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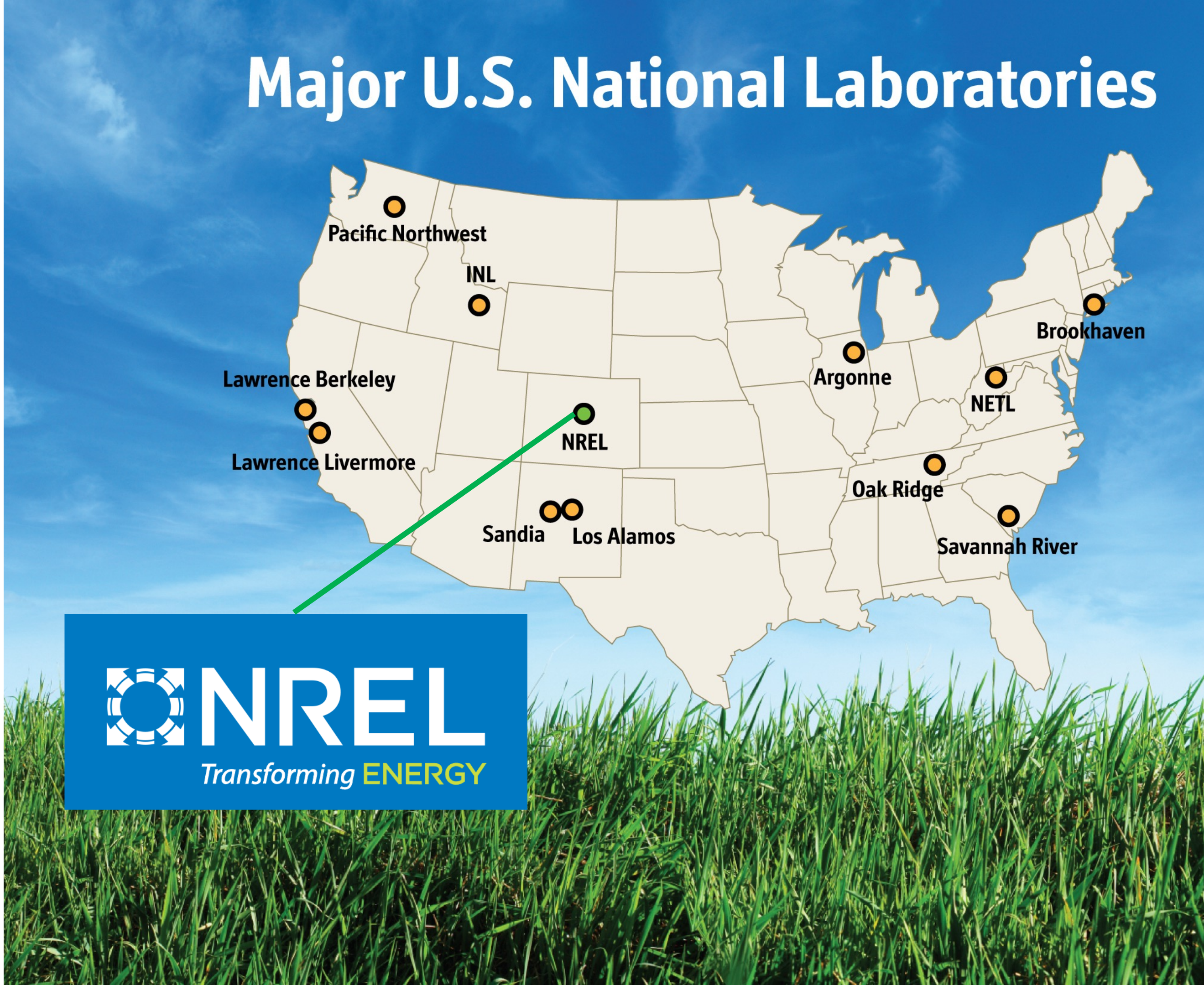
Electric Transportation and Distribution Infrastructure: a Heavy-Duty Vehicle Deep Dive

Matteo Muratori and **Brennan Borlaug**

ESIG 2021 FALL TECHNICAL WORKSHOP
October 26th, 2021

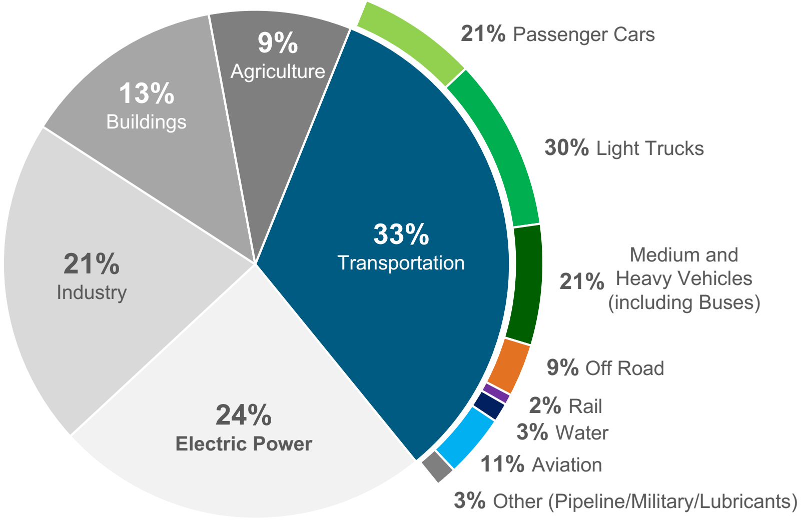
U.S. DOE National Lab System



Commercial Vehicles: the Largest Slice after LDV

- Medium and heavy-duty vehicles **second largest source of transportation GHG emissions** (~21% of total)
- Current MHDVs are a **major source of local air pollutants** that negatively impact urban air quality and human health, and **disproportionally affecting disadvantaged communities** located near freight corridors, ports and distribution centers
- **Zero emissions vehicles** (BEV and FCEV) offer a viable decarbonization pathway.
    - While commercial deployment is still limited there are growing opportunities as technology has advanced greatly over the last decade (see *Rise of EVs*)

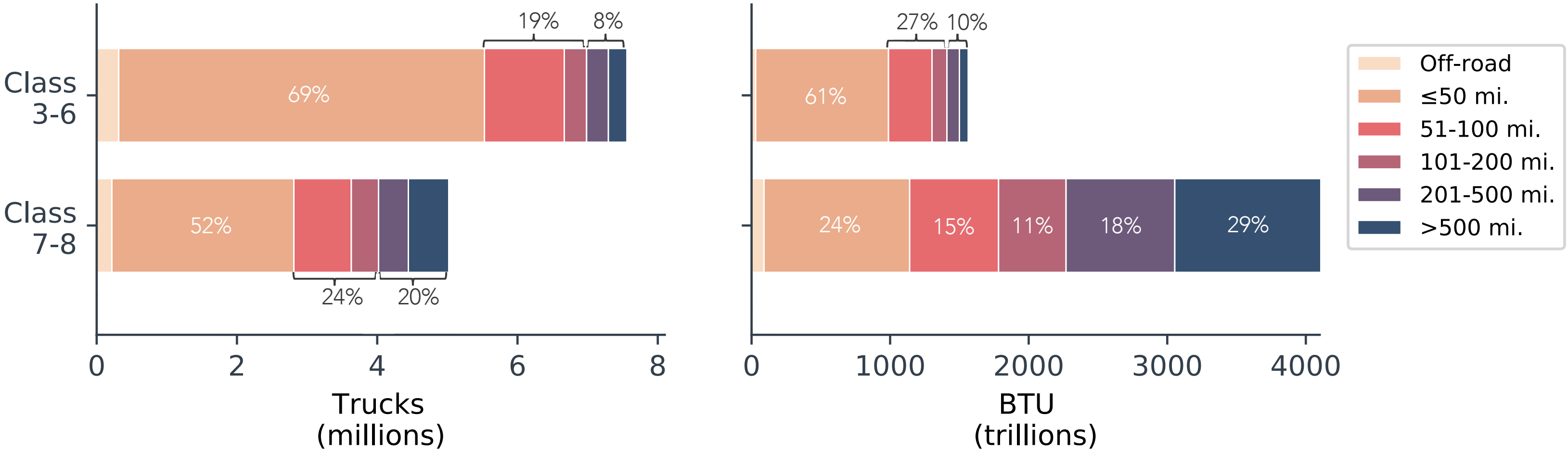
2019 U.S. GHG Emissions



Aviation and water include emissions from international bunker fuels. Fractions may not add up to 100% due to rounding.

Data Source: EPA GHG Inventories

Not all Trucks are the Same, nor Used the Same Way!!

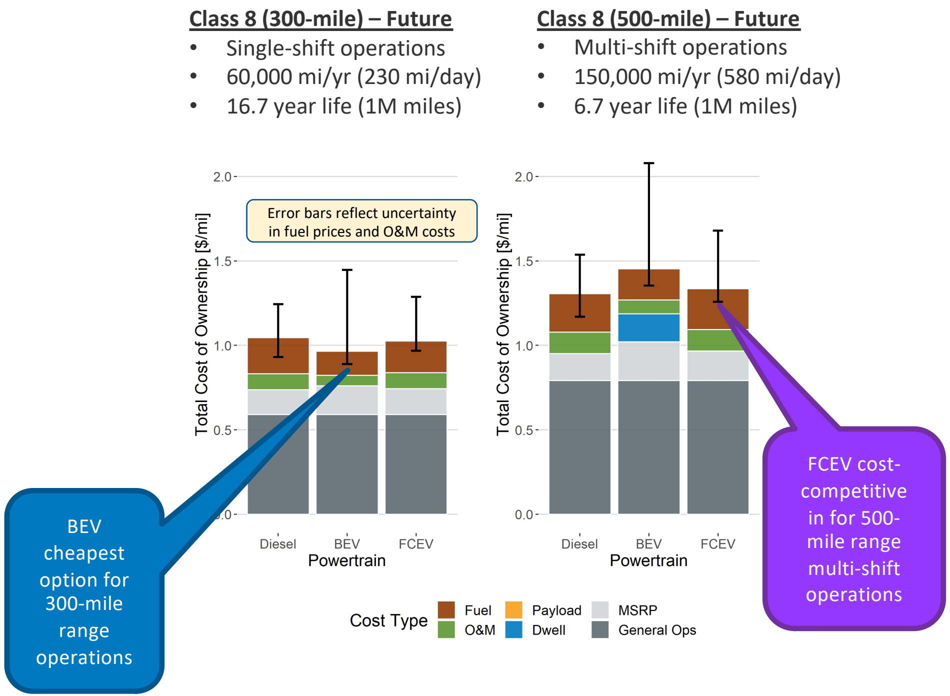


Source: Borlaug et al. 2021. Heavy-duty truck electrification and the impacts of depot charging on electricity distribution systems. Nature Energy.

- ~10% of HD trucks have an operating range of 500 miles or more, whereas **~70% operate within 100 miles**.
- Although the total energy consumption is skewed towards long-range operations, **~40% of energy is used by trucks that operate within 100 miles**.
- Recent industry trends (e.g., the rise of e-commerce and low driver retention) produced a shift away from interregional and national hauls in favor of decentralized hub-and-spoke distribution models, which culminated in a **37% decrease in the average length of haul from 2000 to 2018** (not factored into Fig. 1).

Total Cost of Ownership: Multiple Solutions Needed and Cost-Parity in Sight

- Adoption driven by economics: Once tipping points are hit r**apid scale-up expected**
- **BEVs,** can be cost-competitive over the next decade, provide a solution for most buses and short-haul operations, ~ 60% of truck energy use
- But long-range, charging logistics, and extreme fast charging remain technological uncertainties: **centrally-fueled H_2 FCEVs** could support some use-cases
- **Biofuels** can also help address legacy vehicles, fleet turnover can take decades



Source: Hunter et al. 2021. Spatial and Temporal Analysis of the Total Cost of Ownership for Class 8 Tractors and Class 4 Parcel Delivery Trucks. NREL/TP-5400-71796

Deep Dive: Charging Behavior & Grid Impacts of Short-Haul Electric Class 8 Semi Trucks

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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:

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

Data:

https://data.nrel.gov/submissions/162

Code:

https://github.com/NREL/hdev-depot-charging-2021

Fleet Operating Data

Fleet DNA

Considered 14 Class 7/8 tractor fleets from nine different companies in Fleet DNA database:

- 2,105 operating-days (VMT > 10 mi.)

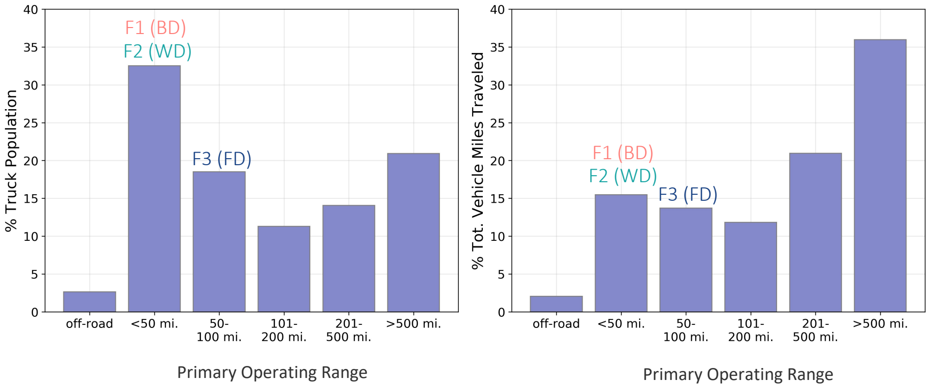
Supplementary Table 1. Summary of short-haul delivery fleets studied

Fleet ID	Vocation	Location	Time Period	Weight Class	Powertrain	# Vehicles	Vehicle Days	Operating Range
1	Beverage delivery	San Francisco, CA	Oct.–Nov. 2012	8	Parallel hybrid/ conventional diesel	6	84	≤50 miles
2	Warehouse delivery	Los Angeles, CA	Aug. 2012	7	Conv.	9	111	≤50 miles
3	Food delivery	Denver, CO	Dec. 2014–Jan. 2015; Apr.–May 2015	8	Conv.	21	325	≤100 miles

Selected fleets fit **short-haul trucking segment**:

- Fleet 1 and Fleet 2 vehicles travel **20,000 – 30,000 miles per year** and operate within 50 mi. of depot – **local delivery operations**
- Fleet 3 vehicles travel **30,000 – 40,000 miles per year** and typically operate within 100 mi. of depot – **local/regional delivery operation**

2002 VIUS[9] Operations Distributions – Class 7/8 Tractors



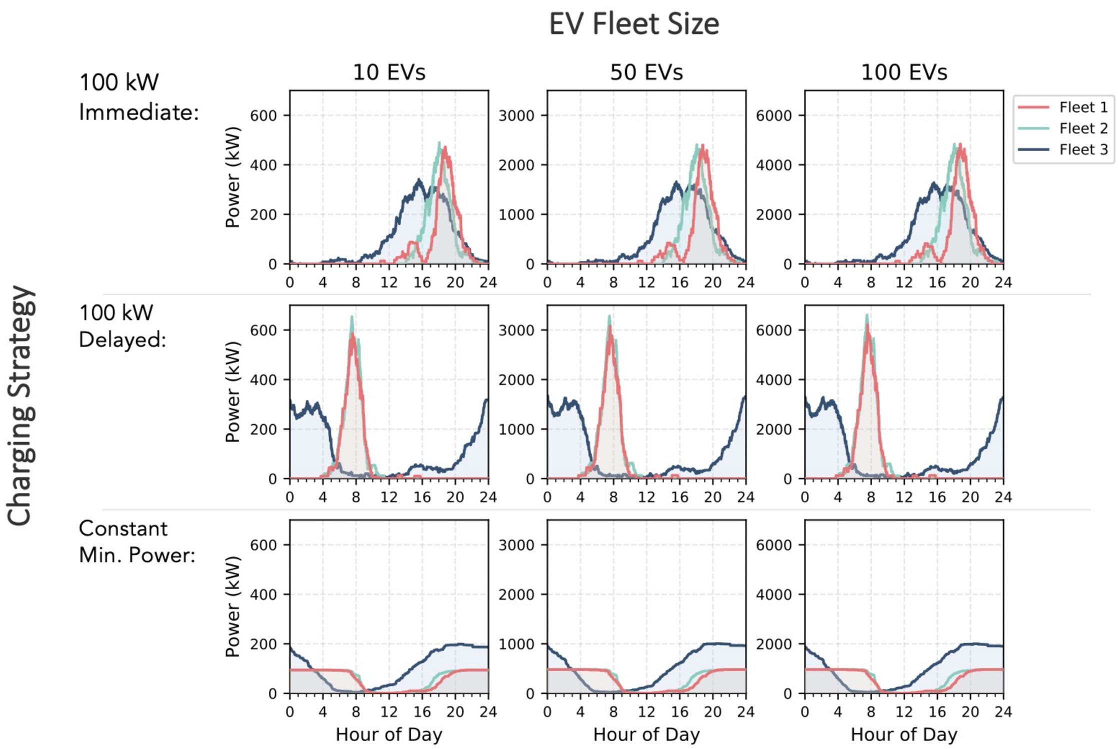
Insight 1: Limited Daily VMT and Abundant Charging Opportunity

- For Fleet 1 and Fleet 2, the **max. daily driving distance** is within 200 mi. while for Fleet 3, 89% of vehicle days are <300 VMT and 99% <500 VMT.

- **All fleets have ample opportunity for depot charging**, averaging 14 hours of downtime per day.
  - 74% of days have >12 hours and 96% have >8 hours of downtime.

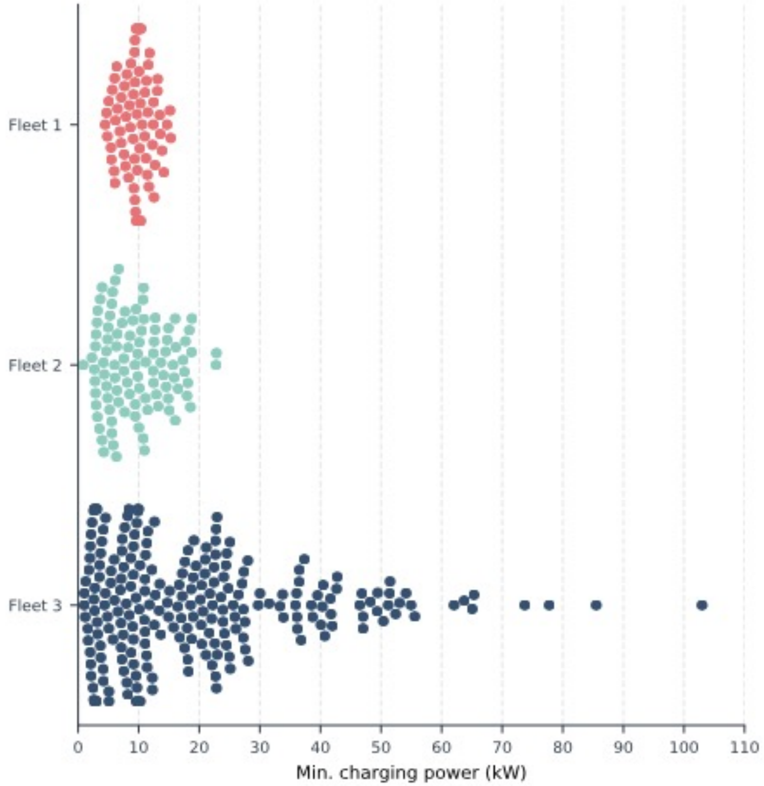
Insight 2: Multiple Charging Options

Managed Charging Greatly Reduces Peak



- With **unmanaged charging** (“100 kW immediate”), peak demand coincides with the typical system-level peak period (5 pm – 9 pm)
- Through **scheduled charging** (“100 kW delayed”), peak demand may be shifted 8-12 hours throughout the course of the night
- With **intelligent modulation** (”Constant min. power”), peak demand can be greatly reduced.
- **All charging loads (15-mins) freely available to download [LINK]**

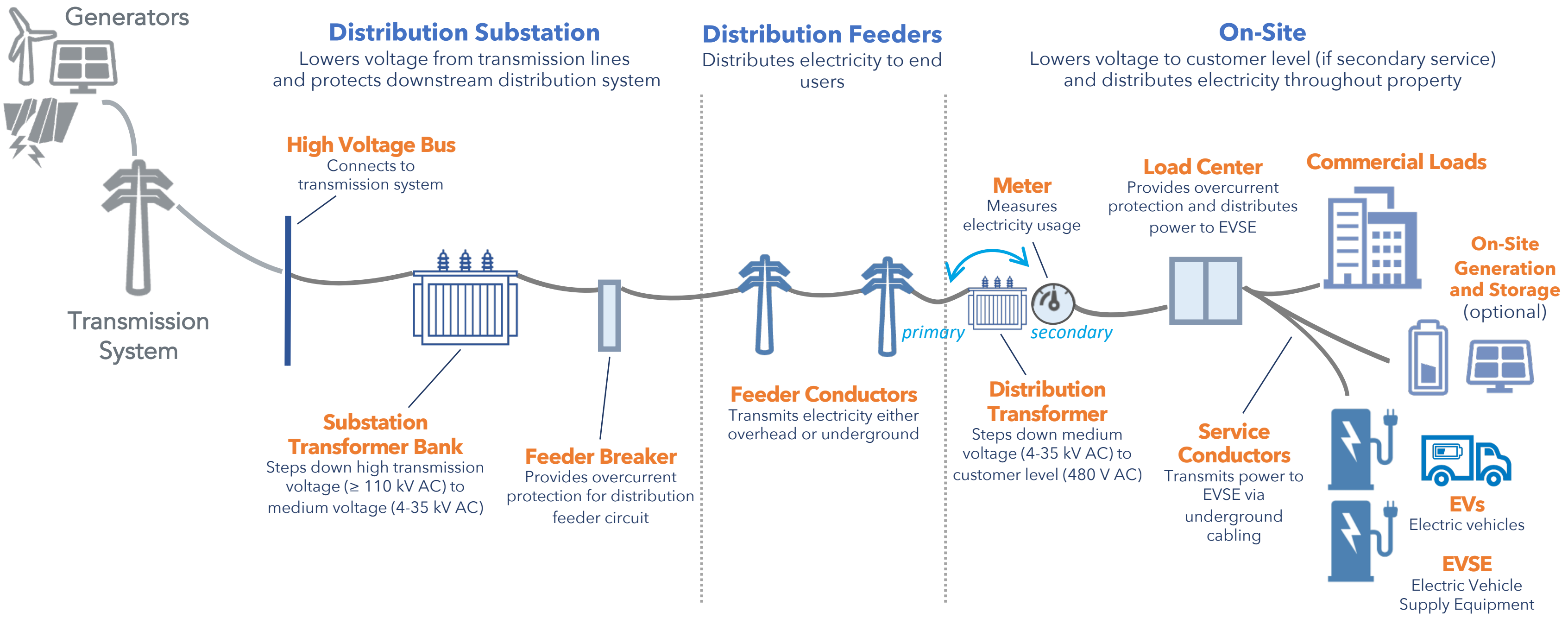
Insight 3: Charging Infrastructure Requirements



- **Financial benefit to low-power charging**:
  - For **utilities**, it produces lower peak demand and a smooth and predictable load profile
  - **Fleet managers** save on the capital costs of EVSE (purchase and installation of 50 kW 62–81% cheaper than 350kW).
  - In addition, fleets can save on electricity costs from **reduced demand charges**, if present.

- We found that **16, 23 and 103kW per vehicle** charging power levels were sufficient for electric trucks to fully recharge when off shift, all **<u>much lower than is generally assumed.</u>**
  - Depot-level peak < than sum of individual vehicles charging due to the asynchronous charging

Distribution Network Scheme



Basic diagram of **secondary electrical distribution system**. Larger commercial customers may elect to own their own transformer and connect directly to the medium-voltage **primary network**, in which case the meter would be located on the opposite side of the distribution transformer

Summarizing the Typical Cause, Cost, and Timeline for Distribution System 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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Approach: Review of 10 public data and literature sources, supplemented by internal expert elicitation by industry co-authors

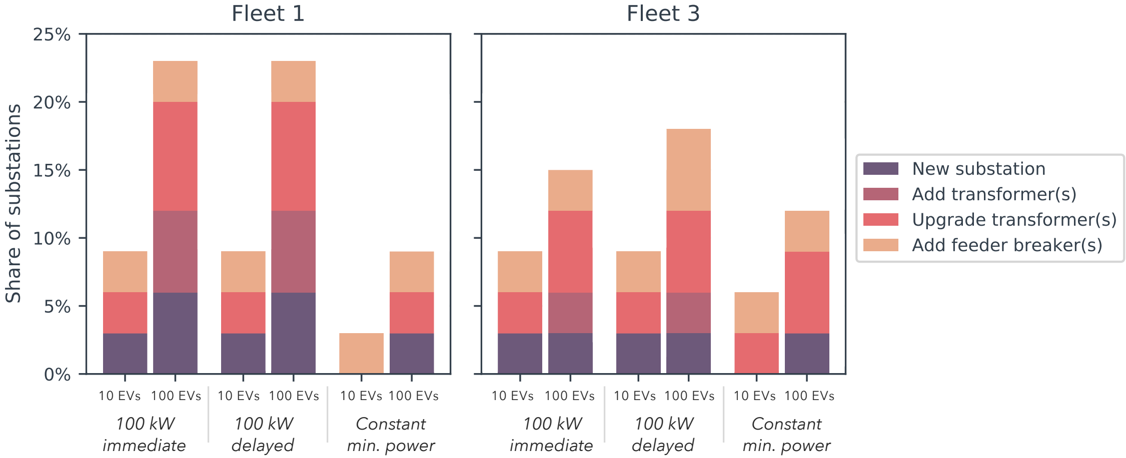
Table 1 | Summary of electricity distribution system upgrades for depot charging

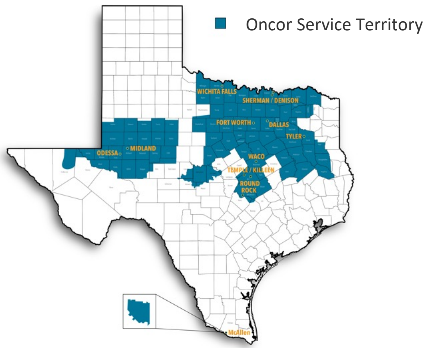
Component category	Upgrade	Typical cause for upgrade	Typical cost[a]	Typical timeline (month)[a]
Customer on-site	50 kW DCFC EVSE	EVSE addition	Procurement, U$20,000–36,000 per plug; installation, U$10,000–46,000 per plug[b]	3–10
	150 kW DCFC EVSE		Procurement, US$75,000–100,000 per plug; installation, 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.

Insight 4: Impact on Distribution Systems

- **Oncor conducted a substation load integration study**, for both average and peak demand days for 36 substations (close proximity to existing warehouse clusters).
- Magnitude of peak charging demand more predictive of substation upgrades than timing
- Majority (~80%) of substations could supply 100 EVs charging at 100 kW without upgrades; Nearly all (~90%) could supply 100 EVs charging at minimum power levels





Summary of Insights

- **A lot of heavy trucks drive fairly low daily mileage and offer multiple charging options.**
- Certain short-haul operations may be **electrifiable with low-power depot-based EVSE** (light-duty power levels).
- **Depot charging provides load flexibility** (from long predictable dwell times), enabling peak demand to be reduced through **managed charging strategies**.
- **Distribution system upgrades (especially substations) are costly**, and perhaps just as important, **time consuming**.
- Distribution substations may be more capable of handling near-term heavy-duty depot electrification than is generally assumed, **especially with "right-sized" EVSE**.
- **Tons of variability** - fleet operating schedules and charging requirements vary; available grid capacity depends on location and time of day. Fleet operators considering electrification should engage early with their local utility to establish a feasible power delivery schedule.

Concluding Remarks

Emerging topic:

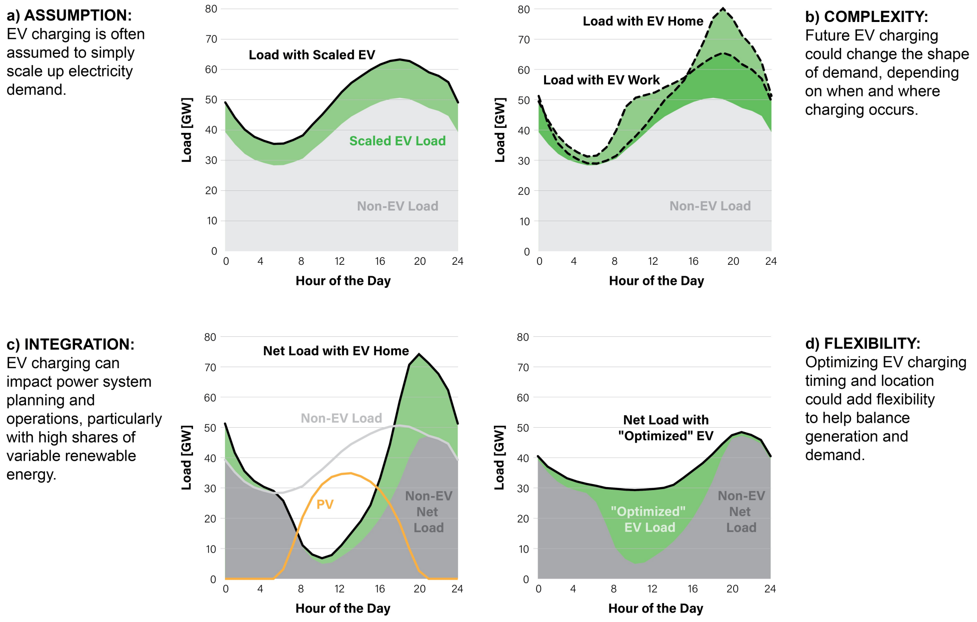
Vehicle electrification is rapidly transforming the transportation-energy landscape across multiple modes and with cross-sectoral impacts.

Need:

More nuanced demand-side modeling to assess **EV charging needs and flexibility**

EV integration opportunities: **solutions for synergistic improvement** of the efficiency and economics of electromobility and evolving electric systems

When **and** ***where*** **EV charging occurs will be as important as** ***how much*** **electricity is needed**



Source: Muratori and Mai, 2021. The Shape of Electrified Transportation. Env. Research Letter.

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Questions?

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This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding was provided by the U.S. DOE Vehicle Technologies Office. The views and opinions of the authors expressed herein do not necessarily state or reflect those of the U.S. Government or any agency thereof. Neither the U.S. Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. The authors are appreciative of the continuous support provided by the DOE over the years and would particularly like to thank program managers Jake Ward and Heather Croteau for their guidance and feedback on this project. We would also like to acknowledge Eric Miller (NREL) and the NREL's FleetDNA team for their help in accessing and working with the vehicle operating data. Adam Fowler and Ron Shipman (Oncor) both played notable roles in the execution of the case study substation load analysis. Finally, we would like to thank Andrew Meintz (NREL), Patrick Bean (Tesla) and Myles Neumann (Tesla) for useful comments and insights.

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Supplemental

Current Momentum for Heavy-Duty Electrification

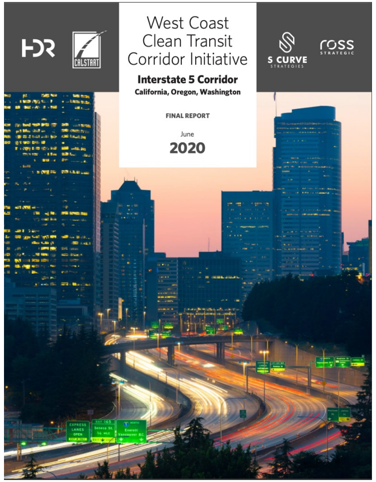
Recent policy momentum for heavy-duty truck electrification:

- In June 2020, **CARB adopted Advanced Clean Trucks (ACT) regulation** requiring the sale of zero-emission heavy-duty trucks starting in 2024 and requiring **40% ZEV truck tractor sales by 2035**[6].
    - This year (2021), New Jersey announced plans to become the first state to adopt CA's mandate
- In June 2020, electric utilities in California, Washington, and Oregon provide a **roadmap for freight and delivery EV charging infrastructure** along I-5 and adjoining highways[7].
- In July 2020, Governors from 15 states (+ Washington, D.C.) signed **joint MOU committing to 100% of M/HDV sales be ZEVs by 2050** with an interim target of 30% ZEV sales by 2030[8].

CALIFORNIA
AIR RESOURCES BOARD

California takes bold step to reduce truck pollution

First-of-its-kind requirement for electric trucks will help communities hardest hit by air pollution



MONEY

Tesla stock closes at record highs on electric Semi news

Dalvin Brown USA TODAY
Published 9:43 a.m. ET Jun. 11, 2020 | Updated 4:19 p.m. ET Jun. 16, 2020

RESEARCH SPOTLIGHT

WoodMac: 54,000 Electric Trucks on US Roads by 2025

That's a 27-fold increase over today's fleet, and the expansion of charging infrastructure will be nearly as dramatic.

KELLY MCCOY | AUGUST 11, 2020

2021: The Year the Rubber Meets the Road for Electric Trucks

January 13, 2021 | By Jessie Lund

HEAVY-DUTY

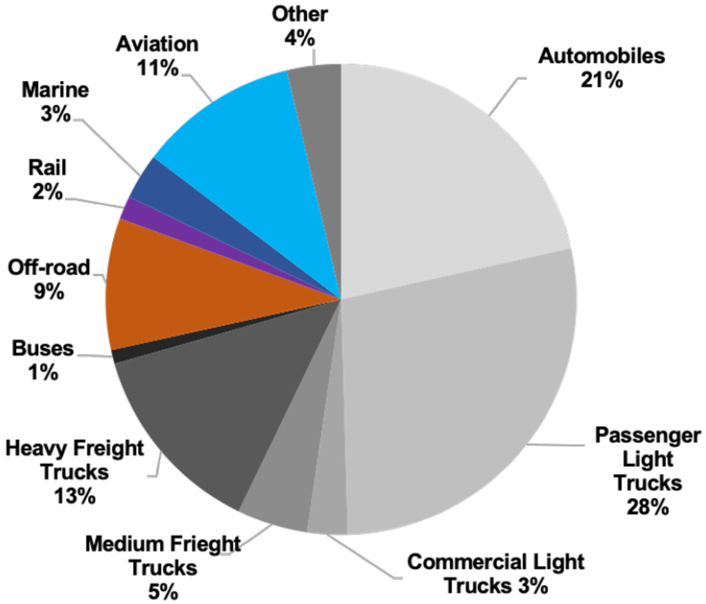
Daimler Trucks N.A. Opens Order Books For All-Electric Freightliner ECascadia, EM2

By Jason Morgan
on Apr 6, 2021

[6] California Air Resources Board – CARB, June 25, 2020, https://ww2.arb.ca.gov/news/california-takes-bold-step-reduce-truck-pollution
[7] West Coast Clean Transit Corridor Initiative Study, June 17, 2020, https://www.westcoastcleantransit.com/resources/WestCoastCleanTransitNewsRelease-Website.pdf
[8] New York State, Gov. Cuomo, July 14, 2020, https://www.governor.ny.gov/news/governor-cuomo-announces-new-york-and-14-states-and-dc-ramp-electrification-buses-and-trucks

Medium- and Heavy-Duty Vehicle (MHDV) Breakdown

2019 U.S. Transportation Energy Use (31.4 Quads)



Marine and Aviation include international energy use. Fractions may not add up to 100% due to rounding.

- **Commercial light trucks** (3%, <10,000 lbs.) aligned with light-duty vehicle efforts
- **Buses** (1%) are being targeted for rapid battery electrification
- **Medium** (5%) and **heavy-duty** (13%) are the largest pieces and while commercial deployment is still limited there are already cost-effective applications and growing opportunities for zero emissions vehicles
    - ~3.6M registered Class-8 trucks in the U.S., consuming ~27B gallons of diesel/year

➢ **Multiple solutions needed** for various MHDV applications

Three Charging Strategies

a) 100 kW, Immediate

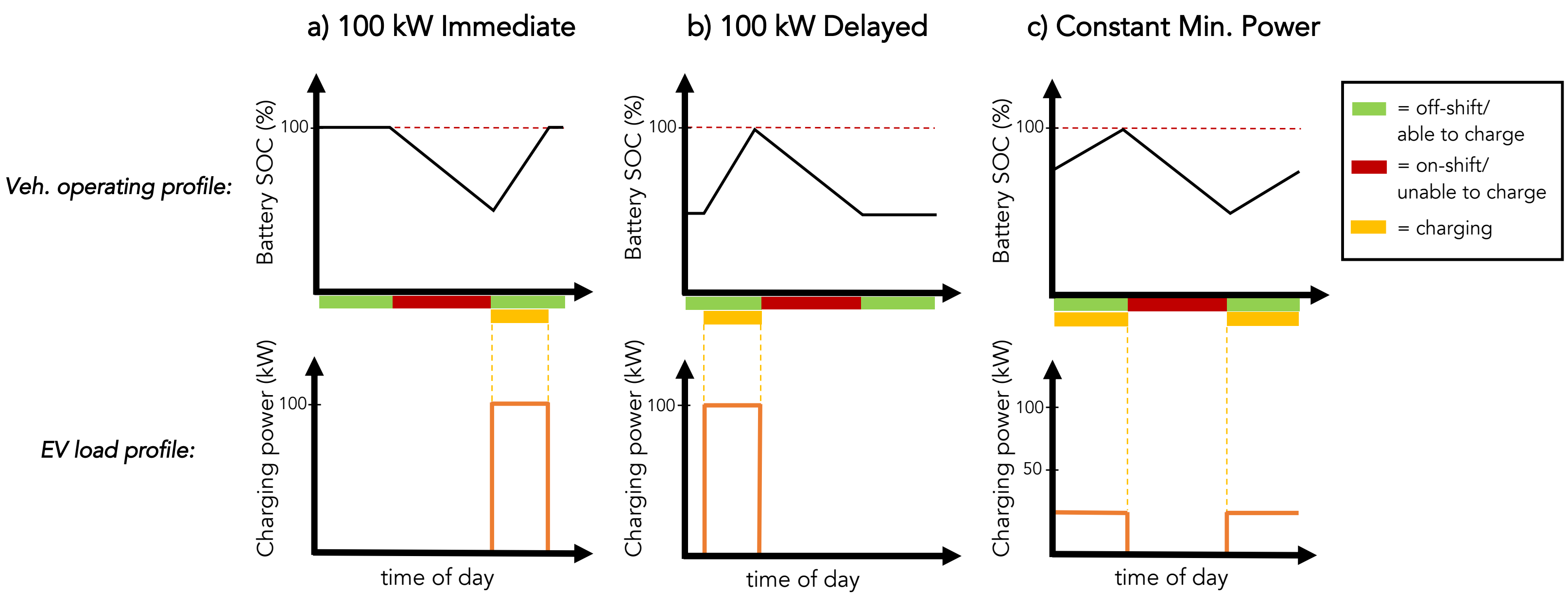
Unmanaged charging case where 100 kW charging is performed “as soon as possible” (*i.e.*, 15 min. after designated shift period) and continues until either (1) all depleted energy is recharged; or (2) the next shift starts.

b) 100 kW, Delayed

100 kW charging is performed “as late as possible” beginning at either (1) the latest possible time to fully recharge all depleted energy prior to the next designated shift period; or (2) immediately in the case where there is not enough time to fully recharge depleted energy prior to the next shift.

c) Constant, Min Power

Charging is performed whenever a vehicle is available (to charge) at the lowest possible rate to fully recharge the day’s depleted energy. This strategy aims to reduce each individual vehicle’s peak demand (though not necessarily the fleet’s).



Peak Depot Charging Loads

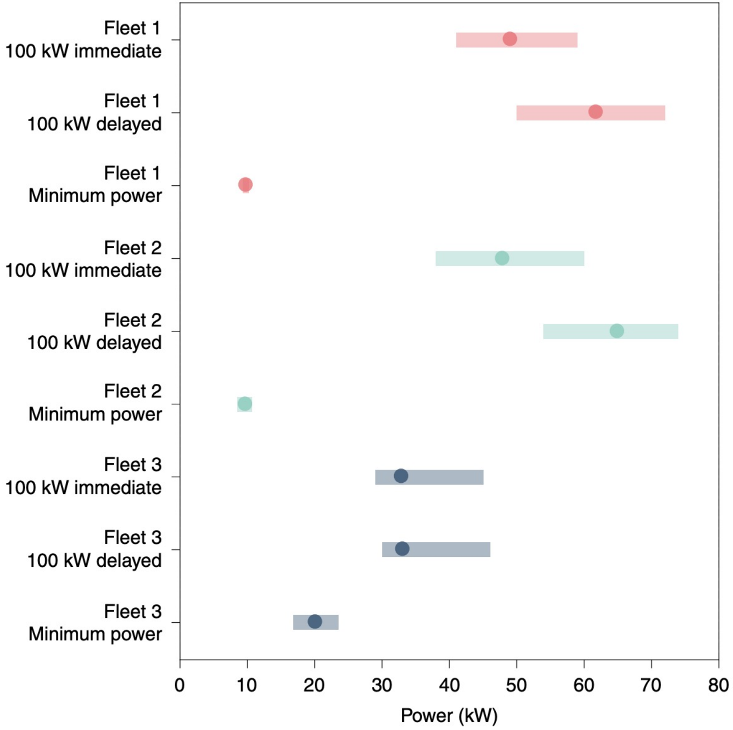


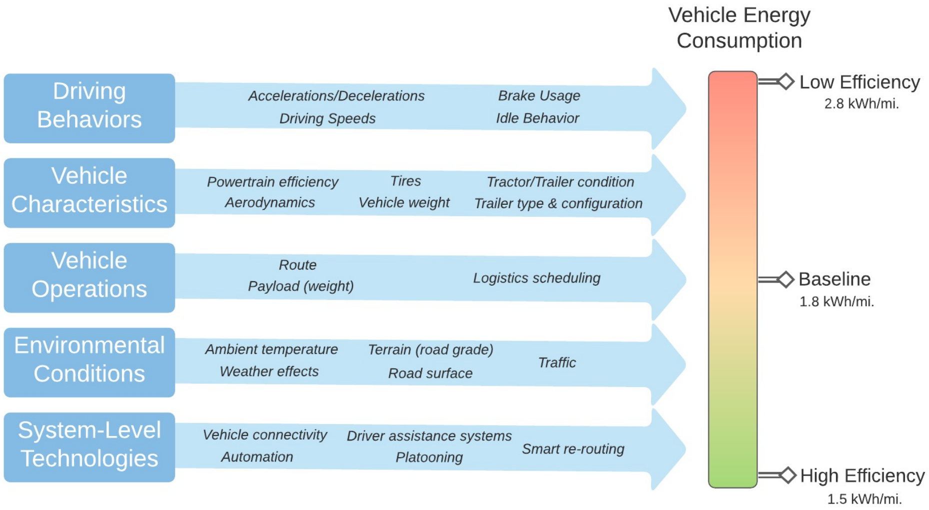
Fig. 6 | Peak depot charging load normalized per vehicle. Variation (bars) in per-vehicle contribution to peak depot charging load for each fleet and charging strategy with the average profile values overlayed (dots).

Note that per-vehicle contributions to the peak depot charging load are lower than the individual vehicle charging power levels due to the asynchronous charging behaviours from multiple vehicles.

Slower charging (constant minimum power strategy) led to much lower peak loads (<10 kW per vehicle for Fleets 1 and 2, and 20kW per vehicle for Fleet 3), which mitigates electricity demand charges and enables the use of less expensive EVSE.

In addition, the daily variance in peak load is reduced when vehicles are charged at slower rates, which results in an improved predictability for both utilities and fleet managers.

Energy Consumption Rate Sensitivity Analysis



Supplementary Table 2. Sensitivity of fleet load profile outcomes to variations in vehicle energy consumption rate

Outcome	High Efficiency – 1.5 kWh/mi	Baseline – 1.8 kWh/mi	Low Efficiency – 2.8 kWh/mi
Minimum charging power	F1: 13 kW/vehicle F2: 20 kW/vehicle F3: 86 kW/vehicle	F1: 16 kW/vehicle F2: 23 kW/vehicle F3: 103 kW/vehicle	F1: 24 kW/vehicle F2: 36 kW/vehicle F3: 161 kW/vehicle
Average daily energy required	F1: 114 kWh/vehicle/day F2: 124 kWh/vehicle/day F3: 196 kWh/vehicle/day	F1: 137 kWh/vehicle/day F2: 148 kWh/vehicle/day F3: 235 kWh/vehicle/day	F1: 214 kWh/vehicle/day F2: 231 kWh/vehicle/day F3: 365 kWh/vehicle/day
Per-vehicle peak depot load contribution (constant minimum power)	F1: 8.1 kW/vehicle F2: 8.0 kW/vehicle F3: 16.7 kW/vehicle	F1: 9.7 kW/vehicle F2: 9.6 kW/vehicle F3: 20.0 kW/vehicle	F1: 15.1 kW/vehicle F2: 15.0 kW/vehicle F3: 31.2 kW/vehicle

Looking Forward

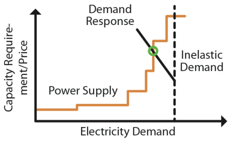
- Geospatial analysis of **fleet depot locations** could inform degree to which depots are located on shared electrical infrastructure (clustering) – Utilities want to know this in order to prepare

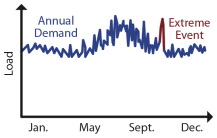
- Extend analysis to consider both **operational and economic feasibility** of a broader share of operating segments:
  - First-Mile (Drayage)
  - Regional
  - Long-haul

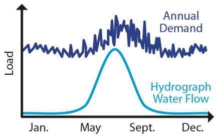
EVs can support the grid in multiple ways providing values for different stakeholders, including non-EV owners

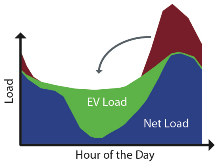
Smart electric vehicle-grid integration can provide flexibility – the ability of a power system to respond to change in demand and supply – by charging and discharging vehicle batteries to support grid planning and operations over multiple time-scales

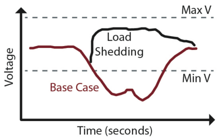
Power System Application	**Generation Capacity and Transmission/ Distribution Planning**	**Resilience To Extreme Events**	**Seasonal Planning (Hydro/Long-Term Storage Dispatch)**	**Commitment and Dispatch Decisions**	**Balancing and Power Quality**	**Support End Consumers**
Time scale	*Multi-year*	*Years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

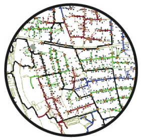












Source: Muratori et al. 2021. The rise of electric vehicles—2020 status and future expectations. Progress in Energy.