Integrating Electric Vehicles into the Grid

Brennan Borlaug
National Renewable Energy Laboratory

December 3, 2024

U.S. Department of Transportation Workshop:
State EV Infrastructure Planning
Tijuana, Baja California, Mexico

Major U.S. National Laboratories

NREL: 3,000+ workforce dedicated to energy efficiency and renewable energy

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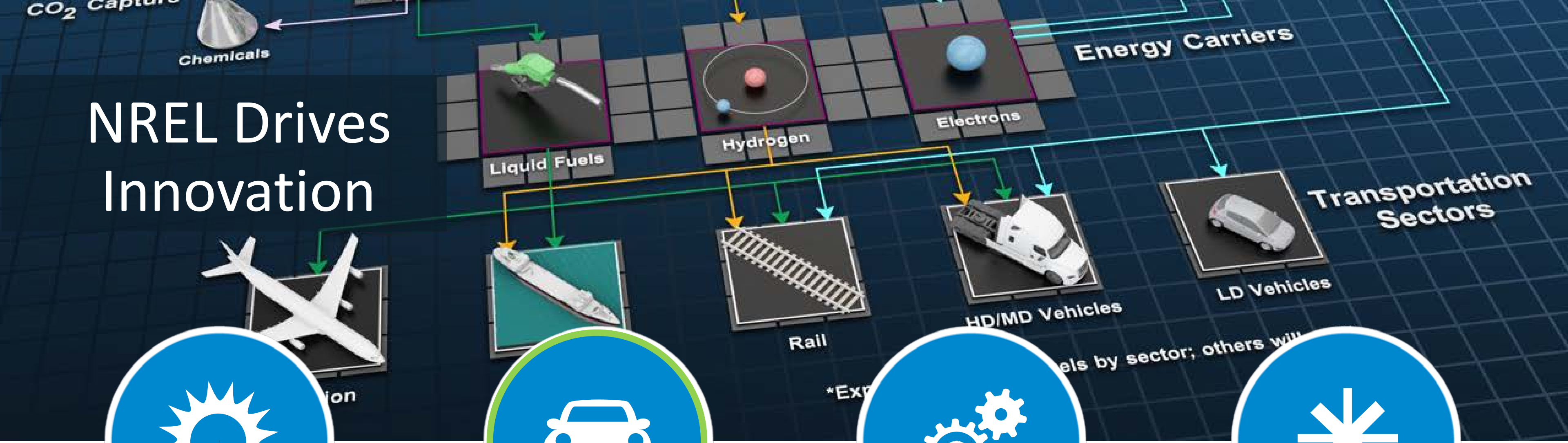
NREL Drives Innovation



Renewable Power

Solar

Wind

Water

Geothermal

Sustainable Transportation

Bioenergy

Electrification

Hydrogen

Energy Efficiency

Buildings

Advanced Manufacturing

Government Energy Management

Energy Systems Integration

Grid Integration

Hybrid Systems

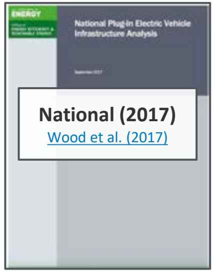
Security and Resilience

NREL EV Infrastructure Studies

https://www.nrel.gov/transportation/evi-x.html

EVI-X

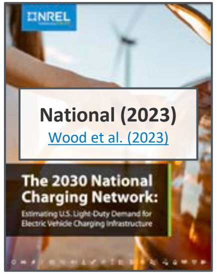
NREL Track Record: >10 studies spanning a decade



ENERGY

National Plug-in Electric Vehicle Infrastructure Analysis

National (2017)
Wood et al. (2017)



NREL

The 2030 National Charging Network:
Estimating U.S. Light-Duty Demand for Electric Vehicle Charging Infrastructure

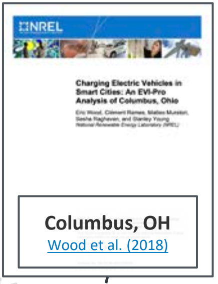
National (2023)
Wood et al. (2023)

NREL

Measuring the Benefits of Public Chargers and Improving Infrastructure Deployments Using Advanced Simulation Tools

Preprint

Seattle, WA
Wood et al. (2015)



NREL

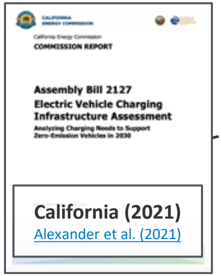
Charging Electric Vehicles in Smart Cities: An EVI-Pro Analysis of Columbus, Ohio

Columbus, OH
Wood et al. (2018)

NREL

Regional Charging Infrastructure for Plug-In Electric Vehicles: A Case Study of Massachusetts

Massachusetts
Wood et al. (2017)

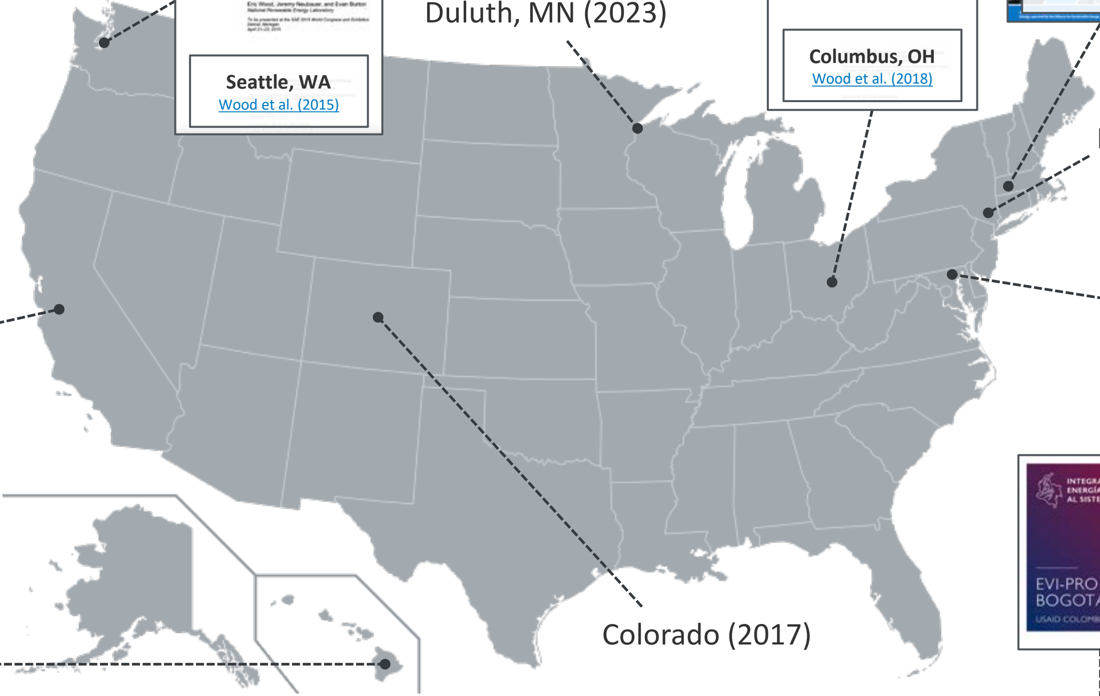


CALIFORNIA ENERGY COMMISSION

COMMISSION REPORT

Assembly Bill 2127
Electric Vehicle Charging Infrastructure Assessment
Analyzing Charging Needs to Support Zero-Emission Vehicles in 2030

California (2021)
Alexander et al. (2021)



Duluth, MN (2023)

New York *(forthcoming)*

California (2014)
California (2018)
Indio, CA *(forthcoming)*

Hawaii *(forthcoming)*

Colorado (2017)

NREL

Meeting 2025 Zero Emission Vehicle Goals: An Assessment of Electric Vehicle Charging Infrastructure in Maryland

Maryland
Moniot et al. (2019)

INTEGRACIÓN EFICIENTE DE ENERGÍAS RENOVABLES VARIABLES AL SISTEMA COLOMBIANO

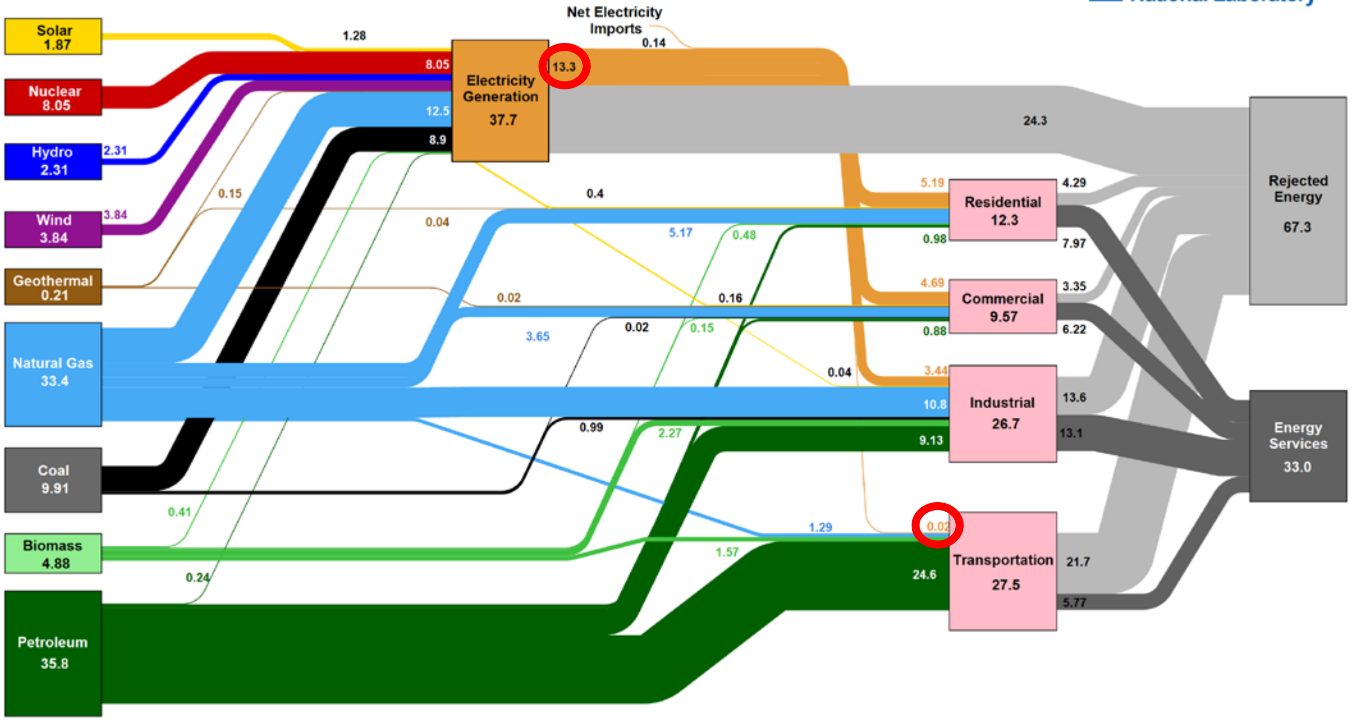
EVI-PRO FOR
BOGOTÁ COL

Bogotá, Colombia
NREL. (2023)

Background

U.S. Transportation & Electricity Sector:
Historically Distinct & Unconnected

Estimated U.S. Energy Consumption in 2022: 100.3 Quads



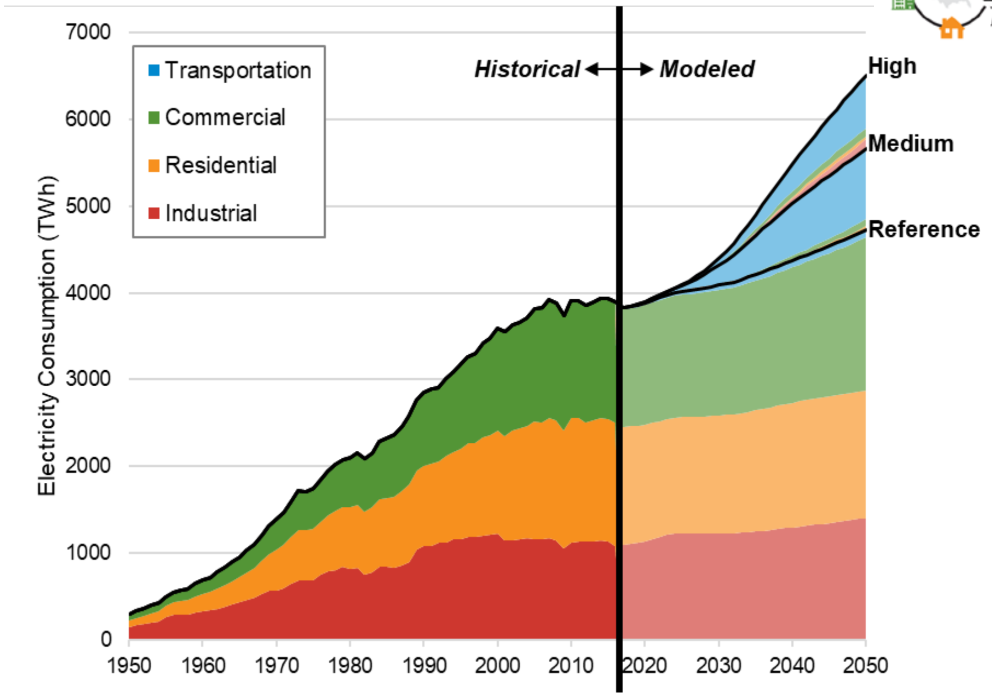
Source: LLNL July, 2023. Data is based on DOE/EIA SEDS (2021). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant heat rate. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 0.65% for the residential sector, 0.65% for the commercial sector, 0.49% for the industrial sector, and 0.21% for the transportation sector. Totals may not equal sum of components due to independent Rounding. LLNL-MI-410527

EV-Grid Integration: *Why is it important?*

- U.S. electricity demand has been flat for nearly 20 years.
- **Electricity demand growth expected to resume** as all major end use sectors transition from fossil fuels to electricity.
- **Transportation electrification** is expected to be one of the **main contributors to future electricity demand growth**.

EFS High scenario, 2050:

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



Source: NREL's Electrification Futures Study

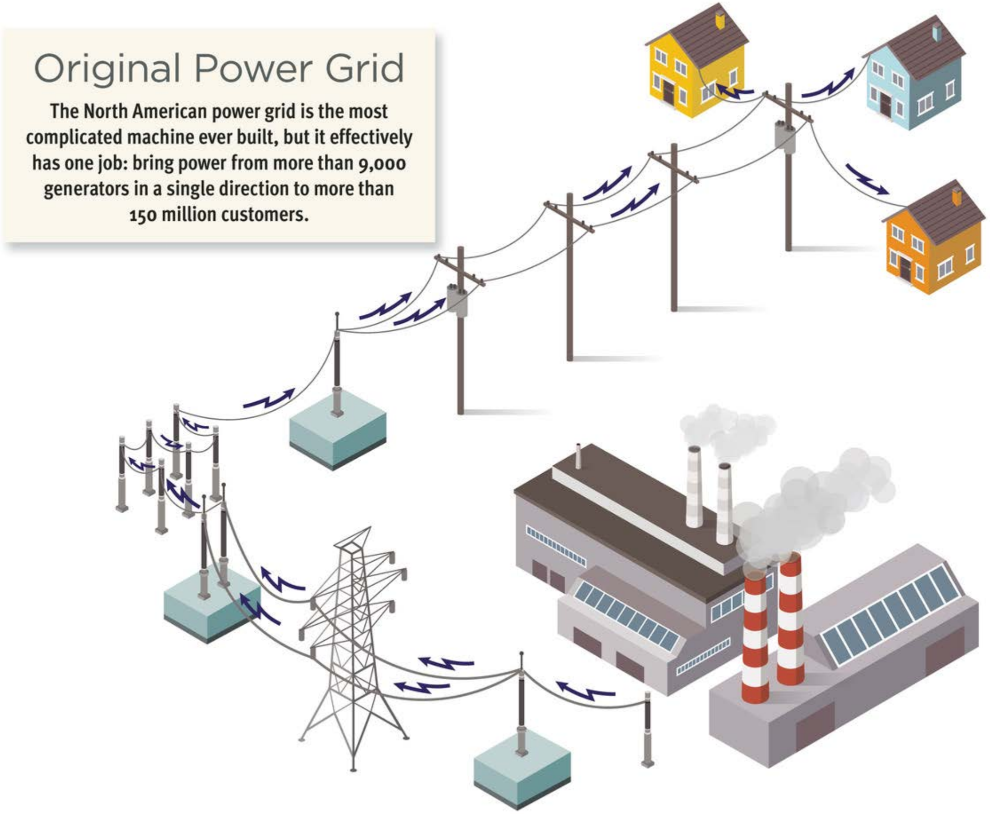
Transport Electrification + Grid Decarbonization = Mutually Beneficial

The electric power system is undergoing profound changes…

The traditional 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 of demand-side flexibility**.

Traditional Paradigm: Centralized Supply Dispatched to Match Fixed Demand



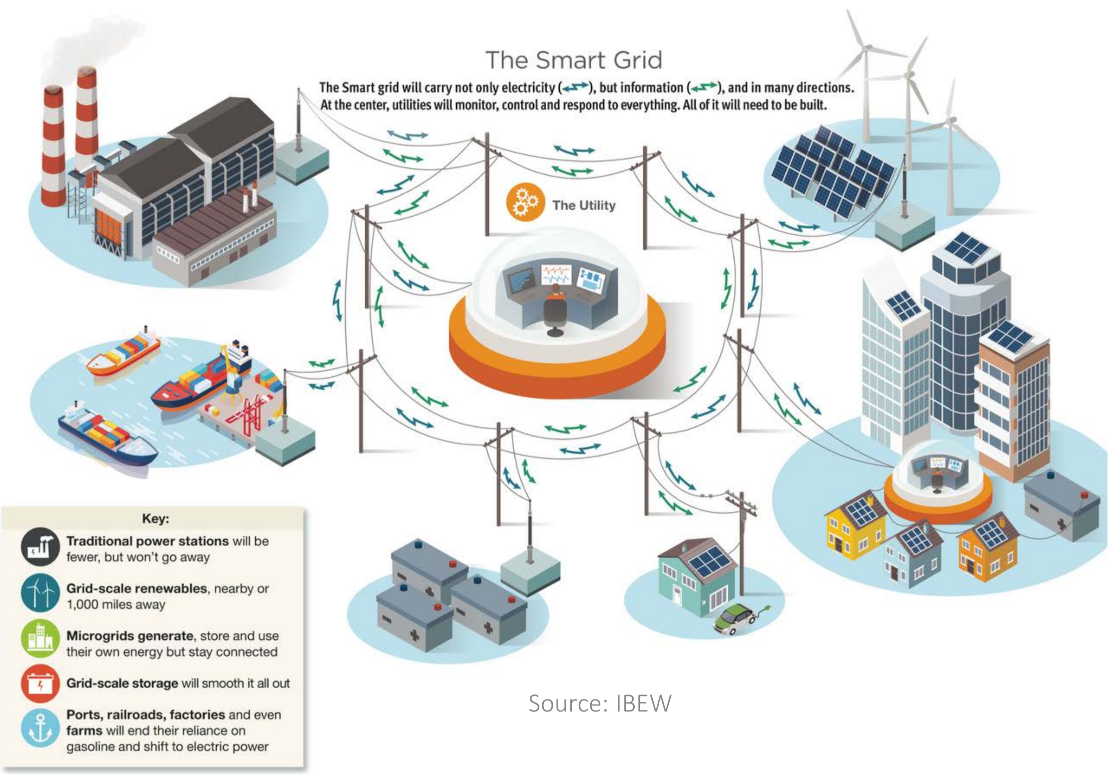
Original Power Grid

The North American power grid is the most complicated machine ever built, but it effectively has one job: bring power from more than 9,000 generators in a single direction to more than 150 million customers.

Source: IBEW

- **Centralized Generation**: Large, centralized power plants (coal, nuclear, gas) supply most electricity.
- **One-Way Power Flow**: Electricity flows from generators to customers.
- **Minimal Information Exchange**: Customers only receive delayed or aggregated data (e.g., monthly bills) from utilities with little control over their usage or costs.
- **Demand Treated as Fixed**: Demand is treated as fixed and predictable with generation dispatched to meet the demand. There is limited flexibility or responsiveness to changes in consumption patterns or generation capacity.

New Paradigm: Distributed Demand Dynamically Managed to Match Variable Supply



The Smart grid will carry not only electricity (⟷), but information (⟷), and in many directions. At the center, utilities will monitor, control and respond to everything. All of it will need to be built.

Traditional power stations will be fewer, but won't go away

Grid-scale renewables, nearby or 1,000 miles away

Microgrids generate, store and use their own energy but stay connected

Grid-scale storage will smooth it all out

Ports, railroads, factories and even **farms** will end their reliance on gasoline and shift to electric power

Source: IBEW

- **Distributed & Variable Generation**: Generation is increasingly decentralized, comprised of variable renewable sources like solar and wind which have the lowest marginal cost. Customers may also act as producers (prosumers) feeding energy back to the grid.

- **Bidirectional Power & Information Flow**: Electricity and data move dynamically in both directions between utilities and customers, enabling greater flexibility and resiliency.

- **Demand is Dynamically Managed**: Technologies like EVs, smart appliances, dynamic pricing, and demand response enable flexible energy use, while distributed energy resources and grid storage align demand with renewable supply.

Managing EVs
on the Grid

EVs are Unique Distributed Energy Resources

Distributed energy resources refer to a diverse group of devices and technologies that interface with the electricity system at the distribution level. Examples include distributed generation and storage and grid-interactive devices (including EVs and EV chargers), buildings, and microgrids.

EVs are like stationary storage…

…except they're not stationary and have a primary objective to provide mobility.

EVs are like any other appliance…

…except they're not just energy consumers. They can provide energy to the home or even the grid through bidirectional (vehicle-to-grid) charging.

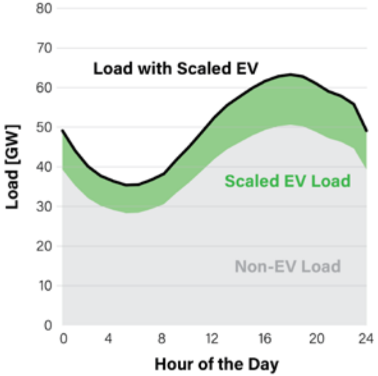
EVs are like solar panels…

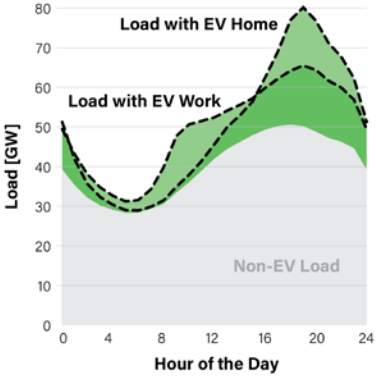
…except they can store energy and many of the benefits of EVs can be realized through managed charging (V1G) without bidirectional charging (V2G).

EVs are unique distributed energy resources!

EVs Can Be Flexibly Charged

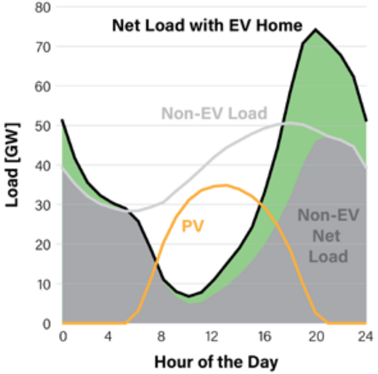
a) ASSUMPTION:
EV charging is often assumed to simply scale up electricity demand.

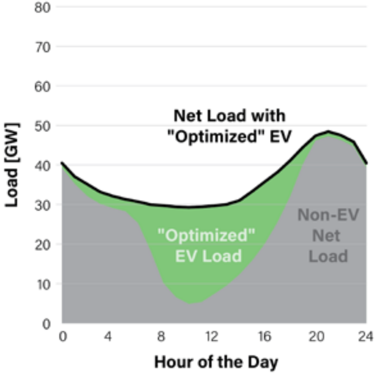




b) COMPLEXITY:
Future EV charging could change the shape of demand, depending on when and where charging occurs.

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.

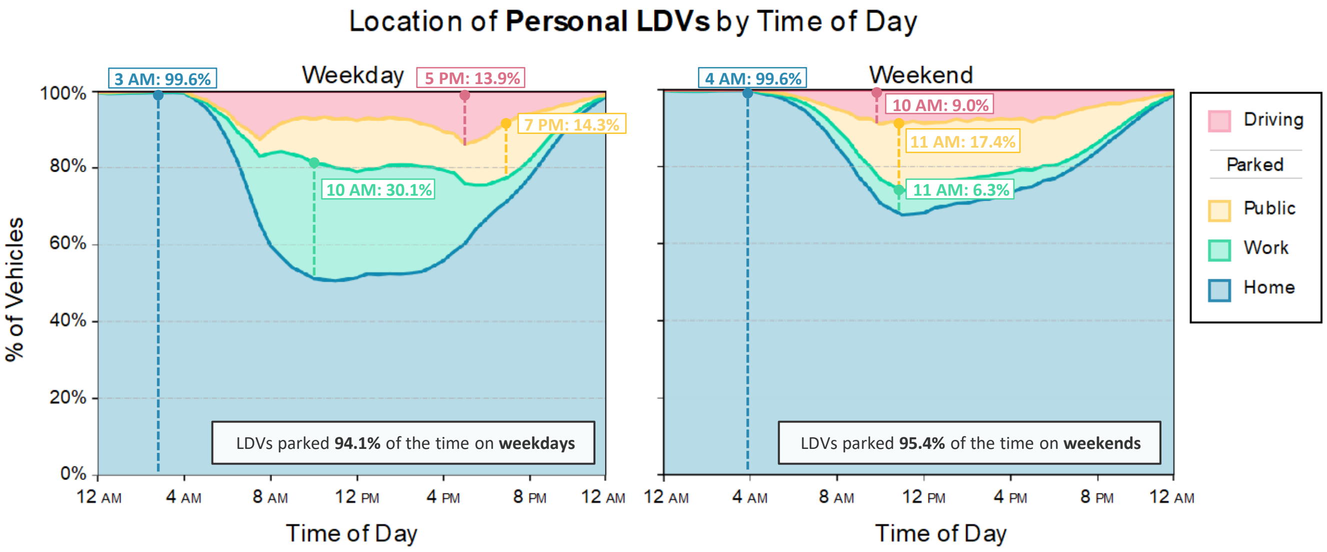
When, where, and how EVs charge will be as critical as how much electricity is demanded.

Source: Muratori & Mai (2020)

EVs are Parked Most of the Time

Analysis of 2017 National Household Travel Survey (NHTS) confirms that personal **LDVs are parked most of the day** and could potentially provide **EVMC services** with access to EVSE and proper incentives in-place.

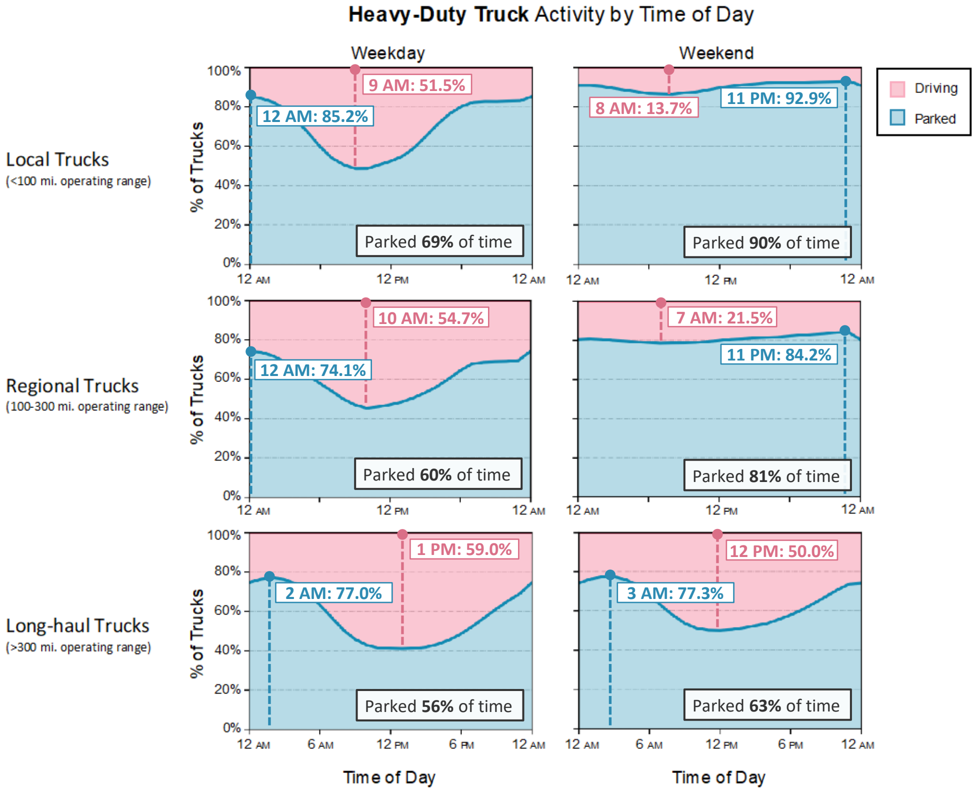
- **Weekdays:** Parked **94.1%** of the time (86.1%-99.6% depending on hour of day)
- **Weekends:** Parked **95.4%** of the time (91.0%-99.6% depending on hour of day)



EVs are Parked Most of the Time: **Even Heavy Trucks**

Analysis of Class 8 tractor telematics data[1] suggests that:

- **HD freight trucks are driven more than LDVs…**
- …however, still spend a **significant share of each day parked**, possibly providing EVMC services with access to EVSE and proper incentives in-place.
- **Weekdays**: Parked 56% (long-haul) to 69% (local) of the time.
- **Weekends**: Parked 63% (long-haul) to 90% (local) of the time.



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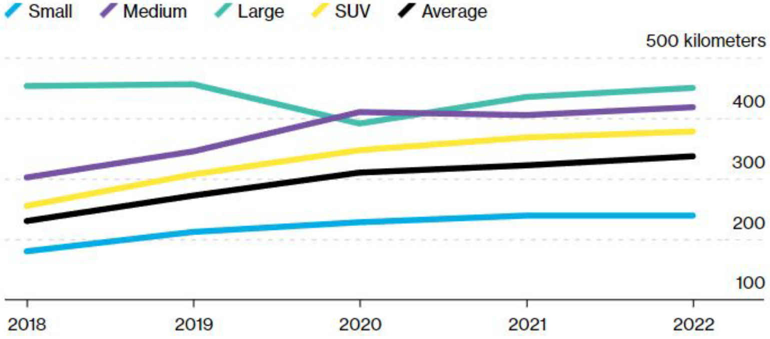
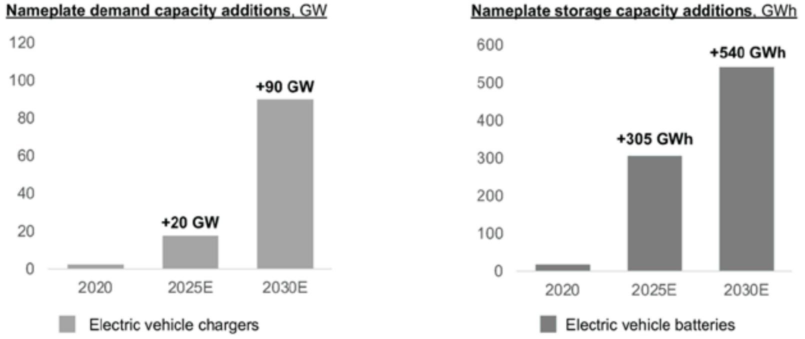
[1] Described in Borlaug et al. (2022)

EV Batteries are Oversized for Most Daily Travel


EV Driving Range Increasing 10% Per Year

Average EV range by segment

Source: BloombergNEF.
Note: Uses EPA-equivalent ranges. Data based on BEV models sold in China, Europe and the US. These three markets accounted for 93% of global EV sales in 2022.


Annual EV charger and EV battery capacity additions: Demand, Storage (2020-2030E)

Source: Downing et al. (2023)

In U.S., drivers average <40 miles (<64 km) per day…

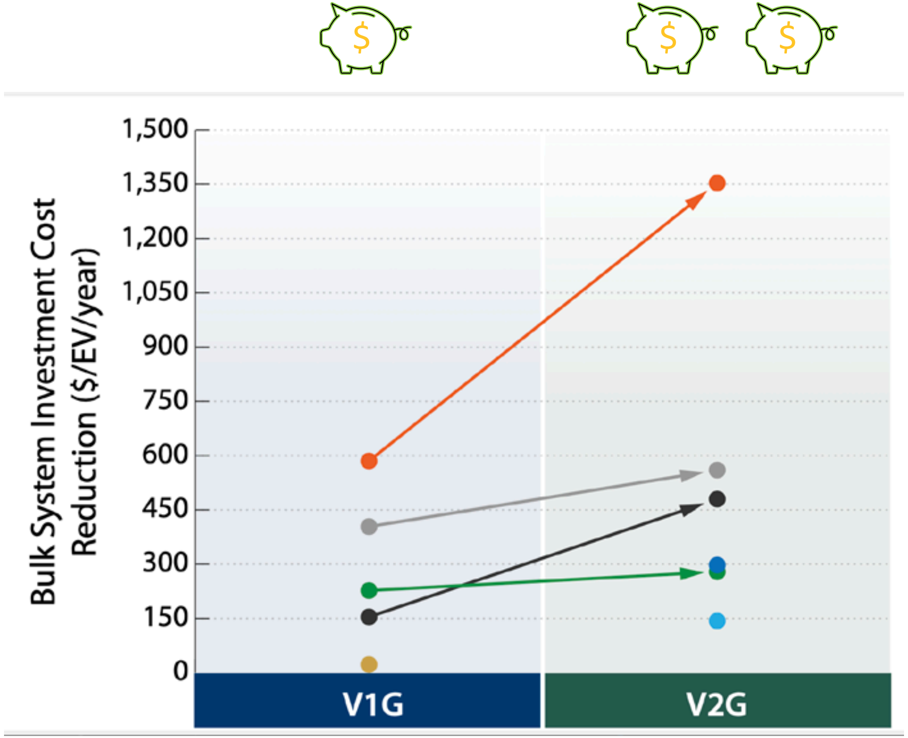
- 1-2 charge events per week with long-range EV
- Around 12 hours of 240V Level 2 charging per week (~7% of time)
- Around 55 hours of 120V Level 1 charging per week (~33% of time)

EVs can add significant storage capacity to the grid…

- U.S. battery storage capacity is growing rapidly, expected to exceed 30 GW (60-120 GWh) by end of 2024.
- At the same time, EV sales are growing rapidly and could significantly increase battery storage capacity on the grid if enabled (+90 GW, +540 GWh by 2030).

Bidirectional Charging (V2G) Can Provide Extra Savings

- **Managed charging (V1G)** is shown to consistently provide hundreds of dollars in investment cost savings per EV each year.
- **Bidirectional charging (V2G)** can lead to further cost savings; but the extent depends on system characteristics, EV adoption and willingness to participate, flexibility limitations, and enablement costs.
- Effective V1G and V2G programs recognize that **EVs are first-and-foremost vehicles** (i.e., primary purpose to provide mobility).

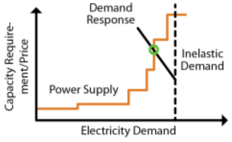


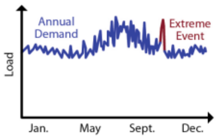
Source: Anwar et al. (2022)

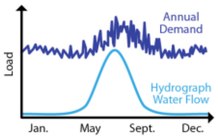
EVs Can Provide Multiple Benefits for the Grid

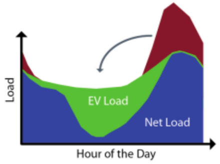
Smart electric vehicle-grid integration can provide flexibility – the ability of a power system to respond to change in demand and supply – by charging and discharging vehicle batteries to support grid planning and operations over multiple time-scales

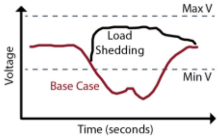
Power System Application	**Generation Capacity and Transmission/ Distribution Planning**	**Resilience To Extreme Events**	**Seasonal Planning (Hydro/Long-Term Storage Dispatch)**	**Commitment and Dispatch Decisions**	**Balancing and Power Quality**	**Support End Consumers**
Time scale	*Multi-year*	*Years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





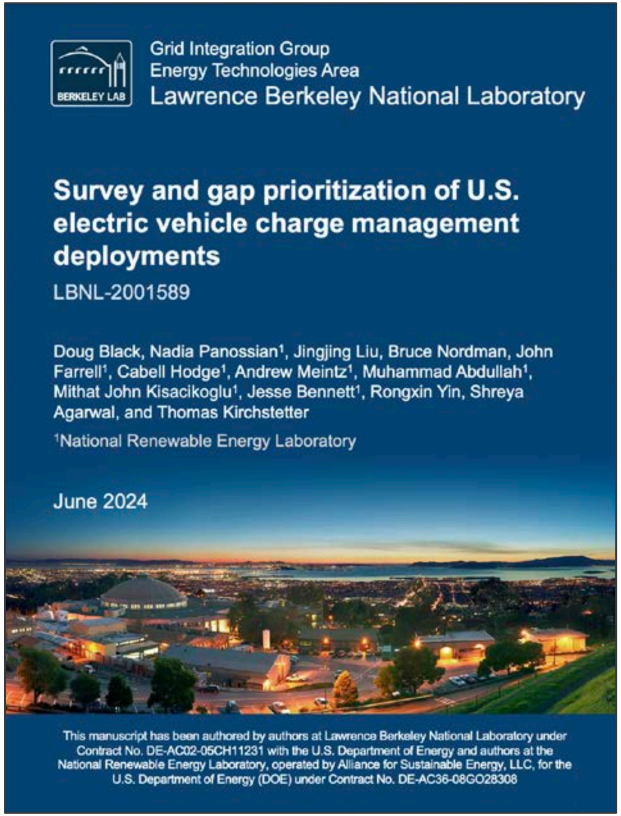






Source: Anwar et al. (2022)

Barriers to Managed EV Charging



BERKELEY LAB

Grid Integration Group
Energy Technologies Area
Lawrence Berkeley National Laboratory

Survey and gap prioritization of U.S. electric vehicle charge management deployments

LBNL-2001589

Doug Black, Nadia Panossian[1], Jingjing Liu, Bruce Nordman, John Farrell[1], Cabell Hodge[1], Andrew Meintz[1], Muhammad Abdullah[1], Mithat John Kisacikoglu[1], Jesse Bennett[1], Rongxin Yin, Shreya Agarwal, and Thomas Kirchstetter

[1]National Renewable Energy Laboratory

June 2024

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Black et al. (2024)

- **Coordination Challenges**: Limited integration of EV charging with other site loads (e.g., appliances or industrial systems) persists due to inconsistent communication protocols and insufficient site-level load visibility.
- **Fragmented Standards**: The absence of unified communication standards and certification processes hinders interoperability across utilities, EVs, and charging infrastructure, slowing widespread adoption.
- **Economic Value Uncertainty**: Despite broad recognition of the value of managed EV charging, detailed quantitative estimates and tools to assess its financial benefits are often lacking.
- **Policy and Regulatory Gaps**: The lack of clear policies or incentives for managed charging reduces motivation for investment and participation by utilities and private stakeholders.

Managing Tradeoffs: Bulk and Distribution Systems

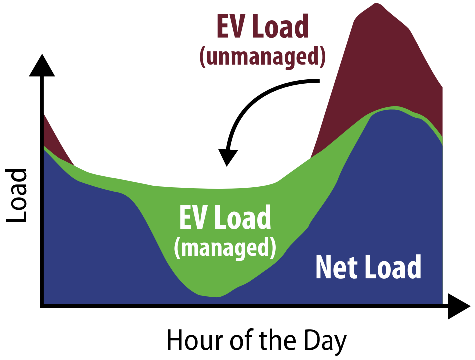
Bulk power systems can leverage managed EV charging to balance large-scale supply-demand mismatches…

…but this may inadvertently cause **distribution** overloads if not coordinated with local systems.

The optimal strategy involves a **coordinated and multi-layered approach** that balances the needs of both the bulk and distribution systems.

Unlocking EV Managed Charging: **Worth the Effort**

Value of Electric Vehicle Managed Charging



Managed EV charging can support grid planning and operations

Reduce Bulk Power Systems Investment Costs
20–1350 $/EV/year

Reduce Bulk Power Systems Operating Costs
15–360 $/EV/year

Reduce Renewable Energy Curtailment
23–2400 kWh/EV/year

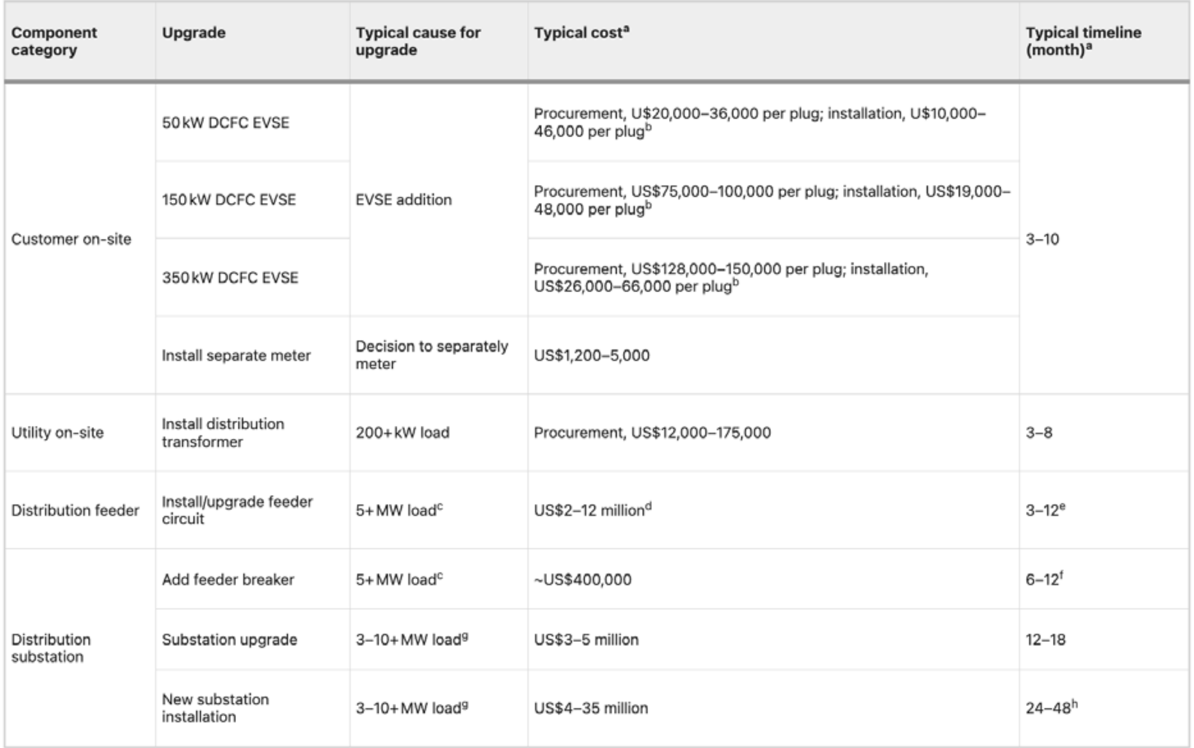
Reduce Distribution Systems Investment Costs
5–1090 $/EV/year

Increase Distribution Systems EV Hosting Capacity
30–450%

Source: Anwar et al. (2022)

Deploying EV Infrastructure on the Grid

EV Infrastructure Deployment Costs & Timelines



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]

Source: Borlaug et al. (2021)

Distribution system upgrades are expensive and can take several years to complete, creating a significant bottleneck for widespread and rapid EV charging infrastructure deployment.

[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.

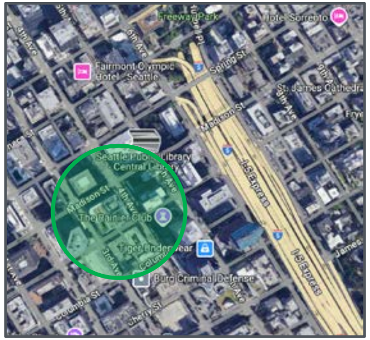
Some EV Demands are Spatially Flexible

Spatially flexible EV charging demands can be met by strategically **installing EVSE in locations with existing grid capacity**, reducing the need for costly upgrades.

Home = No spatial flexibility

Depot = No spatial flexibility

Corridor DCFC = High spatial flexibility

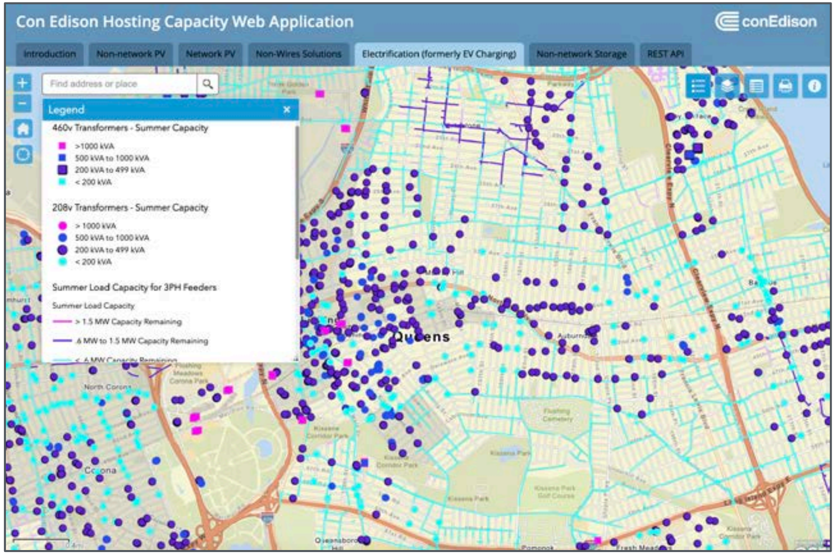


Community DCFC = High spatial flexibility

Best Practice: Utility Hosting Capacity Maps

Utility EV hosting capacity maps can help developers identify areas capable of supporting new EV charging infrastructure deployments without costly and time-consuming grid upgrades. Best practices for EV planning include:

- **Granular Load Data**: Shows existing distribution transformer, feeder, and/or substation loading levels.
- **Location-Specific Constraints**: Highlights voltage limits, thermal constraints, and the remaining hosting capacities of grid infrastructure.
- **Frequently updated**: Ensures the maps remain accurate and reflect the latest grid conditions.

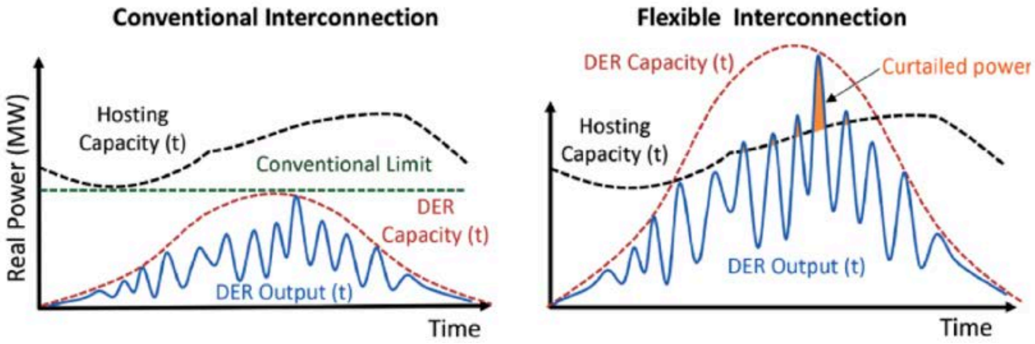


ABOVE: Con Edison "Electrification Map". Atlas of U.S. distribution utility hosting capacity maps: https://www.energy.gov/eere/us-atlas-electric-distribution-system-hosting-capacity-maps

Flexible Grid Connections

Flexible grid connections improve distribution system utilization and speed up EV infrastructure deployment timelines while ensuring the grid is not overloaded. It involves:

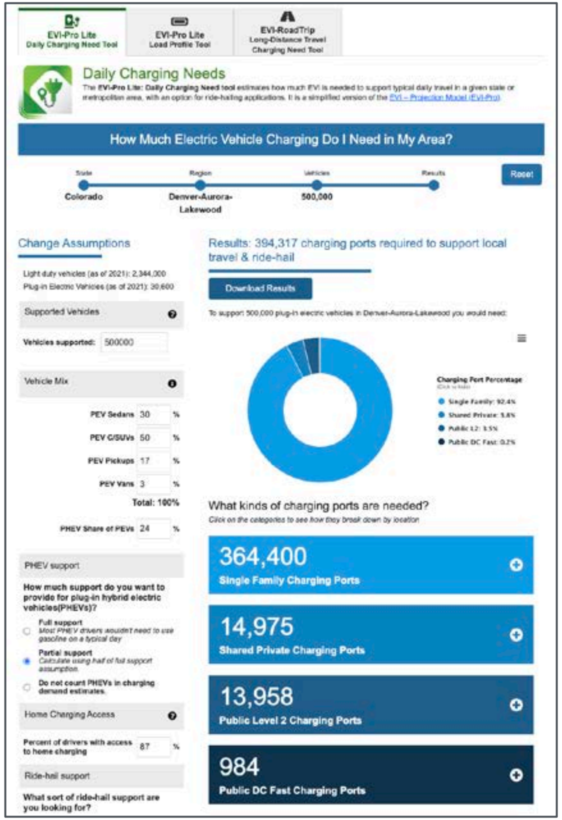
- Managing grid loads through V1G or distributed energy resources to ensure that they are **within distribution system hosting capacity limits**.
- At the same time, **upgrading the grid** with high certainty that demand will be realized.



Source: Yu & Martini (2024)

Publicly Accessible Planning Tools

- **NREL Tools**
  - **EVI-Pro Lite**: Interactive web tool for estimating regional charging needs and associated electricity demands based on user-defined scenarios.
  - **EVI-LOCATE**: Interactive web tool for developing comprehensive EV station deployment plans.
  - **EVI-FAST**: Financial analysis tool for EV charging infrastructure.
- **Non-NREL Tools**
  - **AFDC Station Locator**: Displays publicly accessible alternative fueling stations in the United States, Canada, and soon-to-be Mexico.
  - **EPRI eRoadMap**: Mapping tool that estimates the power and energy needs for electrifying transportation at the local level.
  - **IEA EV Charging & Grid Integration Tool**: Generates EV load profiles for different vehicle classes and charging use cases.



Daily Charging Needs

The **EVI-Pro Lite: Daily Charging Need** tool estimates how much EVI is needed to support typical daily travel in a given state or metropolitan area, with an option for ride-hailing applications. It is a simplified version of the EVI – Projection Model (EVI-Pro).

How Much Electric Vehicle Charging Do I Need in My Area?

State: Colorado
Region: Denver-Aurora-Lakewood
Vehicles: 500,000
Results

Change Assumptions

Light duty vehicles (as of 2021): 2,344,000
Plug-in Electric Vehicles (as of 2021): 30,600

Supported Vehicles

Vehicles supported: 500000

Vehicle Mix

PEV Sedans 30 %
PEV C/SUVs 50 %
PEV Pickups 17 %
PEV Vans 3 %
Total: 100%

PHEV Share of PEVs 24 %

PHEV support

How much support do you want to provide for plug-in hybrid electric vehicles(PHEVs)?

○ **Full support** *Most PHEV drivers wouldn't need to use gasoline on a typical day*
● **Partial support** *Calculate using half of full support assumption*
○ **Do not count PHEVs in charging demand estimates.**

Home Charging Access

Percent of drivers with access to home charging 87 %

Ride-hail support

What sort of ride-hail support are you looking for?

Results: 394,317 charging ports required to support local travel & ride-hail

To support 500,000 plug-in electric vehicles in Denver-Aurora-Lakewood you would need:

What kinds of charging ports are needed?

Click on the categories to see how they break down by location

364,400 Single Family Charging Ports
14,975 Shared Private Charging Ports
13,958 Public Level 2 Charging Ports
984 Public DC Fast Charging Ports

https://afdc.energy.gov/evi-x-toolbox#/evi-pro-ports

Conclusion

Summary

- Transportation and electricity systems were historically distinct and unconnected.
- The rise of EVs changes this dynamic, as they are expected to be a major driver of electricity demand growth.
- EV demands are often flexible–both spatially and/or temporally.
- Managed EV charging can shift EV demands temporally.
- Capacity-aware siting ensures EV infrastructure is deployed in locations that minimize disruption and costly upgrades to the grid.
- Beyond transportation, the power sector is undergoing a major transition to a more distributed and interconnected system, driven by growth in renewables.
- With proper planning, transportation electrification and grid decarbonization can be mutually beneficial, producing a highly integrated, low cost, and sustainable energy system.

Thank You!

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Brennan Borlaug,
Senior Research Analyst,
National Renewable Energy Laboratory
brennan.borlaug@nrel.gov

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