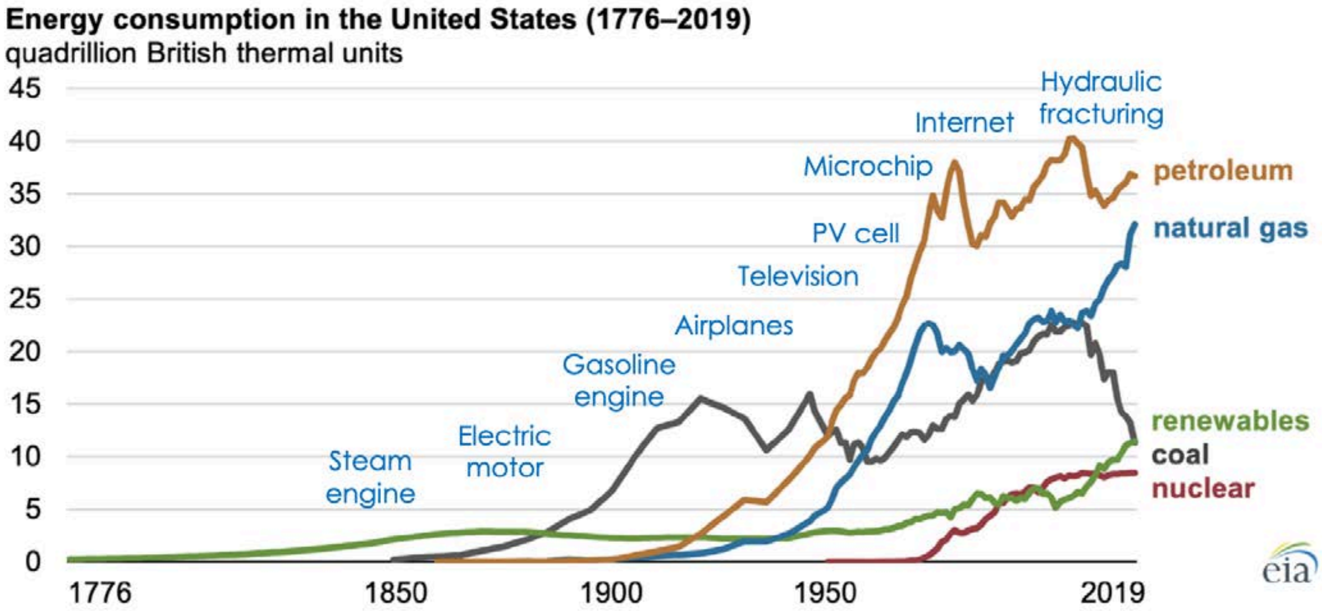
Energy Is Foundational to Our Lifestyle and Consumption has Been Growing Steadily for over a Century…



Source: U.S. Energy Information Administration, *Monthly Energy Review*

Fossil fuels – petroleum, natural gas, and coal – have dominated (80% or more) U.S. energy consumption for more than 100 years.

…but Fossil Fuels Have Major Geopolitical and Environmental Implications

Air pollution kills an estimated seven million people worldwide every year, concentrated in disadvantaged communities.

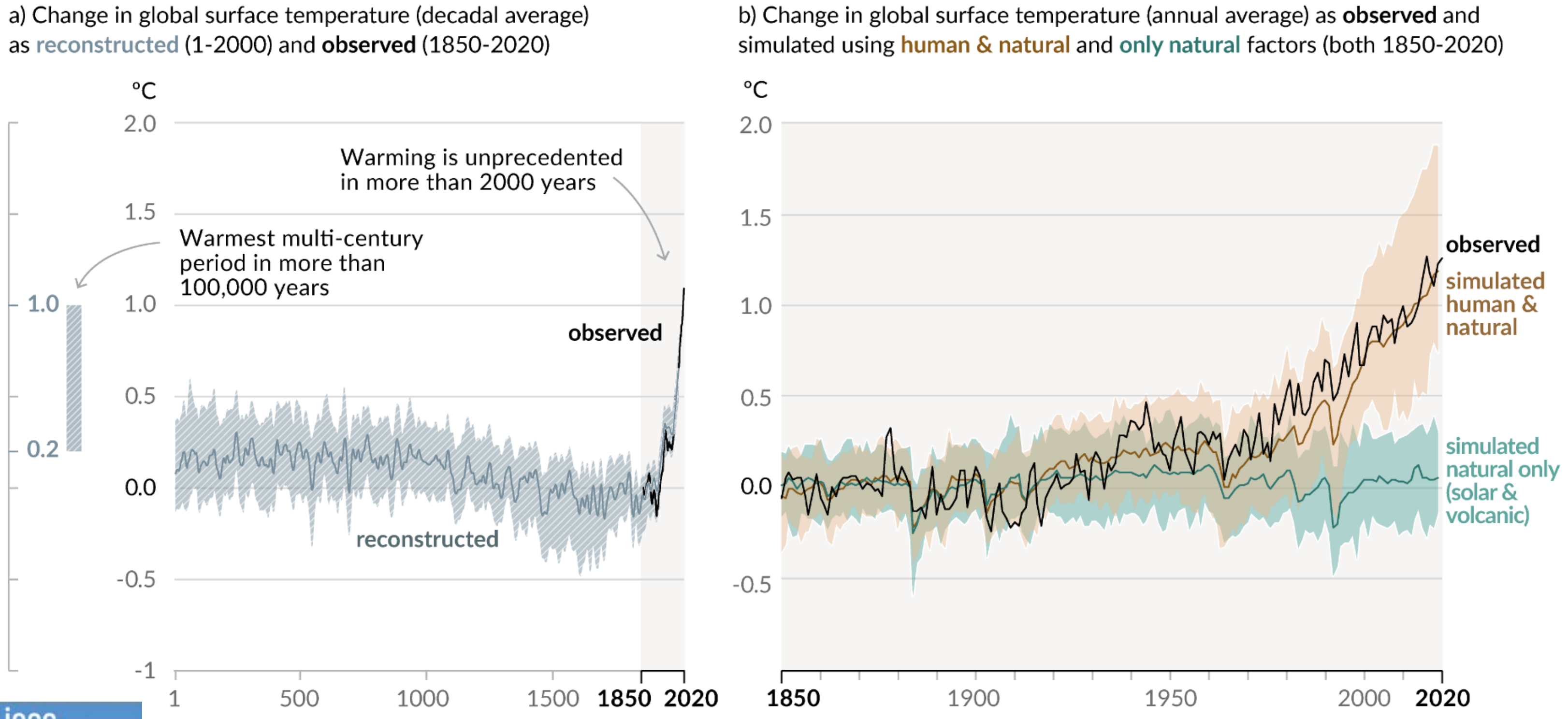
Source: World Health Organization National Institute of Health

Water and Land Are Suffering Large-Scale Contamination

Source: US Department of the Interior

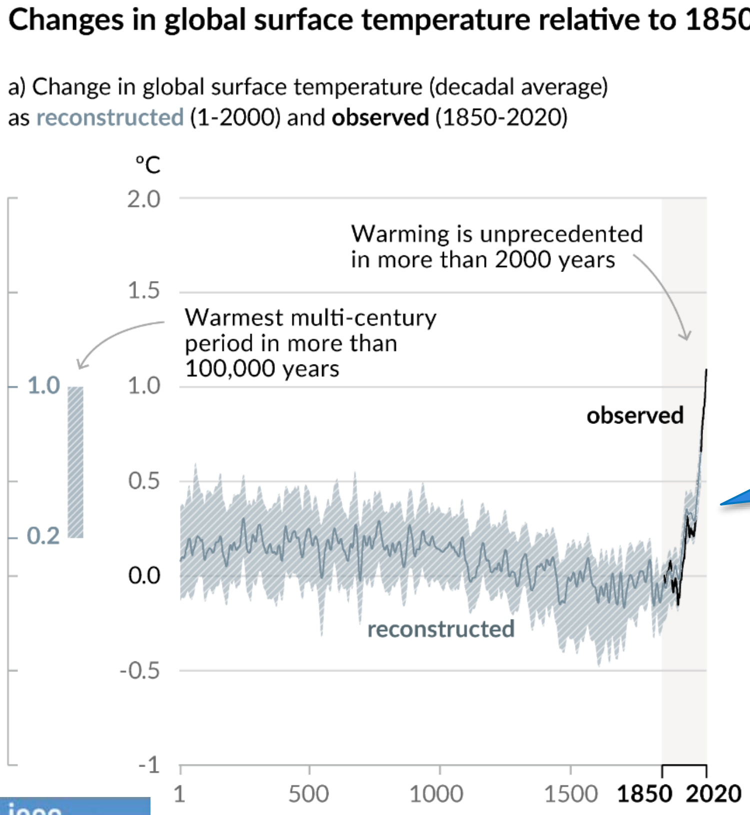
Climate Change Is Often Referred to as Our Generation's Biggest Challenge

Changes in global surface temperature relative to 1850-1900



Source: IPCC Sixth Assessment Report

Climate Change Is Often Referred to as Our Generation's Biggest Challenge

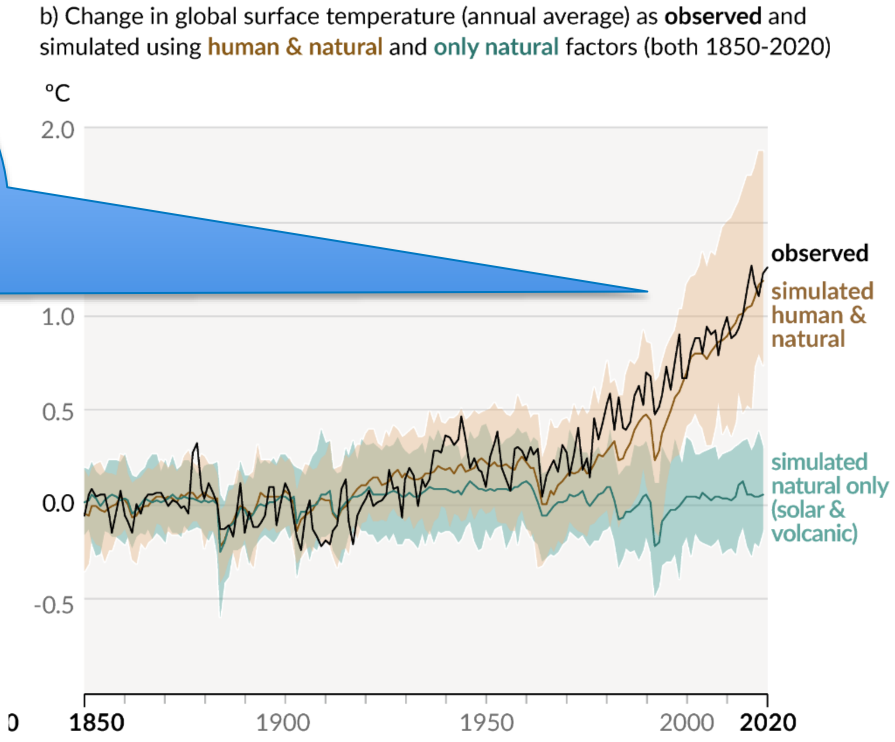


Source: IPCC Sixth Assessment Report

Recent changes in the climate are widespread, rapid, and intensifying, and **unprecedented in thousands of years.**

Climate Change Is Often Referred to as Our Generation's Biggest Challenge

It is indisputable that **human activities are causing climate change**, making extreme climate events, including heat waves, heavy rainfall, and droughts more frequent and severe.



Source: IPCC Sixth Assessment Report

[Credit: Shari Gearheard | NSIDC]

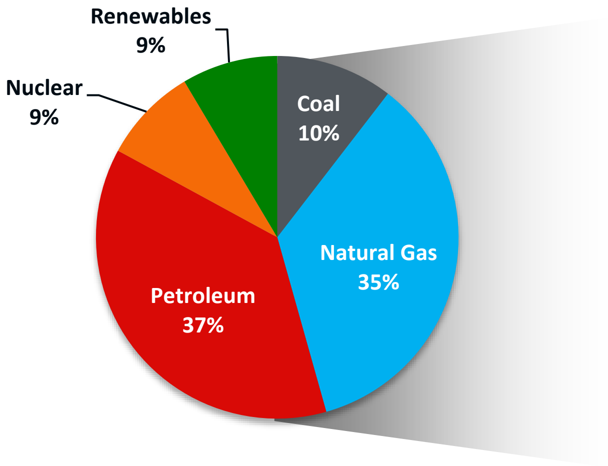
There's no going back from some changes in the climate system. However, some changes could be slowed, and others could be stopped.

Strong, rapid, and sustained emissions reductions are necessary to limit global warming and improve air quality.

ENERGY SYSTEMS DECARBONAZATION

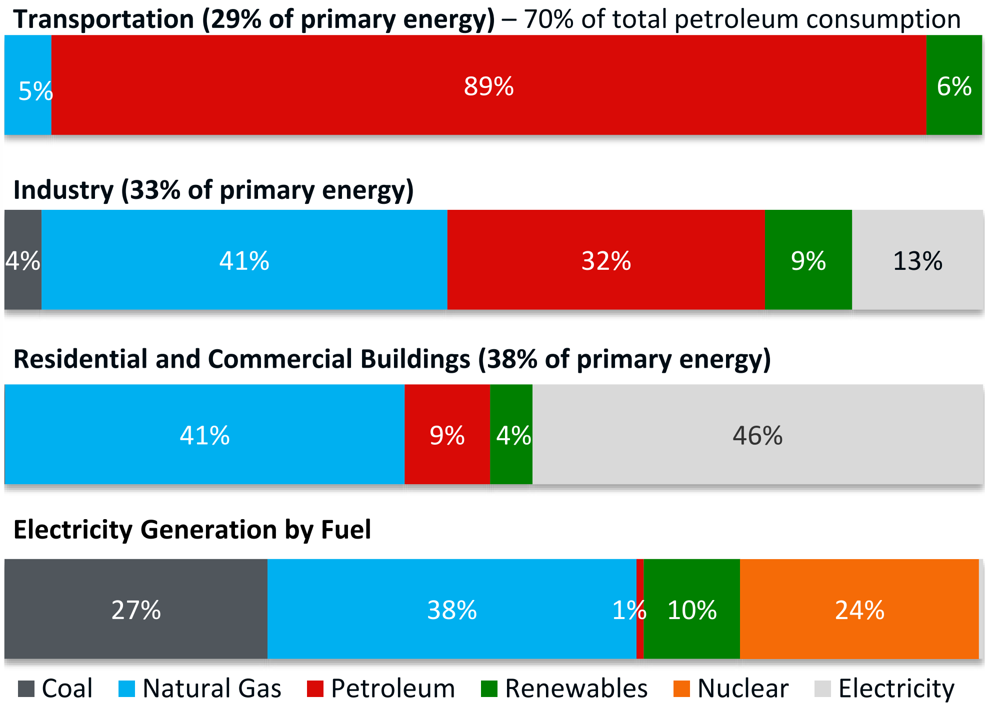
2022 Energy Snapshot: Not All Sectors are the Same

U.S. Primary Energy By Fuel (2022)

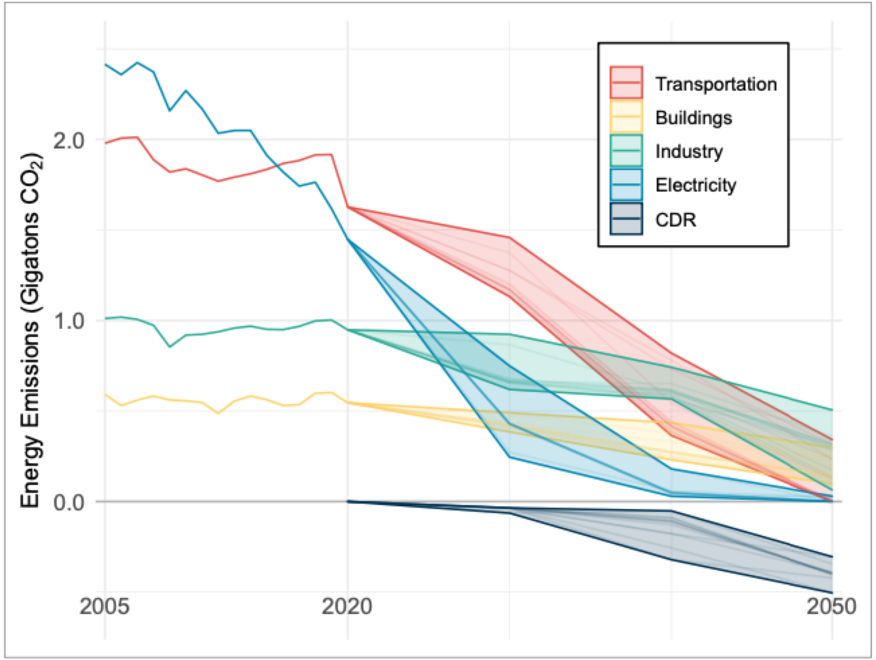


Source: Matteo Muratori (NREL). Data from U.S. Energy Information Administration Annual Energy Review. End-use electricity consumption excludes associated electrical system energy losses. Total shares of energy use by sector allocate electrical system energy losses to end uses.

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



The Transition to Net-Zero is Critical and Will Require Major Changes to the Entire Energy Supply-Demand Ecosystems, with Different Solutions for Different Sectors

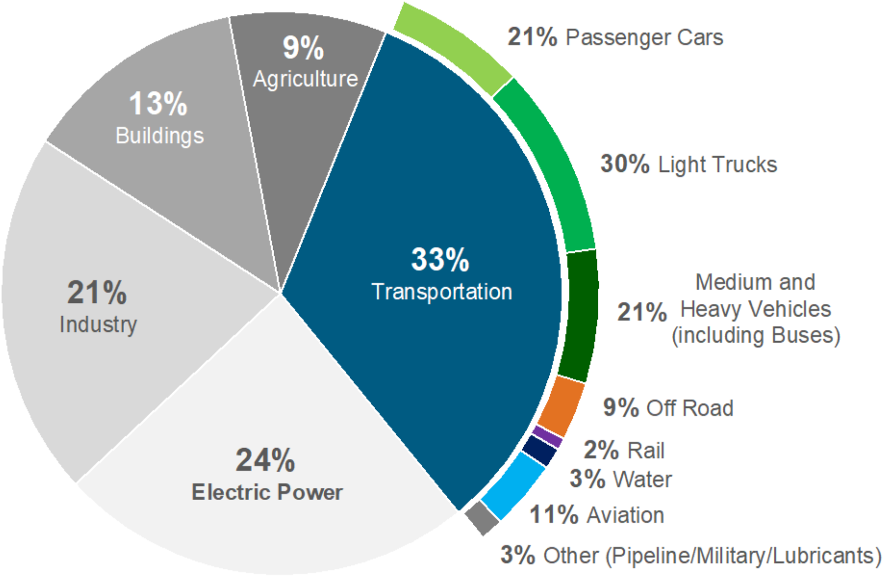


Source: WhiteHouse.gov

THE TRANSPORTATION SECTOR

Transportation Is the Least-Diversified Energy Sector (90% Petroleum) and Largest Source of GHG Emissions…

2019 U.S. GHG Emissions



Source: US National Blueprint for Transportation Decarbonization

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

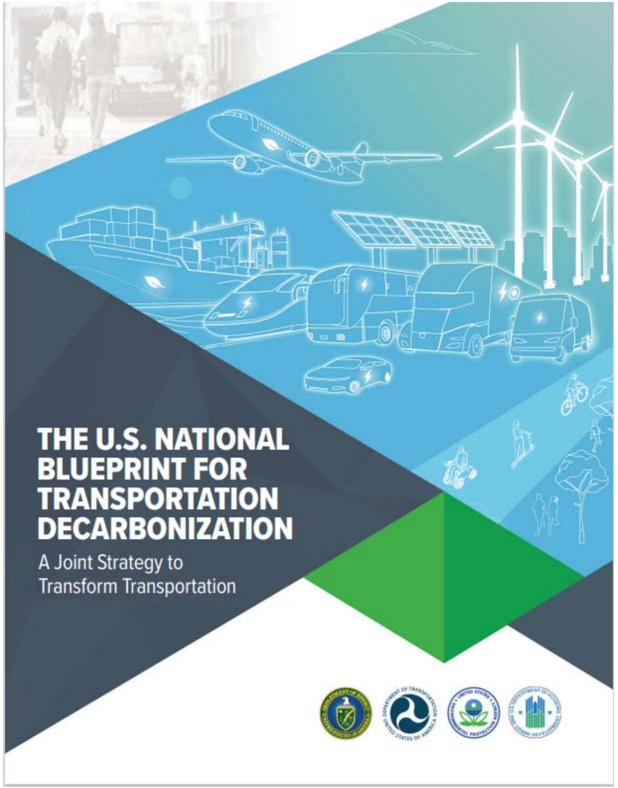
- Responsible for **poor air quality** (disproportionate impacts)
- The **second largest household expenditure**
- Main driver of **global petroleum demand**

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

Three Complementary Strategies to Decarbonize Transportation (U.S. Whole-of-Government Approach)

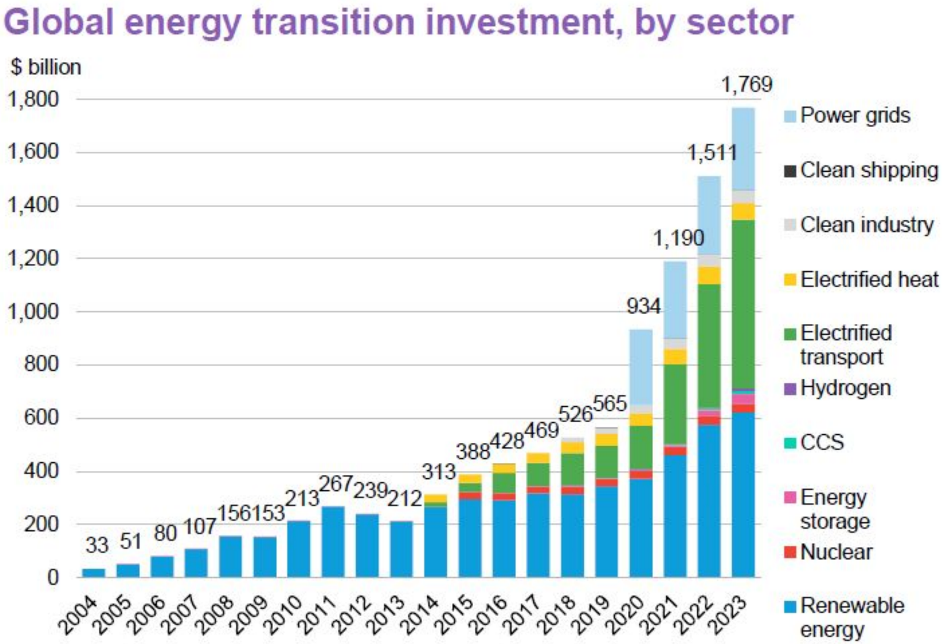
Prioritizing land-use decisions and community design solutions that prioritize access	Expanding options to enable shifts in more efficient vehicles and transport modes	Deployment of zero-emission vehicles, fuels and associated infrastructure

Source: US National Blueprint for Transportation Decarbonization



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

ELECTRIC VEHICLES

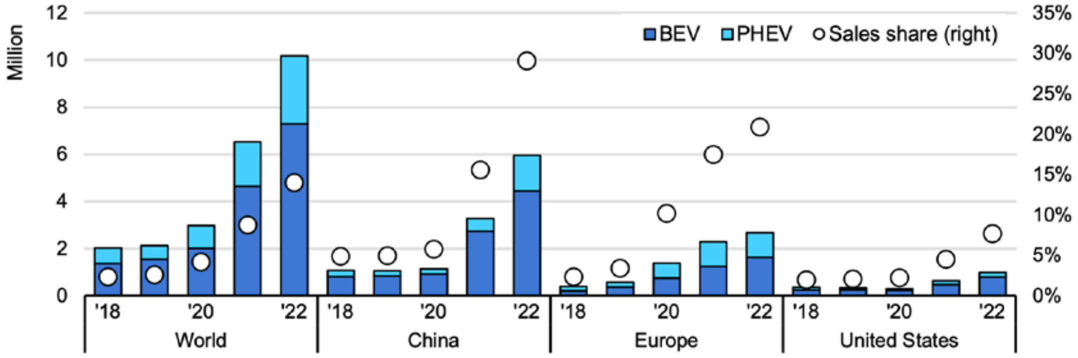
Battery Electric Vehicles: a Success Story

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 medium- and heavy-duty trucks and other applications (off-road, planes, ships, etc.).

EV sales grew to capture 14% of the global market in 2022, reaching over 10 million sales worldwide ($425 billion)

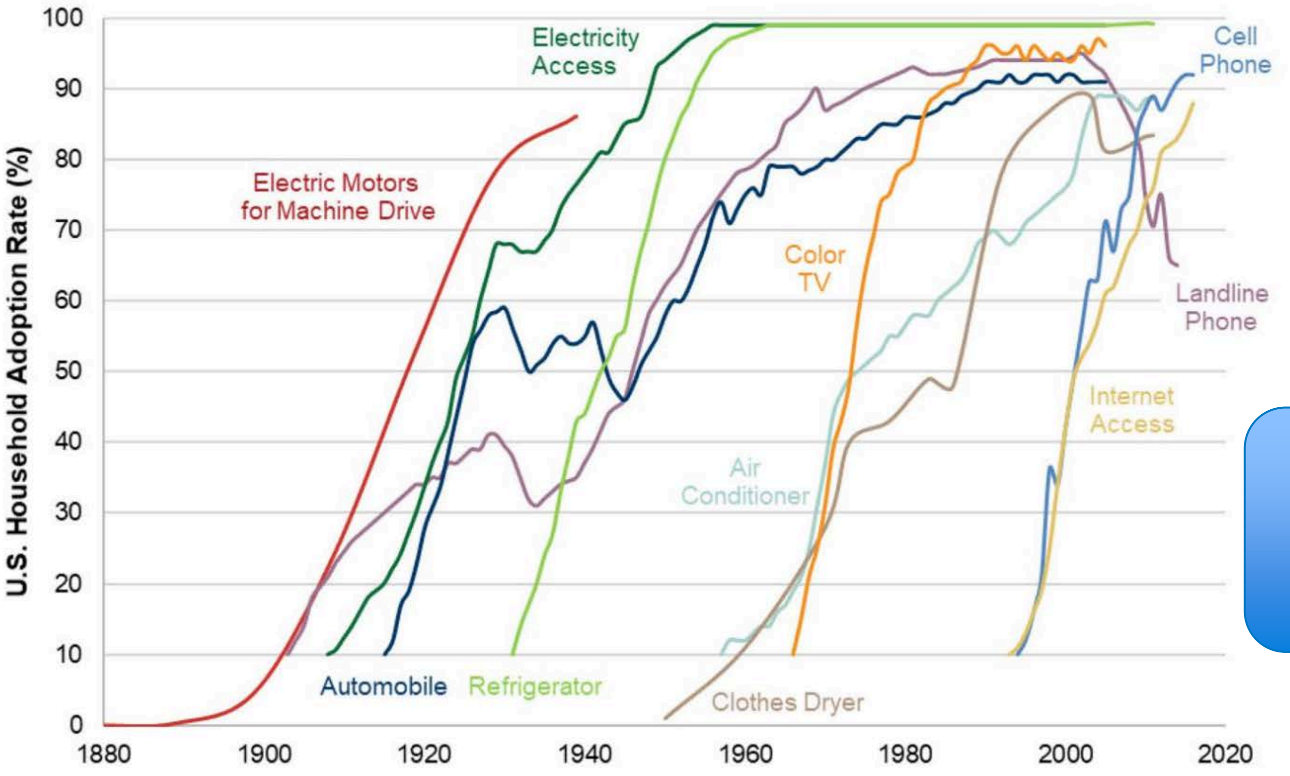
2018-2022 Electric Car Registrations and Sales Share



Source: IEA Electric Vehicles

- One in ten vehicles sold in the U.S. is electric now (over 1.4M EVs sold in 2023)!
- The future is already here; it's just not very evenly distributed. Some counties have 30+% sales, some are closer to 0.
- Electrification of road transport is rapidly moving beyond cars.

Technology Adoption: S-curves



Source: NREL's Electrification Futures Study

Driven by:

Superior performance

Low enough cost

Meets a need

Example: What Difference 13 Years Made for the Automobile in New York City

Easter morning 1900: 5th Ave, New York City. Spot the automobile.

Source: U.S. National Archives

Easter morning 1913: 5th Ave, New York City. Spot the horse.

Source: George Grantham Bain Collection

EVs are Coming Now:
Infrastructure and Electricity Supply Implications

Charging Infrastructure

It's critical to develop a charging ecosystem for personal and commercial vehicles that **increases convenience** (*i.e.*, not just replace gasoline/ diesel stations, but develop solutions to charge conveniently when vehicles are parked).

- The charging network will be heterogenous: convenience is fast and slow, charge when vehicles are parked.
- Infrastructure needs to be accessible, reliable, affordable, and **plan for peaks/extremes** (*e.g.*, holiday weekends, extreme events, *etc.*)

Implications for Electricity Systems

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

Key Network Planning Concepts

There's No Place Like Home

In the near-term, most EVs will do most of their charging at home. But in the long-term, at least 25% of EVs won't have the ability to charge at home. **Charging away from home is necessary for both groups.**

Convenience is Fast (and Slow)

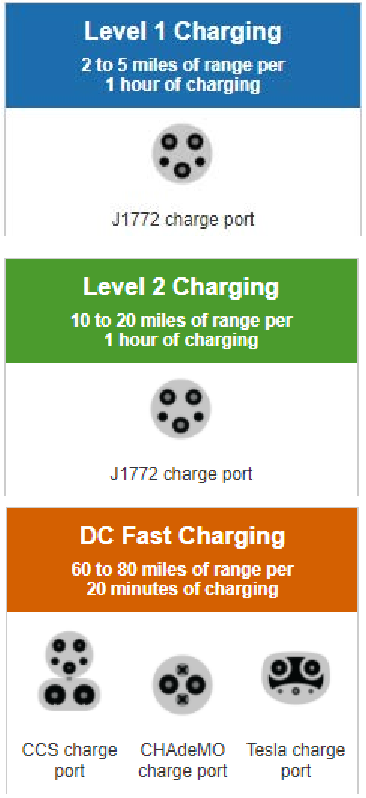
Extreme fast charging (XFC) is necessary for road trips. Slow charging at home/work makes EVs MORE convenient than gasoline by eliminating fuel stops. **Charge EVs opportunistically.**

Corridors vs. Communities

Most people do most of their driving within their community. But infrequent, long-distance travel is a key consideration when purchasing a vehicle. **Corridor needs are relatively small, but expensive and critical for adoption.**

Coverage vs. Capacity

In the early stages, emphasis should be placed on establishing coverage to enable mobility. As networks mature, attention should shift to increasing capacity to meet demand from a growing fleet. **Establish coverage, then build capacity.**



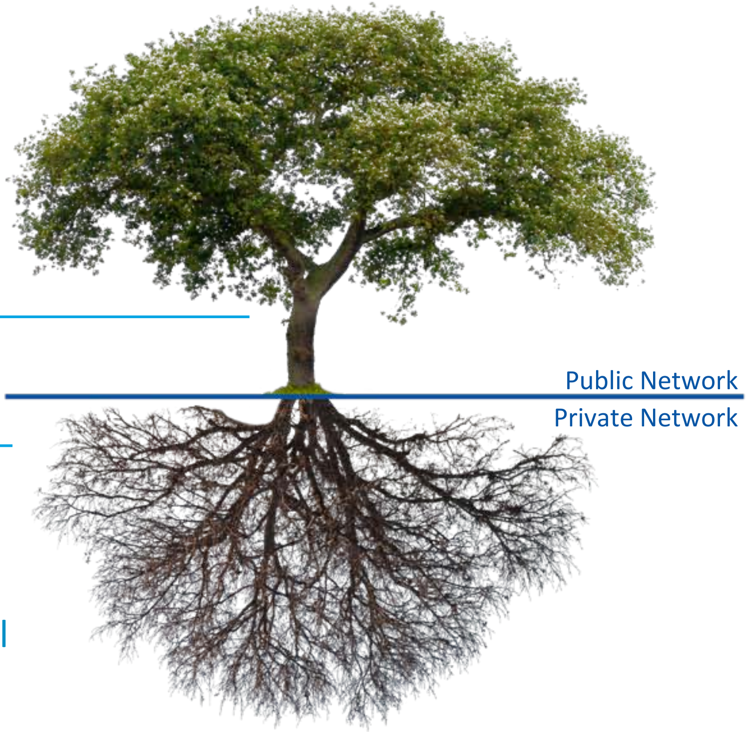
Source: U.S. Department of Transportation

Growing the National EV Charging Network

The Branches: Destination Charging
at offices, recreation, dining, other longer-dwell public locations

The Trunk: Fast Charging
along corridors and at short-dwell locations

The Roots: Home Charging
at residences and commercial fleet depots



All three parts are needed to create a convenient, affordable, reliable, equitable charging experience for all Americans.

For more details on charging network design: The 2030 National Charging Network

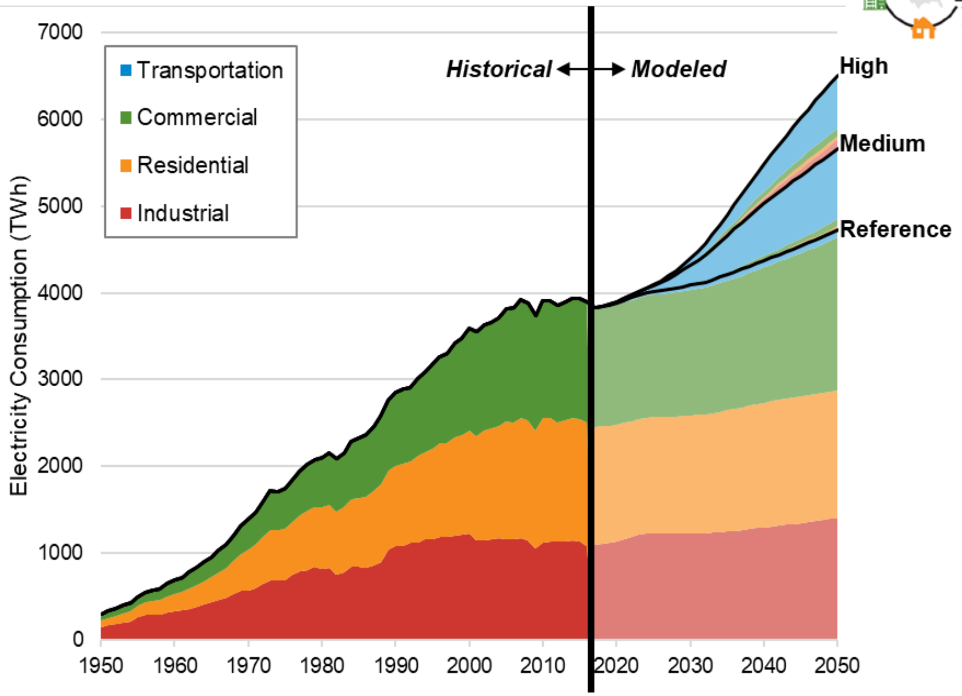
VEHICLE-GRID INTEGRATION

Impact on Electricity Demand

All sectors are seeing a transition from fossil fuels to electricity, but transportation has the largest growth potential

EFS High scenario, 2050:

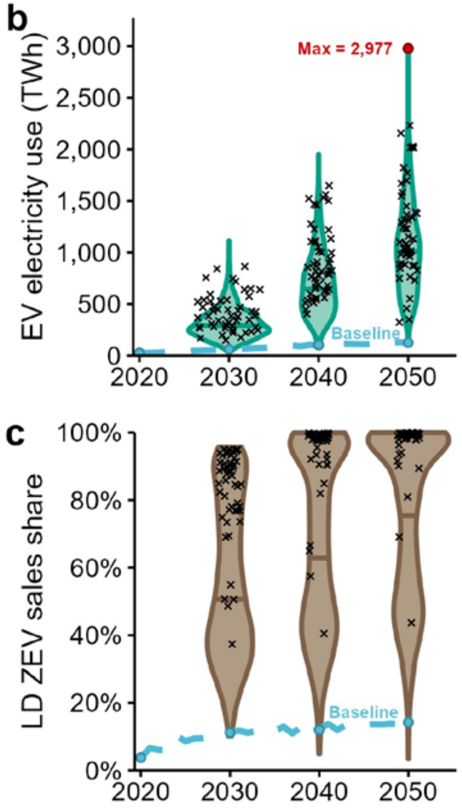
- Transportation share of electricity use increases **from 0.2% in 2018 to 23% in 2050** (1,424 TWh electricity consumption increase), and more recent net-zero studies show even more aggressive growth.



Source: NREL's Electrification Futures Study

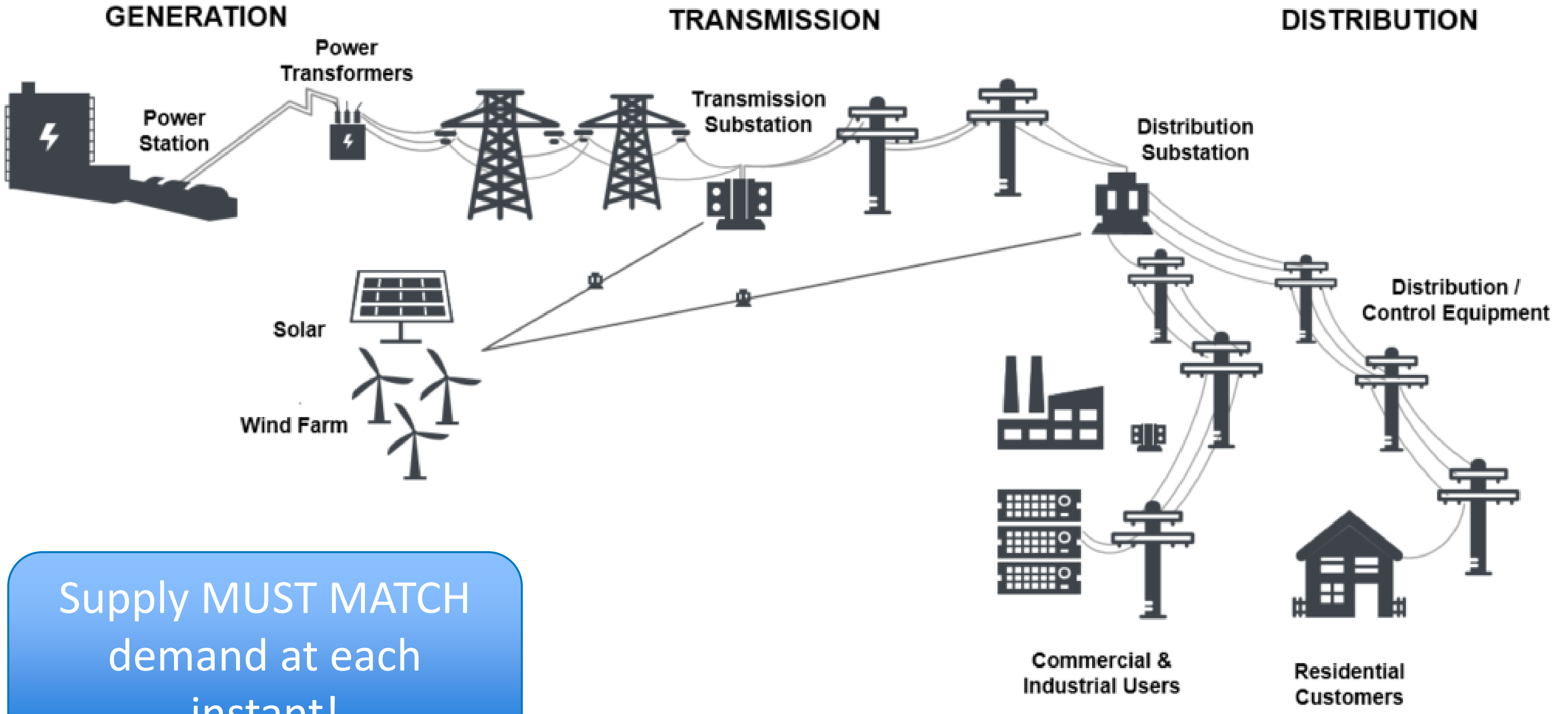
Decarbonization Will Require Rapid Transition to EVs, Leading to Major Electricity Demand Growths

- **Rapid EV adoption:** Scenarios achieving deep decarbonization without reductions in travel demand reach 100% ZEV sales by 2040 (and really high adoption already in 2030).
- **Major growth in clean electricity supply:** Our results show up to 3,000 TWh needed in 2050 to charge EVs (extreme case, probably closer to 1,500). And hydrogen production for transportation couple require an extra 1,000 TWh.
- **Managing travel demand:** 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.

What Does the Electricity Grid Look Like?



Supply MUST MATCH demand at each instant!

Source: The Science Thinkers

The Grid is Also Transforming

The **electric power system is undergoing profound changes**.

The traditional system paradigm of dispatching central generation to match demand is evolving into a **more integrated supply-demand system** in which demand-side distributed resources (generation, energy storage, and demand response) respond to supply-side requirements, mainly driven by variable renewable generation.

EVs are expected to be one of the largest sources (and often the single largest) of **demand-side flexibility**.

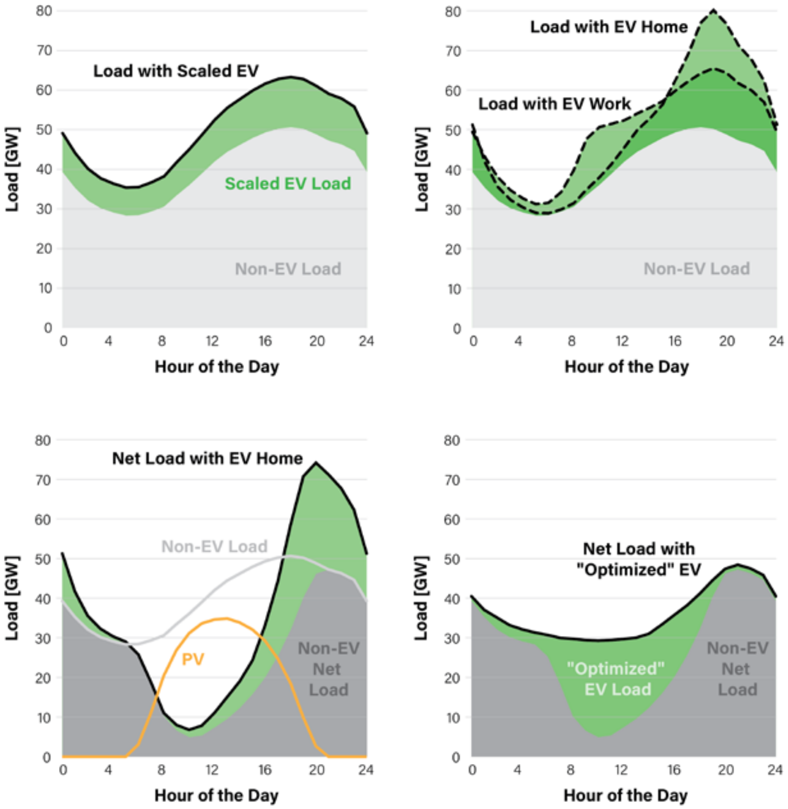
When and *Where* EV Charging Occurs Will Be as Critical as *How Much* Electricity Is Needed

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.

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

New class of models needed to assess the integration opportunities of EVs on the power system

NREL Produces First Ever County-Level Hourly EV Charging Data

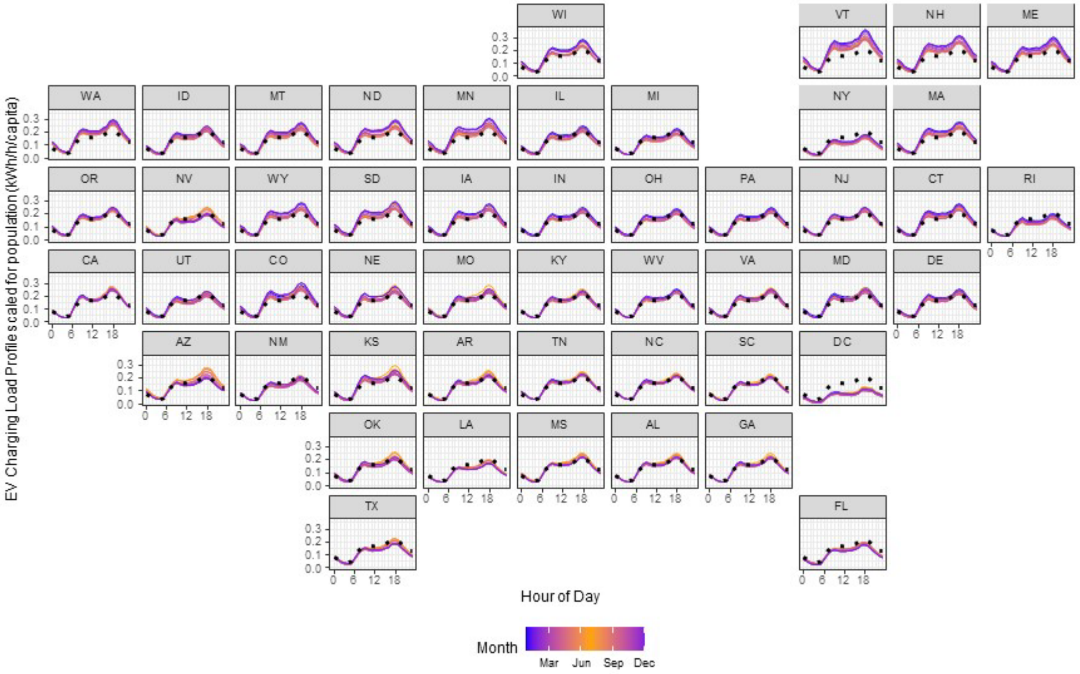


Figure ES-2. State-level per-capita EV charging load profiles for an average weekday for the All EV Sales by 2035 scenario for projected year 2035 under the immediate and ubiquitous charging strategy, for the contiguous United States, with seasonal variation shown by line color (blue for winter and orange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

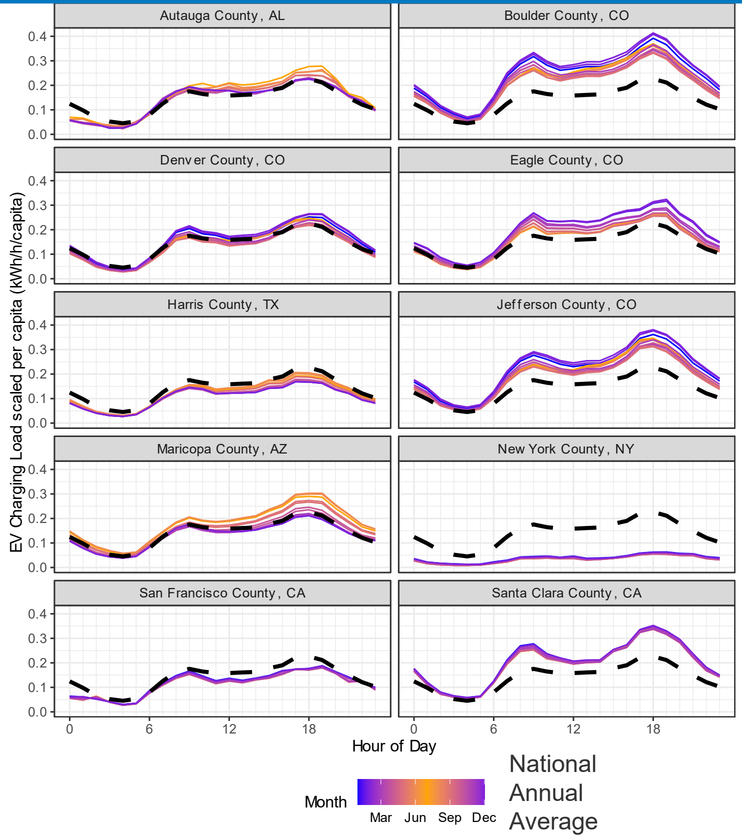
Source: Yip et al. (2023) Highly Resolved Projections of Passenger EV Charging Loads for the Contiguous United States

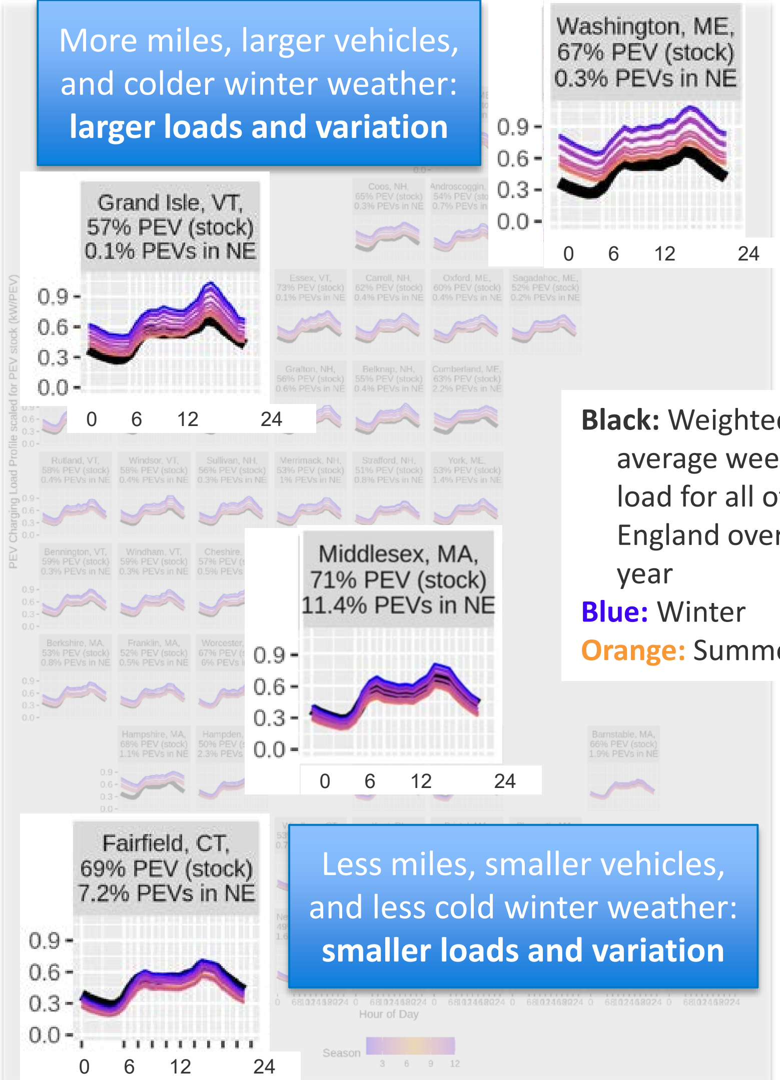
TEMPO

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
- Created three EV adoption scenarios for 2020–2050 and added associated data to demand-side grid platform, enabling power system modeling

Significant Heterogeneity in EV Load and Shape



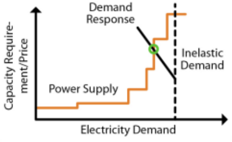


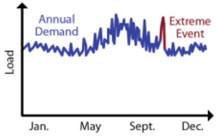
Source: Yip et al. (2023) Highly Resolved Projections of Passenger EV Charging Loads for the Contiguous United States

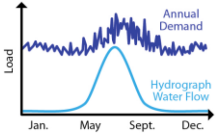
EVs Can Support the Grid in Multiple Ways Providing Values for Different Stakeholders, Including Non-EV Owners

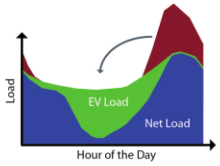
Smart electric vehicle-grid integration can provide flexibility – the ability of a power system to respond to change in demand and supply – by charging and discharging vehicle batteries to support grid planning and operations over multiple time-scales

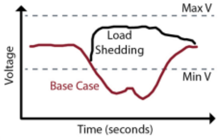
Power System Application	**Generation Capacity and Transmission/ Distribution Planning**	**Resilience To Extreme Events**	**Seasonal Planning (Hydro/Long-Term Storage Dispatch)**	**Commitment and Dispatch Decisions**	**Balancing and Power Quality**	**Support End Consumers**
Time scale	*Multi-year*	*Years (planning), hours (real-time response)*	*Months*	*Days to Hours and Sub-Hours*	*Seconds to sub-seconds*	*Years (planning), hours (real-time response)*
Vehicle-Grid Integration value	Ability to reduce peak load and capacity requirements and defer distribution systems upgrades if reliable EV charging flexibility is available	Load response to natural events (heat waves, tornados) or human-driven disasters, load postponement over days, and support microgrid management and grid restoration (V2G)	No role for EVs	Leverage EV charging flexibility to support supply dispatch and load-supply alignment (tariff management), variable renewables integration, operating reserves, energy arbitrage (V2G)	Provide voltage/frequency regulation and support distribution system operations	Tariff management (e.g., mitigate retail demand charges), complement other distributed energy resources (smart load, generation and storage), and minimize equipment aging/upgrades

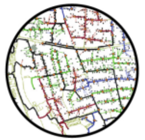








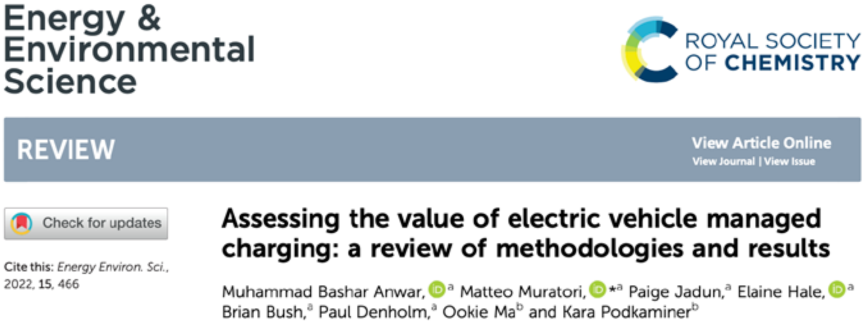




Source: Muratori *et al.* 2021. The rise of electric vehicles—2020 status and future expectations. Progress in Energy.

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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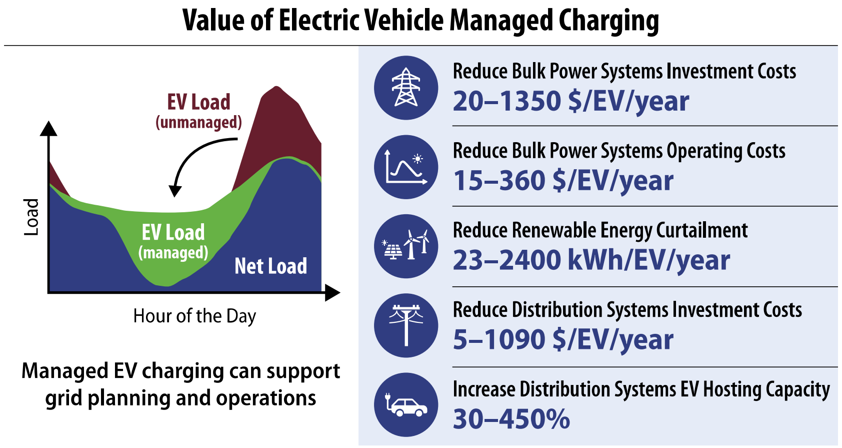
Assessing the value of electric vehicle managed charging: a review of methodologies and results
Muhammad Bashar Anwar,[a] Matteo Muratori,*[a] Paige Jadun,[a] Elaine Hale,[a] Brian Bush,[a] Paul Denholm,[a] Ookie Ma[b] and Kara Podkaminer[b]

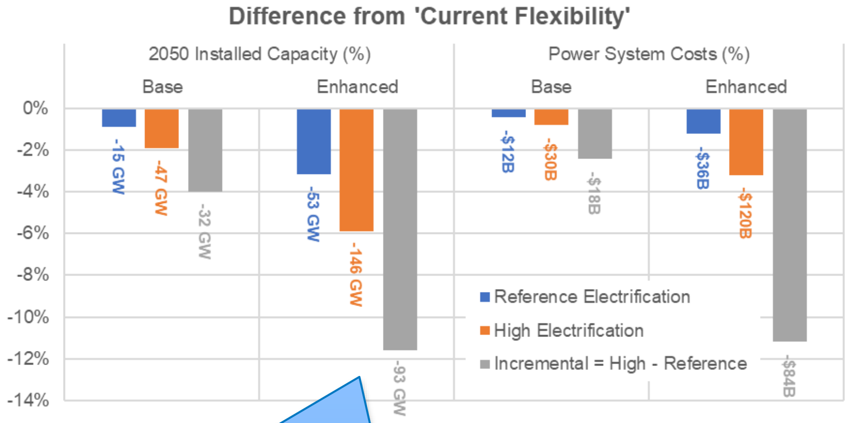


Source: Energy Environ. Sci., 2022, 15, 466-498

Bulk Electricity System Case Study 1

- In the EFS study, we used the ReEDS **capacity expansion model to dispatch the flexible portion of the load** (2/3 of the total is from EVs) considering constraints on flexibility (how much loads can be shifted).

- Flexible loads can partially mitigate the power sector infrastructure needs and associated costs from electrification, particularly by serving as a **resource to meet peak demands and planning reserves**.



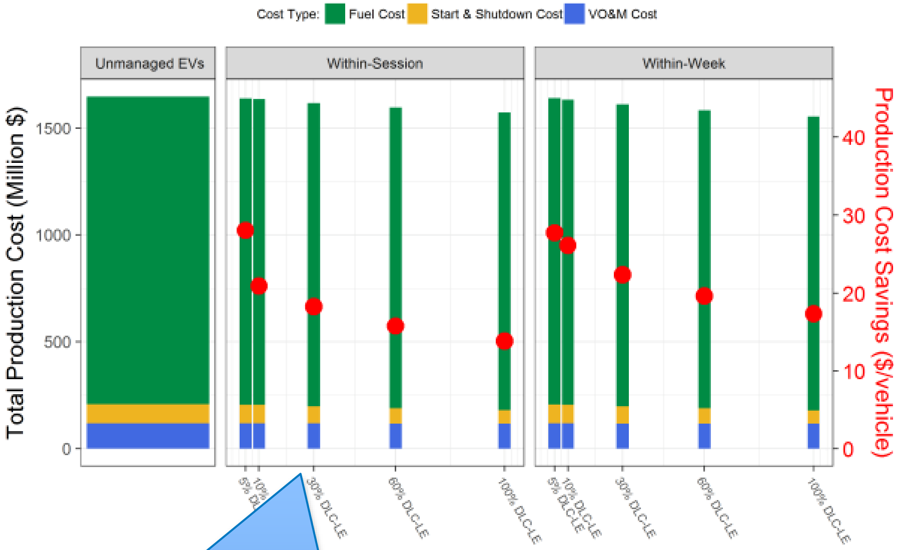
Demand-side flexibility can reduce electricity generation capacity requirements by over 10% saving $84B

Source: NREL's Electrification Futures Study

Bulk Electricity System Case Study 2

- We integrated TEMPO and PLEXOS (production cost model) to estimate the **value of EV managed charging for bulk power system operation** for a future ISO-NE power system with 84% clean generation and 45% EV share.

- Production cost savings of \$14–\$65 per vehicle-yr, CO_2 emissions reductions of 0.1–0.4 metric tons CO_2 per vehicle-yr, net-peak load reductions of 0.1–0.4 kW/vehicle-yr.

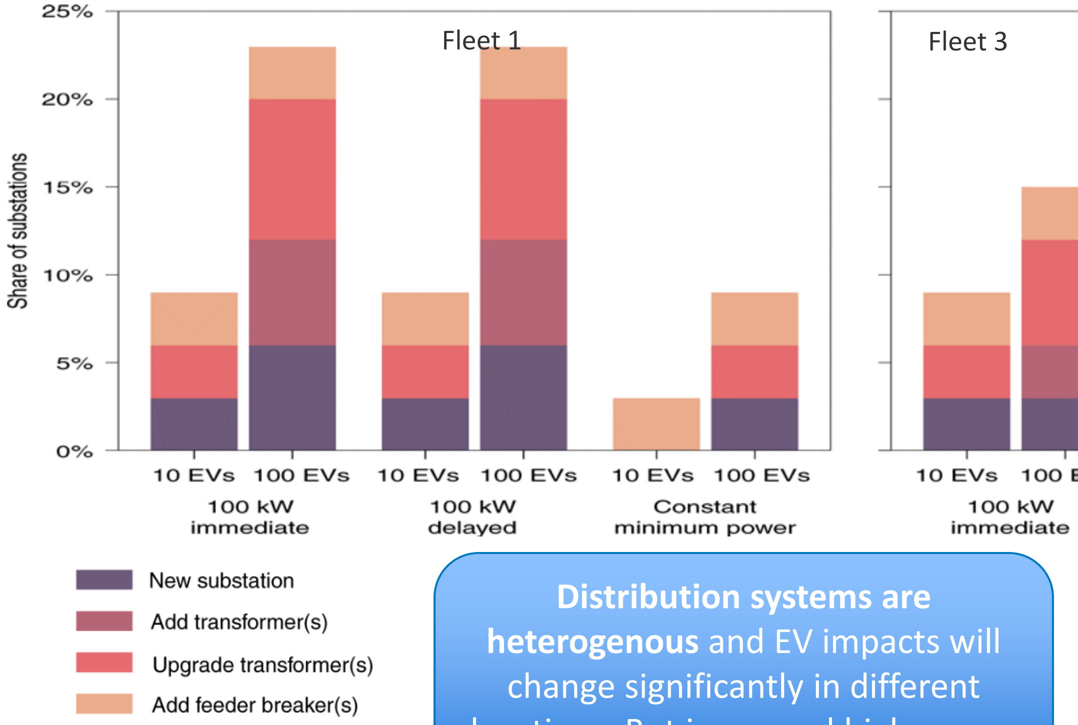


Declining marginal value: the per-vehicle savings decline as more vehicle participate.

Source: Forward-Looking Estimates of Bulk Power System Value

Distribution System Case Study

- Load integration study for 36 substations within the Oncor service territory (Texas) for **Class-8 truck depot charging** (~70% of trucks typically operate within 100 miles)
- **Each EV contributes an ~10-74 kW peak load** to the system
- Most (78–86%) substations studied can supply 100 battery electric trucks with 100 kW per vehicle without additional upgrades



Distribution systems are heterogenous and EV impacts will change significantly in different locations. But in general high-power requires more significant upgrades.

Source: Borlaug et al. Nature Energy, 2022

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 **grid 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, our research is finding ways for **EVs to support grid planning and operations across several timescales and to fully exploit the synergies between EVs and renewables**.
  - **Join us or reach out to explore opportunities to collaborate!**

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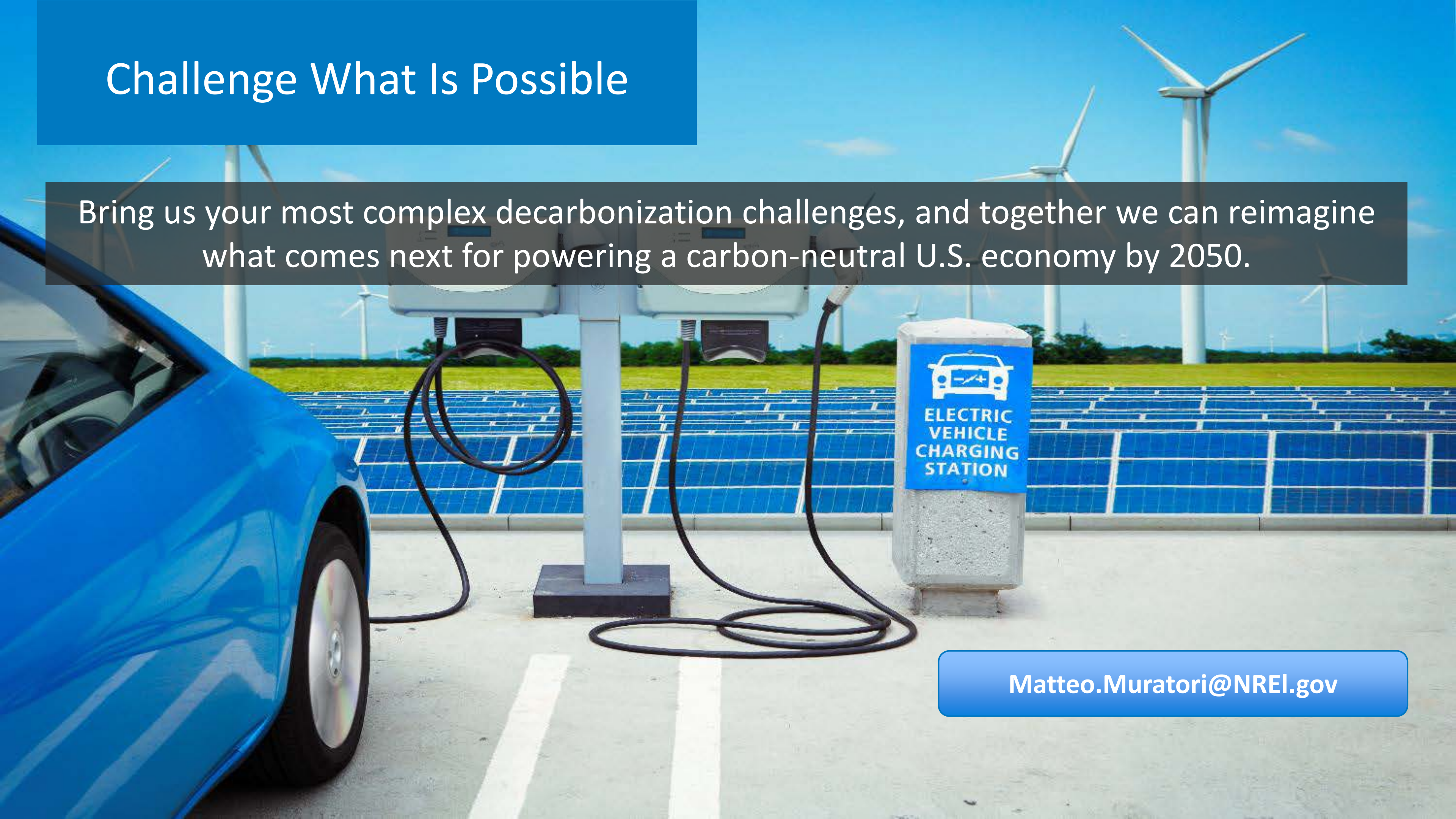
Challenge What Is Possible

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.



Matteo.Muratori@NREl.gov

Energy Systems Decarbonization – Perspectives on Electric Vehicles and Grid Integration

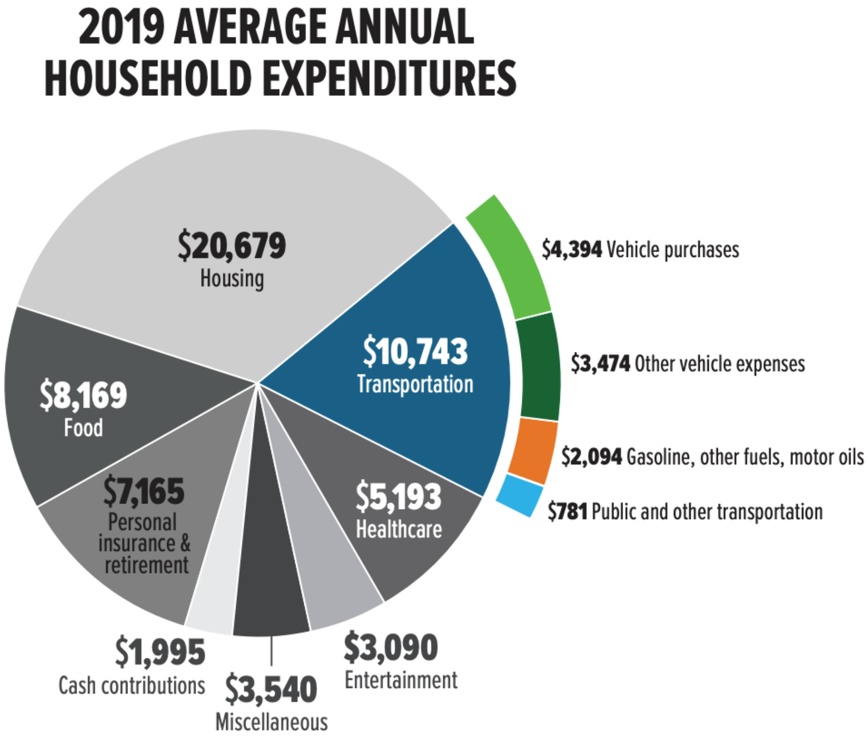
Abstract: The imperative for strong and rapid emissions reductions to mitigate global warming and enhance air quality necessitates a transition to net-zero emissions. This shift requires significant changes throughout the entire energy supply-demand ecosystems, tailored to various sectors. Transportation stands as the least-diversified energy sector and the largest source of U.S. GHG emissions. As the primary catalyst for vehicle decarbonization when paired with clean electricity, electric vehicles (EVs) will play a pivotal role in the future. EVs are poised to drive substantial growth in electricity demand and presents a unique opportunity to provide demand-side flexibility that is crucial for future renewable-dominated electricity systems. Smart integration of EVs can strengthen the grid, reducing costs and enhancing resilience. At NREL, laying the scientific groundwork to actualize this vision: our research is finding ways for EVs to support grid planning and operations across several timescales and to fully exploit the synergies between EVs and renewables.

Bio: Dr. Matteo Muratori is a Distinguished Researcher at the National Renewable Energy Laboratory (NREL) where he also manages the Transportation Energy Transition Analysis (TETA) group to explore system-level sustainable solutions for the transformation of the transportation sector, including solutions to support the adoption of clean vehicles and fuels, supporting infrastructure, and the synergies between transportation and electricity systems. NREL is the United States' premier laboratory for the research and development of renewable energy technologies and energy efficiency and is widely regarded as the world's leading research institute in this field. In 2021 and 2022 Dr. Muratori served as the Chief Analyst for Sustainable Transportation at the US Department of Energy. A native of Italy, Dr. Muratori has authored or co-authored over 100 technical publications cited over 8,000 times, including IPCC and NCA reports. He holds B.S. and M.S. *summa cum laude* degrees in energy engineering from Politecnico di Milano (ranked top University in Italy) and M.S. and Ph.D. degrees in mechanical engineering, along with a minor degree in statistics, from The Ohio State University.

SUPPLEMENTAL

Transportation Is the Second Largest Household Expenditure

- Transportation is currently the second-largest household expense in the U.S., with the **average family spending more than $10,000 a year on transportation costs**—almost 20% of the $60,574 average annual household expenditures.
- **Owning and operating private vehicles** accounted for more than 70% of the total transportation costs, and **gasoline expenses represented another 21%**.



Source: US National Blueprint for Transportation Decarbonization

…but the Landscape Is Changing Rapidly

Battery costs have declined 90% since 2010 with pack prices expected to be $100/kWh by 2026.

– BloombergNEF (2022)

Sales of electric cars topped 10 million globally in 2022 – **14% of sales** (1 vehicle in 7 sold was an EV).

– International Energy Agency (2023)

Amazon places an order for **100,000 electric delivery vans**, with thousands on the road today.

– Business Insider (2022)

U.S. EPA proposed rules to ensure that **two-thirds of new cars** and a **quarter of new heavy trucks** sold in the United States by **2032** are all-electric.

– New York Times (2023)

2022 EV sales reached 20% in California, 90% in Norway.

– International Energy Agency (2023)

Six major **automakers to phase out new gas vehicles** by 2035 in leading markets.

– Car and Driver (2021)

California **bans new combustion engine** cars starting in 2035.

– Cal Matters (2022)

Cheaper to save the climate than to destroy it: **renewable energy prices** are now significantly below those for coal and gas.

– Forbes (Lazard)

Tesla delivers first **500-mile range electric semi trucks** to PepsiCo.

– CNN (2022)

Transitioning to Automobiles Solved One Problem and…

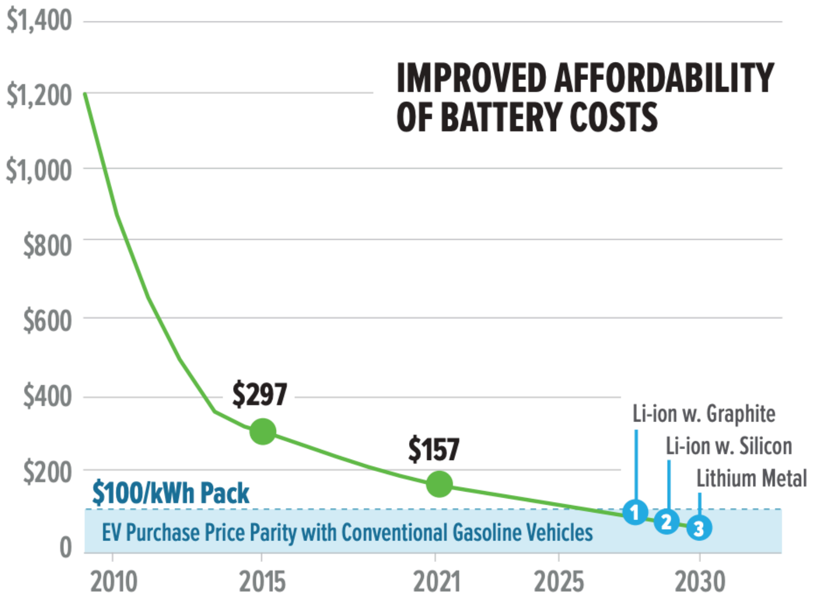
Great Horse Manure Crisis of 1894

1953 New York City Smog Event

Source: Public domain, Street-Cleaning and the Disposal of a City's Wastes, George E. Waring. 1898; Public domain, U.S. Library of Congress

What Is Driving the EV Success - Technologies

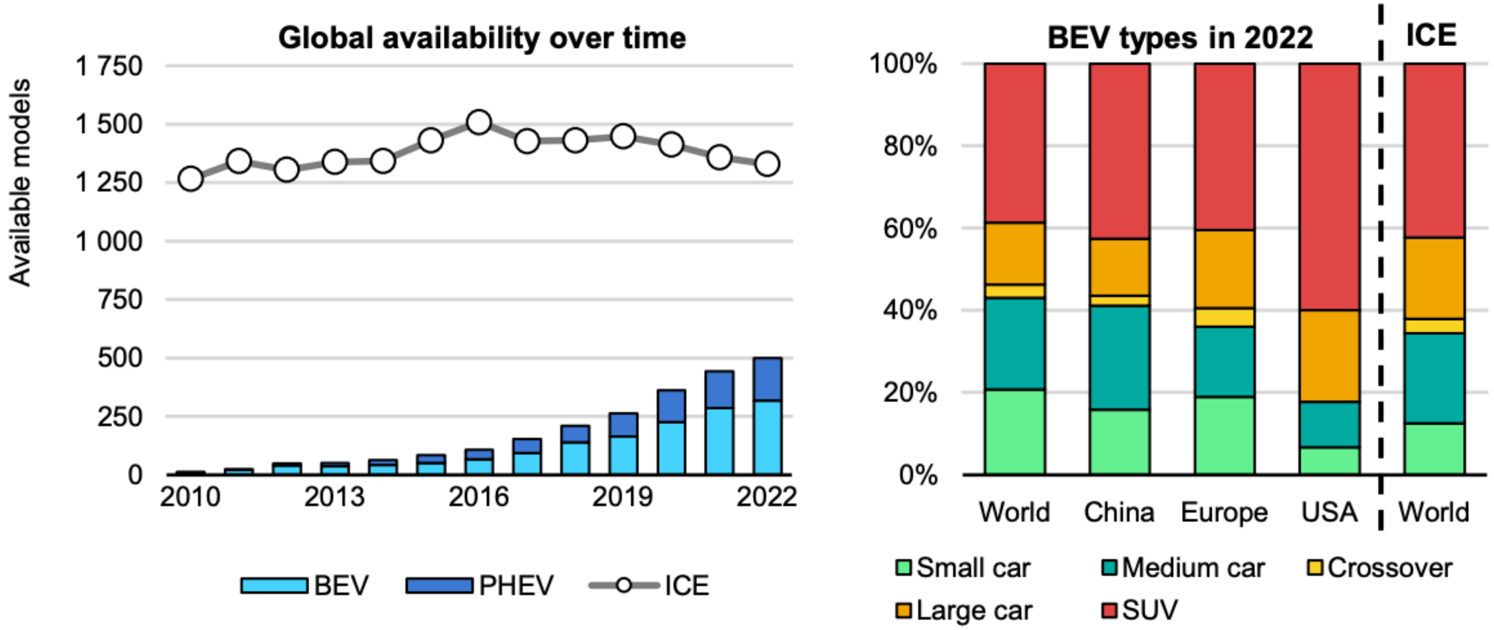
- **Battery pack cost** dropped by 85% since 2010, reaching ~$150/kWh today
- EVs **already cost-competitive** for some users, over the vehicle life
- Consensus that **$80-100/kWh needed for MSRP-parity** (~$60 cell level)
- **Multiple pathways** to achieve that cost
- Three major **challenges/goals**:
  - Continue reducing battery costs
  - Eliminate dependance on critical materials
  - Develop safe batteries that charge in <15 minutes



Source: US National Blueprint for Transportation Decarbonization

What Is Driving the EV Success – Vehicle Availability

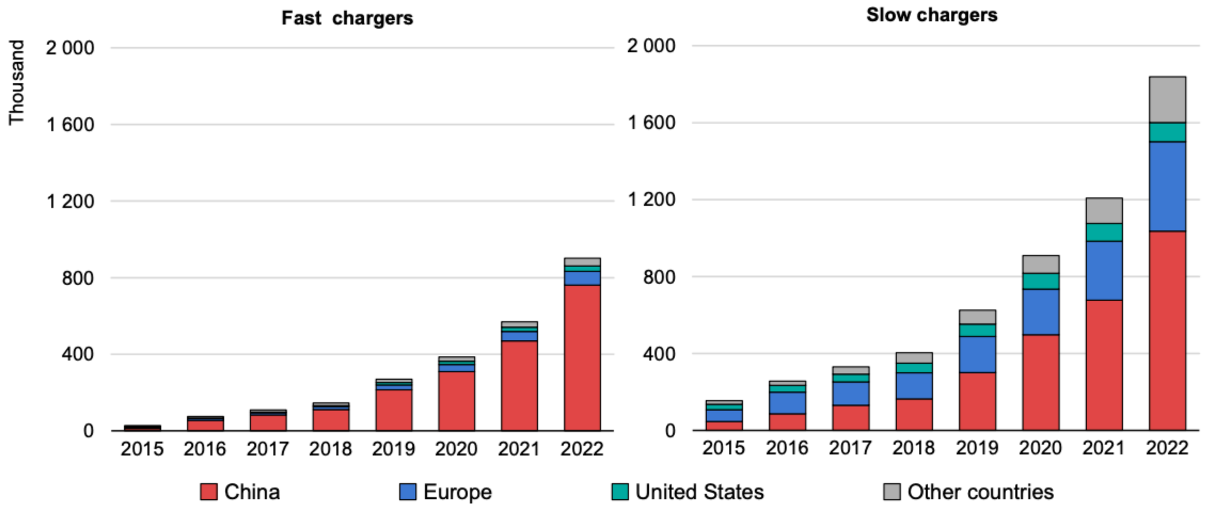
Figure 1.5 Car model availability by powertrain, 2010-2022 (left), and breakdown of available cars by powertrain and segment in 2022 (right)



Source: IEA Global EV Outlook 2023

What Is Driving the EV Success – Charging Infrastructure

Figure 1.13 Installed publicly accessible light-duty vehicle charging points by power rating and region, 2015-2022



Note: Values shown represent number of charging points.
Source: IEA analysis based on country submissions.

Installed publicly accessible charging points have increased by around 55%, with accelerated deployment led by China and Europe.

Source: IEA Global EV Outlook 2022

What Is Driving the EV Success – EVs are already Clean

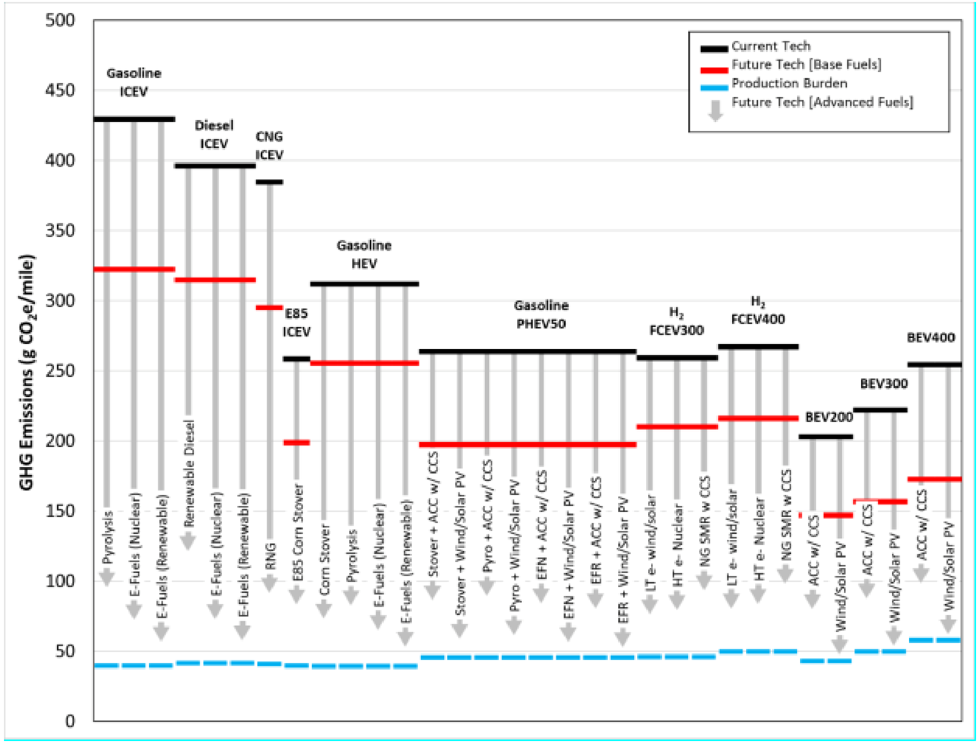


Figure ES-1. C2G GHG emissions of various vehicle-fuel pathways for small SUVs assuming high technology progress. Analysis was performed using GREET2020.

- TODAY, an EV SUV in the US emits ~50% LESS GHG emissions than a conventional gasoline vehicle, considering the entire life-cycle (yes, including battery manufacturing).
- In about 10 years we estimate that EVs will not only emit about 80% less than a future advanced gasoline vehicle (about 85% less than today’s gasoline vehicles), but they will also offer ~$5,000 lower lifetime vehicle and fuels cost!

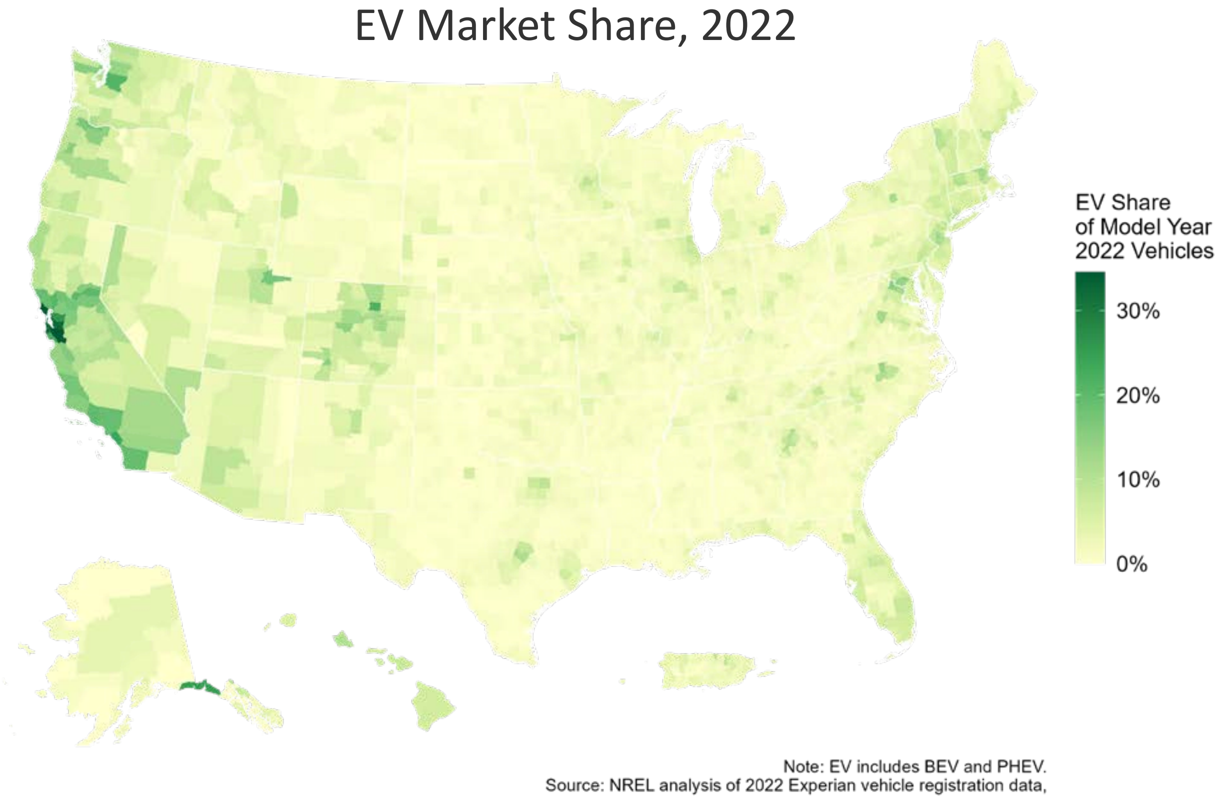
Source: [ANL Cradle-To-Grave LDV Report]

Moving Beyond Cars

Where and *when* EV charging occurs will be as critical as *how much* electricity is needed

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

– William Gibson



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

Global Competitive Context

- Future **energy leadership** will not be tied to petroleum.
- **China currently leads** the global EV deployment:
  - 50% of global EV cars
  - 80% of global public fast chargers
  - 95% of 2019 electric buses
- The battle ground is rapidly moving to global supply chains and control over raw materials and processing.

Source: The Economist (Briefing)

nature energy

ARTICLES

https://doi.org/10.1038/s41560-021-00855-0

Check for updates

Heavy-duty truck electrification and the impacts of depot charging on electricity distribution systems

Brennan Borlaug[1], Matteo Muratori[1]✉, Madeline Gilleran[1], David Woody[2], William Muston[2], Thomas Canada[3], Andrew Ingram[3], Hal Gresham[3] and Charlie McQueen[3]

Paper

Link to Paper

Data

Link to Data

Code

Link to Code

Critical to Understand Charging Loads and Prepare for Effective Grid Integration (Distribution Upgrades)

Higher energy demands increase the likelihood for upgrades further upstream in the distribution system which are **more expensive** and **take longer** to complete.

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Distribution systems are heterogenous and EV impacts will change significantly in different locations. But in general high-power requires more significant upgrades.

Table 1 | Summary of electricity distribution system upgrades for depot charging

Component category	Upgrade	Typical cause for upgrade	Typical cost[a]	Typical timeline (month)[a]
Customer on-site	50 kW DCFC EVSE	EVSE addition	Procurement, U$20,000–36,000 per plug; installation, U$10,000–46,000 per plug[b]	3–10
	150 kW DCFC EVSE		Procurement, US$75,000–100,000 per plug; installation, US$19,000–48,000 per plug[b]	
	350 kW DCFC EVSE		Procurement, US$128,000–150,000 per plug; installation, US$26,000–66,000 per plug[b]	
	Install separate meter	Decision to separately meter	US$1,200–5,000	
Utility on-site	Install distribution transformer	200+ kW load	Procurement, US$12,000–175,000	3–8
Distribution feeder	Install/upgrade feeder circuit	5+ MW load[c]	US$2–12 million[d]	3–12[e]
Distribution substation	Add feeder breaker	5+ MW load[c]	-US$400,000	6–12[f]
	Substation upgrade	3–10+ MW load[g]	US$3–5 million	12–18
	New substation installation	3–10+ MW load[g]	US$4–35 million	24–48[h]

[a]Cost and timeline ranges include procurement, engineering, design, scheduling, permitting and construction and installation; estimates are project-specific and vary greatly. [b]Costs reflective of 2019 and expected to continue to fall in future years; EVSE installation includes upgrading or installing service conductors and load centres; per-unit installation costs are reduced as the number of installed units increase. [c]Feeder extensions or upgrades (including new feeder breakers) are typically required for new loads >5 MW, especially for voltages <20 kV; new loads >12 MW may require a dedicated feeder. [d]Feeder extensions or upgrades tend to be more expensive in urban areas than in rural areas. [e]Timeline for feeder extensions includes jurisdictional permitting for construction, obtaining easements and right-of-way, and procurement lead times. [f]Timeline for adding a new feeder breaker depends on substation layout and the time required to receive clearance for construction. [g]The decision to upgrade an existing substation versus to build a new one is largely dependent on the layout of the existing substation and whether there is sufficient room for expansion. [h]Additional time may be required for regulatory approval for the transmission line construction. DCFC, direct current fast charging.

Source: SACE Assessment of Medium- and Heavy-Duty Vehicle Electrification

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