NREL
Transforming ENERGY

Transforming ENERGY Through SUSTAINABLE MOBILITY

Electric Vehicles: A Sustainable Solution for Transportation Systems

Matteo Muratori, PhD **KEYNOTE**

CSM 2024 4th Conference on Sustainable Mobility
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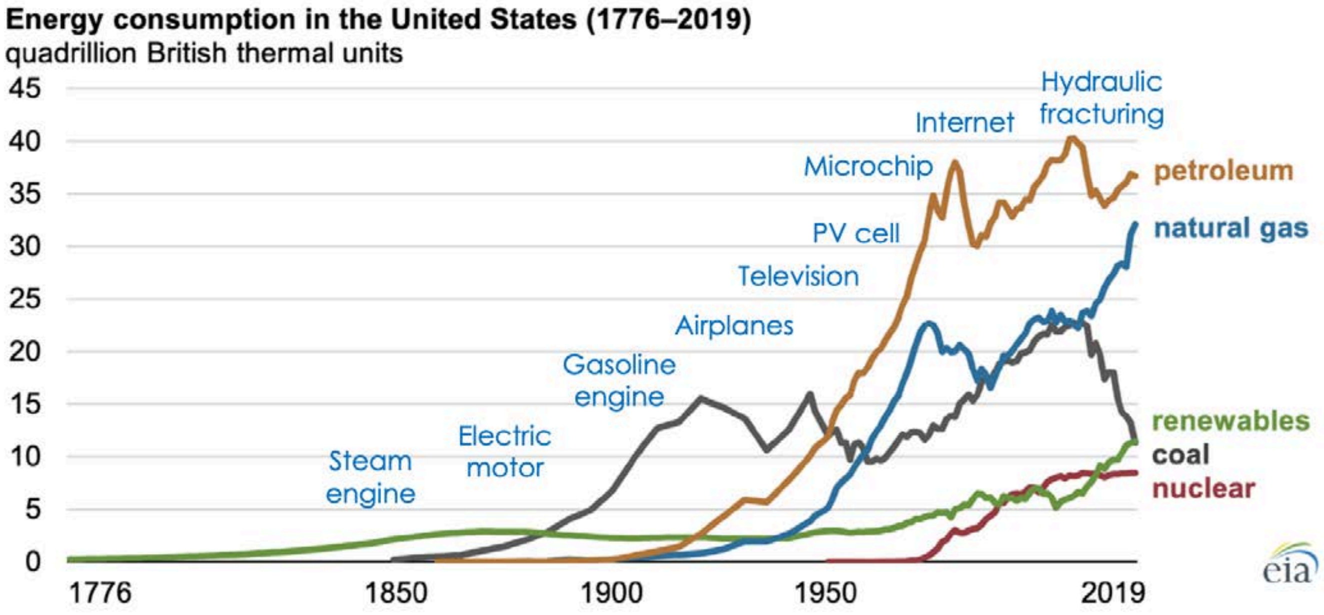
Energy is foundational to our lifestyle and consumption has been growing steadily for over a century…



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

Fossil fuels – petroleum, natural gas, and coal – have dominated (80% or more) 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.

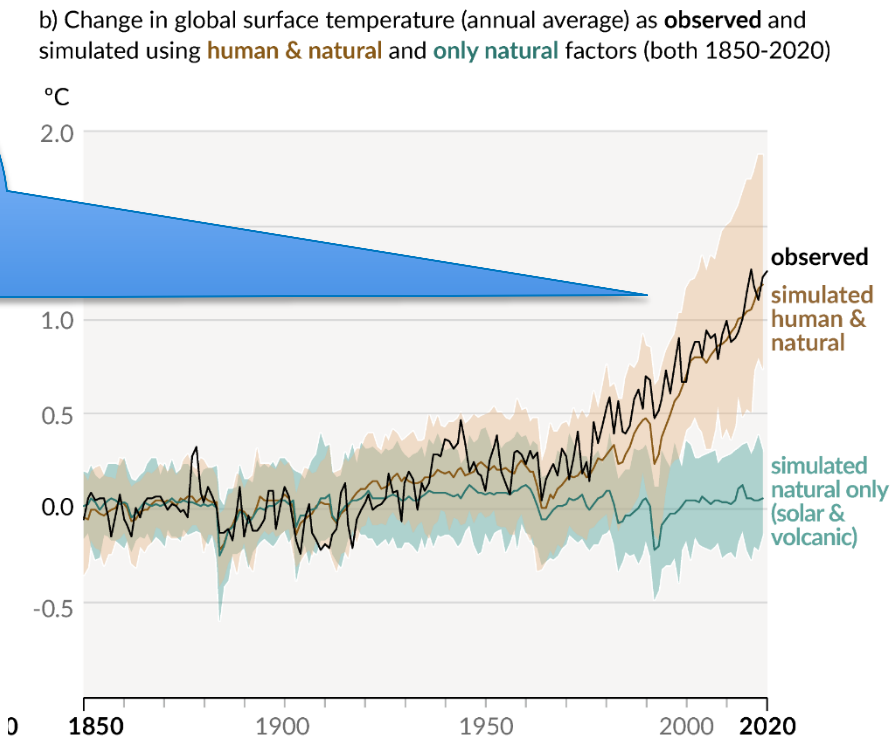
Source: National Institutes of Health

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

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.



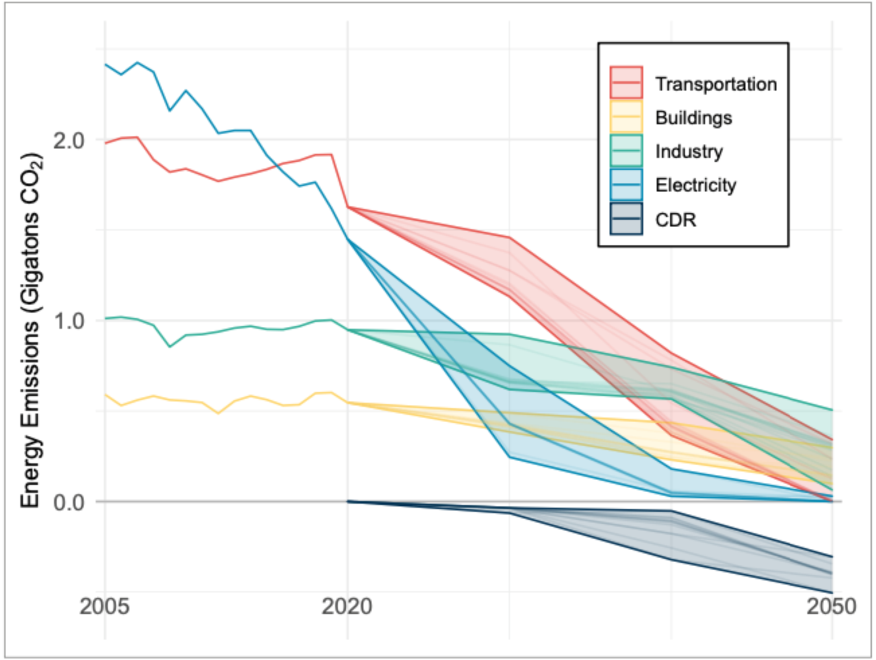
Source: IPCC Sixth Assessment Report

[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.

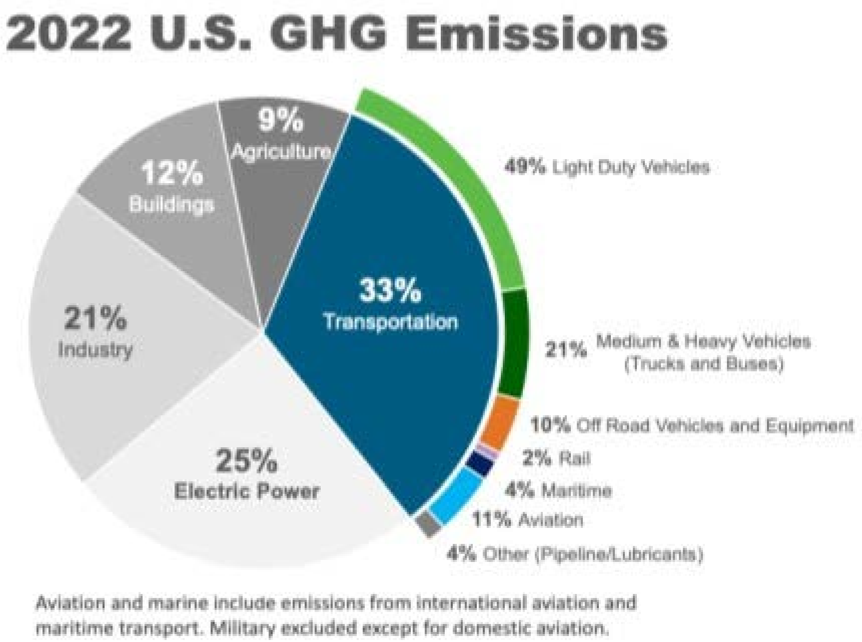
Strong, rapid, and sustained emissions reductions are necessary to limit global warming and improve air quality.

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

Transportation is the least-diversified energy sector (90% petroleum) and largest source of GHG emissions



Source: U.S. 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**.

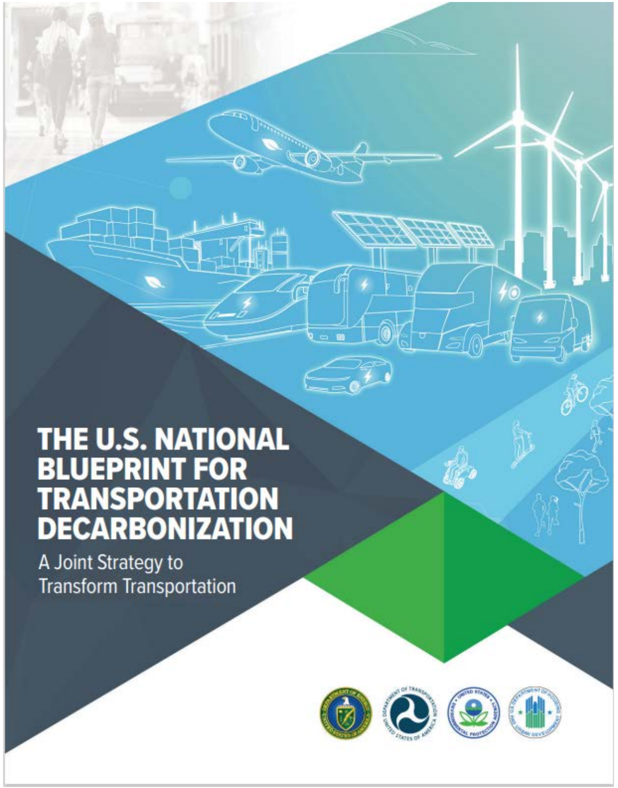
Three complementary strategies to decarbonize transportation (U.S. whole-of-government approach)

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: U.S. National Blueprint for Transportation Decarbonization



ELECTRIC VEHICLES (EVs)

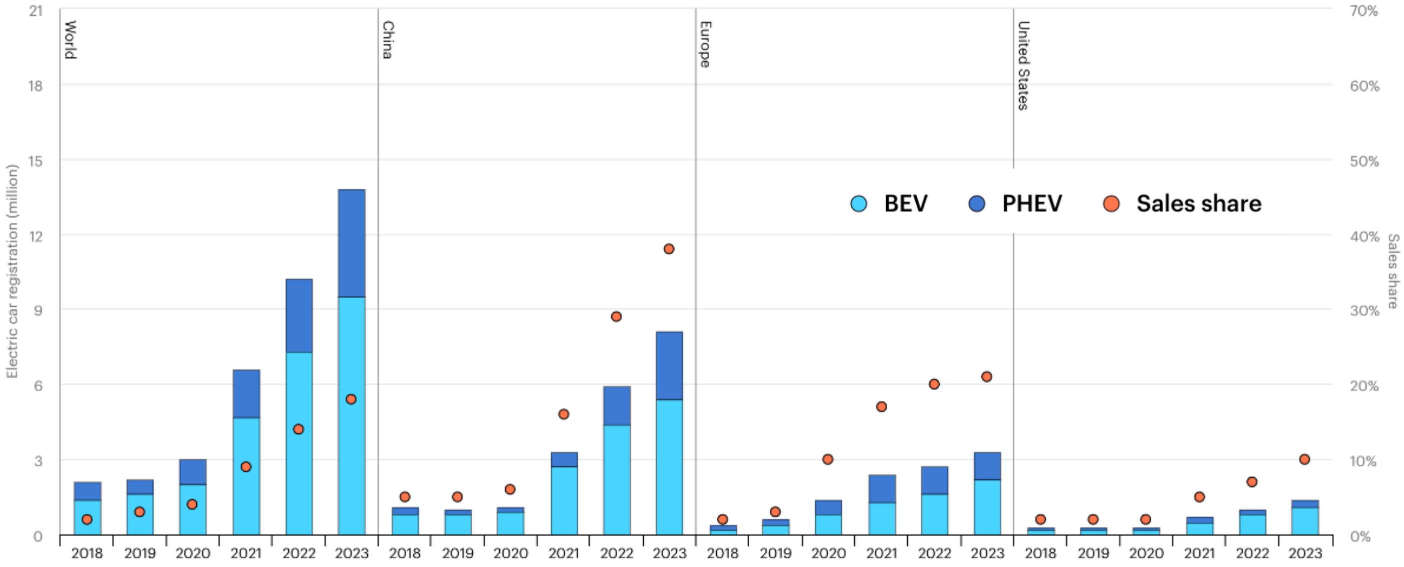
As the primary enabler for vehicle decarbonization, electric vehicles will play a pivotal role in the future

Source: IEA

- EVs offer a **pathway to decarbonize on-road transportation** when coupled with clean electricity.
  - 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 break new records to capture 18% of the market in 2023, reaching over 14 million sales worldwide

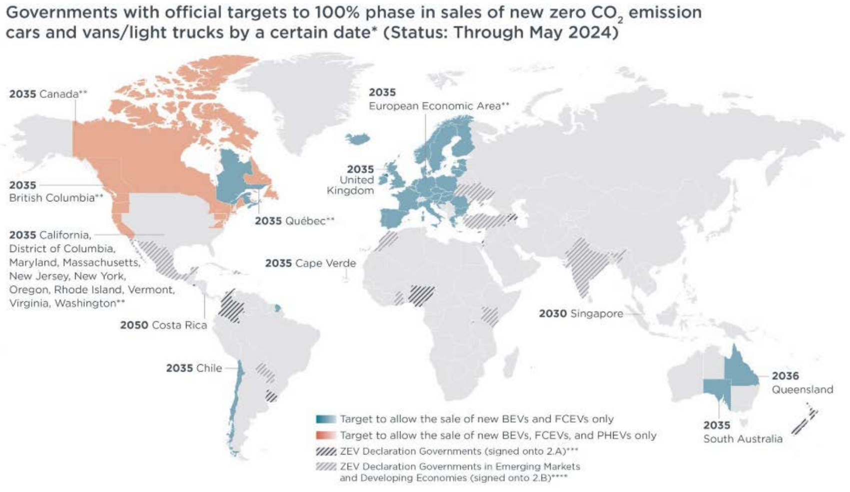
2018–2022 Electric Car Registrations and Sales Share

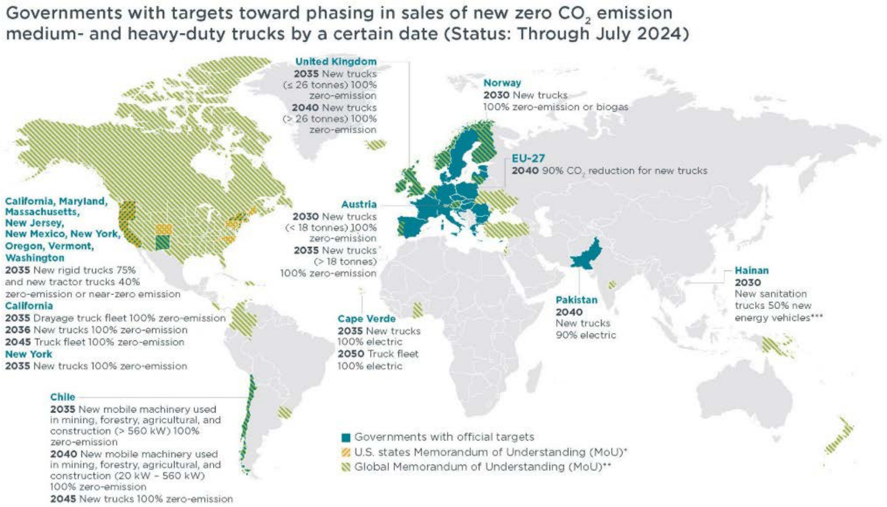


Source: IEA

One in 10 vehicles sold in the United States is now electric—more than 1.4 million EVs sold in 2023, a 50% increase from 2022!

Many phase-out targets set to end the sale or registration of internal combustion engine vehicles





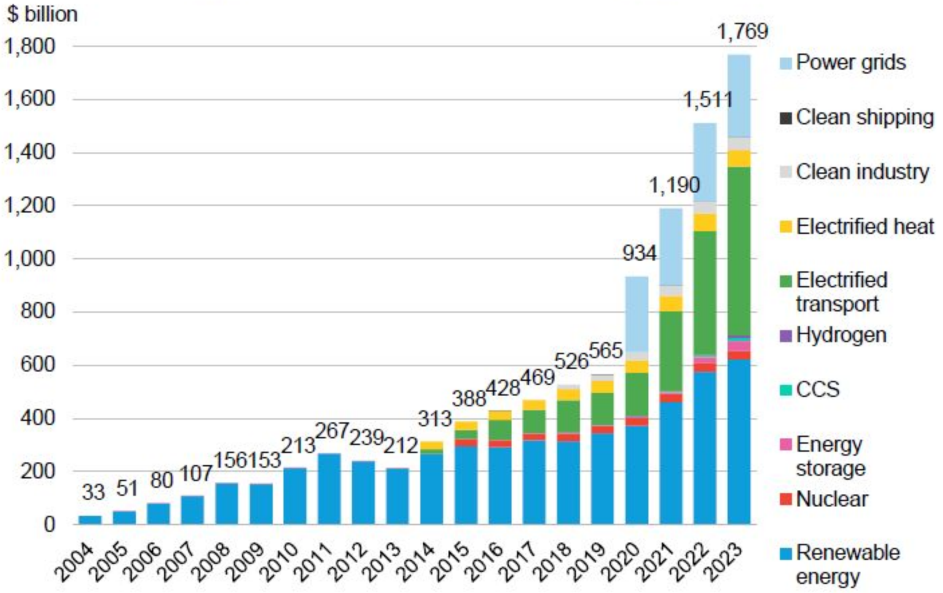
Source: International Council on Clean Transportation

Strong government signals supporting a transition to zero-emissions vehicles, with EVs playing a key role.

Not only government targets: MAJOR industrial investments support a transition to EVs

- Low-carbon energy global investments totaled **$1.8 trillion in 2023**.
- **Electrified transportation overtook renewables**, with $634 billion invested in 2023–an impressive 36% increase from 2022!

Global Energy Transition Investment by Sector



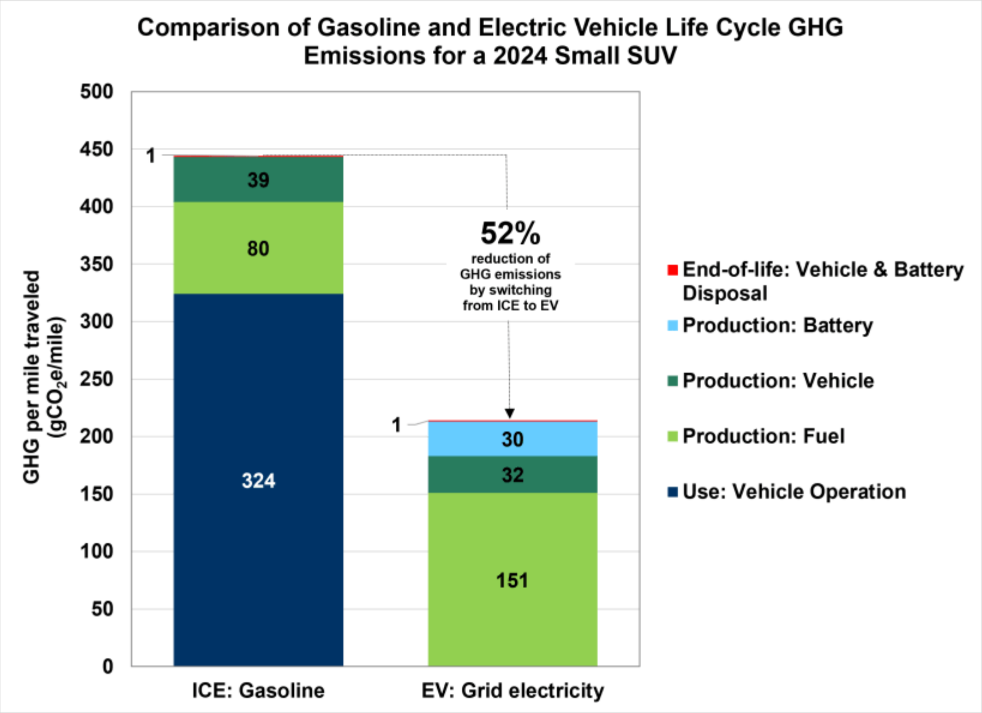
Note: Start years differ by sector, but all sectors are present from 2020 onwards. See methodology for more information. Most notably, nuclear figures start in 2015 and power grids in 2020. CCS refers to carbon capture and storage.

Source: BloombergNEF

The rest of this talk: Zoom-in on EVs

- Sustainability
- Affordability
- Manufacturing
- Charging Infrastructure
- EV-Grid Integration

Are EVs green? Yes!

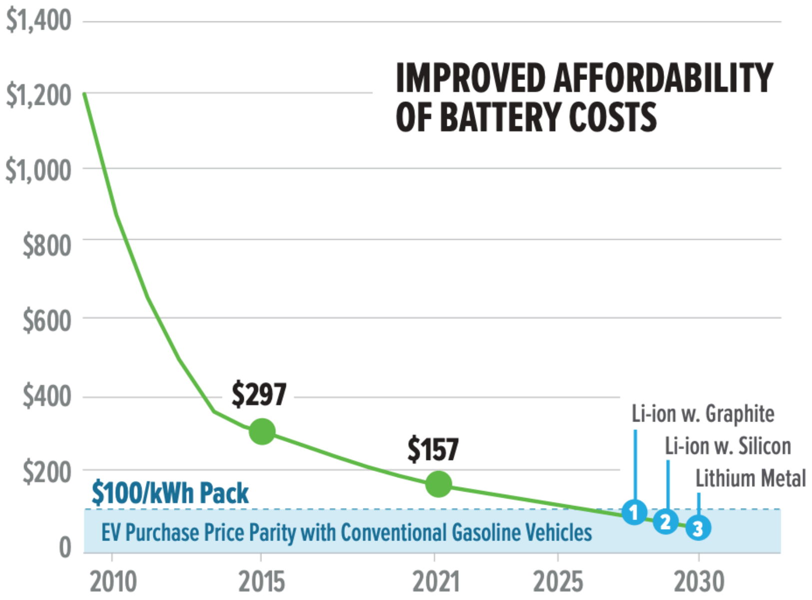


Source: U.S. Department of Energy

- Today, an electric SUV in the United States emits **~50% LESS GHG** than a conventional gasoline vehicle, considering the entire life-cycle (yes, including battery manufacturing).
- In about 10 years we estimate that **EVs will emit about 80% less than a future advanced gasoline vehicle** (about 85% less than today's gasoline vehicles).
- Bonus point (from the same study): EVs will also offer ~$5,000 lower lifetime vehicle and fuels cost!

Are EVs affordable? Getting there

- **Battery pack cost** has dropped by 90% since 2010, reaching ~$150/kWh today.
- Consensus that **$80-100/kWh needed for MSRP-parity** (~$60 cell level)
  - **$75/kWh achieved in China in 2024** thanks to a sharp fall in raw material prices coupled with manufacturing overcapacity
  - **Two-thirds of EVs available in China are already cheaper to purchase** (MSRP) than their internal combustion engine equivalents.



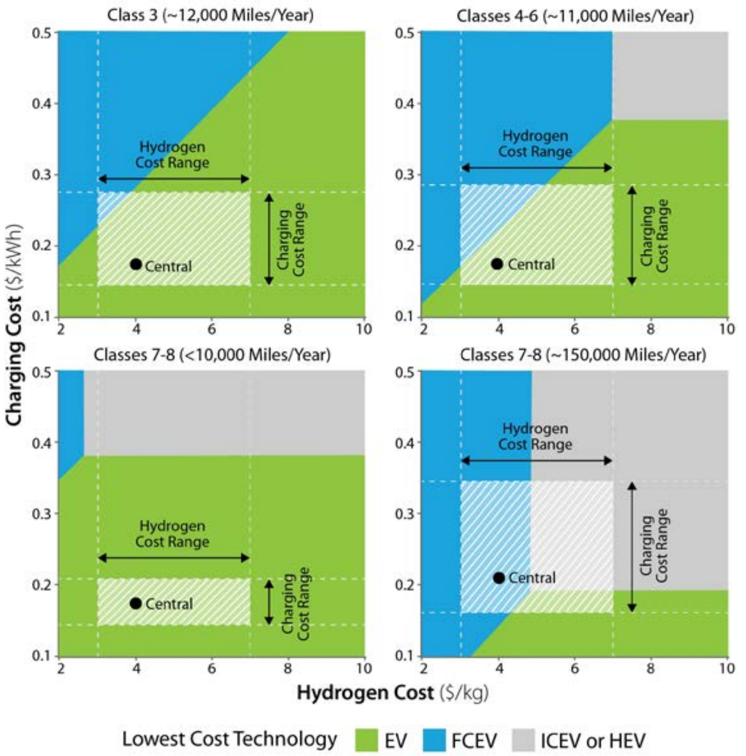
Source: U.S. National Blueprint for Transportation Decarbonization

EVs are already cost-competitive for many applications—considering total cost of ownership—and competitiveness will keep improving

With continued improvements in vehicle and fuel technologies, **ZEVs reach total cost of driving parity by 2035** for all commercial vehicle classes and applications.

- **EVs are coming now**: Considering tech progress and IRA incentives, Class 3–6 EVs and short-haul Class 7–8 EVs with 150–300 miles of range achieve parity before 2028.
- **Fuel cell electric vehicles (FCEVs) can provide solutions** for long-haul and challenging applications (if hydrogen price reaches $4–5/kg).

2035 Projections

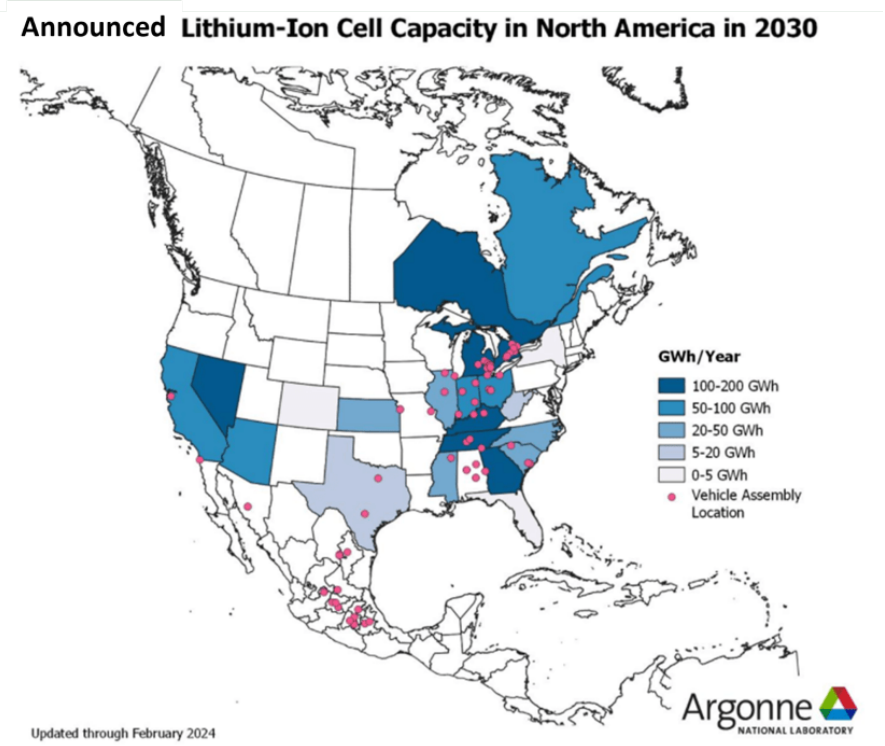


Source: Ledna *et al.* 2024

Decarbonizing transportation is a major opportunity with far-reaching implications for consumers, energy, infrastructure, geopolitics, and industrial competitiveness

Industrial Competitiveness

- The U.S. **automotive industry**: 10M vehicles produced each year (+5–7M imported), 3% of GDP (over $100B exports), employ 4.3M workers
- Over $160B in battery and EV investments in North America (1,400 GWh/year by 2030): Could **supply ~14M- 18M EVs annually**.



Source: Gholke *et al.* 2024

Where to charge EVs?

Recent survey shows that **6 in 10 Americans who aren't yet sold on EVs were concerned about where and when they would charge** (61%) and how far that charge will take them (55%).

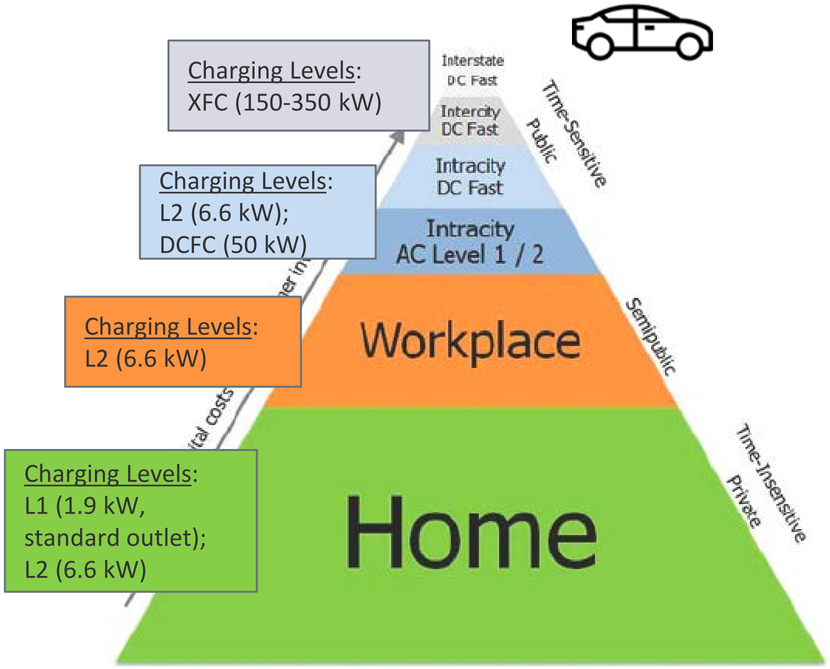
Source: UC Davis

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

- 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.*).

EV charging technology: A variety of solutions

LDV Paradigm:



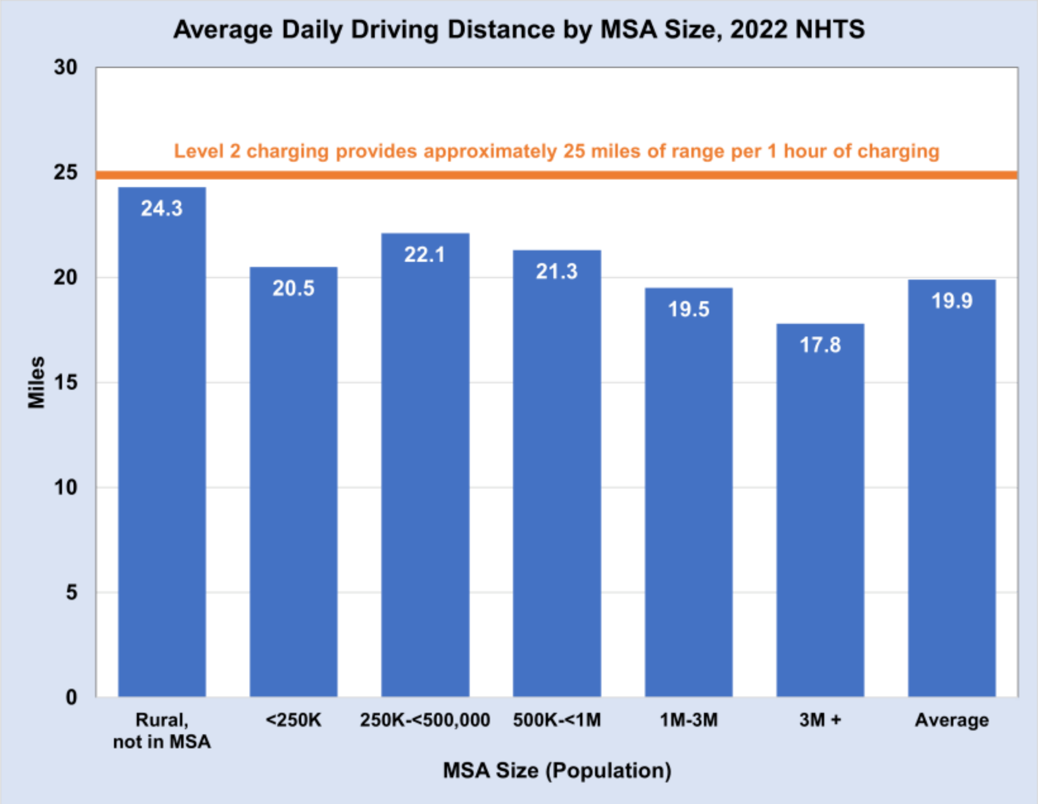
Source: Transportation Research Board and National Research Council

Charging EVs includes a lot **more options** than "gasoline stations"

- **Home charging can cover most needs** (~95% of trips <30 miles) but not everyone has access.
- **Workplace** is next biggest opportunity.
- **Public charging (L2 and DCFC) is critical to build consumer confidence and enable long-distance travel**.

A similar breakdown applies to **commercial vehicles** (buses and trucks): Charging overnight at depot can cover most needs conveniently and affordably.

"Slow charging" is actually pretty fast



Source: Vehicle Technologies Office

A driver can easily get more miles from an hour of Level 2 charging while their EV is parked than the average person drives in a day.

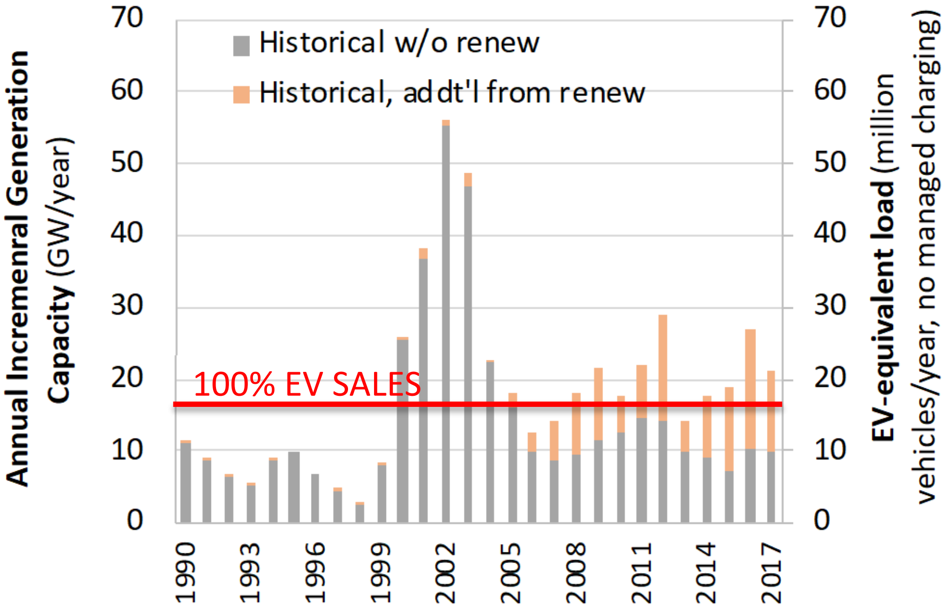
Implications for the grid

- EVs are poised to **drive substantial growth in electricity demand** (after decades of stagnation) and will require investments in generation, transmission, and distribution systems.

- Vehicles are underutilized assets parked ~95% of the time: **EVs 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.

Will the grid support widespread EV adoption?



Source: U.S. DRIVE 2019

- Based on historical growth rates, **sufficient electricity supply is expected** to be available to support a growing EV fleet as it evolves over time, even for 100% EV sales.
- EVs offer **opportunities to better utilize assets** as the cost of the additional infrastructure is spread across more units of electricity sold.

The grid is also transforming

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

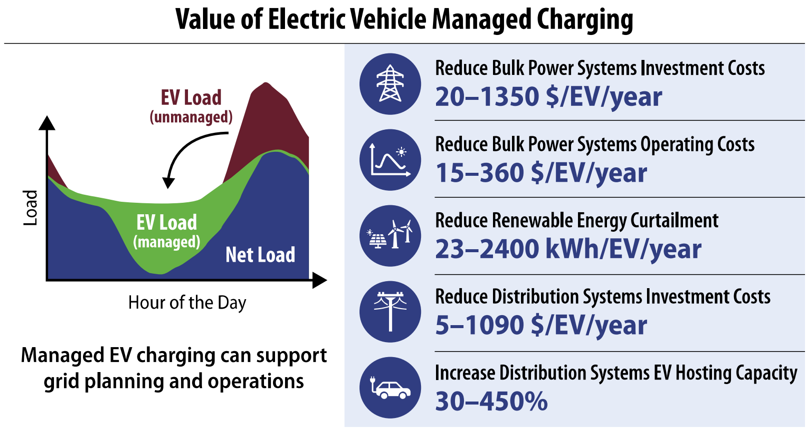
The traditional system paradigm of dispatching central generation to match demand is evolving into a **more integrated supply-demand system** in which demand-side distributed resources respond to supply-side requirements, mainly driven by variable renewable generation.

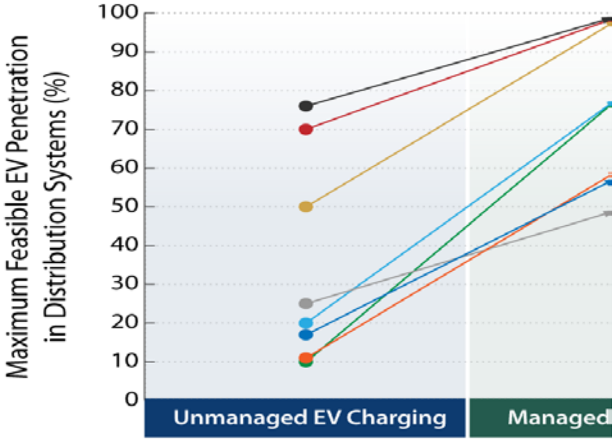
California Public Utilities Commission: *"EV drivers have contributed $806 million more in revenues than associated costs, driving rates down for all customers."*

Smart EV charging enables synergistic improvement of the efficiency and economics of mobility and electricity systems

Vehicles are underutilized assets parked ~95% of the time. **Managed EV charging can satisfy mobility needs while also supporting the grid**:

- Demand-side flexibility offers **grid benefits over multiple timescales**
- Supports and **complements the expected large-scale renewable** deployment.





Sources: Muratori *et al.* 2021 and Anwar, Muratori, *et al.* 2021

Key actions and research needs (1/5)

- **Sustainability**
- Affordability
- Manufacturing
- Charging Infrastructure
- EV-Grid Integration

A. Continue to **decarbonize the grid**

- 99% of new electricity generation capacity installed in the United States in 2024 was from renewables.

B. **Decarbonize vehicle manufacturing**, including innovations in new vehicle materials and advanced processes, including recycling.

Key actions and research needs (2/5)

- Sustainability
- **Affordability**
- Manufacturing
- Charging Infrastructure
- EV-Grid Integration

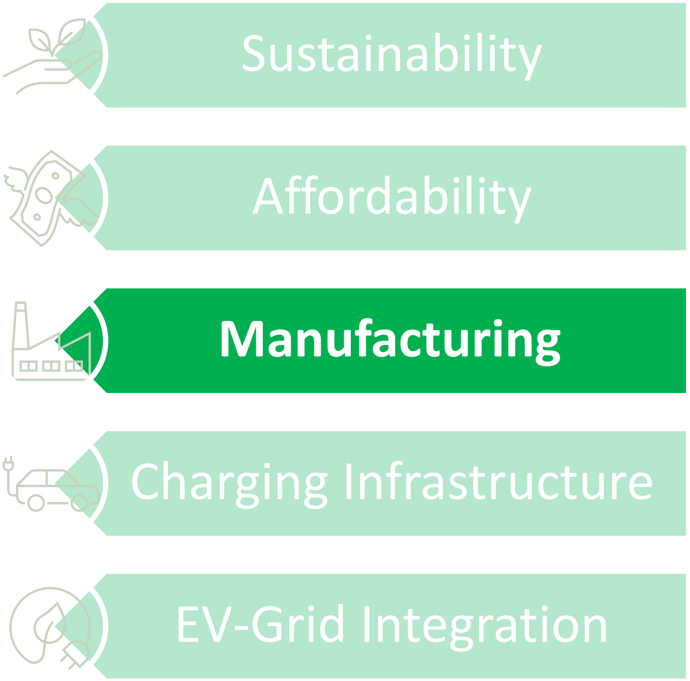
A. Continue to **drive innovation in batteries** to further reduce costs and improve performance

B. Enable cheap charging (vehicle grid integration)

C. Improve **vehicle efficiency** (*e.g.*, new materials and controls):

more efficiency → smaller batteries → lower costs (and less electricity).

Key actions and research needs (3/5)

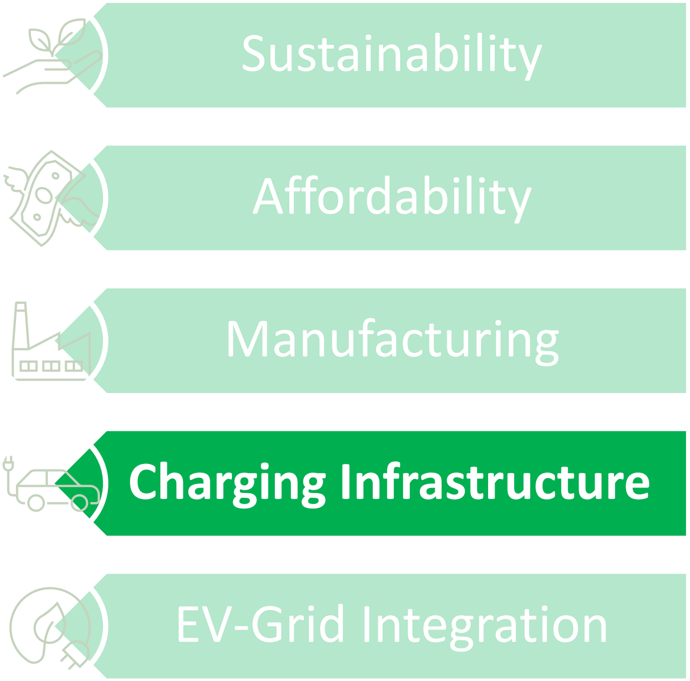


A. Develop **robust workforce and supply chain (and recycling) solutions** to ensure we can **manufacture and deploy** enough clean techs

- Future energy leadership will not be tied to petroleum; the **battle ground is moving to materials and processing**
- Ensure resulting jobs and economic opportunities are distributed **equitably**.

B. Continue to **innovate on new materials/processes** and automation.

Key actions and research needs (4/5)



A. **Interoperability and reliability:** Enable all vehicles to change everywhere anytime

B. **Convenience:** Deploy consumer-centric infrastructure
   - Intercity fast charging network
   - Solutions for people without home/depot charging and underserved communities (no single answer)

C. **Reducing costs** (of technologies and soft costs)

D. **Cyber-security**

Key actions and research needs (5/5)

- Sustainability
- Affordability
- Manufacturing
- Charging Infrastructure
- **EV-Grid Integration**

A. **Forward-looking planning** of grid-related investments to support rapid EV uptake

B. Enable smart **integration of EVs** for synergistic improvement of the efficiency and economics of e-mobility and the power grid

   - **Technical solutions**: how to best use EV resources?
   - **Market reforms** to enable full grid-edge participation.

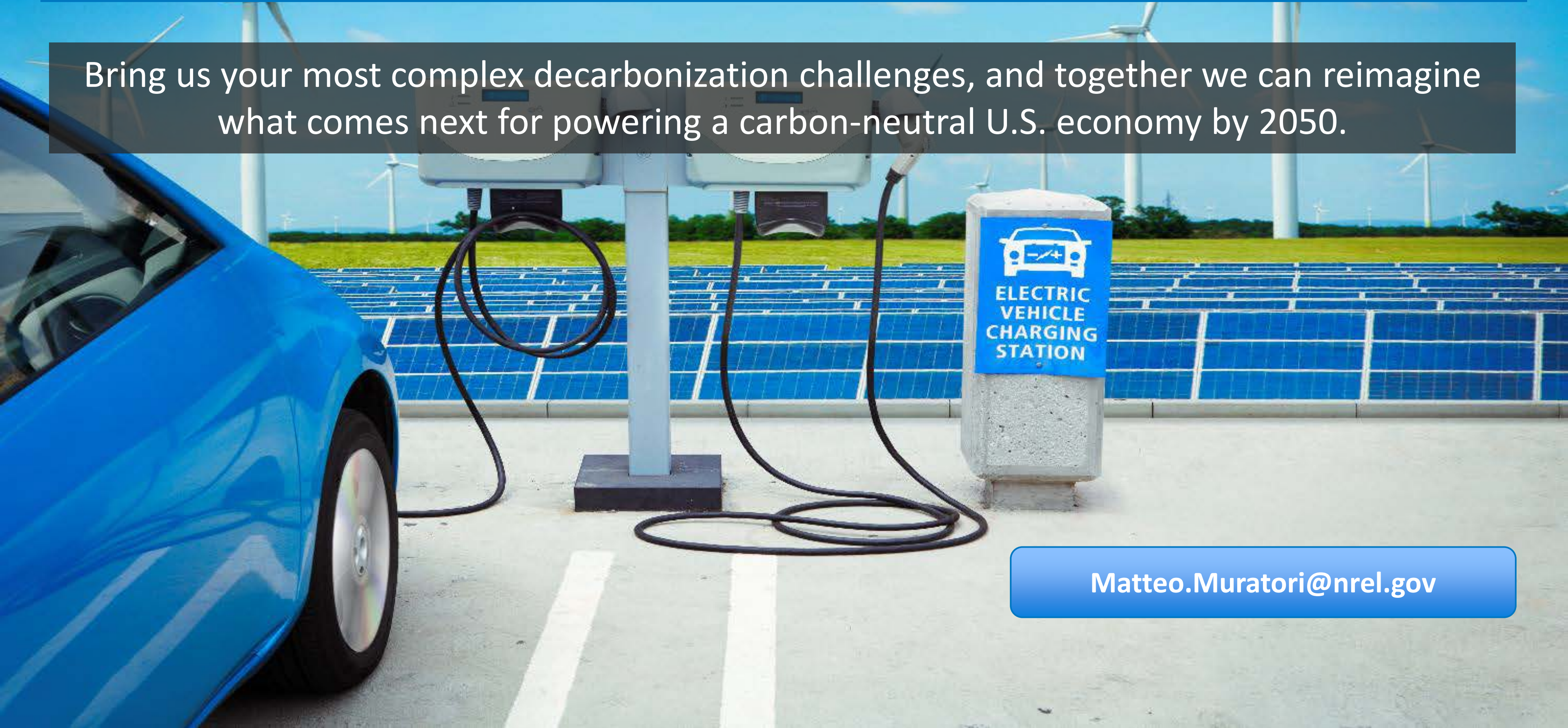
Transportation and energy systems are at a turning point

After more than a century or petroleum dominance, we envision a future transportation system that will be optimally **integrated** with smart buildings, the electric grid, and other infrastructure to **fully leverage and support renewable energy** and achieve an economically competitive, secure, and sustainable future for all.

Join us or reach out to explore opportunities to collaborate!

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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ABSTRACT and BIO

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 enabler for vehicle decarbonization when paired with clean electricity, electric vehicles will play a pivotal role in the future.

This talk summarizes the current status of EV technologies and markets, future projections, and opportunities associated with a conversion to EVs for all on-road vehicles. Moreover, 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.

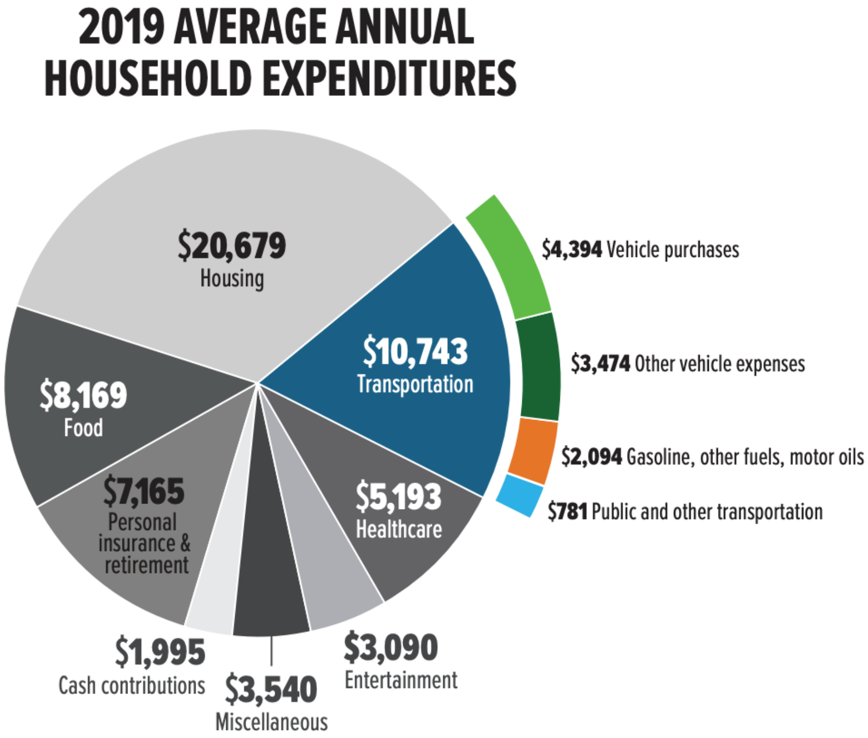
Bio: Dr. Matteo Muratori is a Distinguished Researcher at the National Renewable Energy Laboratory (NREL) where he also manages the Transportation Energy Transition Analysis group to explore system-level sustainable solutions for the transformation of the transportation sector. NREL is the United States' premier laboratory for the research and development of renewable energy and energy efficiency technologies 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 U.S. Department of Energy.

A native of Italy, Dr. Muratori has authored hundreds technical publications cited over 9,000 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 United States, 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: U.S. National Blueprint for Transportation Decarbonization

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

Transitioning to automobiles solved one problem and…

Great Horse Manure Crisis of 1894

1953 New York City Smog Event

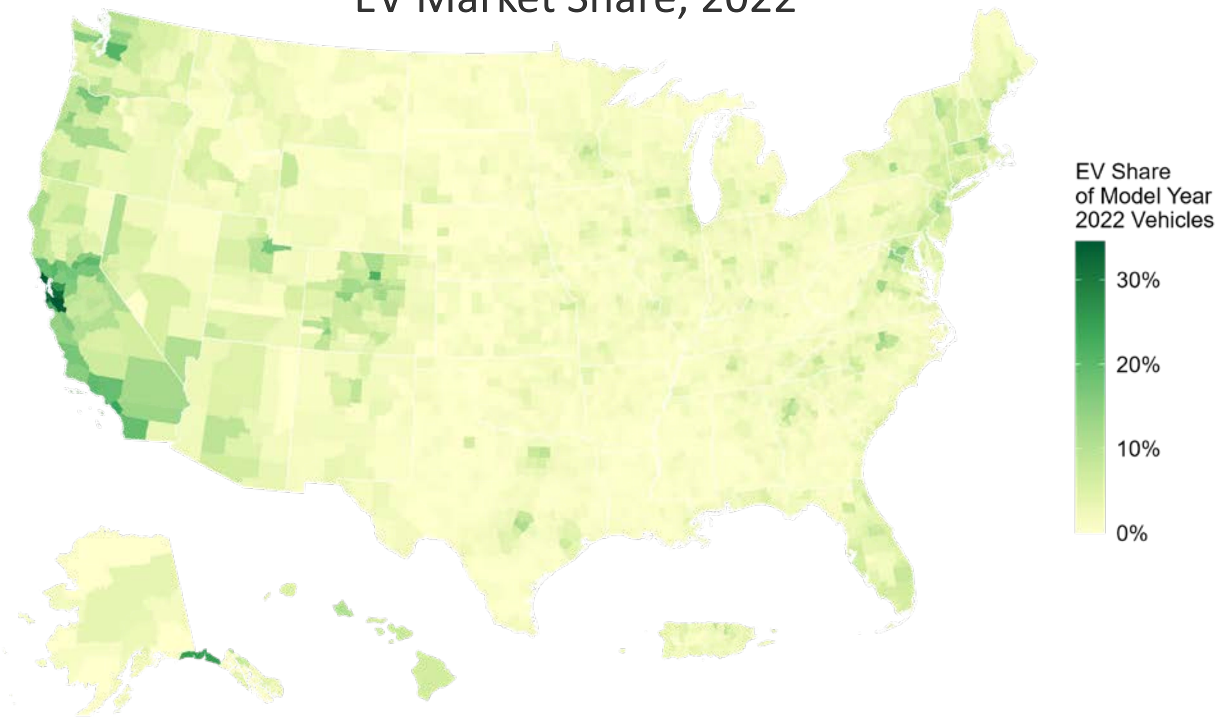
Source: George E. Waring. 1898; Public Domain, U.S. Library of Congress

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

EV Market Share, 2022

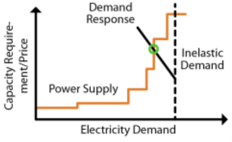


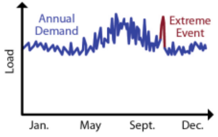
Note: EV includes BEV and PHEV.
Source: NREL analysis of 2022 Experian vehicle registration data,
Source: Yip *et al.* (2023)

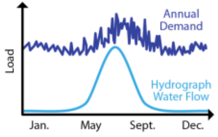
EVs can support the grid in multiple ways, providing values for different stakeholders including non-EV owners

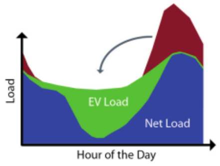
Smart electric vehicle-grid integration can provide flexibility – the ability of a power system to respond to change in demand and supply – by charging and discharging vehicle batteries to support grid planning and operations over multiple time-scales

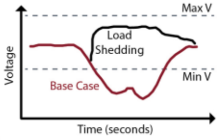
Power System Application	Generation Capacity and Transmission/ Distribution Planning	Resilience To Extreme Events	Seasonal Planning (Hydro/Long-Term Storage Dispatch)	Commitment and Dispatch Decisions	Balancing and Power Quality	Support End Consumers
Time scale	*Multi-year*	*Years (planning), hours (real-time 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

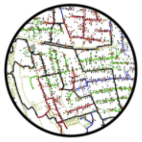












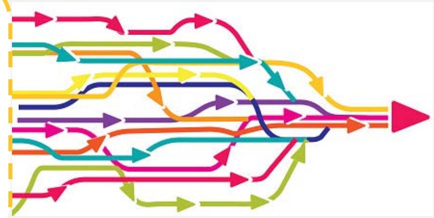
Source: Muratori *et al.* 2021.

Transportation decarbonization – A coordinated approach

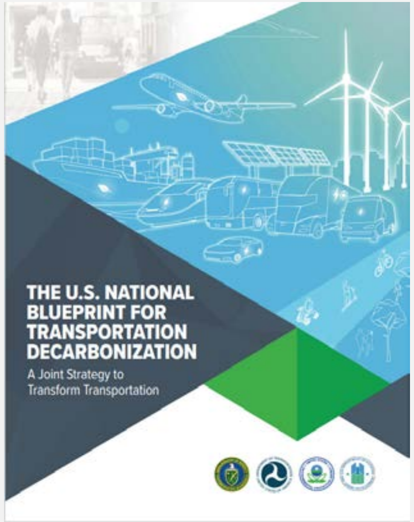
Four-agency memorandum of understanding signed 9/22/23 established a historic, whole-of-government approach to transportation decarbonization:

- Consistent and expanded stakeholder outreach
- Clear signals to industry
- We have implemented bold strategies that:
    - Set up **realistic, achievable** pathways based on innovation and science
    - Be strategic – **make choices**
    - **Leverage market forces** for **widescale** deployment of **cost-effective** clean technologies
    - Focus on **incremental solutions** to deploy and deliver results by 2030
    - Address full **lifecycle emissions** and integration with the **electric grid**.

Underpinned by a singular aligned transportation decarbonization vision/blueprint



"Hope is not a plan."



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Thank You

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