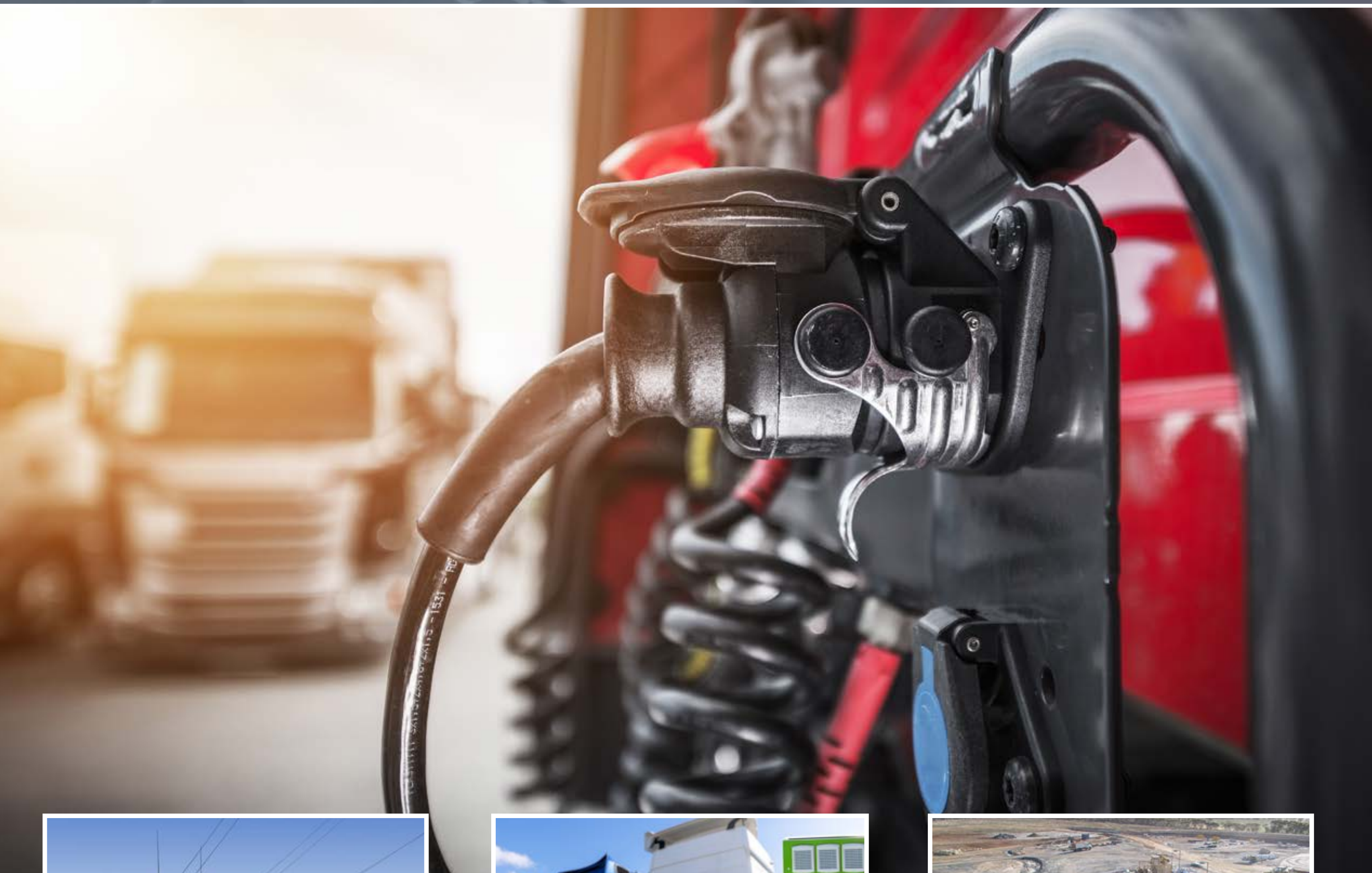
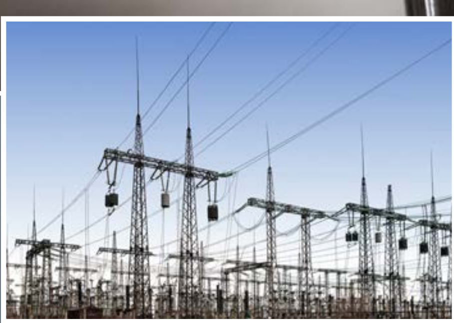
Charging Infrastructure Challenges for the U.S. Electric Vehicle Fleet

December 2022





Prepared by the American Transportation Research Institute

Charging Infrastructure Challenges for the U.S. Electric Vehicle Fleet

December 2022

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LIST OF ACRONYMS

AADTT	Annual Average Daily Truck Traffic
ATRI	American Transportation Research Institute
BEV	Battery Electric Vehicle
BTS	Bureau of Transportation Statistics
CO_2	Carbon Dioxide
DOE	U.S. Department of Energy
DOT	Department of Transportation
DCFC	Direct-Current Fast Charging
DRC	Democratic Republic of the Congo
EIA	U.S. Energy Information Administration
ESG	Environmental, Social and Corporate Governance
FERC	Federal Energy Regulatory Commission
FHWA	Federal Highway Administration
GAO	Government Accountability Office
GHG	Greenhouse Gases
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies
GVWR	Gross Vehicle Weight Rating
HOS	Hours-of-Service
HVIP	Hybrid and Zero-Emission Truck and Bus Voucher Incentive Program
ICE	Internal Combustion Engine
IEA	International Energy Agency
kW	Kilowatt
kWh	Kilowatt Hour
MHDV	Medium- and Heavy-Duty Vehicle
MW	Megawatt
NHS	National Highway System
PSC	Public Service Commission
PUC	Public Utility Commission
SQM	Química y Minera de Chile
RAC	Research Advisory Committee
ROI	Return on Investment
UNICEF	United Nations International Children’s Emergency Fund
VMT	Vehicle Miles Traveled

INTRODUCTION

In 2019 the Business Roundtable updated and modernized its statement on the purpose of the corporation to include actions to "protect the environment by embracing sustainable practices across our businesses."[1] This statement highlights a key push within all industries, including trucking, to decrease air pollution and carbon dioxide (CO_2) emissions. This new corporate sustainability focus comes at a time when government is encouraging alternatives to fossil fuels to decrease environmental impacts, and trucking industry suppliers are working to provide the industry with the equipment and energy sources needed to achieve sustainable practices.

Recognizing this, the American Transportation Research Institute (ATRI) Research Advisory Committee (RAC) voted in May 2021 to pursue two related research studies.[2] The first, released in May 2022, quantified the environmental impacts of traditional diesel engines with trucks that run on electricity and hydrogen across the life-cycle of each vehicle type.[3] This second report provides an assessment of the infrastructure needs for electrification of the U.S. vehicle fleet, with an emphasis on the trucking industry. This analysis will focus on three infrastructure components that may prove challenging for electrifying the nation's vehicle fleet: electricity infrastructure; the infrastructure that supports battery production for electric vehicles; and the charging infrastructure.

The U.S. trucking industry relies heavily on medium- and heavy-duty trucks in its operations. At the present time, these trucks primarily burn gasoline and diesel fuel, which produce CO_2 when consumed. Most scientific bodies agree that CO_2 and other greenhouse gases (GHG) contribute to climate change, which has led the public and private sectors to seek alternatives to traditional carbon-based fuels.

There are currently efforts in all sectors of the U.S. economy to decrease CO_2 emissions, with the electric utility sector being the most aggressive. Once the largest emitter of CO_2, electric utilities have decreased emissions over the past two decades by shifting from coal to natural gas and renewable energy.[4] Transportation, which last decade overtook the electric utility sector's place as the largest emitter of CO_2, has also been in the process of shifting to new energy sources to decrease its carbon footprint. In recent decades, these alternatives have included ethanol and biodiesel among others.

Another alternative energy option for vehicles is electricity. Overall, electricity has lower CO_2 emissions during trucking operations than diesel or gasoline.[5] That said, electric vehicles require large lithium-ion batteries; the production of these batteries has a much higher carbon footprint than does production of a traditional internal combustion engine (ICE).[6]

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[1] Business Roundtable, "Our Commitment" (accessed on November 2022), https://opportunity.businessroundtable.org/ourcommitment/.
[2] ATRI's Research Advisory Committee is comprised of industry stakeholders representing motor carriers, trucking industry suppliers, labor and driver groups, law enforcement, federal government, and academics. The RAC is charged with annually recommending a research agenda for the Institute.
[3] Jeffrey Short and Danielle Crownover, *Understanding the CO_2 Impacts of Zero-Emission Trucks*, American Transportation Research Institute (May 2022), https://truckingresearch.org/2022/05/03/understanding-the-co2-impacts-of-zero-emission-trucks/.
[4] Ibid.
[5] Ibid.
[6] Ibid.

The U.S. battery electric vehicle (BEV) fleet, which is more than 99.8 percent cars, has grown rapidly since 2010.[7] The number of electric passenger cars in the U.S. is slightly more than 1.5 million – which is still less than one percent of all the 276 million registered U.S. vehicles (cars and trucks).[8] Nearly one-third of those electric passenger cars were sold in 2021 due to increasing availability and government-based incentives.[9] BEV trucks in the medium- and heavy-duty vehicle (MHDV) classification have a gross vehicle weight rating (GVWR) of more than 10,000 lbs. As of the beginning of 2022 there were fewer than 1,500 electric MHDV trucks operating in the U.S.[10]

The trucking industry is comprised of more than 12 million freight trucks, of which 2.925 million are heavy-duty Class 7/8 combination trucks used in long-haul operations.[11] This latter group of trucks is referred to as combination trucks in many of the datasets utilized in this analysis, and this research will interchangeably use the term long-haul truck to describe them in this report. Electrification of such a significant vehicle population faces several potential headwinds. To identify the most critical, ATRI reviewed all aspects of vehicle electrification, with a focus on trucking. The result of that initial research was documentation of three key infrastructure-related challenges that will impact truck electrification, each described below.

Challenge One – U.S. Electricity Supply and Demand. To supply the required amount of energy to the trucking industry, utilities will have to expand infrastructure to generate more electricity, and transmit and distribute that electricity to locations where trucks need to charge. With a shift toward electrification, trucking will be one of many new consumers of electricity, competing with passenger vehicle owners for access to low-cost, reliable electricity. This new energy consumption is set against the backdrop of an aging U.S. electricity infrastructure and instances where peak-period demand has exceeded available supply.[12] Additionally, some states are better equipped to implement electrification than others. Since trucking operates across all states and in both rural and urban settings, the industry will need affordable and reliable access to electricity in myriad locations throughout the country.

Challenge Two – Electric Vehicle Production. As noted above, there are more than 12 million freight trucks registered in the U.S. These vehicles are almost exclusively equipped with a diesel or gasoline internal combustion engine (ICE). A move toward industry electrification requires the replacement of ICE trucks with BEV trucks. This, of course, also requires a major ramp-up of lithium-ion battery production. Suppliers of the raw materials utilized in batteries, for instance, will need to expand mining operations to meet demand, and battery manufacturers will likewise need to grow. The ability of trucking companies to switch from ICE to BEV is dependent on reasonably priced and

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[7] California Energy Commission, "Dashboard: Light-Duty Vehicle Population in California" (accessed on November 8, 2022), https://www.energy.ca.gov/data-reports/energy-almanac/zero-emission-vehicle-and-infrastructure-statistics/light-duty-vehicle.
[8] Stacy Davis and Robert Boundy, *Transportation Energy Data Book Edition 40*, Oak Ridge National Laboratory (February 2022), Table 6.2 – Hybrid and Plug-In Vehicle Sales 1999-2021, https://tedb.ornl.gov/wp-content/uploads/2022/03/TEDB_Ed_40.pdf.
[9] Ibid.
[10] Baha M. Al-Alawi et al., *Zeroing In on Zero-Emission Trucks*, CALSTART (January 2022), https://calstart.org/wp-content/uploads/2022/02/ZIO-ZETs-Report_Updated-Final-II.pdf.
[11] American Trucking Associations, *ATA American Trucking Trends 2021*, (November 10, 2021).
[12] Jennifer Hiller, "The U.S. Electric System Is Leaning on Customers to Avoid Blackouts," *The Wall Street Journal* (November 12, 2022), https://www.wsj.com/articles/the-u-s-electric-system-is-leaning-on-customers-to-avoid-blackouts-11668205522.

easily accessible BEV truck materials – without expanded mining and processing infrastructure to support battery demand, prices will likely increase.

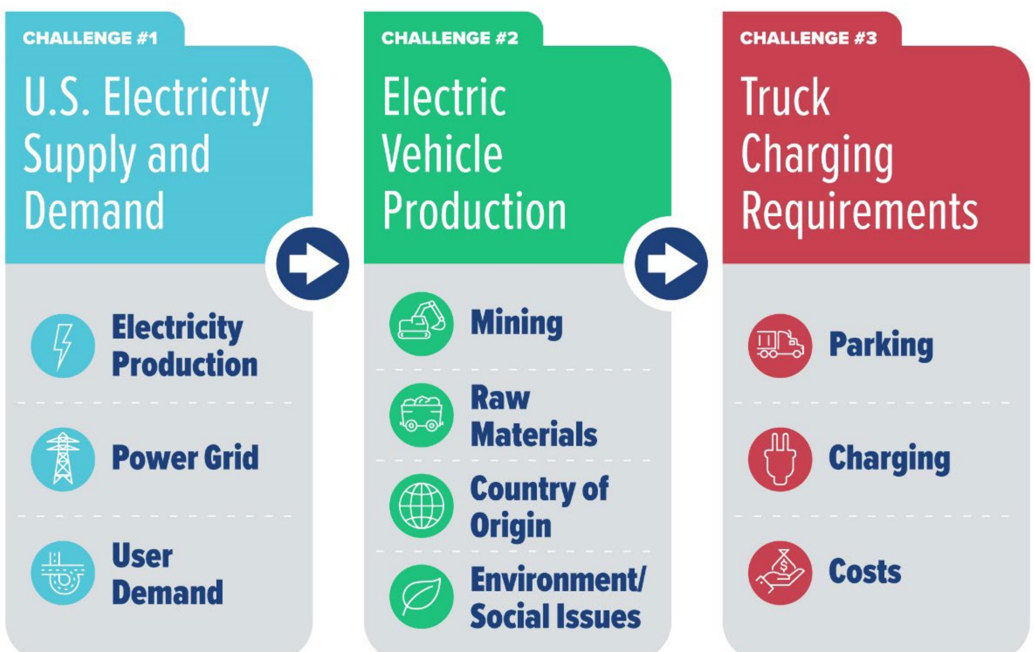
Challenge Three – Truck Charging Requirements. Vehicle refueling is accomplished today through a relatively quick transfer of gasoline or diesel that is sourced from well-established private fueling facilities. This model would change substantially through vehicle electrification due to recharging times and vehicle trip ranges. At the very least, an entirely new set of infrastructure – in the form of vehicle charging stations – will be required. It is not yet clear how large this network will need to be nor the costs necessary to build it.

This report analyzes the status of each of these three interdependent challenges facing national vehicle electrification, particularly for trucks. It is the intent of this research to help trucking industry stakeholders better understand the short- and long-term realities of industry-wide electrification.

Research Methodology

This report generated analyses on three critical components of building and managing a national BEV charging infrastructure (Figure 1) – all of which must interact in a highly coordinated fashion if BEVs are to be a feasible tool to address climate change.

Figure 1: Summary of Challenges



ATRI researchers developed and applied different methodologies, all using publicly available data, to the three “challenges” to bring clarity and insight to multiple issues that presently lack adequate knowledge and data on which to base planning and decision-making.

The first challenge focused on collecting and assessing data relating to migrating the existing electricity infrastructure to a grid that can ultimately support more than 270 million BEV vehicles in the U.S. The Challenge One analysis separately assessed existing and future electricity generation requirements for power plants, transmission and distribution system requirements, and how electricity is allocated by end-users.

The second challenge assessed BEV production requirements, including raw material sourcing and mining, as well as lithium-ion battery production needs and issues, and it identified environmental and social issues that would need to be addressed from an environmental, social and corporate governance (ESG) standpoint.

The third challenge used publicly available data sets to calculate infrastructure and charging requirements for the U.S. truck fleet. To date, most charging assessments have focused on single vehicle needs rather than fleet-wide charging requirements. This analysis also extrapolated the truck fleet requirements into parking space and charging space needs for the U.S. truck fleet. Finally, Challenge Three juxtaposed trucking operations and business models with charging requirements and limitations.

It should be noted that ATRI calculations in this research utilize multiple decimal places in the various analyses; however, the research tables and figures are typically rounded to the nearest hundredth place for clarity and presentation purposes. As a result, tables and figures that include rounded numbers are marked in the report with an asterisk (*).

CHALLENGE ONE: U.S. ELECTRICITY SUPPLY AND DEMAND

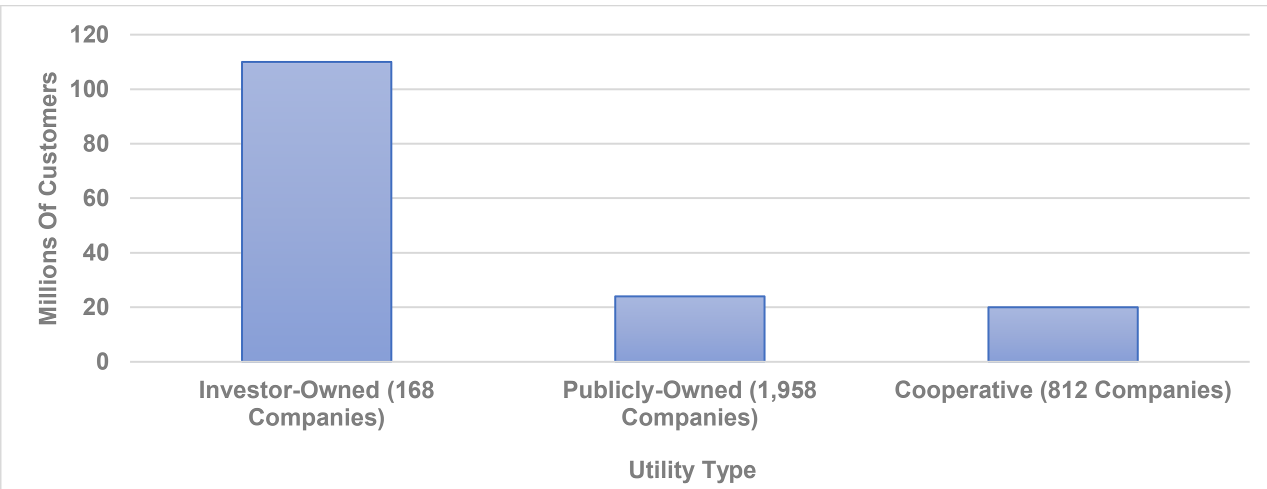
Electric Utilities Background

According to the U.S. Energy Information Administration (EIA) there are nearly 3,000 electric utilities in the U.S. These entities generally fall into three categories:

- investor-owned utilities;
- publicly-owned utilities; and
- cooperatives (not-for-profit electricity providers).[13]

Figure 2 shows the number of utilities and customers for each of the three categories.

Figure 2: U.S. Utility Customers



More than half of U.S. states rely at least in part on a monopolistic electric utility model.[14] To address the monopolistic tendencies of single providers, the utilities are regulated to ensure affordable costs and reliable services. This regulatory oversight is often provided through public utility commissions (PUCs), which are also referred to as public service commissions (PSCs).

One goal of PUCs is to keep consumer costs reasonable through review and approval of electricity rates. PUC-approved rates are tied to revenue requirements, which are a utility's operating expenses and investment costs, and the rate of return on the investments. PUC approval is also required for any investments in power plants. Utilities must justify power plant investments and innovation, but ultimately, the cost is passed to electricity consumers.[15]

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[13] U.S. Energy Information Administration, "Investor-owned utilities served 72% of U.S electricity customers in 2017" (August 15, 2019), https://www.eia.gov/todayinenergy/detail.php?id=40913.
[14] Wayne Winegarden, "Competitive Energy Markets, Not Monopoly, Delivers Affordable, Reliable, And Low-Emission Energy," *Forbes* (June 7, 2021), https://www.forbes.com/sites/waynewinegarden/2021/06/07/competitive-energy-markets-not-monopoly-delivers-affordable-reliable-and-low-emission-energy/?sh=6f77e7bdcd9a.
[15] Kathryne Cleary and Karen Palmer, "US Electricity Markets 101," Resources for The Future (March 3, 2020), https://www.rff.org/publications/explainers/us-electricity-markets-101/.

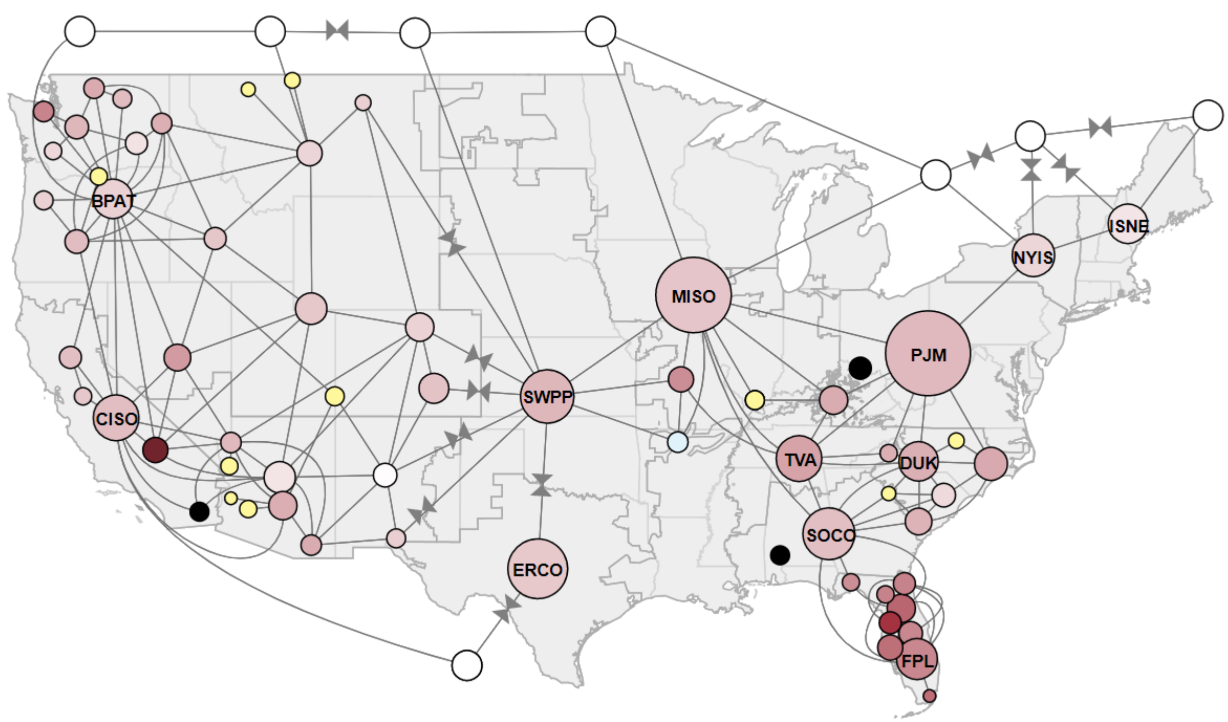
PUCs have an ever-evolving oversight role as renewable fuels and new technologies make their way into the utility marketplace. Ultimately, the role of a PUC is to assess and approve changes brought by utilities while at the same time maintaining electricity affordability and reliability.[16]

While there is significant oversight of electric utilities, electricity prices per kilowatt hour (kWh) vary widely across the country, which raises certain cost challenges for interstate fleets. In the lower 48 states, the average price is 10.7 cents per kWh, with average prices as high as 18.7 cents per kWh (in Connecticut) and as low as 7.7 cents/kWh (in Louisiana).[17]

The Electrical Grid

In the lower 48 states the electricity grid is interconnected and there are more than 80 electric grid balancing authorities to ensure that the resources needed from each electric utility are available to meet the demand of consumers across their jurisdictions.[18] The complexity of this network of interconnections and balancing authorities is illustrated in Figure 3.[19]

Figure 3: EIA Demand Data for the U.S. Grid

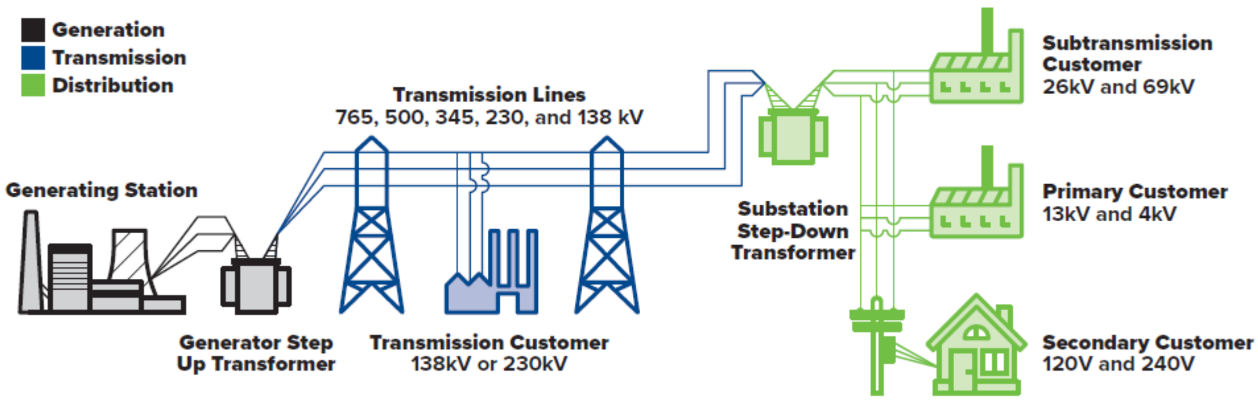


[16] Carl Pechman, "Regulation and the Monopoly Status of the Electric Distribution Utility," National Resource Research Institute (June 2022), https://pubs.naruc.org/pub/B284311B-1866-DAAC-99FB-C52B7A570087.
[17] U.S. Energy Information Administration, "State Electricity Profiles – 2019" (accessed on November 2022), https://www.eia.gov/electricity/state/archive/2019/.
[18] There are three main interconnected electricity grids:
- The Eastern Interconnection (which covers the U.S. east of the Texas panhandle);
- The Western Interconnection (which covers west of the Texas panhandle); and
- The Electric Reliability Council of Texas (ERCOT) which covers most of Texas.

[19] U.S Energy Information Administration, "Hourly Electric Grid Monitor" (accessed on October 12, 2022), https://www.eia.gov/electricity/gridmonitor/dashboard/electric_overview/US48/US48 .

In general terms, electricity generated at a power station (also known as a generating station or power plant) is delivered through a transformer to transmission lines that transport the electricity long distances to a local substation transformer. The substations move the electricity to lower-power distribution lines that are ultimately connected to customers. The producer-to-consumer flow of electricity is depicted in Figure 4.[20]

Figure 4: Illustration of the Key Power Grid Components



For additional background information on U.S. power generation, transmission and distribution please see Appendix A.

U.S. Electricity Consumption

The EIA places electric utility customers into four key use categories: residential; commercial; industrial; and transportation. Transportation-specific applications are presently limited to rail, and thus are significantly smaller than the other sectors, as shown in Figure 5.[21]

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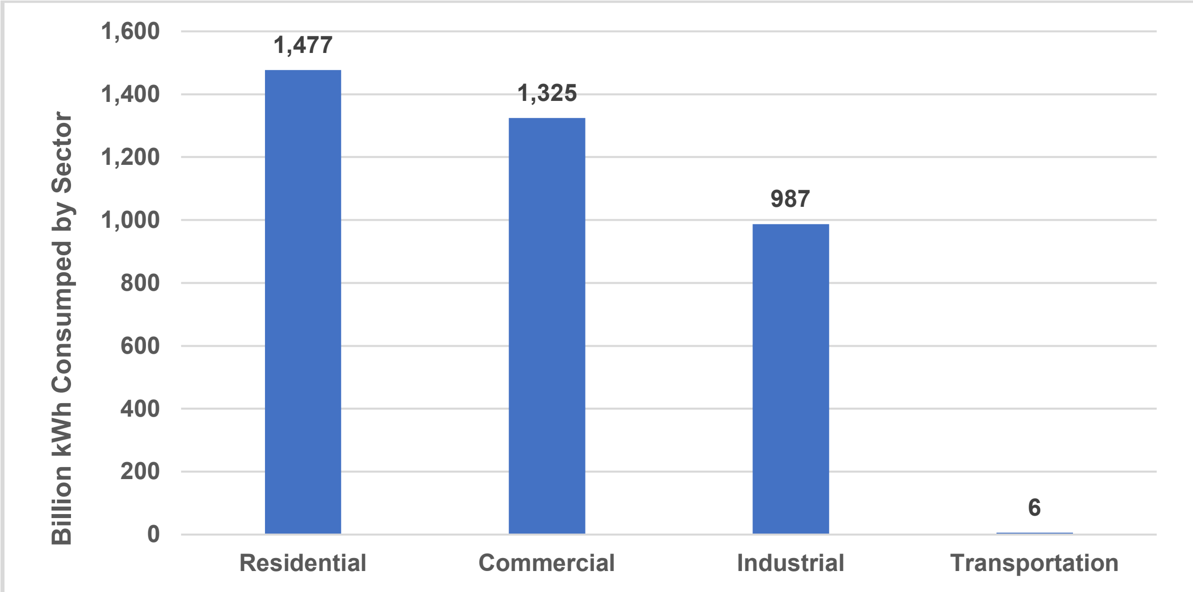
[20] This recreated graphic is based on the following source: North American Electric Reliability Cooperation, "Understanding the Grid" (August 2013), https://www.nerc.com/AboutNERC/Documents/Understanding%20the%20Grid%20AUG13.pdf.

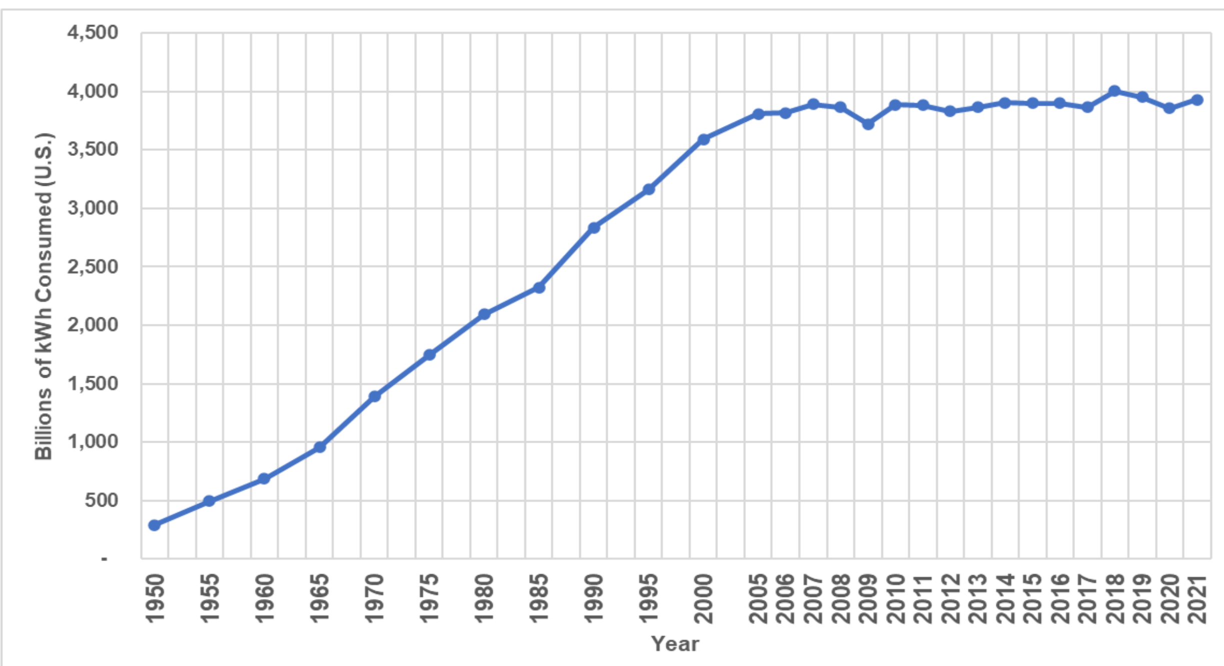
[21] The transportation category does not include electricity currently consumed by electric cars and trucks – those generally fall into the residential and commercial categories.

Figure 5: Electricity Consumption by Sector[22]



Electricity consumption in the U.S. is typically near 4,000 billion kWh annually, as shown in Figure 6. This trend has been fairly consistent in recent years, but there was a strong period of growth in consumption between 1950 and 2000.

Figure 6: U.S. Consumption of Electricity by Year



[22] U.S. Energy Information Administration, "Electric Power Monthly" (May 2022), Data Table 5.1, Data from March 2022, https://www.eia.gov/electricity/monthly/.

This growth began to plateau after 2000 and has since maintained a steady level.[23] A shift to electrification in surface transportation, however, would likely restart consumption growth dramatically.

Significant Energy Losses Between Generation and Consumption

U.S. electricity generation figures are larger than consumption figures. In 2021 there were 4,204 billion kWh produced, while consumption was at 3,930 kWh. This difference represents 274 billion kWh that are produced but not delivered to end-users, a 6.5 percent difference between electricity generation and consumption (not including net imports).[24] Most of this loss occurs at transformers and during transmission and distribution; the issue is often referred to as "line losses." The National Association of Clean Air Agencies describes the issue as follows:

> "System average line losses are in the range of six to ten percent on most U.S. utility grids, but they increase exponentially as power lines become heavily loaded. Avoiding a small amount of peak electricity demand in the highest peak hours can reduce line losses by as much as 20 percent."[25]

While the electricity infrastructure in the U.S. experiences line losses between electricity generation and consumption, for the purposes of this research, the methodologies assume a one-to-one ratio of generation to consumption; i.e. a megawatt of generation equates to a megawatt of consumption.

U.S. Electric Vehicle Fleet Consumption

More than 136 billion gallons of gasoline and nearly 44 billion gallons of diesel were consumed by roadway users in 2019.[26] Replacing this energy with electricity will require significant increases in the amount of electricity produced and consumed in the U.S., as documented on a limited basis in past research (Appendix B).

U.S. Light-Duty Vehicle Fleet

To quantify the potential electricity consumption of the entire U.S. vehicle fleet outside of trucking, the research team first obtained statistics for two categories of light-duty vehicles (short-wheelbase and long-wheelbase).[27] For this analysis, Bureau of Transportation Statistics (BTS) and Federal Highway Administration (FHWA) fleet size and vehicle miles traveled (VMT)

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[23] This trend is due to several factors. Population and housing growth is one source of increased electricity consumption – from 1950 to 2000 for instance, the number of U.S. households increased from 43.5 million to 104.7 million. This was coupled with the rapid adoption of air conditioning and other home appliances. By the 2000s, however, consumption growth began to plateau, due in part to the implementation of energy saving strategies and standards. Vehicle electrification may, however, lead to a new growth pattern in consumption similar to what was seen between 1950 and 2000. Sources: *U.S Census Bureau, "Table HH-1. Households by Type: 1940 to Present"* (November 2021); *U.S. Department of Energy, "History of Air Conditioning"* (July 20, 2015); *American Council for an Energy-Efficient Economy, "Why Is Electricity Use No Longer Growing?"* (February 2014).

[24] It should be noted that the U.S. annually has net imports of electricity of more than 40 billion kWh from Canada and Mexico.

[25] National Association of Clean Air Agencies*, Implementing EPA's Clean Power Plan: A Menu of Options* (May 21, 2015), https://www.4cleanair.org/event_meeting_notes/implementing-epas-clean-power-plan-a-menu-of-options/.

[26] Federal Highway Administration, "Table MF-27: Highway Use of Motor Fuel" (November 2020), Highway Statistic Series 2019, https://www.fhwa.dot.gov/policyinformation/statistics/2019/mf27.cfm.

[27] Light-Duty Vehicles Short WB - passenger cars, light trucks, vans, and sport utility vehicles with a wheelbase (WB) less than or equal to 121 inches. Light-Duty Vehicles Long WB - large passenger cars, vans, pickup trucks, and sport utility vehicles with wheelbases (WB) greater than 121 inches.

figures were utilized. An average miles per kWh for each vehicle type (representing fuel economy) was next estimated as follows.

For short-wheelbase BEVs, an average miles per kWh of 3.14 was identified. To accomplish this, the research team identified the top ten BEV car models by sales in 2019 and averaged their U.S. Department of Energy (DOE) fuel economy figures for 2017-2019.[28] The average miles per kWh figure for long-wheelbase vehicles was 2.08, based on a similar methodology used for short-wheelbase BEVs and using the same source.[29]

Using the input metrics above, total electricity consumption for the light-duty vehicles was calculated and is shown in Table 1.

Table 1: Electricity Consumption Estimates: Automobiles, Light Trucks, Vans, Other*

Vehicle Type	Fleet Size (2019)	Miles per kWh	Total Annual Vehicle Miles Traveled (Billions)	Average Annual Miles Per Vehicle	Billions of kWh Required Annually	Annual kWh per Vehicle
Light-Duty - Short Wheelbase	194,348,815	3.14	2,254	11,599	717.9	3,694
Light-Duty - Long Wheelbase	59,465,369	2.08	670	11,263	322.0	5,415
Total	253,814,184	-	2,924	-	**1,039.9**	-

The electricity that would be consumed by the U.S. light-duty vehicles is significant. At 1,039.9 billion annual kWh, it represents 26.3 percent of all electricity consumed in the U.S. in 2019.

U.S. Medium- and Heavy-Duty Truck Fleet

The research team next estimated the electricity needs of a future fully electrified U.S. trucking fleet. Key datasets utilized include total U.S. truck registrations, sourced from BTS, fleet size by truck type from EIA, and VMT from FHWA.[30] While our subsequent analyses use two different truck categories from FHWA, to develop a more granular view of industry needs for trucks Class

[28] U.S. Department of Energy, “Find and Compare Cars” (accessed on October 2022), https://www.fueleconomy.gov/feg/findacar.shtml; Argonne National Laboratory, “U.S. PEV Sales by Model (In Order of Market Introduction)” (November 2019), https://afdc.energy.gov/data/10567. EVs were on the market prior to 2017 were excluded from this figure because there have been small improvements in battery technology for energy efficiency – when including the 2011 through 2019 models the average using this approach was 3.07 miles per kWh.
[29] Less data is available for long-wheelbase EVs, as for all those found they were introduced in 2022. More models are set to be launched for the U.S. market in late 2022 and 2023, however the three models included give an estimate to the kind of energy efficiency that can be expected of these new EVs.
[30] Bureau of Labor Statistics, “Number of U.S. Aircraft, Vehicles, Vessels, and Other Conveyances” (accessed on October 13, 2022), https://www.bts.gov/content/number-us-aircraft-vehicles-vessels-and-other-conveyances. American Trucking Associations, *ATA American Trucking Trends 2021*, (November 10, 2021); Federal Highway Administration, “Table VM-1: Annual Vehicle Distance Traveled in Miles and Released Data – 2019” (accessed on October 13, 2022), Highway Statistics Series 2019, https://www.fhwa.dot.gov/policyinformation/statistics/2019/vm1.cfm.

3-8, ATRI used four EIA categories, and assumed a combination truck population of 2.925 million.

Additionally, current estimates of vehicle efficiency (in miles per kWh) were identified using spec sheets for vehicles from California's Hybrid and Zero-Emission Truck and Bus Voucher Incentive Program (HVIP).[31] FHWA's annual VMT figures for single unit trucks (123.8 billion miles) were evenly distributed among trucks categorized as light-medium-, medium- and heavy-duty single unit trucks on a per vehicle basis. From these datasets, calculations were developed for the billions of kWh required annually and annual kWh per truck. The results are shown in Table 2.

Table 2: U.S. Truck Fleet Electricity Consumption Estimates*

Truck Type	Fleet Size (2019)	Miles per kWh	Total Annual Vehicle Miles Traveled (Billions)	Average Annual Miles Per Truck	Billions of kWh Required Annually	Annual kWh per Truck
Light-Medium-Duty	3,830,000	1.64	50.75	13,250	30.9	8,079
Medium-Duty	3,440,000	0.75	45.58	13,250	60.8	17,667
Heavy-Duty Trucks – Single Unit	2,144,790	0.64	28.42	13,250	44.4	20,703
Heavy-Duty Trucks – Combination	2,925,210	0.42	175.31	59,929	417.4	142,688
Total	12,340,000	**-**	300.05	**-**	**553.5**	**-**

The electricity that would be consumed by the U.S. trucking fleet is also significant – at 553.5 billion annual kWh it represents 14.0 percent of all electricity consumed in the U.S. in 2019 (3,954 billion kWh). Within the trucking category, long-haul combination trucks would make up the largest roadway consumer of electricity, using 417.4 billion kWh or 10.6 percent of all U.S. consumption in 2019. It should be noted that in Table 2, FHWA's VMT mileage of 59,929 includes considerable local truck tractor activity. In ATRI's 2019 *Operational Costs of Trucking* report, long-haul truck tractors reported an average of 93,955 miles per year.[32] Applying this figure to the methodology would generate a much larger estimate for electricity demand by the long-haul segment of industry – which moves the majority of freight tonnage in the U.S.

In summary, with full electrification of today's light-, medium- and heavy-duty vehicles in the U.S., an additional 1,593.8 billion kWh of electricity would be needed. This represents an

[31] California Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project, "HVIP Eligible Vehicles" (accessed on August 11, 2022), https://californiahvip.org/vehiclecatalog/.
[32] Dan Murray and Seth Glidewell, *An Analysis of the Operational Costs of Trucking: 2019 Update*, American Transportation Research Institute, (November 2019).

increase in annual U.S. electricity consumption of **40.3 percent** to power all vehicles listed in Tables 1 and 2.

Electricity Infrastructure Issues in the U.S.

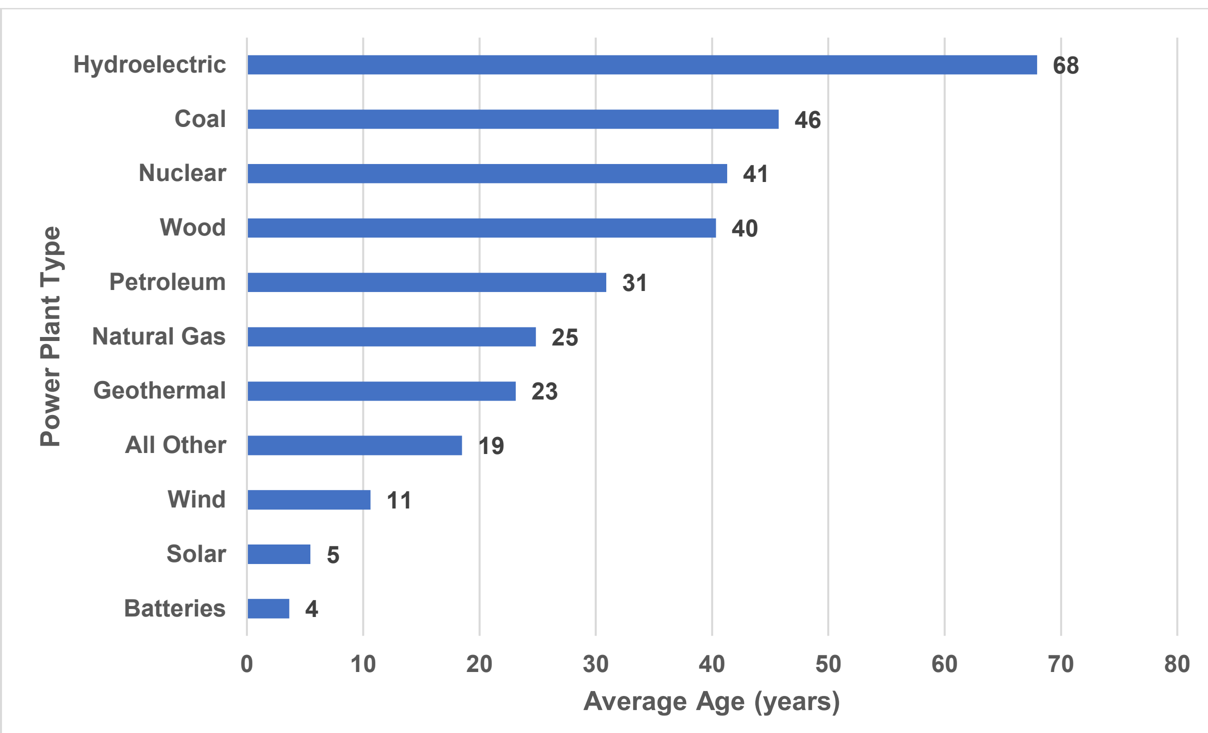
Based on the above background information and analysis, the research team has identified the following key issues related to the electricity generation needed to meet the demands of electric vehicles.

<u>Electricity Issue One: U.S. Electrical Infrastructure is Aging while Demand is Set to Increase</u>

As discussed earlier, the demand for electricity in the U.S. grew between the 1950s and 2000s and then plateaued. Much of the original infrastructure used to generate this growth is still in use today. The age of this infrastructure is a concern for all electricity users. Aging infrastructure does not benefit from the most recent advances in technology, and it is ultimately less reliable. Older infrastructure is also closer to its end of usable life, and thus will need costly replacement in the near term.

To better understand the age of U.S. power generating infrastructure, the research team looked at the age of more than 24,600 power stations. These power stations were next distributed into categories, and the average age of each power station type was then calculated (Figure 7).[33]

Figure 7: Average Age of Power Plants in the U.S., by Type



[33] U.S. Energy Information Administration, "Form EIA-860 detailed data with previous form data (EIA-860A/860B)," (updated on September 22, 2021), https://www.eia.gov/electricity/data/eia860/.

Hydroelectric, coal and nuclear power plants are oldest in age. As discussed in Appendix A, these sources offer steady power levels and operate during peak and off-peak time periods, which is critical to the continuous provision of electricity. Newer infrastructure tends to be associated with renewable energy systems, which are often used to support hydroelectric, coal and nuclear during off-peak time periods.

In addition to power plants, the distribution system used to deliver electricity is also aging. As an example, a U.S. DOE report estimated that 70 percent of power transformers and transmission lines were at least 25 years old, with many being substantially older.[34]

While transformers are built to last up to 40 years, the risk of fire increases with time; loose parts, degradation of insulation, and power overloads all increase the chance of fire.[35] Proper and regular maintenance can prolong a transformer's life expectancy, which is crucial when considering the financial and logistical issues associated with replacement. Obviously, outages during any transformer maintenance or replacement can cost impacted businesses millions of dollars.[36]

Transmission lines vary in life expectancy based on whether they are overhead or underground. Overhead high-voltage transmission lines can last up to 100 years.[37] Underground transmission lines have a shorter life span with varying life expectancy estimates of 40 to 60 years depending on conditions, geography, and maintenance.[38]

It should finally be noted that an estimated 60 percent of distribution lines have outlived their 50-year life expectancy.[39]

Electricity Issue Two: Electrical Outages Could Halt Surface Transportation

The convergence of an aging electrical grid, severe weather, and the limitations of renewable energy sources (e.g. energy production that depends on weather conditions with wind or sun) have resulted in the increased length and frequency of power outages. According to the EIA, the average annual time U.S. customers spent without electricity in 2020 was approximately 8 hours on average, a rise of 4.5 hours since 2013.[40] In 2020 there were 180 major disruptions to the power grid compared to approximately two dozen in 2000.[41]

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[34] Power Magazine, "Clinging to Power: Why Extending Transformer Life Is Key" (August 1, 2018), https://www.powermag.com/clinging-to-power-why-extending-transformer-life-is-key/.
[35] Ibid.
[36] Ibid
[37] Jon T. Leman and Robert G. Olsen, "Overhead or Underground Transmission? That is (Still) the Question," *Transmission and Distribution World* (February 24, 2022), https://www.tdworld.com/intelligent-undergrounding/article/21215620/overhead-or-underground-transmission-that-is-still-the-question.
[38] Ibid; National Grid, *Undergrounding high voltage electricity transmission lines: The technical issues* (January 2015), https://www.nationalgrid.com/sites/default/files/documents/39111-Undergrounding_high_voltage_electricity_transmission_lines_The_technical_issues_INT.pdf.
[39] Glen Anderson, Megan Cleveland, and Daniel Shea, *Modernizing the Electric Grid: State Role and Policy Options*, National Conference of State Legislatures (November 2019), https://www.ncsl.org/research/energy/modernizing-the-electric-grid-state-role-and-policy-options.aspx; Jenifer Weeks, "U.S. Electrical Grid Undergoes Massive Transition to Connect Renewables," *Scientific American* (April 28, 2010), https://www.scientificamerican.com/article/what-is-the-smart-grid/.
[40] U.S. Energy Information Administration, "U.S. electricity customers experienced eight hours of power interruptions in 2020" (November 10, 2021), https://www.eia.gov/todayinenergy/detail.php?id=50316.
[41] Ibid.

Power Generators. A first source of electricity outage may be a disruption at a power generator. In cases where power plants are unable to produce enough energy to keep up with demand, the electrical frequency of the entire system drops resulting in either blackouts or brownouts. When demand is lower than supply and too much electricity is released, heat is produced beyond what the equipment can manage, possibly resulting in damage.[42] A typical response to low demand would be for a power plant to either slow down production or try to send the excess elsewhere.[43]

During a blackout, all electricity to a given area turns off. During a brownout, electricity is still flowing to end users but at a lower or unstable voltage (e.g. flickering lights). Brownouts can be more damaging to electrical equipment than blackouts; devices such as computers, for instance, are not designed to function with inconsistent and insufficient voltage over sustained periods of time.

Brownouts and blackouts can be unintentional, resulting directly from issues with electrical supply. They can also be caused intentionally by power generation operators in order to distribute the electrical supply evenly or to protect the grid from damage and cascading failures.

In the case of a cascading failure, disconnection of a transformer or the downing of a transmission line causes the electrical load to be shifted onto other parts within the system; if they are unable to manage the increased burden, these parts also fail. That failure then spreads out resulting in large-scale blackouts that are difficult and costly to fix, and it could leave electric vehicles without a means to recharge.

One example of cascading failures resulting in widespread blackouts in the U.S. was the 2003 Northeast Blackout that left over 50 million consumers without power for hours. The origin of the blackout was a downed transmission line and a software bug that left operators unaware that they needed to redistribute the electrical load.[44] *Within two hours of the first transmission line failure, an area of 3,700 miles was without power, including New York City where the power was out for 29 hours at a cost of $1 billion. The total cost across all geographies was found to be roughly $6 billion.*[45]

Power lines. The vast majority of transmission and distribution infrastructure in the U.S. is above ground. While this makes disruptions to the system easier to locate and repair, it also leaves them incredibly exposed and vulnerable to environmental phenomena. Furthermore, a 2017 National Academies report states that:

> "Overhead transmission lines are not directly insulated and instead require minimum separation distances for air to provide insulation. If trees or objects are allowed to get too close and draw an arc, short circuits of the energized conductor can result. When they are heavily loaded, transmission line conductors

[42] Kirby et al., *Frequency Control Concerns in the North American Electric Power System*, Oak Ridge National Laboratory (December 2002), https://info.ornl.gov/sites/publications/Files/Pub57419.pdf.
[43] National Association of Clean Air Agencies, *Implementing EPA's Clean Power Plan: A Menu of Options* (May 21, 2015), https://www.4cleanair.org/event_meeting_notes/implementing-epas-clean-power-plan-a-menu-of-options/.
[44] U.S.-Canada Power System Outage Task Force, *Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations* (September 2006), https://www.energy.gov/sites/default/files/oeprod/DocumentsandMedia/BlackoutFinal-Web.pdf.
[45] Electricity Consumers Resource Council, *The Economic Impacts of the August 2003 Blackout* (February 2004), https://elcon.org/wp-content/uploads/Economic20Impacts20of20August20200320Blackout1.pdf.

heat up, expand, and sag lower into the right-of-way, which increases the likelihood of a fault at times of peak transmission loading."[46]

Above ground transmission and distribution systems infrastructure is also extremely vulnerable to severe weather conditions, which accounted for 58 percent of all power outages between 2002 and 2013.[50] Climate change is thought to have made such events more frequent and severe – with one report indicating that there has been a 67 percent increase in power outages due to severe weather conditions since 2000.[51] A recent Government Accountability Office (GAO) report in March 2021 concluded that the U.S. DOE and the Federal Energy Regulatory Commission (FERC) both needed to take additional action in order to reduce the risk of serious harm to the electric grid as a result of weather events.[52] Two states, Texas and California, have seen large power outages in recent years due to weather conditions.

The failure of the power grid during the 2021 Texas Power Crisis was caused in part because of electric heating to combat unusually cold temperatures. The resulting high demand combined with downed power lines strained the power grid and eventually left 4.5 million customers in Texas temporarily without power.[47]

California has had to initiate multiple rolling blackouts over the years in response to more frequent heat waves, both to keep the grid from collapsing and to reduce the risk of power cables igniting dried out vegetation and setting off wildfires.[48] *The prolonged drought is also a concern; California's electricity generation is made up of 19 percent hydropower.*[49] *As droughts in the west persist, reservoirs dry up resulting in the shutdown of hydropower plants.*

Additionally, in 2021 Hurricane Ida caused 1.2 million people to lose power, and damaged more than 30,000 utility poles across the Southeastern U.S.[53] In 2022 Hurricane Ian hit South Florida, landing near Fort Myers. Due to winds and flooding, electricity to 2.6 million Florida customers was lost during the storm.[54]

Overall, more outages are anticipated in the future. The Wall Street Journal reports that "grid operators around the country have recently raised concerns that the intermittence of some

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[46] The National Academies of Sciences, Engineering, and Medicine, *Enhancing the Resilience of the Nation's Electricity System* (2017), https://nap.nationalacademies.org/catalog/24836/enhancing-the-resilience-of-the-nations-electricity-system.

[47] Federal Energy Regulatory Commission, "Final Report on February 2021 Freeze Underscores Winterization Recommendations" (November 16, 2021), https://www.ferc.gov/news-events/news/final-report-february-2021-freeze-underscores-winterization-recommendations.

[48] Zeeshan Aleem, "California's heat wave caused rolling blackouts for millions," *Vox* (August 15, 2020), https://www.vox.com/2020/8/15/21370128/california-blackouts-rolling-power-outage.

[49] Casey Crownhart, "Droughts are cutting into California's hydropower. Here's what that means for clean energy," *MIT Technology Review* (April 1, 2022), https://www.technologyreview.com/2022/04/01/1048726/droughts-are-cutting-into-californias-hydropower-heres-what-that-means-for-clean-energy/.

[50] Executive Office of the President, *Economic Benefits of Increasing Electric Grid Resilience to Weather Outages* (August 2013), https://www.energy.gov/sites/prod/files/2013/08/f2/Grid%20Resiliency%20Report_FINAL.pdf.

[51] Climate Central, "Power OFF: Extreme Weather and Power Outages" (September 2020), https://www.climatecentral.org/climate-matters/power-outages.

[52] U.S. Government Accountability Office, "Electricity Grid Resilience: Climate Change Is Expected to Have Far-reaching Effects and DOE and FERC Should Take Actions" (March 2021), https://www.gao.gov/assets/gao-21-423t-highlights.pdf.

[53] U.S. Energy information Administration, "Hurricane Ida caused at least 1.2 million electricity customers to lose power" (September 15, 2021), https://www.eia.gov/todayinenergy/detail.php?id=49556#.

[54] Associated Press, "Floridians Endure Slow Wait for Power Knocked Out by Ian," *U.S. News & World Report*, (October 4, 2022), https://www.usnews.com/news/business/articles/2022-10-04/in-ians-wake-florida-residents-brave-a-slow-wait-for-power.

electricity sources is making it harder for them to balance supply and demand and could result in more shortages."[55] These concerns are exacerbated by state governments taking non-renewable production plants offline before enough renewable generators have been put in place to fully meet demand.[56]

Electricity Issue Three: Variable Electricity Rates Could Negatively Impact Trucking

The time periods used for vehicle charging may also be a concern. One study indicated that even when public charging is available, nearly all electric vehicle users prefer to charge at home.[57] This could be due to several factors, including ease of charging and billing when using an at-home smart charger, along with incentives from utilities for off-peak rates.

A second study, however, found that daytime charging is preferable to nighttime residential charging from an emissions perspective.[58] This in part is because solar power generation and transmission occurs during the day. The authors state that "locally optimized controls and high home charging can strain the grid," and they "urge policymakers to reflect generation-level impacts in utility rates and deploy charging infrastructure that promotes a shift from home to daytime charging."[59]

The time of day that trucking companies will charge depends on numerous factors, including:

- Vehicle/Battery Range – can a driver operate throughout a workday and charge when off-duty?
- Electricity Price Variation – at what time will electricity be least costly?
- Shipper-Based Delivery Times – shippers dictate delivery times, and charging will have to be scheduled around those shipper scheduling requirements. Using variable pricing to balance electricity consumption will influence industry adoption of BEV trucks. That said, depending on the condition of the grid, such policies could be needed to ensure that peak demand does not result in a supply/demand imbalance.

Electricity Issue Four: Meeting State-Level Electric Vehicle Demand may be Difficult

The research team estimated how much electricity roadway vehicles would need for full electrification on a state-by-state basis. This assessment required several data inputs, including state electricity consumption and road use statistics for 2019.[60] This year was utilized as it was the best available across all base datasets and avoided the anomalies of the 2020 COVID-19 shutdowns.

The goal of this state-level electricity needs assessment is to understand the quantity of electricity annually that would be consumed by BEV vehicles and compare that consumption to

[55] Katherine Blunt, "America's Power Grid Is Increasingly Unreliable," *The Wall Street Journal* (February 18, 2022), https://www.wsj.com/articles/americas-power-grid-is-increasingly-unreliable-11645196772.
[56] Ibid.
[57] John Galloway Smart and Shawn Douglas Galloway, *Plugged In: How Americans Charge Their Electric Vehicles*, Idaho National Laboratory (July 1, 2015), https://inldigitallibrary.inl.gov/sites/sti/sti/7323604.pdf.
[58] Siobhan Powell et al., Charging infrastructure access and operation to reduce the grid impacts of deep electric vehicle adoption, Nature Energy (September 22, 2022), https://www.nature.com/articles/s41560-022-01105-7.
[59] Ibid.
[60] Federal Highway Administration, "Highway Statistics 2019" (accessed on October 14, 2022), https://www.fhwa.dot.gov/policyinformation/statistics/2019/.

current electricity consumption. While the consumption figures are large, this does not mean that demand could not be met. Pricing mechanisms and existing unused capacity would likely play a role in meeting this demand. It does however show that a significant increase in electricity will be consumed in each state, with some states needing more than others.

The following methodology was used to identify state-level electricity needs. FHWA's 2019 Highway Statistics was the source of state-level VMT data by vehicle type.[61] Highway Statistics Table VM-2 was used to identify mileage by state for rural and urban roads. These mileage figures were next assigned to four vehicle types (automobile, light truck, single unit truck and combination truck) using the percentage of mileage distributions by roadway type found in Highway Statistics Table VM-4.[62]

The VMT data, categorized by state and vehicle type, were next divided by vehicle efficiency assumptions. The efficiency metric used was miles per kilowatt hour to determine the kWh needs for each state. The following assumptions were made for the four vehicle categories used in this analysis (Table 3), and methods for identifying these assumptions were previously described.[63]

Table 3: Vehicle Economy*

	Miles per kWh
Automobile	3.14
Light Truck	2.08
Single Unit Truck	0.92
Combination Truck	0.42

Finally, the kilowatt hours that were generated and consumed in 2019 by each state are sourced from total retail sales of electricity data from EIA's state electricity profiles.[64]

It should be noted that this assessment does not include consumption growth that could result from population and travel pattern changes, nor does it speculate on technological breakthroughs that might increase vehicle efficiency, home or business efficiency improvements, or home use of solar.
State calculations confirm a large increase in demand for electricity by passenger vehicles and trucks.

[61] Ibid.
[62] Single unit was identified by averaging by VMT all trucks with the exception of heavy-duty combination.
[63] The single unit truck miles per kWh figure is based on the three single unit truck miles per kWh figures identified in Table 2; additionally, these figures were weighted by VMT to arrive at 0.92.
[64] U.S. Energy Information Administration, "State Electricity Profiles" (November 2, 2020, accessed on October 14, 2022), https://www.eia.gov/electricity/state/archive/2019/.

As shown in Figure 8, states would consume at minimum 25 percent more electricity as a result of full car and truck electrification. Seven states, including California, will see an increase in consumption larger than 50 percent. Additional breakouts by vehicle type are available in Appendix C.

Figure 8: Full Fleet Electric Vehicle Consumption as a Percentage of Current Generation

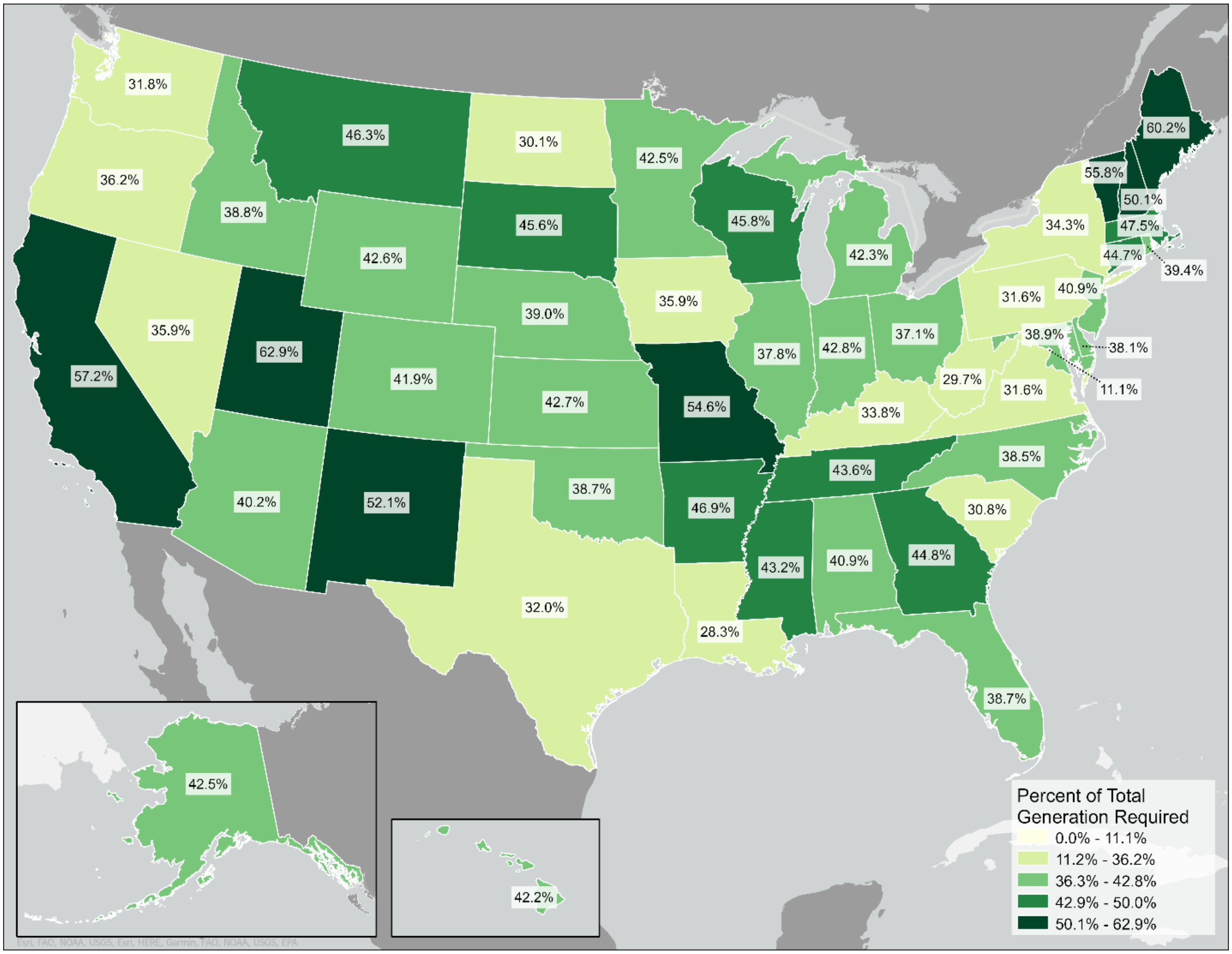

Table 4 below breaks out the data for passenger cars and freight trucks by state, and shows the total consumption percentage in rank order from highest (Utah) to lowest (DC).

Table 4: Percent of Current Generation that would be Consumed by a Fully Electrified Fleet (by State)

Rank	State	Single-Unit and Combination Trucks	Car and Light Truck	Total
1	Utah	33.7%	29.2%	62.9%
2	Maine	23.2%	37.1%	60.2%
3	California	16.4%	40.9%	57.2%
4	Vermont	14.1%	41.7%	55.8%
5	Missouri	24.4%	30.2%	54.6%
6	New Mexico	18.3%	33.8%	52.1%
7	New Hampshire	10.5%	39.6%	50.1%
8	Massachusetts	9.5%	38.0%	47.5%
9	Arkansas	23.8%	23.1%	46.9%
10	Montana	18.4%	27.9%	46.3%
11	Wisconsin	16.9%	28.9%	45.8%
12	South Dakota	21.6%	24.0%	45.6%
13	Georgia	16.4%	28.4%	44.8%
14	Connecticut	13.7%	31.0%	44.7%
15	Tennessee	19.2%	24.4%	43.6%
16	Mississippi	17.8%	25.4%	43.2%
17	Indiana	19.5%	23.3%	42.8%
18	Kansas	19.8%	22.9%	42.7%
19	Wyoming	23.7%	18.8%	42.6%
20	Minnesota	14.2%	28.4%	42.5%
21	Alaska	8.6%	33.8%	42.5%
22	Michigan	11.7%	30.6%	42.3%
23	Hawaii	5.3%	36.9%	42.2%
24	Colorado	11.3%	30.6%	41.9%
25	Alabama	15.0%	25.9%	40.9%
26	New Jersey	8.1%	32.8%	40.9%
27	Arizona	14.3%	25.9%	40.2%
28	Rhode Island	9.1%	30.3%	39.4%
29	Nebraska	16.4%	22.6%	39.0%
30	Maryland	9.6%	29.3%	38.9%
31	Idaho	15.5%	23.3%	38.8%
32	Oklahoma	18.1%	20.6%	38.7%
33	Florida	11.0%	27.7%	38.7%
34	North Carolina	11.4%	27.1%	38.5%
35	Delaware	13.1%	25.0%	38.1%
36	Illinois	16.7%	21.0%	37.8%
37	Ohio	15.3%	21.8%	37.1%
38	Oregon	16.4%	19.8%	36.2%
39	Nevada	10.8%	25.2%	35.9%
40	Iowa	17.6%	18.3%	35.9%
41	New York	8.9%	25.4%	34.3%
42	Kentucky	14.3%	19.5%	33.8%
43	Texas	12.5%	19.4%	32.0%
44	Washington	9.6%	22.2%	31.8%
45	Virginia	9.4%	22.2%	31.6%
46	Pennsylvania	11.3%	20.3%	31.6%
47	South Carolina	9.4%	21.4%	30.8%
48	North Dakota	16.3%	13.8%	30.1%
49	West Virginia	12.8%	16.9%	29.7%
50	Louisiana	11.9%	16.5%	28.3%
51	District of Columbia	1.1%	10.1%	11.1%

Strategies for Increasing Electricity Generation

Meeting the electricity needs of the nation's BEV cars and trucks will require additional capacity and new infrastructure; although, with considerable resources, it is realistic to upgrade the electricity grid.

According to the American Society of Civil Engineers, there is a large investment gap between the existing infrastructure investment rates and what is needed to ensure a viable electricity grid in the future.[65] Between 2020 and 2029 this gap is estimated to be $208.1 billion. By dramatically expanding infrastructure investments, many of the issues described above could be mitigated.

Alternatively, expansion of renewable energy and/or alternative vehicle power systems could also reduce the electricity generation needs.

[65] American Society of Civil Engineers and EBP US, *FAILURE TO ACT: Electric Infrastructure Investment Gaps in a Rapidly Changing Environment* (2020), https://infrastructurereportcard.org/wp-content/uploads/2021/03/Failure-to-Act-Energy-2020-Final.pdf.

CHALLENGE TWO: ELECTRIC VEHICLE PRODUCTION

Vehicle electrification efforts face challenges beyond access to affordable and reliable electricity and ubiquitous charging infrastructure – today's fleet of ICE-powered vehicles will have to be replaced with new and very different vehicles.

Looking specifically at trucking, ICE and BEV trucks have many similarities in their body and chassis. The one key difference, however, is that today's ICE engine and fuel tank(s) will be replaced by electric motors and large lithium-ion batteries. To achieve this, a new vehicle-related set of supply chains is required across the entire vehicle life-cycle, including expanded mining and processing of raw materials, battery manufacturing, maintenance and battery recycling.

Electric Vehicle Batteries

During its early years as an electric car manufacturer, Tesla was able to purchase and retrofit an existing vehicle assembly plant in Fremont, CA to build electric vehicles.[66] This investment, and subsequent investments by both start-up and well-established electric vehicle manufacturers, demonstrates that many of the tasks associated with vehicle manufacturing are the same for ICE and BEV cars and trucks. Life-cycle analysis models (i.e. the Argonne National Laboratory's GREET model) assume that ICE and BEV trucks have the same body and chassis materials in their weight and emissions calculations.[67]

The one key difference between the two vehicle types, motors aside, is that the BEV stores energy in a large lithium-ion battery. Therefore, in the near term the most noticeable challenge is found at the very beginning of the vehicle life-cycle, as the automotive industry increasingly consumes large quantities of battery-related raw materials.

For years lithium-ion batteries have been a key component of devices such as rechargeable batteries and smartphones, which require very small amounts of raw material compared to a vehicle. To power vehicles, production of batteries had to scale up, with quantities of raw materials such as lithium and cobalt moving from just ounces in a smartphone to hundreds or thousands of pounds in a vehicle.

For trucks, this battery (and the raw materials that comprise it) will likely be the largest cost center within the vehicle – ACT Research estimates that the battery pack for a Class 8 BEV truck accounts for roughly 55 percent of the cost of the truck.[68] Regardless of fleet size these truck cost increases will be noticeable. For example, a typical new Class 8 diesel truck tractor may cost roughly $135,000 to $150,000; a comparable Class 8 BEV truck may price at $400,000 to $500,000.[69] Operating margins for truckload carriers were approximately 10 percent of revenue in 2021; the extreme increase in marginal operating costs that would result

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[66] Dana Hull, "2010: Tesla gets ready to take over the former NUMMI auto plant in Fremont," *The Mercury News* (September 16, 2010), https://www.mercurynews.com/2010/09/16/2010-tesla-gets-ready-to-take-over-the-former-nummi-auto-plant-in-fremont/.

[67] Argonne National Laboratory, *The Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET®) Model* (2021), https://greet.es.anl.gov/index.php.

[68] Jim Stinson, "Money and range: Experts note roadblocks to EV adoption," Transport Dive (September 14, 2021), https://www.transportdive.com/news/act-expo-electric-trucks-battery-infrastructure/606386/.

[69] Claire Buysse, "How Much Does an Electric Semi Really Cost?," International Council on Clean Transportation (February 24, 2022), https://theicct.org/cost-electric-semi-feb22/.

from a potential 3+ fold increase in equipment costs would most certainly erase these margins unless the costs can be passed on to consumers.[70]

To ensure BEV truck adoption occurs, it is critical that the materials for lithium-ion batteries are readily available from diverse, redundant sources – and that the supply is free of disruptions. One method for reducing battery costs and side-stepping geopolitical issues would be to increase domestic mining of battery materials. While new regulatory and permitting issues would arise, other costs such as maritime shipping would be reduced or eliminated.

<u>Raw Materials for BEV Trucks</u>

Raw materials used in lithium-ion batteries are mined from the earth either from the surface, from bodies of water or underground. The materials used in lithium-ion batteries vary. Those materials that are unique to a typical BEV battery and not found in an ICE include the following:

- Cobalt
- Graphite
- Lithium
- Nickel

These materials were the focus of this analysis, but it should be noted that copper and manganese are also critical to BEV batteries and motors.

There is concern that the mining of the raw materials for batteries will have large global impacts related to environmental and social issues. The World Bank found that "the technologies assumed to populate the clean energy shift … are in fact significantly MORE material intensive in their composition than current traditional fossil-fuel-based energy supply systems."[71] The report concluded that when considering wind, solar and battery storage for vehicles, "it is in the area of transportation that the impacts on particular metals' future markets is probably most pronounced."[72]

There is a large body of work on the environmental and social impacts of mining minerals for vehicle batteries and other clean energy uses. A succinct summary of the environmental and social issues related to mining the BEV materials is offered by the International Energy Agency (IEA) below.

- "Significant greenhouse gas (GHG) emissions arising from energy-intensive mining and processing activities."
- "Environmental impacts, including biodiversity loss and social disruption due to land use change, water depletion and pollution, waste-related contamination and air pollution."
- "Social impacts stemming from corruption and misuse of government resources, fatalities and injuries to workers and members of the public, human rights abuses including child labor and unequal impacts on women and girls."
- "[Related] supply disruption, which could slow the pace of clean energy transitions."[73]

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[70] Alex Leslie and Dan Murray, *An Analysis of the Operational Costs of Trucking: 2022 Update*, ATRI (August 2022), https://truckingresearch.org/wp-content/uploads/2022/08/ATRI-Operational-Cost-of-Trucking-2022.pdf.
[71] Daniele La Porta Arrobas et al., *The Growing Role of Minerals and Metals for a Low Carbon Future*, World Bank Group (June 2017), https://documents.worldbank.org/en/publication/documents-reports/documentdetail/207371500386458722/the-growing-role-of-minerals-and-metals-for-a-low-carbon-future.
[72] Ibid.
[73] International Energy Agency, *The Role of Critical Minerals in Clean Energy Transitions* (May 2021), https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions.

Lithium as a Case Study

As noted, there are multiple materials needed for BEVs. Lithium offers an excellent example of the complexity of mining BEV materials. According to Barron's, "the value of global lithium sales will grow 20-fold between 2020 and 2030," and "lithium prices are up roughly 400 percent over the past year."[74] The following lithium mining synopsis creates context for this growth.

Lithium is an alkali metal that is highly reactive with water and is flammable. The global lithium supply predominantly comes from two types of mining, hard-rock mining and salt-flat mining, both described below.

> Hard-Rock Mining: This approach extracts small amounts of lithium from rock such as granite.[75] Currently, Australia leads in lithium production using this approach at 60,627 US tons in 2021.[76] The mines are first excavated, bringing the rock to the surface. From there the excavated material is crushed and physically separated, producing a concentration of crystals that contain lithium. This concentration can then be shipped for processing, which often takes place in China. Processing of the concentrate is done through a heating and cooling process and acid roasting. The end result is a number of lithium products, most notably lithium carbonate, a stable form of lithium that can be used to produce batteries. This is an energy-intensive and costly process, and also includes use of highly corrosive compounds (e.g. hydrofluoric acid) as extraction reagents.

> Salt-Flat Mining: Salt-flats are the remnants of lake beds that contain briny water with minerals such as lithium. To extract lithium, the brine is pumped to a series of evaporation ponds, increasing the mineral concentration. When the lithium concentration is high enough, it is pumped to a processing station where unwanted elements are removed and treated chemically to isolate the lithium. Chile is the largest producer of lithium from brine, making 28,660 US tons in 2021.[77]

Cost. Overall, salt-flat mining is less expensive than hard-rock mining, particularly since pumping water is less labor-intensive, and the majority of the extraction work is done by the sun.[78] The tradeoff is time; it can take 12-18 months for the excess water to evaporate whereas hard-rock mining can be done as fast as equipment and shipping will allow.

Lead Time. The time between mineral discovery and full production varies by country and mining approach. For example, the lead time is seven years for brines in South America versus four years for hard-rock mines in Australia.[79] As demand for lithium increases, this lead time

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[74] Al Root, "China Is Winning the Lithium Wars. What It Means for Tesla and Other EV Stocks," *Barrons* (May 18, 2022), https://www.barrons.com/articles/china-ev-batteries-lithium-mining-51652889888.
[75] SGS Minerals Services, "Hard Rock Lithium Processing" (2013), https://www.sgs.com/-/media/sgscorp/documents/corporate/brochures/sgs-min-wa109-hard-rock-lithium-processing-en.cdn.en.pdf.
[76] U.S. Geological Survey, "Mineral Commodity Summary: Lithium" (January 2022), https://www.usgs.gov/centers/national-minerals-information-center/lithium-statistics-and-information.
[77] Ibid.
[78] Adam Webb, "Lithium Sector: Production Cost Outlook," S&P Global Marketing Intelligence (May 10, 2019), https://pages.marketintelligence.spglobal.com/lithium-sector-production-costs-outlook-MS-demo-confirmation.html.
[79] International Energy Agency, *The Role of Critical Minerals in Clean Energy Transitions* (May 2021), https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions.

can play a critical role in pricing and availability. Time is a critical factor when the demand for lithium is increasing dramatically over what the current supply chains can provide.

Energy Use and CO_2. Hard-rock mining is far more energy-intensive than salt-flat mining and requires extracting rock and then crushing and heating the mined materials. For every metric ton of lithium produced, hard-rock mining releases more than 33,000 lbs. of CO_2, three times that of brine mining.[80] Hard-rock lithium mines also produce large amounts of waste material (some of which is toxic) at both the extraction and separation stages.

Water depletion through evaporation is a concern for salt-flat mining. Estimates range considerably; researchers have found that in some operations only 233 gallons were evaporated per pound of lithium extracted, while others had to evaporate 1.2 million gallons of water to obtain a pound of lithium.[81]

Geopolitical and Social Issues. There are also geopolitical and social issues related to lithium mining. In Chile, for example, the government regulates salt-flat mining, while private enterprises operate them.[82] These enterprises often have ties to foreign companies and governments, particularly China. Química y Minera de Chile (SQM), one of Chile's largest mining companies, is owned in part by China's Tianqui Lithium Corporation which has a 23.7 percent stake. Two other Chinese companies have signed agreements with the Chilean government to grant them rights for lithium exploration and support for future Chinese mining operations.[83]

There are also agreements on royalties that these companies must pay to the Chilean government to help keep the benefits of mining within the country, but a combination of corruption, public opposition and protests has shut down mining operations in the past.[84] In 2012 the Chilean government had to cancel a new lithium concession (an agreement for land access and extraction) after it was accused of unfairly privileging SQM. Additionally, there are past instances where concessions have been canceled in Chile after it was discovered that company interests were "making kickback payments to politicians in all the mainstream political parties."[85] Citizen support for mining is also wavering. Protestors have targeted mining as environmentally dangerous and exploitative – shutting down access to one of SQMs mines in 2019.[86]

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[80] Catherine Early, "The new 'gold rush' for green lithium," *BBC* (November 24, 2021), https://www.bbc.com/future/article/20201124-how-geothermal-lithium-could-revolutionise-green-energy.
[81] James J.A. Blair et al., *Exhausted: How We Can Stop Lithium Mining From Depleting Water Resources, Draining Wetlands, And Harming Communities In South America*, NRDC (April 2022) https://www.nrdc.org/sites/default/files/exhausted-lithium-mining-south-america-report.pdf.
[82] Ibid.
[83] Evan Ellis, "Chinese advances in Chile," *Global Americans* (March 2, 2021), https://theglobalamericans.org/2021/03/chinese-advances-in-chile/.
[84] Ibid; Dave Sherwood, "Chile protesters block access to lithium operations: local leader", *Reuters* (October 25, 2019), https://www.reuters.com/article/us-chile-protests-lithium/chile-protesters-block-access-to-lithium-operations-local-leader-idUSKBN1X42B9.
[85] James J.A. Blair et al., *Exhausted: How We Can Stop Lithium Mining From Depleting Water Resources, Draining Wetlands, And Harming Communities In South America*, NRDC (April 2022) https://www.nrdc.org/sites/default/files/exhausted-lithium-mining-south-america-report.pdf.
[86] Dave Sherwood, "Chile protesters block access to lithium operations: local leader," *Reuters* (October 25, 2019), https://www.reuters.com/article/us-chile-protests-lithium/chile-protesters-block-access-to-lithium-operations-local-leader-idUSKBN1X42B9.

As lithium supplies become more critical to U.S. transportation and trucking, these issues will likely increase in intensity. With only one active lithium mine in the U.S., lithium dependence on global competitors such as China is of great concern.[87]

Availability of Raw Materials

Global markets for BEV truck battery materials are meeting current demand, albeit at dramatically higher prices, but material availability will need to be far more robust to meet future demand. Production of the four materials discussed earlier is dominated by a handful of countries (Table 5).[88]

Table 5: Top Producers of Four BEV Materials

	Rank	Country	Production (Tons)	Percent of Total Production
Cobalt	1	Congo (Kinshasa)	132,277	70.6%
	2	Russia	8,378	4.5%
	3	Australia	6,173	3.3%
Graphite	1	China	903,894	82.0%
	2	Brazil	74,957	6.8%
	3	Mozambique	33,069	3.0%
Lithium	1	Australia	60,627	55.0%
	2	Chile	28,660	26.0%
	3	China	15,432	14.0%
Nickel	1	Indonesia	1,102,310	37.0%
	2	Philippines	407,855	13.7%
	3	Russia	275,578	9.3%

Future materials availability, regardless of country source, should also be part of the BEV calculus. Known mineral reserves are those that, based on geological studies, can be reasonably assumed to exist and can be recovered at a reasonable price using standard practices and technologies. The countries with the largest reserves for each type of material is shown in Table 6.[89]

[87] Patrick Whittle, “U.S. seeks new lithium sources as demand for clean energy grows,” *PBS* (March 28, 2022), https://www.pbs.org/newshour/economy/u-s-seeks-new-lithium-sources-as-demand-for-clean-energy-grows.
[88] U.S. Geological Survey, *Mineral Commodity Summaries 2022* (2022), Pages 53, 75, 101, 115, https://pubs.usgs.gov/periodicals/mcs2022/mcs2022.pdf. Production volumes converted from metric tons to US tons.
[89] U.S. Geological Survey, *Mineral Commodity Summaries 2022* (2022) Pages 53, 75, 101, 115, https://pubs.usgs.gov/periodicals/mcs2022/mcs2022.pdf. Production volumes converted from metric tons to US tons.

Table 6: Location of Top Known Reserves

	Rank	Country	Reserves (Tons)	Percent of Total Reserves
Cobalt	1	Congo (Kinshasa)	3,858,085	46.1%
	2	Australia	1,543,234	18.4%
	3	Indonesia	661,386	7.9%
	4	Cuba	551,155	6.6%
	5	Philippines	286,601	3.4%
Graphite	1	Turkey	99,207,900	28.1%
	2	China	80,468,630	22.8%
	3	Brazil	77,161,700	21.9%
	4	Madagascar	28,660,060	8.1%
	5	Mozambique	27,557,750	7.8%
Lithium	1	Chile	10,141,252	41.8%
	2	Australia	6,283,167	25.9%
	3	Argentina	2,425,082	10.0%
	4	China	1,653,465	6.8%
	5	United States	826,733	3.4%
Nickel	1	Australia	23,148,510	23.1%
	2	Indonesia	23,148,510	23.1%
	3	Brazil	17,636,960	17.6%
	4	Russia	8,267,325	8.3%
	5	Philippines	5,291,088	5.3%

Quantifying the Demand for Raw Materials

To better understand the potential mineral demand needed by the U.S. vehicle fleet (trucks and cars) the research team developed a methodology for estimating how much of the four primary battery materials – cobalt, graphite, lithium and nickel – would be needed, first in a typical truck tractor and then in other vehicle types. To generate estimates of battery material requirements of the four key materials, six common battery compositions were averaged.[90] It should be noted that the base data used in this analysis were obtained from IEA mineral requirements for each battery type, which are published in kg of material per 75 kWh.[91] This was then converted to pounds of material per kWh of initial battery storage.

As a first step, the battery storage requirement assumptions for truck tractors were averaged. The truck specification averages were a day cab at 909 kWh of storage and a sleeper cab at 1622 kWh of storage, resulting in 1265.5 kWh of storage; both were derived from the Argonne

[90] Battery types included: NCA, NCA+, NMC 333, NMC 532, NMC 622, NMC 811.
[91] International Energy Agency, *The Role of Critical Minerals in Clean Energy Transitions* (May 2021), Page 89, https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions.

Lab's GREET model assumptions.[92] These figures were multiplied by the pounds per kWh calculations to identify the average weight by material type for a combination truck.

The results, shown in Table 7, are pounds of each raw material required for an average long-haul truck.

Table 7: Raw Material Weight per Truck*

	Cobalt	Graphite	Lithium	Nickel
Truck, Combination: Lbs. of Material per Truck	456.31	2,501.65	324.87	1,590.27

Next, in Table 8, the total raw material weight needed to replace the batteries for 2.925 million truck tractors was calculated and converted from pounds to tons.

Table 8: Raw Material Weight for U.S. Long-Haul Truck Fleet*

	Cobalt	Graphite	Lithium	Nickel
Truck, Combination: U.S. Fleet Requirements (Tons)	667,403	3,658,929	475,162	2,325,936

Finally, since these raw materials will be demanded by all vehicle types in the U.S., single unit trucks and light-duty vehicles were added to the table using the GREET model assumption approach previously described (above Table 7).[93] The results, by vehicle type, are shown in Table 9.

[92] Argonne National Laboratory, *The Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET®) Model* (2021), https://greet.es.anl.gov/index.php; Federal Highway Administration, "Highway Statistics 2019" (accessed on October 14, 2022), https://www.fhwa.dot.gov/policyinformation/statistics/2019/.
[93] Battery storage, found in the kWh/per vehicle column, were derived using GREET model assumptions.

Table 9: Raw Material Weight for All U.S. Vehicles*

Type	Fleet	kWh/per vehicle	Cobalt (Tons)	Graphite (Tons)	Lithium (Tons)	Nickel (Tons)
Light-duty vehicle, short wheelbase	194,348,815	84	2,943,271	16,136,003	2,095,481	10,257,459
Light-duty vehicle, long wheelbase	59,465,369	122	1,307,956	7,170,653	931,208	4,558,296
Truck, single-unit 2-axle 6-tire or more	10,160,433	261	478,103	2,621,124	340,389	1,666,216
Truck, Combination	2,925,210	1265.5	667,403	3,658,929	475,162	2,325,936
Total: U.S. Vehicle Fleet			**5,396,733**	**29,586,708**	**3,842,239**	**18,807,908**

It is clear that light-duty vehicles – passenger cars and trucks – will generate the largest demand for raw materials in the U.S.

Battery Weight and Cargo Capacity

Battery weight may substantially limit the long-haul capabilities of a BEV. As discussed earlier in the baseline analysis, based on the GREET model, the long-haul ICE truck tractor weight is 18,216 lbs., while the BEV's weight (including the battery) is 32,016 lbs.[94] The details are shown in Table 10.

To understand the cargo implications of this weight difference, the ICE and BEV weight examples were paired with an empty 11,264 lb. trailer (per GREET). From that, tare weight was calculated. The tare weight was subtracted from maximum gross weight of 80,000 lbs. to find available revenue weight. Finally, lost revenue weight of 13,800 lbs. was calculated for the BEV truck due to battery size.

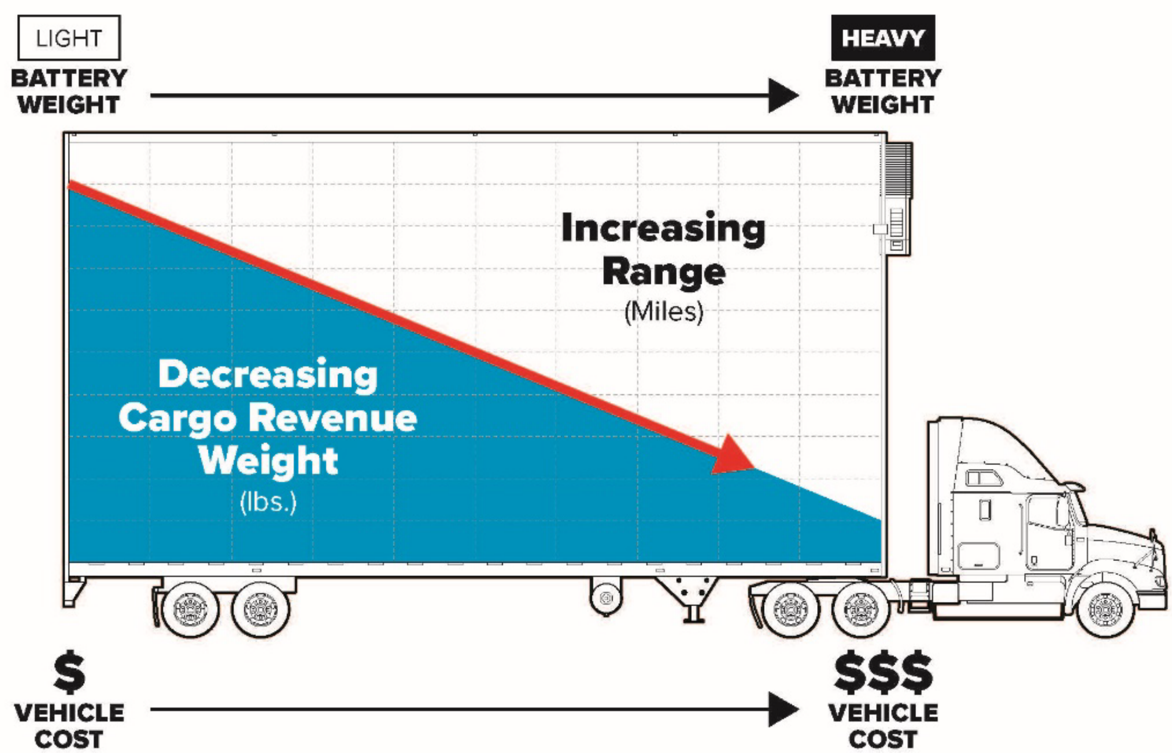
[94] Jeffrey Short and Danielle Crownover, *Understanding the CO_2 Impacts of Zero-Emission Trucks*, American Transportation Research Institute (May 2022), https://truckingresearch.org/2022/05/03/understanding-the-co2-impacts-of-zero-emission-trucks/.

Table 10: Vehicle, Trailer and Cargo Weight

Weight (lbs.)	ICE	BEV
Maximum Gross Weight	80,000	80,000
Tractor Weight	18,216	32,016
Trailer Weight	11,264	11,264
Vehicle Tare Weight	29,480	43,280
Available Revenue Weight	50,520	36,720
Lost Revenue Weight from Baseline	**-**	**-13,800**

This "BEV truck conundrum" is further illustrated in Figure 9. Heavier batteries are able to store more energy, thus increasing a truck's driving range. Heavier batteries cost more since they use more raw materials. While this extra cost and weight can help decrease the number of charging stops, it also decreases the amount of cargo weight that can be carried, resulting in lost revenue.

Figure 9: BEV Truck Conundrum



Vehicle Production Issues in the U.S.

Based on the above background information and analysis, the research team has identified the following key issues related to electric vehicle production.

Vehicle Production Issue One: Demand for Raw Materials will Likely Increase Battery Prices and Shortages

Assuming U.S. and global fleet electrification rates continue to increase, there will be increased demand for raw materials. Meeting this demand – and doing so without significant cost and reliability issues – is critical for the trucking industry.

To assess the battery materials supply and demand question, the research team analyzed global production levels and known reserves of the four raw materials previously discussed to identify the materials needed for replacing the full U.S. car and truck fleet.

First, the quantity of each material required for each new electric long-haul truck and single unit truck (> 13 million vehicles) was calculated.

The results show that the material quantities needed for full electrification of the trucking industry is 1.3 to 7.4 times greater than current production, depending on the material.

As shown in Table 11, trucks would require six times the amount of cobalt than is currently mined globally. In other words, trucks would need **more than six years of current global cobalt production** to meet full electrification in just the U.S.

Table 11: Tons of Material Needed to Replace the U.S. Truck Fleet*

	Cobalt	Graphite	Lithium	Nickel
Annual Global Production (Tons)	187,393	1,102,310	110,231	2,976,237
U.S. Trucking Needs (Combo and SU) (Tons)	1,145,506	6,280,053	815,551	3,992,152
Total Trucking Demand/Years of Global Production	6.1	5.7	7.4	1.3

There are several caveats to this analysis, however. First, the fleet would not be immediately replaced, so this demand would not arise at a single moment in time. On the other hand, all of this demand for materials is new and is in addition to what is currently produced. Finally, this new production level would only supply a single round of batteries. Replacement batteries would be needed approximately every 6.2 years, assuming a useable life of 500,000 miles.[95] This analysis does not include battery material demand for other countries, so those figures are not included in this analysis.

[95] Jeffrey Short and Danielle Crownover, *Understanding the CO_2 Impacts of Zero-Emission Trucks*, American Transportation Research Institute (May 2022), https://truckingresearch.org/2022/05/03/understanding-the-co2-impacts-of-zero-emission-trucks/.

Next, demand for the raw materials needed for cars was calculated and added to the truck figures, thus highlighting the raw material demand of the full U.S. fleet as shown in Table 12. These figures include all trucks and light-duty vehicles (e.g. cars), equating to nearly 267 million vehicles. As an example, cobalt demand for full electrification of the U.S. vehicle fleet would require **28.8 years of cobalt production** at current production levels. Again, this does not include demand calculations for any other country.

Table 12: Tons of Material Needed to Replace all U.S. Vehicles

	Cobalt	Graphite	Lithium	Nickel
Annual Global Production (Tons)	187,393	1,102,310	110,231	2,976,237
Total U.S. Vehicle Fleet Requirements	5,396,733	29,586,708	3,842,239	18,807,908
Total U.S. Vehicle Demand/Years of Global Production	28.8	26.8	34.9	6.3

The last calculation focuses on U.S. fleet raw material needs as compared to available reserves (Table 13).[96] The cobalt that would be needed by the U.S. vehicle fleet is **64.4 percent of global reserves**.

Table 13: Tons of Material Needed versus Global Reserves

	Cobalt	Graphite	Lithium	Nickel
Global Reserves (Tons)	8,377,556	352,739,200	24,250,820	> 100,000,000
Total U.S. Vehicle Fleet Needs	5,396,733	29,586,708	3,842,239	18,807,908
Fleet Needs as a Percent of Known Reserves	64.4%	8.4%	15.8%	< 18.8%

This analysis does not presume that material supplies will quickly become exhausted, as known reserves and requisite mining activities are certain to increase. But the overall quantities of materials needed, and the availability of those materials, will all play a role in pricing and availability – both of which will heavily influence adoption levels for BEV cars and trucks.

[96] That part of the reserve base that could be economically extracted or produced at the time of determination. The term “reserves” need not signify that extraction facilities are in place and operative. Reserves include only recoverable materials. Further definition can be found at: U.S. Geological Survey, *Mineral Commodity Summaries 2022* (2022), Appendix C, https://pubs.usgs.gov/periodicals/mcs2022/mcs2022.pdf. Production volumes converted from metric tons to US tons.

After some period of time when capital investments in mining are optimized, traditional economic theory indicates that economies of scale would reduce battery costs. However, that would not likely occur until raw material supplies are meeting future demand, and a sizeable percentage of vehicles are already BEVs.

Vehicle Production Issue Two: BEV Environmental and Social Issues are Considerable

Environmental and social issues will likely impact BEV battery costs and availability. As a result, companies that monitor ESG performance may have difficulty sourcing batteries.

Both environmental and human rights groups have researched the significant harm associated with international mining of BEV raw materials.

Environmental Issues

Mining and processing raw battery materials has both global and local impacts on emissions. As shown in Table 14, to meet the battery production requirements of the full U.S. vehicle fleet there will be significant air quality impacts.[97] For CO_2 emissions, the impact is global. Locally, air pollution in the form of nitrogen oxides, sulfur oxides and particulate matter becomes important to the country of origin. However, U.S. vehicles that no longer have tailpipe emissions are essentially "exporting" air quality issues to other countries.

Table 14: Select Mining and Processing Emissions

	Cobalt Mining & Processing Emissions (Tons)	Lithium Mining & Processing Emissions (Tons)	Graphite Mining & Processing Emissions (Tons)	Nickel Mining& Processing Emissions (Tons)	Total Mining & Processing Emissions (Tons)
CO2	19,537,037	45,814,111	136,380,260	274,437,614	476,169,022
NOx	35,804	68,290	414,613	395,348	914,055
PM10	334,622	12,539	160,252	485,648	993,061
PM2.5	36,439	8,837	79,527	247,146	371,949
SOx	279,504	58,936	2,218,042	54,541,708	57,098,189

These figures are based on current mining and related impact assumptions from the GREET model. While new methods and technologies may offset mining's environmental impacts, it is also a reality that future mines may have lower ore concentrations than those previously mined. Therefore, future operations could be more costly both in financial and environmental terms.[98]

[97] Argonne National Laboratory, *The Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET®) Model* (2021), https://greet.es.anl.gov/index.php.
[98] Arjan de Koning et al., "Metal supply constraints for a low-carbon economy?" Resources, Conservation and Recycling 129 (February 2018), https://www.sciencedirect.com/science/article/pii/S0921344917303762.

Social Issues

As with many economic endeavors, there are likely to be winners and losers. In the raw materials source country, those who are impacted by environmental issues generally experience more negative impacts. In lesser developed countries, labor issues may benefit or harm certain populations more than others.

In 2016, Amnesty International conducted research on cobalt mining in the Democratic Republic of the Congo (DRC) – the top producer of cobalt – and found working conditions that violated numerous United Nation human rights policies.[99] Since the "vast majority" of the 110,000 DRC cobalt mines are unauthorized or illegal, there is no government oversight or enforcement in place. The Amnesty International report further cites UNICEF data from 2014 indicating that an estimated 40,000 children work in DRC mining operations.

For companies and countries seeking to source goods with a certain environmental or social standard, the sourcing of compliant minerals may prove challenging and/or costly in the global market.

Strategies for Addressing Raw Material Issues

This section analyzed shortfalls in the present-day availability of raw materials. There are scenarios, however, that could mitigate these concerns.

First, it is possible that advances in mining production will take place. As demand grows for these materials, the price will increase which will in turn incentivize new exploration and production.

There is also a push by the Biden administration to mine key minerals in the U.S.[100] Domestic production would increase global supply, but it could be difficult to achieve due to environmental and cost concerns. There are several examples of domestic operations that may be able to add to the supply of BEV material.

The U.S. has one active lithium mine, located in Silver Peak, Nevada which produces approximately 3,150 tons each year; overall, the U.S. mines and processes only one percent of the global finished product.[101] There are areas being explored for additional mining, such as Gaston County, North Carolina, which has in the past provided lithium for nuclear weapons through hard-rock mining.[102]

[99] Amnesty International, *"This is what we die for": Human rights abuses in the Democratic Republic of the Congo power the global trade in cobalt* (January 2016), https://www.amnesty.org/en/documents/afr62/3183/2016/en/.
[100] U.S. Department of Energy, "Electric Vehicle (EV) and Fuel Cell Electric Vehicle (FCEV) Tax Credit" (accessed on November 2022), https://afdc.energy.gov/laws/409.
[101] Scott Patterson and Amrith Ramkumar, "America's Battery-Powered Car Hopes Ride on Lithium. One Producer Paves the Way," *The Wall Street Journal* (March 9, 2021), https://www.wsj.com/articles/americas-battery-powered-car-hopes-ride-on-lithium-one-producer-paves-the-way-11615311932.; Jack Ewing and Brendan George Ko, "Race to the Future: How a Quebec Lithium Mine May Help Make Electric Cars Affordable," *The New York Times* (September 20, 2021), https://www.nytimes.com/2022/09/20/business/electric-vehicles-lithium-quebec.html.
[102] Yvonne Yue Li, "North America's EV Future Hinges on a North Carolina Turtle Pond," *Bloomberg*, (November 16, 2022), https://www.bloomberg.com/news/features/2022-11-16/us-seeks-to-mine-lithium-for-electric-vehicle-batteries.

An Idaho cobalt mine opened in October 2022; it could meet about ten percent of U.S. cobalt demand once it is fully operational, but the raw material still must be shipped to Brazil for processing.[103]

Finally, there is significant domestic mining potential in Minnesota for metals such as nickel. The mineral deposit in northeast Minnesota is said to contain "95 percent of the nation's nickel reserves; 34 percent of the nation's copper; 88 percent of the cobalt; 51 percent of the platinum and 48 percent of the palladium."[104]

Advances in battery technology ultimately will have to play a key role in electrification. Batteries must become lighter and more energy dense, and they may ultimately be produced with entirely different materials. There is considerable research presently underway in all of these areas.

[103] Kirk Siegler, "In Idaho, America's first, and only cobalt mine in decades is opening," *Oregon Public Broadcasting*, (October 8, 2022), https://www.opb.org/article/2022/10/08/in-idaho-america-s-first-and-only-cobalt-mine-in-decades-is-opening/.
[104] Twin Metals Minnesota, "Why Minnesota," (accessed on November 23, 2022), https://www.twin-metals.com/why-minnesota/.

CHALLENGE THREE: TRUCK CHARGING REQUIREMENTS

The trucking industry will require and consume an immense amount of electricity to maintain operations. Unlike passenger vehicles, trucks are tasked with moving freight across long distances. To accomplish this, a BEV truck battery will be heavier and require a much larger energy capacity than a BEV car battery.

Long-haul trucks travel larger geographies, logging many more rural miles than car travel. FHWA's VMT statistics indicate that 73.7 percent of car travel is urban, compared with 46.6 percent of long-haul truck travel. [105] Thus, nearly three-quarters of car travel occurs in charging-accessible areas. Long-haul trucking, on the other hand, has less than half of its mileage in charging-accessible areas.

This sentiment is found in the energy literature as well. In a 2022 statement, the EIA noted:

> "Highway charging … presents some specific difficulties. When transport corridors are located in areas with existing grids, the installation of chargers does not have major barriers, provided that the grid is not already congested. But to provide charging in more remote locations, grid upgrade costs can become a barrier."[106]

Consequently, the challenges associated with providing charging services to the long-haul trucking industry are considerable. It is important to understand the regulatory constraints that impact drivers, the ongoing truck parking shortage, and the anticipated charging capacity needs of long-haul trucking.

Truck Charging: Synchronizing Drivers, Parking Availability and Federal Work Regulations

Truck driving schedules are complex; they are built around federal Hours-of-Service (HOS) regulations, shipper contract requirements, access to fueling, congestion avoidance, and access to truck parking locations near customer facilities – all factors that impact or dictate where truck charging should or should not be located.

Federal Hours-of-Service

All commercial truck drivers must abide by federal HOS regulations; typically this means drivers must take 10 hours of rest to earn 14 hours of available on-duty time (which includes 11 hours of driving time).[107]

For truck drivers that operate long-haul and utilize their sleeper berths for HOS compliance, it is imperative that battery charging take place during these mandatory rest periods. In addition,

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[105] Federal Highway Administration, "Table VM-1: Annual Vehicle Distance Traveled in Miles and Released Data – 2019" (accessed on October 13, 2022), Highway Statistics Series 2019, https://www.fhwa.dot.gov/policyinformation/statistics/2019/vm1.cfm.
[106] International Energy Agency, "Global EV Outlook 2022: Securing supplies for an electric future" (May 2022), Page 200, https://www.iea.org/reports/global-ev-outlook-2022.
[107] Depending on schedules and other considerations, drivers do have the ability to split their rest into two periods of 8 hours and 2 hours, or 7 hours and 3 hours.

high-speed Opportunity Charging could be incorporated and expanded to reduce time spent at stationary charging stations.[108]

Truck Parking

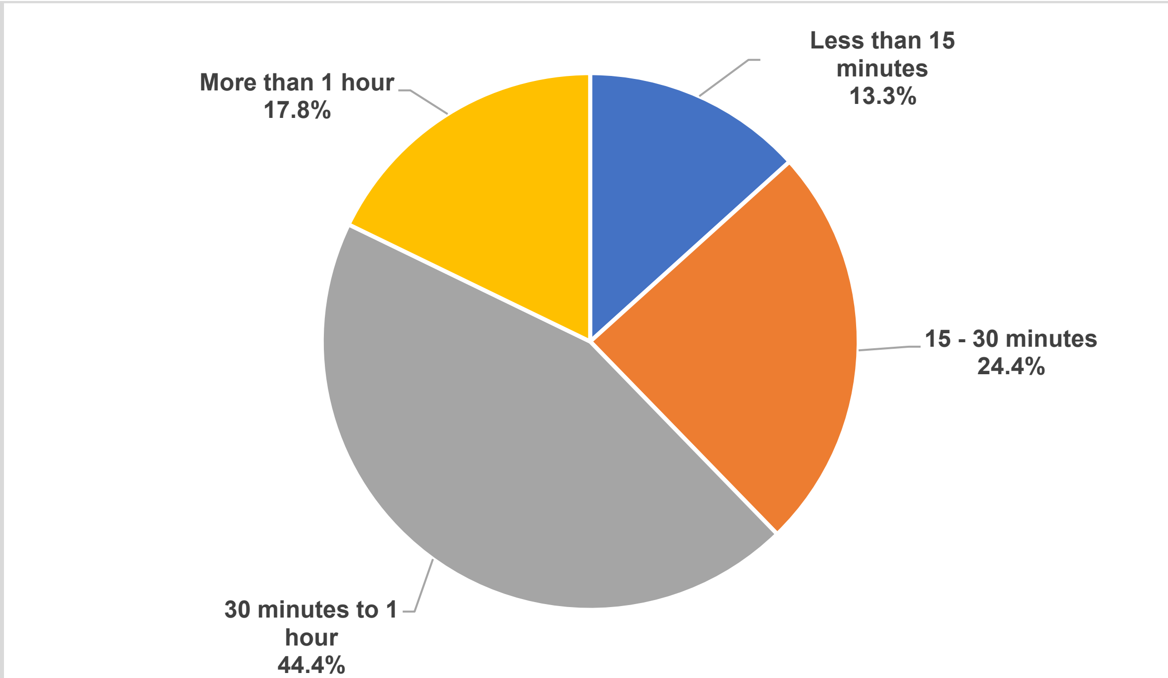
Additionally, this charging will have to take place at existing truck parking locations along interstate trucking routes; it would be cost prohibitive to build an entirely new parking and charging network in the U.S. There are approximately 313,000 truck parking spaces in the country, as inventoried by FHWA in 2019.[109] This includes 40,000 truck parking spaces at public rest areas and 273,000 truck parking spaces at private truck stops.

Truck parking is a significant problem for the trucking industry, identified by drivers as their top industry concern.[110] One ATRI truck parking study found that an average of 56 minutes of drive time per day was lost due to drivers parking early to avoid the risk of not being able to find a place to park later in their duty-cycle; this loss of productivity was equal to nearly $5,000 per driver in lost wages annually.[111]

Drivers report spending significant non-revenue time looking for available parking. Figure 10 shows the amount of time truck drivers spend every day looking for a parking space and underscores that an optimal truck charging network should reduce, rather than exacerbate, truck parking issues.[112]

[108] David Cullen, "Challenges of Charging Commercial Trucks," *Heavy Duty Trucking* (September 20, 2022), https://www.truckinginfo.com/10181496/challenges-of-charging-commercial-trucks.
109 Federal Highway Administration, "National Coalition on Truck Parking: 5th Meeting" (December 1, 2020), https://ops.fhwa.dot.gov/freight/infrastructure/truck_parking/workinggroups/2020/mtg/nctptpwnmtg12012020.pdf.
[110] American Transportation Research Institute, *Critical Issues in the Trucking Industry – 2022* (October 2022), https://truckingresearch.org/atri-research/top-industry-issues/.
[111] Caroline Boris and Rebecca M. Brewster, Managing Critical Truck Parking Case Study – Real World Insights from Truck Parking Diaries, ATRI (December 2016), https://truckingresearch.org/wp-content/uploads/2016/12/ATRI-Truck-Parking-Case-Study-Insights-12-2016.pdf.
[112] American Transportation Research Institute, MAASTO Truck Parking Survey Analysis - February 2020, Mid America Association of State Transportation Officials (2020), https://trucksparkhere.com/wp-content/uploads/2020/03/2019-MAASTO-Survey-Report-FINAL.pdf.

Figure 10: Time Spent per Day to find Parking



Thus, for electrification of long-haul trucks to be feasible, charging must be available at truck parking spaces while drivers are taking mandatory rest periods.

At the nation's approximately 40,000 public rest stop truck parking spaces, commercial charging is not allowable under federal law. This limitation stems from a 1956 regulation that restricts any commercial activity at public rest areas, including fueling or restaurants (though some grandfather clauses exist).[113] This regulation presents myriad challenges to public rest area charging. The likely consequence and implications are that truck charging fees either could not be assessed at public rest areas, could not exceed direct electricity costs, and/or that private sector entities could not provide the charging services.

A change in this rule might be difficult to achieve. Opposition to efforts to commercialize public rest areas is strong. In early 2021, for instance, a broad coalition of fifteen associations lobbied Congress to maintain the ban on commercialization of public rest areas.[114] In a letter to Congress, the group urged legislators to reject proposals that "would allow state departments of transportation to compete against the private sector" through the sale of electric vehicle charging services at Interstate rest areas.[115] Key to this argument is that towns, cities and local retailers are harmed when drivers can remain on the Interstate for products and services.

[113] Jim Stinson, "The debate over EV charging at interstate rest stops," *Transport Drive* (February 26, 2021), https://www.transportdive.com/news/NATSO-commercialization-interstate-rest-stop-electric-charging/595536/.
[114] Including the National Restaurant Association, the National Retail Federation, and the National Association of Truck Stop Operators.
[115] National Association of Truck Stop Operators et al., *Letter on Commercialization of Interstate Rest Areas to 117th House of Congress* (February 22, 2021).

By late 2021 FHWA had issued guidance on the matter clarifying that state Departments of Transportation and local agencies cannot operate or authorize commercial services (including EV charging stations) in most Interstate Right of Ways."[116]

On the private sector side, the business model for electric vehicle charging at the nation's 273,000 private truck stop spaces is unclear. Emerging issues related to charging at private truck stops include disputes between truck stop operators and electric utilities that relate to who is responsible for infrastructure development, oversight of electricity sales, and what amount can be charged per kWh.

How Many Chargers are Needed?

It is also clear that the nation's diesel pumps cannot simply be swapped out for charging stations.

Currently, most long-haul truck drivers refuel at national networks of competing private truck stops and other fueling stations. For long-haul operations, the refueling task is undertaken while a driver is on-duty. Diesel refueling is generally a quick process – a fuel dispenser with a fast flow rate of 60 gallons per minute, for example, could fill a long-haul truck in less than five minutes, while those with an average rate in the range of 20-30 gallons per minute can fill the largest tanks in 10-15 minutes.[117] The refueling task is relatively brief for a truck driver and as a result a low ratio of pumps to trucks is needed since trucks can refuel and leave quickly (Table 15).

Table 15: Mileage and Refueling Time for a Diesel Truck

Truck Type	Assumed Fuel Economy (mpg)[118]	Capacity per Tank (gallons)	Mileage Range	Refueling time at 25 gallons per minute
Long-Haul Truck Example	6.2	300	1860	5-12 minutes

[116] National Association of Truck Stop Operators and SIGMA, "NATSO, SIGMA Praise FHWA for Definitive Guidance on Use of Right-of-Way", News Release (December 14, 2021).; Federal Highway Administration, "Federal Highway Administration (FHWA) Frequently Asked Questions on Electric Vehicle (EV) Charging" (accessed on December 3, 2021), https://www.fhwa.dot.gov/real_estate/right-of-way/corridor_management/ev_charging_faq.cfm.
[117] Fleet Owner Magazine, "High Speed Fuel Pumps" (July 2006), https://www.fleetowner.com/news/article/21672898/highspeed-fuel-pumps; Carlo Cunanan, et al., *A Review of Heavy-Duty Vehicle Powertrain Technologies: Diesel Engine Vehicles, Battery Electric Vehicles, and Hydrogen Fuel Cell Electric Vehicles,* Clean Technologies 3, no.2 (June 1, 2021), https://www.mdpi.com/2571-8797/3/2/28/htm.
[118] Federal Highway Administration, "Table VM-1: Annual Vehicle Distance Traveled in Miles and Released Data – 2019" (accessed on October 13, 2022), Highway Statistics Series 2019, https://www.fhwa.dot.gov/policyinformation/statistics/2019/vm1.cfm.

Electric charging takes much longer and will need to occur more frequently due to shorter driving ranges. A long-haul truck that holds 300 gallons of diesel could drive more than 1,800 miles across three days between brief refueling events, hours-of-service limitations aside. A truck with a very large 1,500 kWh battery would have to spend at least four to five consecutive hours recharging each day to do a similar task across 3-4 days.

This calculation assumes ideal conditions, however. There are several factors that impact the time it takes to charge, as shown in Table 16.[119]

Table 16: Factors that Impact Charging Rate

Maximum Vehicle Charge Rate	This is the maximum rate that a vehicle can accept electricity.
Maximum Charging Station Charge Rate	This is the maximum electricity rate that the charger can achieve.
State-of-Charge	At the beginning of each charge, it is optimal for the battery to have a 20% to 80% state of charge; charging outside of this level will increase charging time.
Ambient Air Temperature	68 to 77 degrees F is ideal for charging.
Battery Temperature	It is ideal for battery to already be in use rather than to be charged cold.

Additionally, there are factors that impact vehicle range, which are detailed in Table 17.[120] Many of these factors are shared with ICE vehicles, but some are unique to BEVs.

[119] Osprey, "What affects your EV charging speed?" (March 8, 2022), https://www.ospreycharging.co.uk/post/what-affects-your-ev-charging-speed.

[120] Darya Oreizi, "7 Factors That Affect Electric Vehicle Range," Charged Future (April 6, 2020), https://www.chargedfuture.com/7-factors-that-affect-electric-vehicle-range/; AA Motoring, "Five things that impact the range of your electric vehicle," Driven (October 11, 2018), https://www.driven.co.nz/advice/car-care/five-things-that-impact-the-range-of-your-electric-vehicle/; American Automobile Association, *AAA Electric Vehicle Range Testing* (February 2019), https://www.aaa.com/AAA/common/AAR/files/AAA-Electric-Vehicle-Range-Testing-Report.pdf.

Table 17: Factors that Impact Electric Vehicle Range

Roadway Type	BEVs operate better on urban roadways, benefiting from frequent regenerative braking.
Speed, Acceleration	Driving behaviors, including higher speeds and quick acceleration, can impact range.
Wind	Headwinds can impact efficiency.
Payload	Cargo weight can impact efficiency.
Ambient Air Temperature	Low and high temperatures are not ideal for BEVs. A temperature of 20°F can cause a 12 percent decrease in efficiency; 95°F can decrease efficiency 4 percent.[121]
Use of Heating and Cooling Systems	Use of heating cooling systems and other secondary equipment can drain batteries.
Battery Degradation	The age of a battery and charging cycles will impact maximum charge, limiting range.
Terrain	Inclines can impact range.

There are several charging options available for electric vehicles of all classes, including Level 1, Level 2 and direct-current fast charging (DCFC). It is clear that Level 1 charging – which is the same technology used in home electrical outlets – is not an option for long-haul trucks.[122] Additionally, Level 2 charging may work at a private facility for smaller trucks (class 3-6 with 100 miles of range) that return to a terminal each night, but it is not feasible for large long-haul trucks.[123]

DCFC is the only economically viable option to meet the needs of long-haul trucking. For this reason, private truck stops have opted for DCFC – which could charge a vehicle at up to 350 kilowatt (kW) while parked at a truck stop, though charging time depends on vehicle capabilities.[124]

Depending on hardware type and related infrastructure, DCFC systems can deliver between 50 to 350 kW or more.[125] For this type of fast charging however, it is recommended to limit stored battery charges to an 80 percent state-of-charge in order to minimize charging times and prolong battery life.[126] Thus, a battery that is meant to hold 1,000 kWh should only be charged to 800 kWh.

[121] American Automobile Association, AAA Electric Vehicle Range Testing (February 2019), https://www.aaa.com/AAA/common/AAR/files/AAA-Electric-Vehicle-Range-Testing-Report.pdf.
[122] This level of charging offers a car 4-6 miles of range per hour – this range would be much lower for a truck. Jessica Shea Choksey, "What is DC Fast Charging?" J.D. Power (May 10, 2021), https://www.jdpower.com/cars/shopping-guides/what-is-dc-fast-charging.
[123] Chris Brown, "Fleet Electrification: Level 2 or DC Fast Charging?," Charged Fleet (July 27, 2020), https://www.chargedfleet.com/10122096/fleet-electrification-level-2-or-dc-fast-charging.
[124] Anne LeZotte, "GM and Pilot Company to Build Out Coast-to-Coast EV Fast Charging Network," Pilot Flying J (July 14, 2022), https://pilotflyingj.com/press-release/19335.
[125] California Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project, "Electric Vehicle Charging 101" (accessed on November 2022), https://calevip.org/electric-vehicle-charging-101.
[126] Electric Vehicle Energy Storage Company, "The Ultimate Guide to DC Fast Charging" (accessed on July 2022), Blog, https://www.power-sonic.com/blog/the-ultimate-guide-to-dc-fast-charging/.

To understand large truck charging times, four hypothetical Class 8 truck mileage scenarios were assessed. To determine these recharge times and ranges, it was assumed that BEV truck efficiency was 0.42 miles per kWh (Table 3) and batteries would only be charged to 80 percent per the earlier recommendations. Additionally, the HVIP spec sheet data for seven trucks was again utilized to determine charge rate. The seven vehicles reviewed could receive power ranging from 120 kW to 250 kW, with an average charging power of 210 kW.[127] The results are shown below in Table 18.

Table 18: Recharge Times at 210 kW

Truck Type	Battery Capacity (kWh)	Mileage Range at 80% charge	80% Recharging Time at 210 kW (Hours)
Long-Haul Truck	750 kWh	252	2.9
	1000 kWh	336	3.8
	1250 kWh	420	4.8
	1500 kWh	504	5.7

These calculations can now be used to determine the optimal charging times and related charging/parking locations.

The research team next estimated the number of chargers that the long-haul trucking industry would need for the entire long-haul truck fleet. To do this, ATRI first utilized the statistics for combination trucks found in Table 19 (which were presented earlier in Table 2) to identify the energy demands of the nation's long-haul trucks.

Table 19: U.S. BEV Combination Truck Electricity Consumption Estimates*

Combination Truck Fleet Size (FHWA)	Miles/kWh	Truck Fleet Annual VMT (FHWA)	Average Annual Miles Per Truck	Total kWh Needed	Average Annual kWh per Truck
2,925,210	0.42	175.3 million	59,929	417.4 million	142,688

Next the team identified the charging needs of these trucks if they were to operate an average of 200 days per year assuming 300 miles per day in range. To attain this mileage, each truck would need a battery capacity of approximately 900 kWh (assuming the 80 percent charge) charged daily.[128]

[127] California Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project, "HVIP Eligible Vehicles," (accessed on August 11, 2022), https://californiahvip.org/vehiclecatalog/.
[128] This uses the methodology from Table 18.

If the full combination truck fleet operated in this manner, 585 million charging "events" per year would be needed, with each charging event lasting 3.4 hours assuming charging power of 210 kW. This equates to an average of 1.6 million charging events per day.

Finally, these metrics were used to calculate the number of chargers needed in the U.S. to charge the U.S. fleet of 2.925 million combination trucks – based on how many charging events each charger would need to complete (Table 20).[129]

Table 20: U.S. BEV Combination Truck Fleet Charger Utilization Matrix

Daily Charging Events Per Charger	Chargers Needed	Time Charging Per Day (Hours)
1	1,602,855	3.4
2	801,427	6.9
3	534,285	10.3
4	400,714	13.7
5	320,571	17.1
6	267,142	20.6
7	228,979	24.0

Truck parking and truck charging will see very similar peaks in demand. As is the case with truck parking, there are times when there are many empty parking spaces, and there will be times when most of the chargers at a given location will not be in use. It should be noted that to reach higher charging events, trucking will have to lose efficiency. Simply put, for a truck charger to be operating all the time, there must be a line of trucks waiting for hours to charge; ultimately this will not be acceptable to the trucking industry. Thus, more chargers will be needed, and those chargers will tend to not be used at their full capacity.

It should be noted that the higher numbers in the "chargers needed" column of Table 20 are not unreasonable. The California Energy Commission identified a need for 157,000 DCFC to support 180,000 medium- and heavy-duty BEV trucks.[130] This is nearly a 1 to 1 ratio of chargers to trucks.

In applying this 1:1 ratio, the U.S. would ostensibly need a DCFC at nearly every truck parking space in the U.S. With only 313,000 total truck parking spaces in the U.S., each charger would

[129] The demand for charging and parking will change daily during any given week. It is necessary to meet peak demand, however, so on certain days of the week there will be underutilized parking and charging. Weekends have the lowest number of parking/charging events, while mid-week (Wednesday and Thursday) have the most. Source: U.S. Department of Transportation, Federal Highway Administration, "Jason's Law Truck Parking Survey Results and Comparative Analysis" (August 2015), https://ops.fhwa.dot.gov/freight/infrastructure/truck_parking/jasons_law/truckparkingsurvey/index.htm.

[130] California Energy Commission, *Assembly Bill 2127 Electric Vehicle Charging Infrastructure Assessment Analyzing Charging Needs to Support ZEVs in 2030* (July 2021), https://www.energy.ca.gov/programs-and-topics/programs/electric-vehicle-charging-infrastructure-assessment-ab-2127.

have to support at least five charging events per day; such efficient scheduling of chargers appears to be impossible – myriad truck drivers simply could not conduct their normal business operations while at the same time precisely coordinating commercial charger use with other truck drivers. Likewise, drivers will likely charge while taking a rest period (e.g. 10 hours off-duty) which is less time than a charging event, but the vehicle cannot move since the driver cannot go on-duty to move the truck during rest.

In order to meet the charging needs identified in the previous section, charging stations will also be needed at shipper and carrier facilities, and new charging stations will be needed off the Interstate system to accommodate truck business models that do not utilize interstates and toll roads.

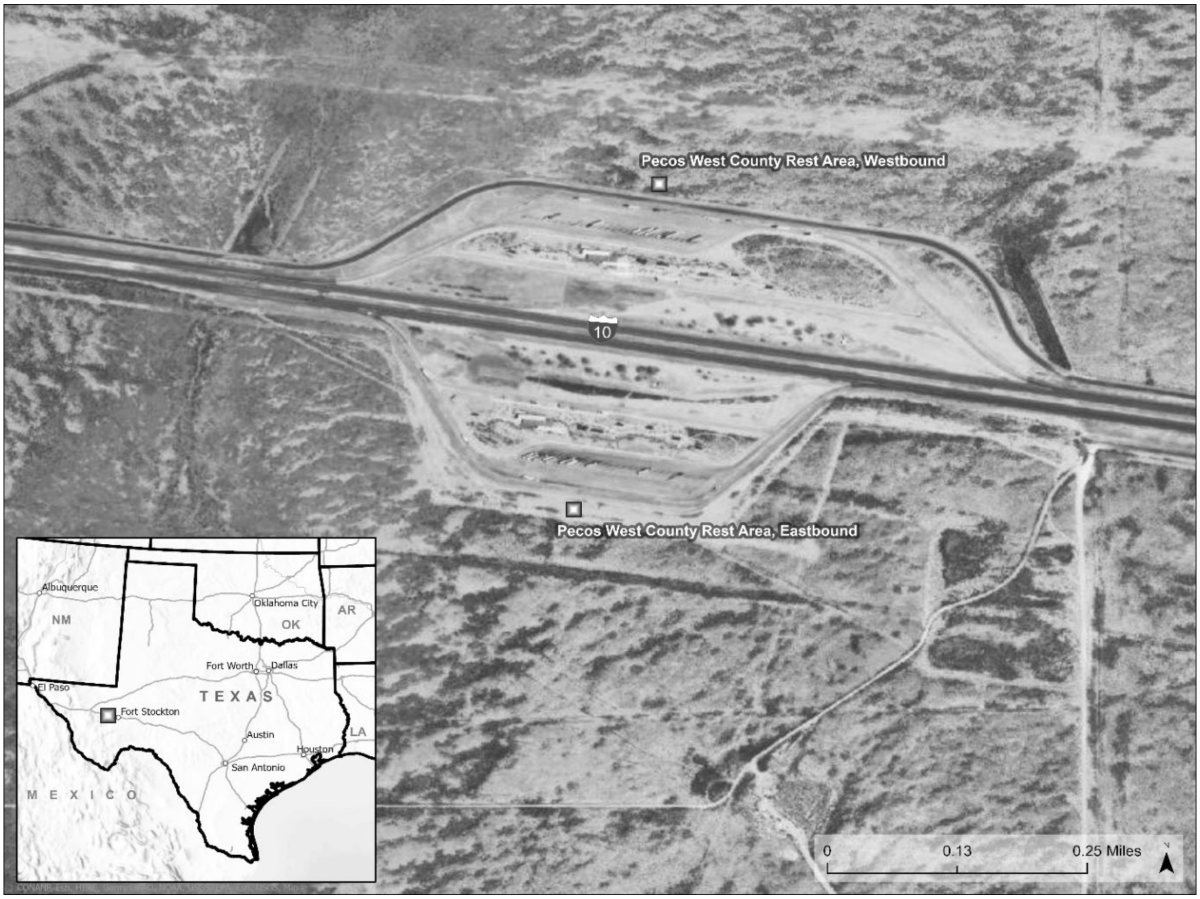
Parking Locations Case Study

To better understand the technical aspects of how trucks will park and charge at a parking location, ATRI applied its truck GPS data to a truck parking/charging scenario.[131]

To do this, the research team selected a truck parking facility and generated two one-week captures of GPS data (one from May 2021 and one from October 2021) and reviewed the average number of unique trucks parking for 30 minutes or more at the location per hour. The location selected was the Pecos West County rest areas on Interstate 10, which lie 26 miles west of Fort Stockton, TX. This location has a rest area on both the west and eastbound sides of I-10, accommodating each direction of traffic. Figure 11 shows the Pecos West County Rest Areas.

[131] Since 2002 ATRI has collected and processed truck GPS data and has used this data in support of myriad local, state, and federal freight analyses. At present, the FPM database is comprised of more than 1 million anonymized GPS-installed trucks in North America, and contains spot speeds, timestamp, location, and anonymous truck identifiers at regular intervals. This resource provides the research team unique access to information related to key truck origins and destinations, route choices, and speeds.

Figure 11: Pecos West County Rest Areas



Since ATRI's large truck GPS database is a sample of the entire truck population, ATRI expanded its sample to represent 100 percent of trucks by applying Annual Average Daily Truck Traffic (AADTT) counts sourced from the Texas DOT.[132] The average daily expansion factor was applied across all hours of parked truck data to better estimate real-world truck counts occurring at each parking facility. Finally, an average daily count of unique parked trucks per day was also determined and expanded to estimate total daily parked truck utilization at each of the two rest areas.

Table 21 shows the average hourly number of trucks parked at the two Pecos West County Rest Areas on I-10.[133] The westbound truck parking location is striped for 34 truck parking spots and has a daily average of 157 unique trucks parked at this rest stop for 30 minutes or more, a ratio of 4.6 truck visits per space. The eastbound truck parking location is striped for 33 truck parking spots and has a daily average of 212 unique trucks parked for at least 30 minutes or 6.4 truck visits per space. Total capacity for these two parking facilities is 67 truck parking spaces with an average of 369 unique truck visits per day. During any given hour of the day there are at least 31 parked trucks.

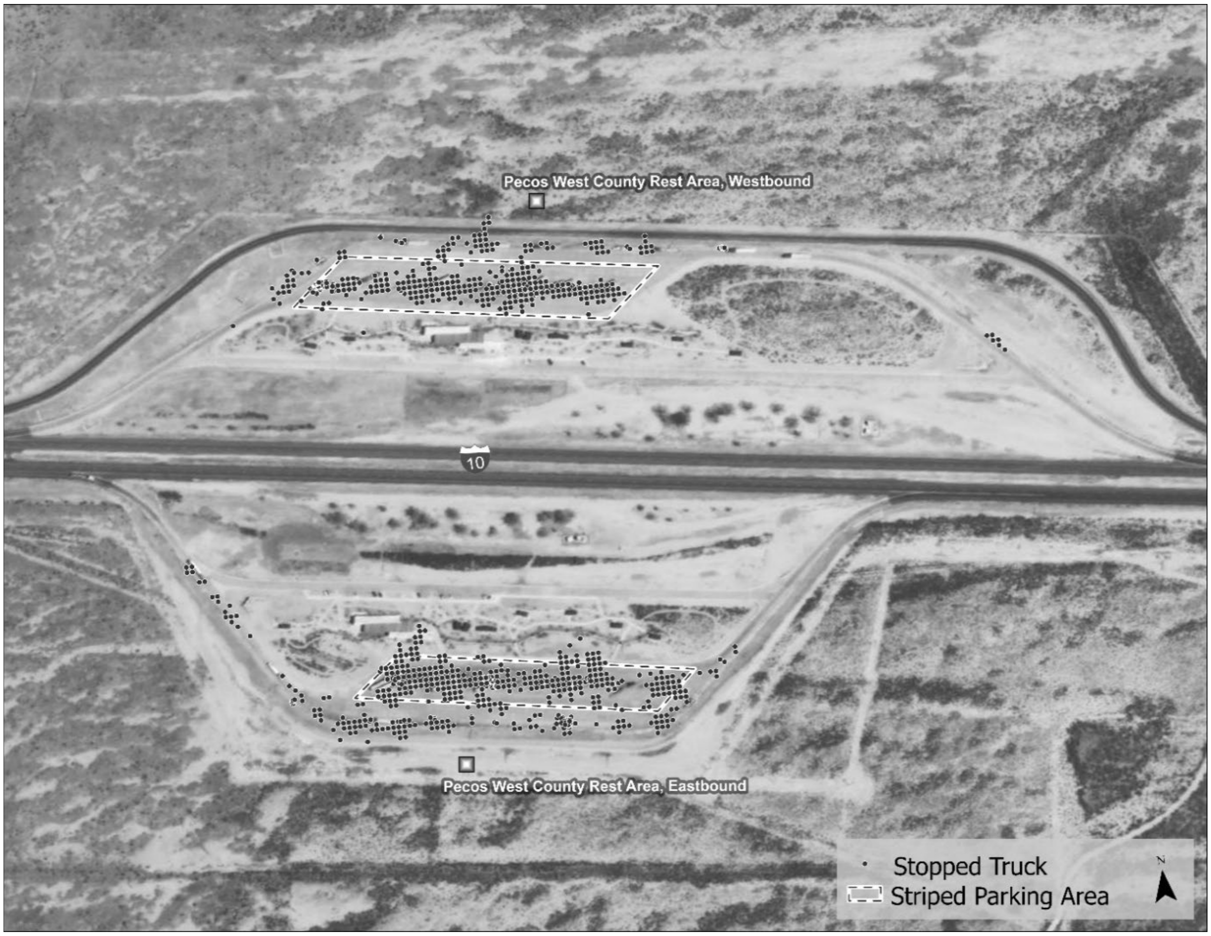
[132] Texas Department of Transportation, "Roadway Inventory" (accessed on October 2022), https://www.txdot.gov/data-maps/roadway-inventory.html.
[133] Hour 0 = Midnight – 12:59 AM; Hour 12 = Noon – 12:59 PM; Hour 23 = 11:00 PM – 11:59 PM.

Table 21: Average Truck Counts per Hour of Day

Westbound		Eastbound	
Hour	Average Expanded Count	Hour	Average Expanded Count
0	27	0	38
1	25	1	38
2	25	2	33
3	26	3	35
4	24	4	33
5	23	5	31
6	26	6	32
7	21	7	32
8	22	8	32
9	15	9	28
10	15	10	21
11	16	11	18
12	15	12	18
13	12	13	22
14	15	14	16
15	18	15	14
16	18	16	19
17	18	17	18
18	17	18	18
19	18	19	22
20	18	20	26
21	18	21	33
22	22	22	35
23	24	23	33

As shown in Table 21, peak demand is between 9:00 p.m. and 2:00 a.m. During that time period this rest area is overcapacity, having more trucks than parking spaces. An example of trucks parking outside of the striped spaces is shown in Figure 12.

Figure 12: Parking Inside and Outside of Striped Locations



Truck Charging Issues in the U.S.

Based on the above background information and analysis, the research team has identified the following key issues related to truck parking.

Truck Charging Issue One: The Truck Parking Shortage Offers a Preview of Future Truck Charging Shortages

Truck parking and truck charging are entirely interconnected. If there are not enough parking spaces, there will not be enough charging spaces. Hence, if there is not a charger at each parking space the issue will be exacerbated.

Time-related charging issues will mirror those found in the Truck Parking Case Study. There are times of day when parking is over-capacity, while other times of day the facility is under-utilized. During the under-capacity period, the chargers will simply not be used.

While truck drivers can create ad hoc parking in undesignated locations, there is no equivalent for trucks that require charging spaces without chargers.

Additionally, charging capacity at busy rest areas will be underutilized. While a truck driver may need to park for 10 hours of rest, the vehicle may only need to charge for half of that time. The parking space and charger cannot be turned over to a different driver once a charge cycle is complete, however, since: 1) during a rest period a driver cannot log in on-duty and move the vehicle; and 2) even if the driver could move the vehicle, there would likely not be a legal parking space in which to move.

Finally, it is unclear how power will be delivered to truck parking locations. Currently, the electricity demands at any given truck parking facility are considerably lower than what would be needed for truck electrification.

For perspective, the Department of Energy estimates that the average household in the U.S. consumes 11,000 kWh of electricity annually, or 30.13 kWh per day.[134] The needs of just a small rest area are tremendous when compared to the average household. The Pecos West County Rest Area (outlined in the case study with 67 striped parking spaces) had on average 369 unique truck visits per day. Of this population, 34.2 percent (126 trucks) stayed at the location for 5 hours or longer. If each vehicle in this 5+ hour subset were to consume 1,200 kWh of electricity during a stop, the daily total electricity consumption would be 151,200 kWh, or 55.18 million kWh per year. This is equal to the daily electricity needs of **5,017 average U.S. households**.

Truck Charging Issue Two: Charging Network Costs – How Much and Who Pays?

The full cost of a charging network is another issue of great concern. High development costs with speculative margins could drive away investments. When private sector capital is brought into vehicle electrification development, return on investment (ROI) at any level will raise the cost to users. Finally, because trucking is a derived demand in the larger economy, the industry will necessarily pass along all cost increases to customers and consumers alike.

To support e-commerce, just-in-time manufacturing and international trade, it is clear that the trucking industry will require DCFC systems.

Unfortunately, there is a dearth of information on the cost of DCFC systems. The California Energy Commission offers some insight through its publication of electric vehicle infrastructure project cost data.[135] Their data show an average DCFC hardware system of 50 kW or greater cost of $33,000 and average installation costs of $79,000 per unit, bringing the total per unit cost of a DCFC system to approximately $112,000.

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134 U.S. Energy Information Administration, "Electricity consumption in U.S. homes varies by region and type of home" (updated May 2019, accessed on November 2022), https://www.eia.gov/energyexplained/use-of-energy/electricity-use-in-homes.php.

135 California Energy Commission, "California Electric Vehicle Infrastructure Project (CALeVIP) Cost Data" (October 19, 2022), https://www.energy.ca.gov/programs-and-topics/programs/clean-transportation-program/california-electric-vehicle.

There is evidence that some unit costs for 150 kW hardware are $75,000 and for 350 kW are $140,000, which would put total costs as high as $219,000 per unit.[136]

Using the earlier charging event estimates from Table 20, a range of estimated costs to support 2.925 million combination trucks, using the conservative $112,000, is shown in Table 22.

Table 22: U.S. BEV Combination Truck Fleet National Charging Network Cost for Equipment and Installation*

Daily Charging Events Per Charger	Chargers Needed	Charger Cost (billions)
1	1,602,855	$179.5
2	801,427	$89.8
3	534,285	$59.8
4	400,714	$44.9
5	320,571	$35.9
6	267,142	$29.9
7	228,979	$25.6

Based on the estimated charging needs discussed earlier, Table 22 shows that if, for instance, the average charger could deliver five 3.4 hour charges per day, 320,571 chargers would be needed for the U.S. combination truck fleet at a cost of at least $35.9 billion. It should be noted that for charging at private truck stops and public rest areas, there is a limitation with the number of chargers (and the cost) due to the scarcity of truck parking spaces. In all likelihood, the number of charging spaces required far exceeds available parking spaces, and thus the additional chargers would be needed at shipper or carrier facilities or in the form of new public parking capacity. Additionally, these figures do not include the cost of utility connectivity work that would be necessary. It also does not conclude who is responsible for development and management of the charging spaces, an issue that is presently contentious.[137]

[136] Michael Nicholas, "Estimating electric vehicle charging infrastructure costs across major U.S. metropolitan areas", The International Council on Clean Transportation (August 2019), https://theicct.org/sites/default/files/publications/ICCT_EV_Charging_Cost_20190813.pdf.
[137] Frank Jossi, "Gas station owners, charging companies oppose Xcel Energy's electric vehicle charging plan," *Energy News Network* (September 27, 2022), https://energynews.us/2022/09/27/gas-station-owners-charging-companies-oppose-xcel-energys-electric-vehicle-charging-plan/.

Maintenance will add to these costs. While there is limited data on the maintenance needs for chargers, one often-cited study found that nearly 23 percent of the DCFCs in the San Francisco Bay area were out of service.[138] The most common problems were found to be:

1) charger screens being unresponsive or blank;
2) chargers were unable to accept payment; or
3) the charger was unable to generate an electrical charge.

Regular charger maintenance, including equipment cleaning, cable inspection and software updates, are critical for daily charger use. While maintenance and regular inspections must be conducted on diesel pumps as well, electrification requires exponentially more units that must be maintained. The DOE estimates that the cost of annual maintenance averages $400 per charger.[139]

A final consideration for chargers is the potential for damage or vandalism. Gasoline and diesel fuel stations almost always have an attendant on duty, while electric charging stations are mostly automated, and do not require a station attendant. Vandalism, such as cutting charger cords, is on the rise and difficult to track; cable cutting and stealing, presumably to extract and sell the copper and other related minerals, is a problem that has happened at numerous locations nationwide.[140] Electric charger repair timelines vary greatly, even taking several months, depending on part availability.[141]

<u>Strategies for Resolving Charging Issues</u>

Meeting the extensive charging needs of the nation's long-haul truck fleet is a substantial endeavor. While there are strategies that could help meet an all-BEV fleet in the U.S. – many are conceptual or rely on future technological advancements.

One approach that is under development is to offer megawatt (MW) charging at truck parking facilities. This would provide up to a 3,750 kW charging rate (3.75 MW). This would greatly decrease charging time, but vehicles will need to be designed to accept this level of charge.

Another approach is embedded roadway charging, where magnetic resonance induction is employed to charge BEVs through a receiver mounted on the undercarriage.[142] This would provide a slower charge rate (25 kW) but would occur while the vehicle is operating. Considering that there are more than 160,000 miles of roadway on the National Highway

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[138] Niraj Chokshi, "A Frustrating Hassle Holding Electric Cars Back: Broken Chargers," *The New York Times* (August 16, 2022), https://www.nytimes.com/2022/08/16/business/energy-environment/electric-vehicles-broken-chargers.html.
[139] Alternative Fuels Data Center, "Charging Infrastructure Operation and Maintenance" U.S. Department of Energy (accessed on October 5, 2022), https://afdc.energy.gov/fuels/electricity_infrastructure_maintenance_and_operation.html.
[140] Rich Rodriguez, "Charging station crisis in California," *Fox26 News* (June 1, 2022), https://kmph.com/news/local/charging-station-crisis-in-california; Steven Loveday, "More Tesla Supercharger Cable-Cutting Exposed: Why Are People Doing It?," *Inside EVs* (May 16, 2022), https://insideevs.com/news/586101/tesla-supercharger-cable-cut-vandals/.
[141] Rich Rodriguez, "Charging station crisis in California," *Fox26 News* (June 1, 2022), https://kmph.com/news/local/charging-station-crisis-in-california.
[142] Kami Buchholz, "Wireless Road Charging for EVs to Debut in 2023," SAE International (June 2022), https://www.sae.org/news/2022/06/wireless-road-charging-for-evs.

System (NHS) alone, and in-road charging would need to be installed in all lanes of roadway (and in both directions), this concept, on a large-scale, would require massive resources.

A third concept is battery swapping. Long-haul trucks would pull into a service station and several tons of depleted batteries would be swapped out with newly charged batteries. Batteries are the most expensive component of a BEV truck and it is unclear how this business model would operate, since a long-haul truck might require several battery swaps each day. There would also be a need to standardize vehicles to allow for swapping, and enhanced electrical infrastructure would need to expand to charging service stations, likely in a warehouse setting.[143]

Another consideration is opportunity charging, where a long-haul vehicle would charge at shipper or carrier facilities for brief time periods, adding a small amount to the state of charge each time.

Finally, for vehicles that need to charge in locations where electrical infrastructure is limited, off-grid charging could be an option. This can be accomplished through local wind generators, solar panels, or by burning fossil fuels (e.g. propane).

[143] Paul Lienert, Nick Carey, and Norihiko Shirouzu, "Inside China's electric drive for swappable car batteries," Reuters (March 2022), https://www.reuters.com/business/autos-transportation/inside-chinas-electric-drive-swappable-car-batteries-2022-03-24/.

FINDINGS

In this report the research team dissected and analyzed the entire U.S. vehicle electrification ecosystem to identify the key issues that must be addressed if BEV adoption in the U.S. were to proceed on a large scale. Ultimately, three overarching challenges emerged, relating to electricity generation and consumption; vehicle charging requirements and the charging infrastructure; and raw materials sourcing. Key findings in each of these are described below.

Challenge	Findings
U.S. Electricity Supply and Demand	**Electricity Needs are Enormous** • Full electrification of the U.S. vehicle fleet will result in a large increase beyond the country's present electricity generation including: ▪ 14 percent for all freight trucks ○ Within this, 10.6 percent for long-haul trucks ▪ 26.3 percent for light-duty vehicles (passenger cars and trucks) ▪ 40.3 percent for all vehicles • Individual states will require from 28 to nearly 63 percent of today's energy generation to meet vehicle travel needs. • Large-scale infrastructure investment is a necessary precursor to electrification.
Electric Vehicle Production	**Battery Materials Dominate BEV Viability** • Tens of millions of tons of cobalt, graphite, lithium and nickel will be needed to replace the existing U.S. vehicle fleet, placing high demand on raw materials. ▪ Depending on the material, this represents: ○ 6.3 to 34.9 years of current global production ○ 8.4 to 64.4 percent of global reserves • BEV production has considerable environmental and social impacts. ▪ Mining and processing produce considerable CO2 and pollution issues. ▪ Exploitation of labor is common in some source countries. • BEV Truck Conundrum – battery weight increases price and range, and decreases available cargo weight. • Major advances in battery technology are key to solving the vehicle problem.
Truck Charging Requirements	**Truck Charging Availability will be the Truck Parking Crisis 2.0** • Using today's truck and charging requirements, more chargers will be needed than there are parking spaces. • Regardless of advances in battery capacity or charge rates, BEV charging will be limited by HOS and parking availability. • Initial equipment and installation costs at the nation's truck parking locations will top $35 billion. • Other barriers include laws preventing commercial charging at public rest areas and the remoteness of many truck parking locations. • There is research underway for myriad strategies to resolve the potential for charging issues. • To understand the truck parking challenges, ATRI quantified the truck charging needs at a single rural rest area, which would require enough daily electricity to power more than 5,000 U.S. households.

In the near term there are discrete applications for BEV trucks. Local and regional truck operations that rely on shorter trips and return the truck to terminals for nightly charging are feasible today.

In the absence of public policies that mandate the purchase of these BEVs, carriers themselves will have to decide if the costs and benefits of a BEV truck fit well with their business models. And those decisions will be conditioned on truck costs, shipper/freight requirements, and access to abundant and inexpensive electricity. Issues arise however if any one or more of these decision-making inputs is not viable. This research confirms that BEV trucks will not be a one-size-fits-all emissions solution for a large swath of the trucking industry.

Producing BEV trucks that meet carriers' operational requirements, including impacts on operations and balance sheets and providing ample charging, must be addressed by the entire supply chain. Utilities must ensure that expanded electrification is feasible as well. It is inappropriate, however, to place these burdens squarely on motor carriers.

APPENDICES

Appendix A: Power Generation, Transmission and Distribution Background

Power Generation

Most electricity in the U.S. is generated by utility-scale power stations. According to the EIA there are more than 11,000 utility-scale electric power stations in the U.S. Facilities with this classification have a generating capacity of at least one MW and use a variety of energy sources, including coal, petroleum, natural gas, nuclear, hydroelectric, solar and wind.

In addition to utility-scale power plants, there are also small-scale electricity generating sources. These facilities have a generating capacity of less than one MW.

Overall, utility-scale power stations produce far more electricity than small-scale systems. In 2021 utility-scale generators in the U.S. had a net electricity generation of approximately 4,116 billion kWh as compared to small-scale net generation of 49 billion kWh.[144]

To account for different levels of usage and assist with redundancy across the entire network, there are three main types of power-generating units.

First are base load power stations. Base load facilities produce a steady/constant minimum supply to meet customer demand throughout a typical day. For the most part, these power stations run continuously and are the most cost-efficient energy sources. Typical base load sources of electricity are coal, nuclear and hydroelectric.

The next type is intermediate load generating units. These adjust electricity supply as demand fluctuates and typical intermediate load generators run on natural gas.

Finally, peak load generating units assist the power grid during peak hours when demand is at its highest. These are often renewables such as wind and solar but can also be natural gas. These generators tend to be the most expensive to operate.

Power Transmission

To transport electricity long distances from a power station, voltage is increased at a transformer and electricity is then moved along transmission lines. There are approximately 300,000 miles of high-voltage transmission lines in the U.S., allowing for regional and interstate energy transmission.[145] There are transformers at both the power generation end and the distribution end of transmission lines to decrease the voltage.

Power Distribution

Power distribution lines connect from a substation to homes and businesses – they are the last segment of the journey from the producer to the consumer. There are approximately 5.5 million

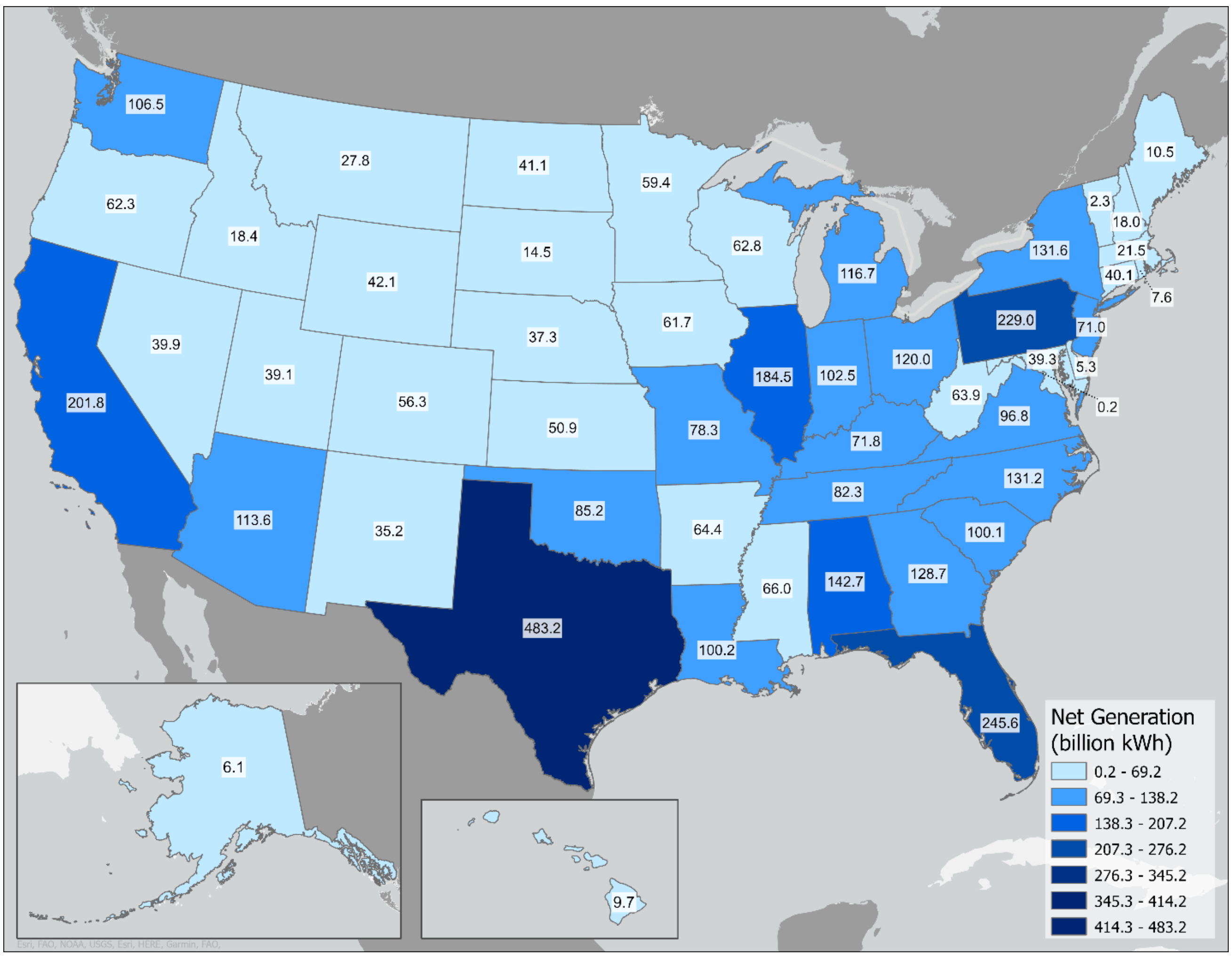
[144] U.S. Energy Information Administration, "Electricity explained: Electricity generation, capacity, and sales in the United States" (accessed on November 2022), https://www.eia.gov/energyexplained/electricity/electricity-in-the-us-generation-capacity-and-sales.php#.
[145] U.S. Department of Energy, "The Smart Grid," (accessed on November 2022) https://www.smartgrid.gov/the_smart_grid/smart_grid.html.

miles of distribution lines in the U.S.[146] Above-ground distribution lines in particular are vulnerable to damage from weather that may, for instance, cause trees or limbs to fall on top of them.

Energy Production by State

Energy production varies by state with four states, with Texas, Florida, Pennsylvania and California producing more than one quarter of the nation's electricity, as shown in Figure A1. Due to the interconnectivity of the grid, however, electricity from a given producer or state is often delivered to customers across state boundaries. There have even been instances where an energy producing entity will have to pay another entity to take the excess electricity (thus giving the electricity a negative value).[147]

Figure A1: Annual Energy Production by State in billions of kWh



[146] Jenifer Weeks, "U.S. Electrical Grid Undergoes Massive Transition to Connect Renewables," *Scientific American* (April 28, 2010), https://www.scientificamerican.com/article/what-is-the-smart-grid/.
[147] Ivan Penn, "California invested heavily in solar power. Now there's so much that other states are sometimes paid to take it," *Los Angeles Times* (June 22, 2017), https://www.latimes.com/projects/la-fi-electricity-solar/.

Appendix B: Past Research on Roadway Vehicle Electricity Needs

There is past research that quantifies the amount of electricity that might be needed for vehicle electrification. At the household level, The Pew Charitable Trusts states that a BEV car with a fuel economy of 30 kWh per 100 miles will use the same amount of electricity each day as a typical U.S. home.[148] The Brattle Group offers a national estimate, finding that electricity demand for 20 million vehicles would be approximately 60 to 95 billion kWh per year.[149] Using these figures, the full U.S. fleet of vehicles, which was more than 276 million registered vehicles in 2019, would require 828 to 1,311 billion kWh annually.[150] As a result, full electrification would increase energy generation and consumption from 21.1 to 33.4 percent, at 2019 levels.

[148] Alex Brown, "Electric Cars Will Challenge State Power Grids," The Pew Charitable Trusts (January 9, 2020), https://www.pewtrusts.org/en/research-and-analysis/blogs/stateline/2020/01/09/electric-cars-will-challenge-state-power-grids.

[149] Michael Hagerty et al., "Getting to 20 Million EVs by 2030 Opportunities for the Electricity Industry in Preparing for an EV Future," The Brattle Group (June 2020), https://www.brattle.com/wp-content/uploads/2021/05/19421_brattle_-_opportunities_for_the_electricity_industry_in_ev_transition_-_final.pdf.

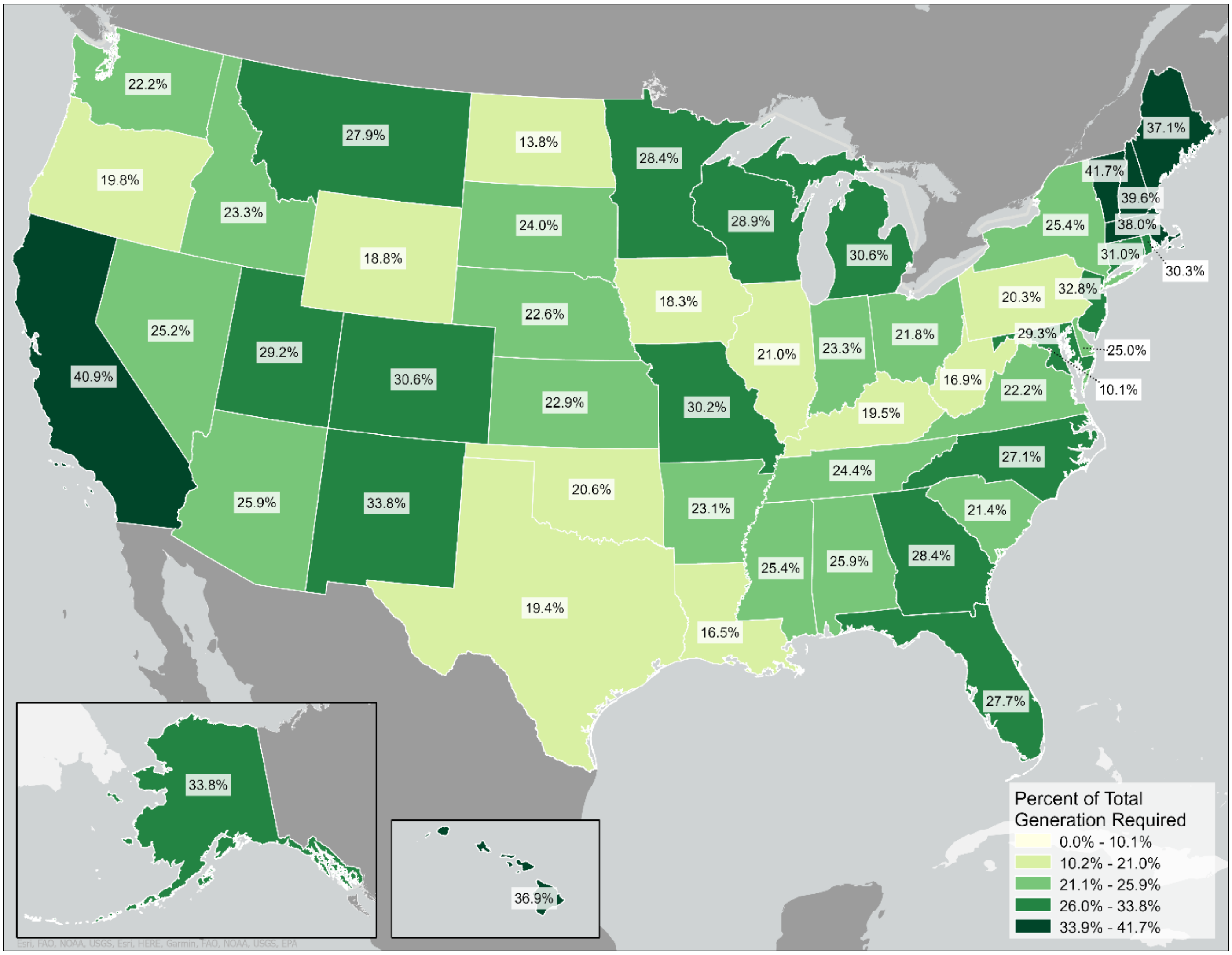
[150] Federal Highway Administration, "Table MV-1: State Motor-Vehicle Registrations – 2019" (November 2020), Highway Statistics Series 2019, https://www.fhwa.dot.gov/policyinformation/statistics/2019/mv1.cfm.

Appendix C: Additional State Electricity Needs Information

Electricity Needs by State: Automobiles and Light Trucks

The percentage of state consumption that will be used by cars and light trucks is generally much larger than trucking industry consumption due to their larger VMT's and vehicle numbers. As shown in Figure C1, the majority of states will see more than 20 percent of consumption needed for passenger vehicles. The largest consumer is predicted to be California, which would use 40.9 percent of what is currently consumed if all passenger vehicles were electrified.

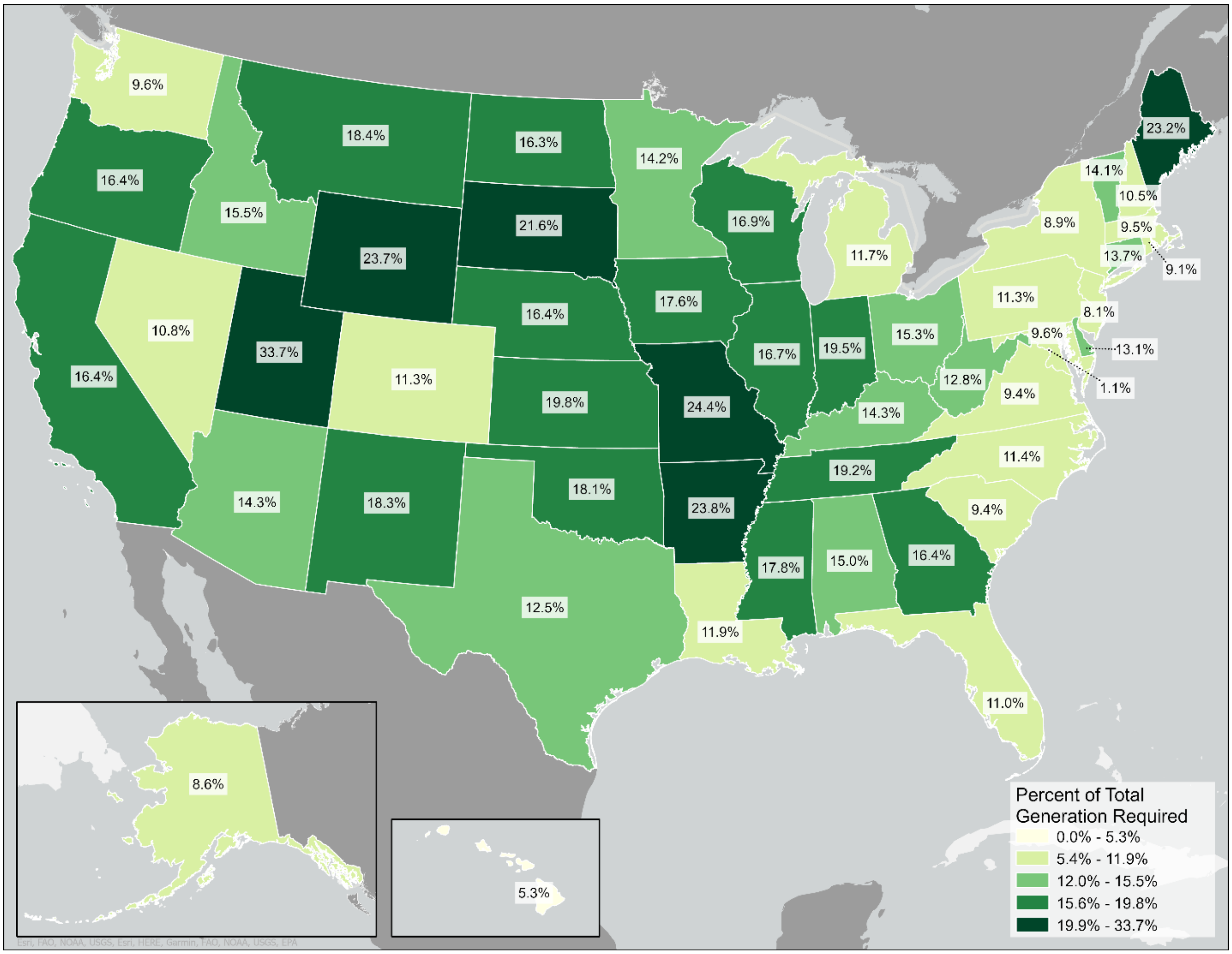
Figure C1: State Electricity Consumption Required for Automobiles and Light Trucks



Electricity Needs by State: Trucking

Medium- and heavy-duty trucks were next assessed. Powering more than 12 million trucks with electricity would require a significant portion of today's state electricity consumption. As shown in Figure C2, many states, particularly those on the east coast with higher population densities, trucks would consume less than 10 percent of today's electricity. Several Western and Midwestern states would require more than 20 percent. On the upper end, Utah would require more than 30 percent.

Figure C2: State Electricity Consumption Required by Medium- and Heavy-Duty Trucks



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