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Infrastructure Requirements for the Mass Adoption of Electric Vehicles

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Executive Summary

We are a mobile society. Beginning more than a century ago, the automobile and the infrastructure that developed around it—everything from interstate highways, gasoline stations, and repair shops to drive-ins that enabled fast food—transformed life in the United States. The invention of the automobile offered individuals the freedom to go where they wanted when they wanted.

Today, a new automotive transformation is underway. Unlike the first, this transformation is being driven by government fiat and lavish taxpayer subsidies. In their stated efforts to reduce carbon emissions, 18 states (as of this writing) have approved regulations that will require all new vehicle sales to be electric vehicles (EVs) beginning in 2035. Similar mandates have been enacted for heavy trucks, which transport most goods in the country, although they will begin later. Meanwhile, the U.S. Environmental Protection Agency has introduced stringent carbon dioxide emissions standards for new vehicles, which the agency admits can only be met by automakers selling more EVs and fewer gasoline-powered vehicles.

While "make-it-so" mandates may be politically popular, physical and economic realities will ultimately prevail. The move to enforce an all-EV future, regardless of claimed environmental merits (which are hotly disputed), requires infrastructure to support it. However, that means far more than installing charging stations at home and work. Too little discussion has been devoted to the scale and cost of the infrastructure needed to deliver the electricity to those charging stations. Even if the additional electricity can be supplied, it must still be delivered—and that remains the least-discussed aspect of this new transformation.

As this study's detailed analysis shows, the physical infrastructure needed to support an all-EV future will entail overall costs ranging between $2 trillion and $4 trillion. That is before considering the impact of higher demand on the costs of materials and labor to build it all and also before considering the additional costs to build more electricity generation.

To enable an EV future that provides the same freedom of movement we enjoy today will require massive upgrades to the entire electrical delivery system. Home chargers, which are called "Level 2" chargers, will require dedicated circuits, like electric stoves and electric clothes dryers do. The main circuit boxes in millions of older homes to which electricity is delivered will need to be upgraded.

To accommodate the increased electricity needed for EV charging (and other electrification goals), electric utilities will also have to upgrade their local distribution systems—the poles and wires running down streets—with millions of larger transformers, thousands (if not millions) of miles of larger wires, and even bigger utility poles to handle the additional weight.

Furthermore, there is the infrastructure needed to replace our country's almost 200,000 retail gasoline stations and more than one million gas pump nozzles.

Providing drivers with a similar level of convenience means installing high voltage "Level 3" chargers to provide relatively quick recharging, which will require installing much larger circuits and transformers.

A network of charging stations along the 220,000 miles of interstate and U.S. highways will also be needed. Consider that a single on-road charging station will have the electric power demand of a small town. High voltage transmission lines must be constructed and extended to those charging stations, in addition to huge transformers and new substations that will be needed to handle the higher electric loads. Yet utilities today must wait as long as five years for delivery of such transformers. Moreover, delivering the additional electricity required for an all-EV world means building several hundred thousand additional miles of new transmission lines or reconductoring (i.e., rewiring with higher capacity wire). However, new transmission lines (135,000 volts and higher) added each year have fallen from 4,000 miles in 2013 to just 500 miles in 2022.

The materials and labor requirements needed to accomplish such an undertaking are daunting. Replacing all internal combustion engine vehicles with EVs, for example, will require almost eight million metric tons of specialized "electrical steel," with important magnetic properties that reduce energy losses. Meeting the demand for that type of steel would require far more than the current capabilities of the existing manufacturing capacity, and 10–20 times more than the planned new capacity. Another example: even more specialized (and costly) "amorphous" electrical steel that is now required because of new U.S. Department of Energy rules to reduce energy for new transformers. Each of these larger transformers can require several thousand pounds of the metal, along with huge quantities of copper, and EVs alone require four times more copper than internal combustion vehicles. The result is that the demand for and prices of copper will soar. Finally, the electricians needed to install new circuits and linemen required to build and modify transmission and distribution lines are already in short supply. As this study documents, the total estimated costs for the required infrastructure upgrades will likely range between $2 and $4 trillion, as shown in the table below.

While it is possible to reduce some of these infrastructure costs, EV charging would have to be restricted. Electric utilities, for example, could control the availability of charging at homes to minimize strains on the system, thus delaying or even eliminating some of the need for expensive system upgrades. Similarly, access to EV chargers along highways could be rationed through waiting, or installing fewer stations each with fewer chargers, which would lead to long wait times for drivers but would reduce grid upgrades. That being said, making it more difficult for EV owners to use their vehicles as they see fit through rationing schemes puts the lie to proponents' claims that EVs are a superior technology.

Electric vehicles could well be a major technological feature in the future of transportation. If so, consumers will adopt them on their own and the necessary infrastructure will be developed in due course, just as it was for automobiles a century ago. Regardless, the forced transformation demanded by many politicians and regulators will be massively expensive and is doomed to failure.

Estimated Total Infrastructure Cost for an All-EV Future

Hardware Category	Estimated Cost ($ Billions)	
	Low	High
Home Chargers (Single-Family & Multi-Family)	$190	$430
Upgrades to Local Distribution System	$1,600	$1,800
Additional & Upgraded Transmission Lines	$600	$1,700
On-Road Charging Stations Substations	$40	$110
Fast-Chargers for On-Road Charging Stations	$5	$5
TOTAL	**$2,435**	**$4,045**

Source: author's calculations

I. Introduction

As of this writing, the U.S. government (along with 18 states)[1] continues efforts to mandate electric vehicles (EVs) for consumers and commercial trucking. There are two types of mandates. The first consists of direct specifications to establish mandatory minimums for the share of EVs as a percentage of all new vehicle sales. The second is indirect mandates, notably the Environmental Protection Agency's (EPA) new vehicle mileage standards, and state "clean fuel" requirements that are considered necessary to reduce carbon emissions.

Much has been made of the materials requirements and economic costs of building enough EVs to replace the 290 million internal combustion vehicles (ICVs)[2] in the U.S., including doing so at the same time as other nations.[3] Generally ignored, however, have been any assessments of the physical hardware requirements needed to establish and operate the electrical infrastructure required to support mass adoption of EVs and, importantly, doing so without compromising the freedom of mobility enjoyed today.

The infrastructure needed to support EVs typically goes far beyond the installation of chargers in people's homes. Regardless of an EV's range, on-road recharging will be essential for their widespread use. However, there are significant but less-discussed costs and hurdles associated with the widespread use of both at-home and on-road charging. For example, placing a multi-port charging station every 50 miles along U.S. interstates and major highways will require thousands of stations, each with dozens of high-voltage Level 3 direct current (DC) chargers. Placing charging stations along minor roads, especially those in remote rural areas of the country, will require thousands more. If EV charging stations are to match the availability of gasoline pumps at today's approximately 195,000 retail gasoline stations,[4] then hundreds of thousands of Level 3 chargers will be needed. That will be true, even assuming a proliferation of slower, at-home overnight charging for EV owners and accounting for the longer time needed to recharge an EV relative to refueling an ICV.[5]

An all-EV future will also require two additional infrastructures related to the deployment of EV chargers. First, a massive power plant construction program will be needed to supply all the electricity that must be directed to on-road energy requirements. Second, a physical delivery system must be built to ensure the delivery of adequate electricity to hundreds of millions of EVs when and where needed. These are analogous to refining enough gasoline and having the necessary infrastructure—storage tanks, pipes, trucks, and fuel pumps—to deliver gasoline to the hundreds of millions of existing ICVs.

Accommodating the additional electricity loads for an all-EV future will require upgrading the high-voltage transmission system that delivers electricity from large electric generating plants. That means more transmission lines to accommodate the increased demand for electricity, along with additional manufacturing and installing thousands of large, high-voltage transformers and related equipment. A single on-road charging station, for example, will have the power demand of a small town.[6]

Similar grid infrastructure upgrades will have to occur at the local level. The mass installation of EV chargers in single-family and multi-family homes, commercial businesses, and charging stations in cities and towns will require upgrades to local distribution systems—the poles, wires, and transformers that run down streets. It will also require upgrades to the infrastructure in buildings themselves, such as the service panels where electricity is delivered, and circuits to handle the heavy load of so-called Level 2 chargers, which run on AC current, operate at 240 volts, and typically draw 50-80 amperes (amps).

Even if one ignores the materials requirements for constructing the additional electric generating capacity and batteries[7] necessary to meet the increased electricity demand, the necessary grid infrastructure upgrades alone will entail massive quantities of materials. Those materials include copper, iron, and specialty steel for transformers and wires, as well as larger utility poles to handle the additional weight of the heavier and more powerful transformers. Additional facilities will be needed to process mined materials and manufacture transformers and wire. Wooden utility poles require harvesting large trees, while new steel poles must be manufactured. Finally, a small army of electricians and linemen will be needed to install the necessary transmission and distribution system upgrades. The overall costs are likely to add up to trillions of dollars.

Infrastructure costs could be reduced if EV charging were restricted, as some EV proponents recommend.[8] For example, electric utilities could regulate (or even control) the availability, timing, and duration of charging EVs at homes to minimize strains on the local systems, thus delaying or even eliminating some of the need for costly system upgrades. Similarly, access to EV chargers along highways could be rationed. Installing fewer charging stations, with each station having fewer chargers, would de facto lead to long wait times for drivers but would reduce required grid upgrades. However, making it more difficult for EV owners to use their vehicles as they see fit by rationing schemes will belie claims that EVs are a superior technology. Because ICV users do not face such restrictions, this report evaluates materials and infrastructure requirements needed to provide EV users with the same convenience enjoyed by drivers of internal combustion vehicles.

II. Comparing Vehicle Fueling Infrastructures

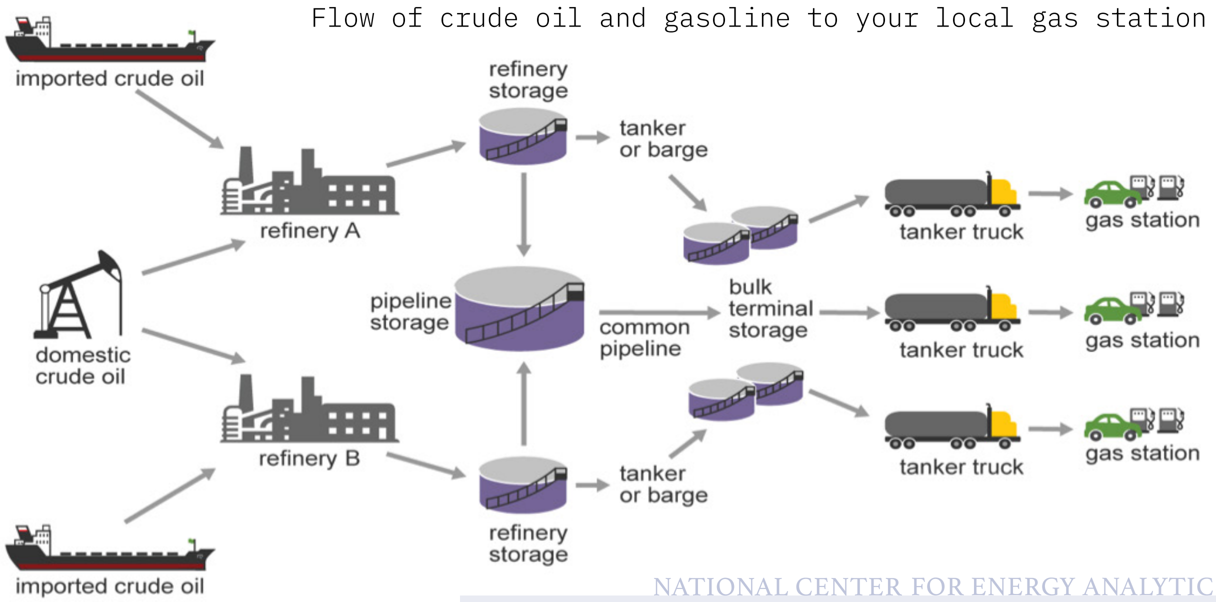
There is a long-established infrastructure that delivers gasoline and diesel fuel for ground transportation and agricultural use. As shown in **Figure 1**, it begins with imported and domestic crude oil that refineries convert into useful fuel, just as the electric infrastructure begins with generating plants. After crude oil is refined into gasoline, diesel, and other petroleum products, it is stored and transported via pipelines, barges, railroads, and trucks to bulk fuel storage terminals. From there, the fuel is distributed by truck to underground storage tanks at retail gasoline stations and, in the case of agricultural use, directly to on-site underground storage tanks at farms and ranches. Finally, the fuel is dispensed into vehicles from gasoline pumps.

A similar infrastructure is needed to deliver electricity to charge EVs. As shown in **Figure 2**, electricity is generated at central station power plants.[9] For fossil fuel and nuclear power generating plants, the fuel must first be processed and delivered. Coal, for example, is mined and transported by railroad car. Natural gas is produced from wells that are drilled, collected in pipeline gathering systems, and delivered to natural gas transmission pipelines, which then transport the gas to electric generating plants. As envisioned by EV proponents, however, the electricity will be generated primarily by wind and solar power plants, as well as some hydroelectric plants.

After the electricity is generated, huge transformers increase the voltage to hundreds of thousands of volts, enabling the electricity to be transported with far lower "losses" along long-distance high-voltage power lines.[10] Losses occur because electric lines have resistance, which causes them to heat up. For example, resistance is why the wires in a toaster glow red. In the physics of electrical engineering, losses decline rapidly at higher voltages. This system of generators and high-voltage lines is called the "bulk power system." Because homes and businesses cannot use electricity at such high voltages, other transformers decrease voltages for local distribution systems. Finally, pole-mounted transformers step down the voltage even further to deliver electricity to homes.

Figure 1

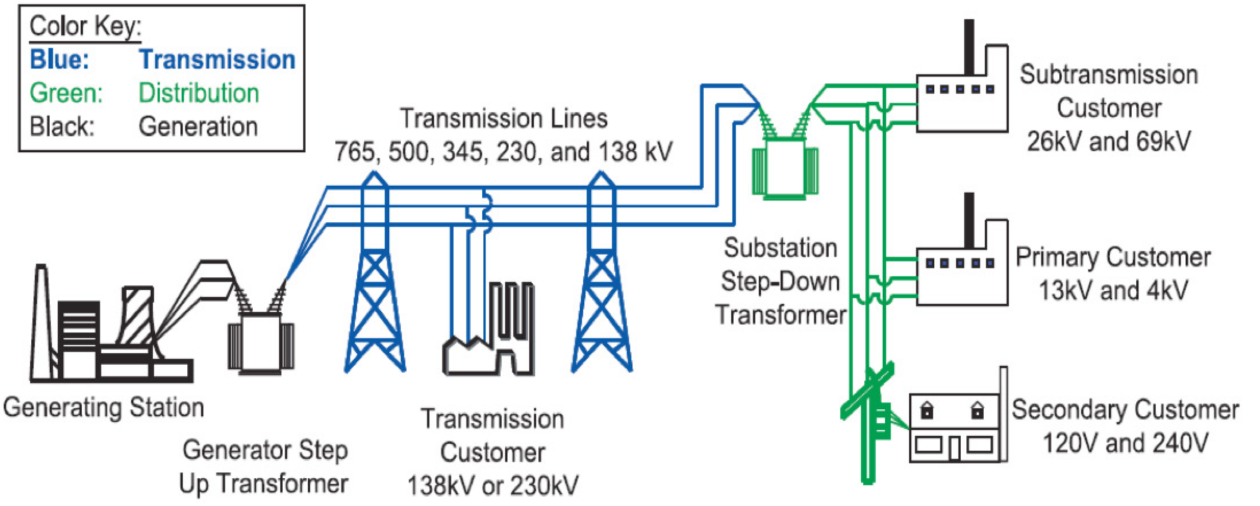
Gasoline Production Infrastructure



Source: U.S. Energy Information Administration, Gasoline Explained

Figure 2

Electric Generation, Transmission, and Distribution Infrastructure



Source: U.S.-Canada Power System Outage Task Force, figure 2.1 (2004)

III. Materials Requirements for Local EV Power Distribution Systems

Infrastructure for local distribution systems to accommodate EV charging can be thought of as being similar to fuel terminals and trucks that service gas stations, but instead haul electricity to distribution points. Likewise, EV retail charging stations are the equivalent of gas stations. Underground gasoline storage tanks and fuel nozzles are similar in function to pole- and pad-mounted transformers.

In the U.S., there are an estimated 60–80 million distribution transformers[11] that either step up or step down the voltage in the lines required for houses or businesses. These transformers are located along six million miles of distribution lines that are owned and operated by almost 3,000 separate utilities.[12] These transformers and distribution lines will need to be upgraded to accommodate the anticipated doubling or tripling of electricity demand[13] that would arise with the mass adoption of EVs. The greater the demand for electricity from EV charging, the larger the load-carrying capacity and physical size of the transformers and distribution lines. The specifics are somewhat different, but the overall impacts are the same for residential customers, workplaces, or standalone on-road charging stations.

A: Residential Overnight EV Charging Infrastructure

Although overnight electricity demand tends to be low, it usually peaks in the early morning and early evening hours. Most residential customers will charge an EV beginning in the early evening after returning from work.[14] Together with other electrification efforts (i.e., replacing natural gas furnaces and water heaters), EV charging likely will double or triple peak electric demand, in turn necessitating distribution system upgrades. On the other hand, if EV charging can be restricted to late-night hours, then peak demand may not increase enough to require upgrading local distribution systems. Nevertheless, even if charging is restricted to off-peak hours late at night, transformer upgrades will still be required. The reason is that a transformer must have a period when usage is low to allow it to cool down (called passive cooling). Otherwise, when the morning peak arrives, a transformer can overheat, causing it to shut down, fail, or even catch fire.

The ultimate outcome—boosting electric capacity or retaining existing capacity—depends on several factors. First, to recharge EVs overnight, most homes and apartment buildings likely will install Level 2 chargers.[15] These operate at 240 volts (like an electric stove or dryer) and typically draw between 30 and 80 amperes (amps) of electricity.[16] Until the early 1980s, most homes were equipped with a service box (also called a "breaker box" or "fuse box")—the entry point for electricity delivered to a home by the electric utility over its local distribution system—that could accommodate a maximum of 100 amps demand. This meant that all the installed lights and appliances collectively could not draw at more than 100 amps at any given time. Newer residential homes usually have a 200-amp service box installed, though some very large homes have 300-amp or even 400-amp service boxes. Most homes with 100-amp service cannot accommodate Level 2 chargers because they draw too much current to be used simultaneously with other appliances. Hence, many older homes will require retrofits to a larger service box. Moreover, a Level 2 charger requires its own circuit, which must also be installed. The U.S. Census Bureau estimates that as of 2022, the U.S. housing stock was about 144 million units,[17] with a median age of 40 years.[18] The states with the oldest median-age housing are located on the West Coast, the Upper Midwest, and, especially, New York and New England. New York has the oldest housing stock, with a median age of 62 years.[19] States with the oldest housing stock are likely to require the most upgrading to larger service boxes.

For multi-family buildings and large apartments, the infrastructure requirements will depend on whether there are separate service boxes and meters for each unit, or a single meter and service box for all the units. In either case, installing large numbers of Level 2 chargers likely will require new service boxes, plus larger circuits to handle the increased loads of the chargers themselves.

In most cases, the increased demand for electricity will also require upgrading the capacity of the transformers that serve individual homes and apartments (see the Appendix: A Primer on Transformer Capacity), as well as the distribution lines (i.e., the wires that are strung on above-ground poles or buried underground).[20]

The local distribution system upgrades needed to provide residential and commercial Level 2 charging will depend on the characteristics of individual distribution lines, as well as efforts to limit increases in peak demand by controlling when EVs can be charged. For this analysis, we assume that local electric utilities do not restrict when consumers can choose to charge an EV.[21] It remains to be seen if consumers will accept rules, inducements, or mandates regarding when one can fuel an EV.

Most local distribution lines operate at between 12,000 and 15,000 volts (12–15 kilovolts or “kV”).[22] The amount of electric current a line can carry depends on numerous factors, including the type of conductor (i.e., copper, aluminum, or a composite using strands of different metals), the cross-sectional size of the conductor (physically larger conductors can carry more load), whether the conductor is buried in the ground or is strung along poles, and the configuration of the wires themselves (i.e., flat, with the wires side-by-side, or in a triangular shape). To determine the appropriate size for a distribution circuit conductor, an electric utility must account for the conductor’s resistance, the length of the circuit, the peak demand the conductor must be able to meet, and how much the voltage is allowed to drop along the circuit.

To determine needed upgrades for local distribution transformers and circuits, we turn to hourly load profiles. These profiles measure the electricity demand over time of an end-user (i.e., a homeowner or commercial business). Load profiles differ by season and by the day of the week.[23] Because residential loads already peak in the early evening, adding EV charging loads will exacerbate the need for distribution system upgrades.[24]

One oft-proposed solution to the increase in residential peak demand from EV charging is to encourage charging during the day when individuals are at work, thus reducing early-evening electrical demand. However, such a shift in EV charging will increase commercial peak loads during the day, when they are already at their highest,[25] thus increasing the need to upgrade the portions of local distribution systems serving commercial customers. The magnitude of the increase will depend on the predominant types of chargers installed at commercial venues. Level 3 chargers will require more upgrades owing to their higher voltage and current requirements, as compared to the slower and far less costly Level 2 chargers that most homeowners will install.

If installing a Level 2 charger requires a larger transformer to handle the additional electric load, then the most likely upgrade will be to a 25 kilovolt-ampere (kVA) unit[26] (see the Appendix), each of which weighs around 600 pounds.[27] For those following the upstream minerals issues of electrification policies, the copper content of a pole-mount 25 kVA transformer is around 30 pounds.[28] This in turn requires mining about three tons of copper ore per transformer.[29]

End-use electrification will require replacing most of the 60-80 million transformers with ones that can handle larger loads. Hence, instead of replacing these transformers as they wear out, they will need to be replaced far sooner. The U.S. electric distribution infrastructure itself is aging, although the average age of much of the equipment is unknown.[30] Thus, estimates of the costs of upgrading distribution transformers to accommodate the increased load should be based on the net increases in costs—that is, the cost difference between replacing a smaller, existing transformer and replacing it with a larger one.

Replacing 60 million distribution transformers would require a dramatic increase in the near-term demand for such products. Delivery schedules will be uncertain, and greater demand for limited supplies will mean higher prices. There will be unavoidable increases in costs for the materials needed, namely copper and specialty steel. There is also the issue of the additional demand for copper in EVs themselves, which require about two to three times the quantity used in internal combustion vehicles—roughly 120 to 180 pounds of copper per EV, versus 50 for internal combustion vehicles, and six times more minerals than overall.[31] If the remaining 255 million of the 260 million cars and light trucks registered in the U.S. today were EVs, their manufacture would require far more copper than the one million metric tons produced in the U.S. each year. [32]

Combined with vehicle mandates abroad, the global demand and price of copper will climb, regardless of the expected innovations that will reduce copper requirements in EVs. Although about one-third of the U.S. copper supply comes from scrap,[33] a key issue in using recycled copper in transformers is the presence of contaminants, which can lower conductivity and degrade transformer capabilities.[34]

The other critical metal used in transformers and EVs is a highly specialized form of steel known as grain-oriented electrical steel (GOES). Transformers and EV motors require this kind of electrical steel because its magnetic properties reduce energy losses.[35] Different transformer designs use different quantities of electrical steel, but a reasonable average is around 1 kg per kVA.[36] Using that value, to replace 60 million 25 kVA transformers would require 1.5 million metric tons of GOES. Another specialty product called amorphous steel can be used as an alternative, but currently, only one company in the U.S. (Metglas, Inc.) manufactures this product. The company can produce 18,500 tons per year and plans to double its capacity.[37]

Most of the GOES manufactured in the U.S. comes from a single plant owned by Cleveland-Cliffs. That plant's annual manufacturing capacity of 300,000 tons is too small to meet increasing U.S. demand. Cleveland-Cliffs not only produces GOES for transformers but also produces non-GOES electrical steel for EVs.[38] The average EV motor is estimated to require 30 kg of non-GOES electrical steel.[39] Replacing all 255 million registered internal combustion vehicles with EVs will require about 7.7 million metric tons of electrical steel.

Furthermore, the U.S. Department of Energy introduced new standards in December 2022 that require transformers to be more energy efficient, come 2027.[40] Achieving that goal will require the use of amorphous steel instead of GOES.[41] Amorphous steel is manufactured in thin sheets that is layered to form a transformer core which yields lower electrical losses within the transformer. However, the utility industry is concerned about the reliability of such designs, as well as the availability of essential electrical steel.[42]

B: Distribution-Level Commercial Charging Stations

Commercial charging stations, especially those in cities, can be thought of as the electrical equivalent of retail gasoline stations. They may be located at gas station-like businesses, or co-located with other kinds of commercial businesses, and provide numerous charging ports. In either case, they need enough ports to provide unfettered access to charging. Many environmental and EV advocates have proposed "smart charging," in which access to charging is restricted, both to reduce infrastructure requirements and to ensure that EVs are charged only with emissions-free electricity, such as from wind and solar power.[43] However, restricting access to charging only to those times when surplus electricity is available, or when low-carbon energy is available, represents a fundamentally different approach than refueling internal combustion vehicles, which have no such restrictions.

In order to accommodate the demand for unfettered access, there must be enough EV charging stations and charging ports to avoid long wait times. Although some drivers wait at retail gasoline stations for a few minutes, most do not. EV charging stations are usually divided into two categories: Level 2, for employees of businesses who do not require fast charging, and Level 3, for those who do require fast charging, like retail outlets or gas stations.

A typical gasoline pump dispenses 10 gallons per minute and draws between five and eight amps to run the pump.[44] The greater the vertical height between an underground storage tank and the pump, the more electricity is required to operate the pump. On average, retail gas stations have six pumps that operate at 240 volts. Consequently, a typical retail gas station can be served with a 200-amp service drop (the electric line to a home or building from a utility pole) which a 15 to 25 kVA transformer can accommodate. Larger stations likely have 300-amp to 400-amp service drops to accommodate numerous pumps and a large convenience store, but can still be served by a small transformer.

By contrast, today's Level 3 chargers typically operate at 480 volts and draw between 100 and 300 amps to provide 150 kW of power. Newer, faster chargers operate at 350 kW, reducing refuel time but drawing far more current.[45]A retail station with six 480-volt, 500-amp Level 3 charging ports would require a transformer with a capacity of 2 MVA,[46] a capacity between 60 and 100 times larger than a typical pole-mounted or pad-mounted transformer. A retail station with 12 Level 3 charging ports would require a transformer with a capacity of at least 4 MVA.

There are an estimated 195,000 retail gasoline stations in the U.S.,[47] with an average of six pumps per station, totalling 1,170,000 refueling nozzles. To determine the need for transformer upgrades (and likely distribution conductor upgrades to handle the increased electric loads), assume that a Level 3 charger will charge the average EV in 30 minutes, which is the time advertised by many manufacturers.[48] That is between three and five times longer than the typical refueling time for an internal combustion vehicle using a 10-gallon per minute pump.

Suppose all EVs refuel at retail stations with a charging time of 30 minutes and no additional wait for a charger to be available. If fueling an internal combustion car or light truck takes 10 minutes, then at least 3.5 million Level 3 chargers would be required.[49] Of course, many EV drivers will charge their vehicles at home or at work using slower Level 2 chargers, thus reducing the demand for on-road local charging by some unknown amount. One could suppose that local charging at home or at work could reduce the demand for public charging at retail stations by half, in turn requiring around 1.7 million Level 3 chargers by 2050. That being said, the more drivers charge at home or work, the more transformer and conductor upgrades will be required for residential distribution systems. If each retail charging station has 12 charging ports to accommodate the greater time needed to recharge, then even with the newest DC chargers, the total number of retail charging stations required to provide Level 3 charging ports will be over 140,000, each requiring capacities of 4 MVA.[50]

The costs of operating commercial Level 3 fast chargers at retail charging stations may be a potential barrier to their installation. The reason is that most electric utilities impose "demand charges" on commercial and industrial customers to recoup the fixed costs of the distribution infrastructure they require.[51] Typically, these charges are based on the peak electric demand of the customer over the billing period (which is usually one month). Because Level 3 chargers draw so much electricity as compared to traditional gasoline pumps, recharging stations will face much higher electric bills—costs they will have to recoup from customers. That, in turn, will mean higher costs for EV owners and fewer overall stations.[52]

C: Distribution Line Upgrades

Local distribution systems are composed of higher voltage primary feeders that serve lateral feeders as well as transformers.

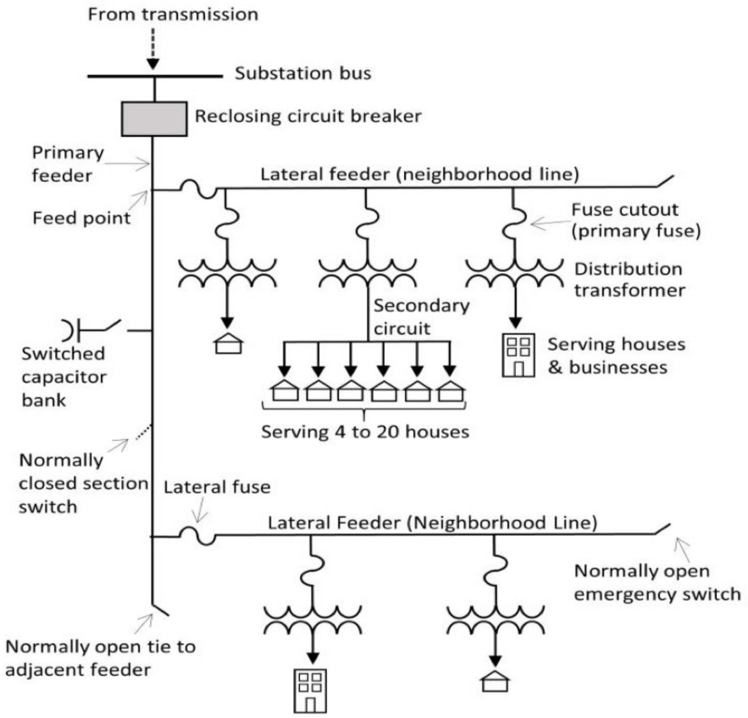
The substation bus at the top of **Figure 3** contains one or more transformers of the kind needed to reduce the voltage of the electricity taken from the bulk power system to a lower voltage on the primary feeder. Electricity is then distributed to secondary (or lateral) feeders. In many cases, transformers are used to reduce the voltage from the primary feeder to secondary feeders. Finally, electricity is delivered to end users, either individuals or groups, again after transformers lower the final voltage.

Because a larger conductor is more costly, distribution circuits are designed to meet simultaneous expected peak demand, rather than maximum potential demand. For example, if a 240-volt, single-phase secondary circuit serves five homes, each having 200-amp service, the maximum power flow would be 240 kW and the circuit size would have to be large enough to handle 1,000 amps of current flow. However, because it is unlikely that all five homes would draw 200 amps at the same time, the circuit can be smaller. So, if the expected simultaneous peak current is 60 amps for all five homes, then the total current flow would be 300 amps and the circuit could be designed to handle a smaller power flow of 72 kW.

If most end users (such as homeowners) install Level 2 EV chargers, then electricity demand will increase. In the example above, if all five homes install 40-amp Level 2 chargers and all five switch those chargers on in the early evening, then the simultaneous load could increase to 100 amps each with an overall power flow of 120 kW. The 67% increase in peak electric demand is likely to require reconductoring the secondary circuit (as well as the lateral feeders) to handle the additional load. As the NREL 2024 report estimates, one should plan for a doubling or tripling of peak electric demand, absent load management policies that prevent consumers from charging EVs when it is most convenient. Regional Transmission Organizations, such as the New York Independent System Operator (NYISO) and PJM Interconnection which coordinate the operations of thousands of generators and high-voltage transmission lines, are also forecasting large increases in electricity demand.[53]

Figure 3

Diagrammatic Overview of a Typical Distribution Feeder



Source: Mike Warwick and Mike Hoffman, "Electricity Distribution System Baseline Report for DOE Quadrennial Energy Review," Battelle Pacific Northwest Laboratory, PNNL-25187, April 2016.

IV. Hardware Requirements for the Bulk Power System

Installing thousands of high-voltage Level 3 charging ports will also require upgrading the bulk power system. In addition to increasing the capacity of transmission lines to meet the higher demand for electricity, hundreds—if not thousands—of new substations will need to be built to accommodate the peak demand at electric charging stations, especially for the large charging stations located along highways.

According to a report prepared by National Grid, a typical highway recharging station requires at least 20 Level 3 chargers. The company analyzed three types of highway facilities: passenger plazas (like highway rest areas), mixed-use plazas (combining facilities for passenger cars and some heavy trucks), and large passenger/truck stops (providing recharging facilities for numerous heavy-duty trucks). According to its report:

> Highway corridor charging will serve as a key component for both passenger cars and trucks. For light-duty vehicles (LDVs), highway charging is crucial to provide seamless access along common passenger

routes, alleviating range anxiety on longer trips. For medium-duty (MD) vehicles, highway charging provides an important complement to depot charging [that is, charging vehicles at a company's private hub] for local fleets with unpredictable duty cycles or, in some cases, may enable small business fleets to electrify without investing in depot charging. For heavy-duty (HD) vehicles, a comprehensive corridor charging network is critical to unlock cost-effective electrification in regional-haul and long-haul segments that have longer, more unpredictable daily duty cycles.[54]

The U.S. Interstate Highway System is approximately 49,000 miles in length. There are an additional 19,000 miles of other freeways and expressways,[55] plus 160,000 miles of major arterial highways (i.e., roads with "U.S. Highway" designations), as shown in **Figure 4**. There also are hundreds of thousands of miles of smaller state highways, which may require smaller, light-duty vehicle charging stations.

Because most of the nation's long-distance heavy truck traffic travels along these highways, our analysis assumes that high-voltage EV charging stations will be located solely along them. We assume charging stations are placed every 50 miles, consistent with infrastructure requirements published by the Federal Highway Administration for EVs.[56] This implies a total of about 4,200 fast-charging stations (220,000 miles / 50 miles).

By 2045, according to the previously referenced National Grid study, the peak charging capacity at a passenger plaza should be at least 10 megawatts (MW) (equivalent to the electricity demand of a typical sports stadium), a mixed-use plaza should have a charging capacity of 20 MW (the electricity demand of a small town), and large passenger/truck stops should have a charging capacity as high as 50 MW (as much power as a modern steel mill). That study assumes an average of at least 20 Level 3 chargers per facility or around 65,000 DC charging ports. Our analysis assumes one such facility every 50 miles. Hence, the same facility type can be assumed to be located every 150 miles, implying about 1,400 of each facility. We assume light-duty EVs can recharge at all stations.

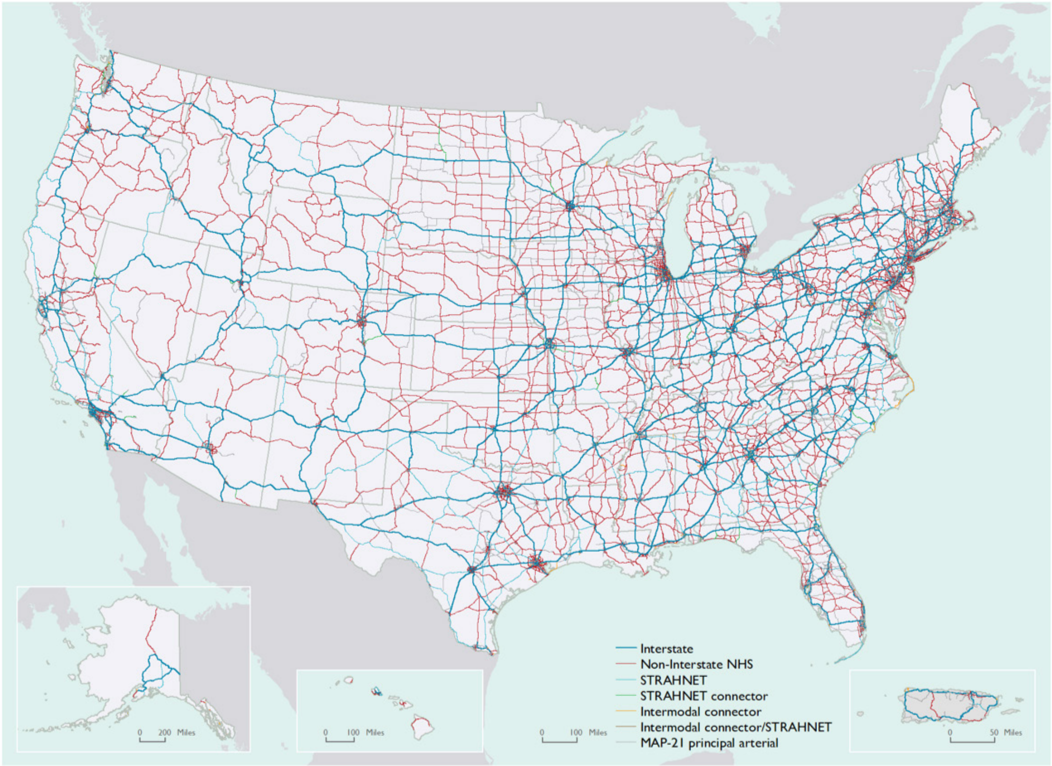
A: Transformer Upgrades

There are at least three reasons why serving highway-based charging stations with peak demands of up to 50 MW likely will

Figure 4

U.S. National Highway System

National Highway System, Intermodal Connectors, and Principal Arterials: 2018



KEY: NHS = National Highway System or the interstate highway system; STRAHNET = Strategic Highway Network or a network of highways that are important to the U.S. strategic defense policy. MAP-21 principal arterials = those rural and urban roads serving major population centers not already categorized above.

Source: U.S. Department of Transportation (DOT), Bureau of Transportation Statistics, National Highway System require direct interconnection to the bulk power grid at voltage levels of 69 kVA or higher.[57] First, lower voltage distribution circuits do not usually follow highways, especially interstates. Second, minimizing losses along great stretches of highway requires higher voltage circuits. Third, the amperage requirements for providing electricity to 20 500-amp Level 3 chargers simultaneously demand larger conductors than are typically found on lower voltage distribution circuits.

For a large passenger/truck stop with 40 fast chargers, each operating at 980 volts and drawing 500 amps, the transformers would need to be sized at 25 MVA.[58] Each facility will also need a smaller step-down transformer to reduce voltage levels from the 980 volts used by the chargers to 240 volts for the accompanying facilities (such as convenience stores and restaurants) Mixed facilities likely would require 20 MVA transformers, and passenger vehicle-only facilities would require transformers sized between 5 MVA and 10 MVA, depending on the number of charging ports.

At present, the wait time for delivery of the largest utility transformers can take several years, and overall transformer costs have soared 71% since 2018.[59] Replacing tens of millions of distribution transformers would require massive quantities of copper, of which nearly all of which would likely be foreign-sourced. Replacing tens of millions of transformers would also vastly exceed the production capabilities of the handful of U.S. transformer manufacturers.[60] Moreover, the U.S. is almost entirely dependent on imports from Asia for large substation transformers—this fact alone raising national security issues.[61]

B: Transmission Line Upgrades

Several studies have estimated the need to increase the capacity of the transmission grid to accommodate the projected increase in United States electricity demand from electrification efforts, together with supplying most of the additional electricity required with zero-emission wind and solar power. Currently, there are around 250,000 miles of high-voltage (230 kV and higher) transmission lines in the U.S., and another 260,000 miles operating at between 100 kV and 199 kV.[62] The U.S. Department of Energy (DOE) recently estimated that the high-voltage transmission system would need to triple by 2040 under a high-growth scenario and increase by almost 60% under a moderate-growth one.[63] This implies a need for more than 300,000 miles of new transmission lines by 2040 (about 19,000 miles annually) under the DOE's "moderate growth" scenario and a staggering 1.5 million miles under the agency's "high-growth" scenario (about 100,000 miles annually). To put it in another way, the U.S. would need to install between 50 miles and 4,000 miles of new transmission lines each day to meet the 2040 estimates of needed transmission capacity. The need for new transmission lines can be reduced by reconductoring existing lines to carry greater amounts of electricity.[64] Nevertheless, reconductoring should not be considered a panacea, as it is still expensive (about 50% of the cost of building a new line) and would not obviate the need for rapid construction to meet growing electricity demand. Thus, contrary to some claims, reconductoring is not a "fast" solution for the need for additional transmission capacity.[65]

Meanwhile, the miles of new transmission lines (135 kV and higher) added each year have fallen from 4,000 in 2013 to just 500 in 2022.[66] Furthermore, there is a growing shortage of skilled linemen needed to maintain existing transmission lines, much less install new ones.[67] Consequently, the prospect of upgrading the needed transmission line capacity—both by adding new lines and reconductoring existing ones to handle larger power flows—is minimal.

Without the additional transmission capacity, it will be physically impossible to meet the electrification and the 100% EV future that proponents seek.

V. Estimating the Cost of Required Infrastructure Upgrades for an All-EV Future

Assuming that the hurdles could be overcome in the timeframes imagined—which is highly unlikely—a 100% EV future by 2050 will cost trillions of dollars for all the supplies of materials, equipment, and skilled labor needed.[68] For example, such costs would go toward:

- Upgrading the capacity of breaker boxes in single- and multi-family homes, and apartments, as well as adding new dedicated circuits for residential EV chargers.
- Upgrading the capacity of millions of distribution transformers, especially the secondary, low voltage transformers that serve residential customers.
- Rewiring millions of miles of distribution circuits to accommodate the increase in peak electric demand.
- Installing thousands of large transformers to handle high voltage, public charging stations.
- Installing thousands of miles of new high voltage transmission lines and reconductoring existing lines to accommodate greater electric demand and delivery of electricity from far-flung wind and solar generating plants.
- Installing millions of privately owned Level 2 chargers at homes and businesses, plus hundreds of thousands of public Level 3 chargers to mimic the existing ability of drivers of internal combustion vehicles to refuel whenever they choose at retail gasoline stations.

A: Level 2 Charger Costs

Level 2 chargers cost between $300 and $1,000, depending on the model and its capabilities.[69] The U.S. Census Bureau estimated there were 82 million single-family homes in 2021, the most recent data available.[70] Equipping that many homes with Level 2 chargers would cost between $25 billion and $82 billion. The cost of installing a Level 2 charger typically exceeds the cost of the charger itself. A 2015 study by the Idaho National Laboratory estimated that the installation cost for a Level 2 charger ranges between $700 and $1,800.[71] A 2020 report by the U.S. Department of Transportation (DOT) estimated an average cost of $1,400.[72] SunRun, which sells Level 2 chargers, estimates an installation cost of $1,750 just for the dedicated 240-volt circuit.[73] J.D. Power estimates the average installation to cost between $1,200 and $2,500.[74] If each of the approximately 82 million single-family homes were equipped with a Level 2 charger and a dedicated circuit for that charger, then the total installation costs would be between $100 billion and $200 billion. Hence, the total cost of putting Level 2 chargers in all single-family homes would be between about $125 billion and $285 billion.

As of 2021, there were approximately 44 million multi-family apartment units in the country.[75] Using the data above, the cost of installing one Level 2 charger for each unit would be between $66 billion and $150 billion.

Ultimately, the cost of equipping and installing a Level 2 charger for all single-family and multi-family units is likely to run between $190 billion and around $430 billion.

B: Local Distribution System Upgrades

Local distribution upgrades primarily mean replacing existing transformers with larger ones and reconductoring distribution circuits to accommodate for greater peak loads. Additional costs, such as larger fuses and capacitors, will also be incurred, but these will be small in comparison.

A 2019 study prepared by the Boston Consulting Group estimated distribution upgrade costs of $5,800 per EV to achieve a penetration level of 10% EVs by 2030 when charging availability is not constrained.[76] Adjusted for inflation, that is equivalent to over $6,800 per EV today. The report also notes that the cost per EV increases as the number of EVs increases. Ignoring that finding to be conservative, replacing the entire light-duty vehicle stock with EVs will require between $1.6 trillion and $1.8 trillion to upgrade the entire distribution system.

Another approach to estimating distribution system upgrade costs is to build up the costs of the components (primarily pole-mounted and pad-mounted distribution transformers) plus rewiring existing distribution lines to handle higher peak loads. Typically, new residential transformers cost several thousand dollars, including installation costs. These costs will increase even further because the new DOE efficiency rule will require the use of amorphous steel in transformers starting in 2027.[77] The DOE estimates its rule will increase the annual cost of replacing distribution transformers by $652 million at current levels, or roughly $600 per transformer.

The need to upgrade distribution transformers will be specific to location. If half of the estimated 60 to 80 million distribution transformers will require upgrading from 10–15 kVA to 25 kVA at an incremental cost of $2,000 for each transformer, plus an additional $1,000 for installation, the overall cost will be between $90 billion and $120 billion.

Similarly, assuming that half of the 5.5 million miles of distribution lines will require reconductoring with higher-capacity lines, a 2018 study estimated the average reconductoring cost to be $300,000 per mile.[78] In the intervening six years, the producer price index for electric utility components increased by approximately 50%.[79] Hence, we calculated a cost of $450,000 per mile, resulting in an overall cost of $1.2 trillion. Adding this to the estimated cost of transformer upgrades results in a cost of $1.3 trillion, like the $1.4 trillion estimate derived from the Boston Consultant estimate.

C: High Voltage Transmission Infrastructure

In addition to increasing transmission lines, a nationwide system of over 4,000 public highway charging stations will require installing large transformers and associated infrastructure to provide electricity to the high-voltage Level 3 chargers required.

The Midcontinent Independent System Operator (MISO) publishes an annual detailed guide to estimate high voltage transmission costs for the states within its footprint. The cost estimates range between $1.7 million and $5.5 million per mile (depending on voltage levels for single-circuit lines) and between $2.4 million and $5.7 million per mile for double-circuit lines (i.e., lines with two separate circuits, each having three lines or six lines in total).[80] Hence, the overall range is between about $2.0 million and $5.6 million per mile. The costs for reconductoring existing lines range between $320,000 and $1.1 million per mile. Assuming 300,000 miles of new transmission lines are constructed, the resulting costs would be between $600 billion and $1.7 trillion.

Each public charging station will require a substation to take power from nearby transmission lines. MISO estimates the costs of these substations to be between $7.1 million and $92.3 million, depending on the voltage levels of the transmission lines.[81] The higher the transmission line voltage, the greater the substation cost because larger capacity transformers are required to step down the voltage levels. Assuming most public charging stations along highways will take power from a lower voltage transmission line of 138 kV, a reasonable range of costs is between $10 million and $25 million per substation with the resulting cost ranging between $40 billion and $110 billion. These costs exclude annual maintenance, which MISO estimates to be around 3.4% of the annual installed cost.[82] Assuming 20 ports per charging station, costing around $50,000 per port, the overall costs of the Level 3 chargers at each charging station will increase costs by an additional $5 billion.

Thus, based on current costs, upgrading the infrastructure required for an all-EV future will require between $2.4 trillion and $3.9 trillion (**see Table 1**). However, with the large increase in demand for raw materials such as copper and steel, components such as transformers, and skilled electricians and linemen, the actual total will almost certainly be higher.

Table 1

Estimated Total Infrastructure Cost for an All-EV Future

Hardware Category	Estimated Cost ($ Billions)	
	Low	High
Single-Family and Multi-Family Chargers	$190	$430
Local Distribution System Upgrades	$1,600	$1,800
New Transmission Lines	$600	$1,700
Substations for Public Charging Stations	$40	$110
Level 3 Chargers at Public Charging Stations	$5	$5
TOTAL	**$2,435**	**$4,045**

Source: author's calculations

Conclusion

Little public attention has been paid to the infrastructure requirements needed for an all-EV future. Meeting those requirements, along with the need to increase the supply of electricity to charge millions of EVs, will be difficult—if not impossible—to achieve 25 years from now and will cost trillions of dollars even if it can be accomplished.

One adverse result of this spending will be higher electricity costs, as electric utilities and transmission owners recoup their investments in new infrastructure. Higher electric costs will result in reduced economic growth, despite promises of a "green" transformation of the economy. European countries have demonstrated that increased reliance on wind and solar power leads to higher electric costs—owing to both the subsidies needed for the generators themselves and the cost of backup supplies needed to compensate for wind and solar power's inherent intermittency. This, in turn, has led to deindustrialization—that is, declining industrial activity— especially in Germany and Great Britain.[84]

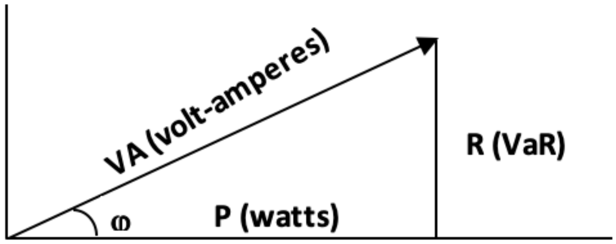
The headlong rush towards EVs is being driven by taxpayer-funded subsidies, as well as by laws and mandates that explicitly or implicitly amount to bans on the sale of internal combustion vehicles. Both the subsidies and mandates ignore the physical and economic realities involved. But reality cannot be ignored and likely will cause that headlong rush to collapse. The question is how much economic damage will occur before the collapse takes place.

Appendix: A Primer on Transformer Capacity.

As shown in Figure 2, transformers are an integral part of the electrical distribution system. Typically, large power stations generate electricity at 11,000 volts (11 kilovolts or "kV"). To transmit that electricity long distances, that voltage is "stepped up" to 220 kV to 880 kV (depending on distances) because doing so decreases electrical losses. Those voltages are far too high for local distribution systems, so other transformers are used to step down the voltage to between 12 kV and 34 kV, which distribution lines can handle.[85] However, those voltages are still far too high for use in a home or business, so a final set of transformers is needed to reduce those distribution voltages to an acceptable level, typically 240 volts for a household.

To understand voltage and current, a useful analogy is a garden hose. Voltage is represented by the diameter of the hose; the larger a hose's diameter, the higher the volume of water that can be pushed through it per unit of time. Current is the actual amount of water that flows through the hose each instant. Wires with larger diameters operate at higher voltages and can carry more current. Transformer capacities are measured in volt-amperes. The largest transformers have capacities of millions of volt-amperes (MVA) and are designed to handle loads on the high-voltage bulk power system. By contrast, the millions of pole-mounted transformers common along residential streets usually have capacities between 4,000 volt-amperes (4 kilovolt-amperes, kVA) and 33 kVA. To understand what is meant by a "volt-ampere," it helps to first understand direct current (DC) and alternating current (AC) circuits. Electric power is measured in watts and equals current, measured in amperes, multiplied by voltage, i.e., P = A x V. For a direct current circuit, with constant voltage and current, A x V represents real power, that is, power that is available to do useful work, such as the power used to write this short primer. In this case, "useful" means the ability to do physical work (i.e., run a motor) and not "reading this appendix is useful."

AC circuits are more complex because both voltage and current oscillate, i.e., "alternate" and hence "AC." In the U.S., the oscillation frequency is normally 60 times per second. In an AC circuit, this cycling creates reactive power. Reactive power occurs because the cycling of voltage and current is not always in phase, as shown in the figure below.



In the figure, the amount of real power is represented by the line **P**, which is measured in watts. It equals current x voltage and is measured in watts. The amount of reactive power is shown by the line **R** and is measured in "volt-amperes reactive" or "VaR." The apparent power is the heavy arrow **VA** and is measured in volt-amperes. The relationship between real power and apparent power is called the power factor and equals **P/A**, and depends on the phase angle, **ɸ**, which measures the degree to which current and voltage are out of phase.

An often-used analogy to describe reactive power is that it is "foam on the beer." When you pour out a glass of beer, the glass has both liquid that you can drink (real power) and foam on top that you cannot (reactive power). The total amount of beer (liquid plus foam) is the apparent power. Although reactive power cannot perform useful work, it is actually crucial for controlling voltage in an AC system.[a]

The lower the power factor, the more current is needed to supply the same amount of useful energy. For electric transmission and distribution systems, a lower power factor means larger sized circuits that are required to calculate more current. It also means more electrical losses, which further increases costs. This is why electric utilities often require industrial customers using large motors that necessarily draw huge currents to ensure the power factors of those motors always exceed some minimum value (usually above 0.90).

Transformer size is measured by apparent power. How much real power a transformer provides depends on the efficiency of the devices connected. The size of transformer required is based on the amount of voltage required and the amount of current that will be delivered. It also depends on whether the transformer is single phase or three phase (three lines of power).[b] The kVA formula for a three-phase transformer is: A x V x 1.732 / 1000. The three lines are out of phase, so the total power delivered is not three times as large and instead increases by the square root of 3, which is approximately 1.732.

For example, a DC charger operating at 800 volts and drawing 100 amps requires a three-phase transformer with a rating of at least 800 x 100 x 1.732 / 1000 = 138 kVA. Transformers come in discreet sizes, so this would mean a 150 kVA transformer, just for one DC charger. By contrast, a typical pole-mounted transformer for a residential home is 15 kVA, based on the expected peak draw of the home. For example, if the utility expects the peak power draw never to exceed 60 amps, then the transformer must be sized to accommodate (60 A x 240 V)/1000 = 14.4 kVA. If the addition of a Level 2 charger increases the expected peak power draw to 100 amps, then the transformer size must be increased to accommodate (100 A / 240 V)/1000 = 24 kVA.

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a. A discussion of why reactive power is needed to maintain system voltage is beyond the scope of this report. For an exhaustive discussion, see Naser Mahdavi Tabatabaei, Ali Jafari Aghbolaghi, Nicu Bizon, and Frede Blaabjerg, eds. Reactive Power Control in AC Power Systems: Fundamentals and Current Issues (Springer Intl. 2017).

b. For an explanation of three-phase power, see Edis Osmanbasic, "Three-Phase Electric Power Explained," engineering.com, Oct. 29, 2017.

End Notes

1. U.S. Dept. of Energy (DOE), Alternative Fuels Data Center, Adoption of California's Clean Vehicle Standards by State.

2. Hedges & Company, US Vehicle Registration Statistics, undated.

3. See, e.g., Mark Mills, "Mines, Minerals, and 'Green' Energy: A Reality Check," Manhattan Institute, July 9, 2020. See also S&P Global, "The Future of Copper: Will the Looming Supply Gap Short-Circuit the Energy Transition?" July 2022.

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5. The EPA limits flow rates for light-duty vehicle gasoline pumps to 10 gallons/minute. Thus, including the time needed for a transaction (credit card at the pump or paying a cashier) requires perhaps 5–10 minutes to refill a 20-gallon gas tank. A typical DC charger operating at 270 kilowatts can recharge an EV battery to 80% of its capacity in about an hour. Often, recharging times are reported disingenuously in terms of miles of range per 30 minutes of charging. See DOE, Alternative Fuels Data Center, Electrical Vehicle Charging Stations.

6. National Grid, "Electric Highways: Accelerating and Optimizing Fast-Charging Deployment for Carbon-Free Transportation," November 2022.

7. Mark Mills, "The Hard Math of Minerals," *Issues in Science and Technology*, Jan. 27, 2022.

8. Herman Trabish, "With Looming EV Load Spikes, PG&E, Duke, Other Utilities Adopt New Rate Design and Cost Recovery Strategies," Utility Dive, Apr. 18, 2023. See also Juuso Liikkanen et al., "Cost-Effective Optimization for Electric Vehicle Charging in a Prosumer Household," *Solar Energy* 267, Jan. 1, 2024, 112112.

9. The introduction of distributed generation (or electricity generated near the point at which it is used rather than a power plant), sometimes called "behind-the-meter" generation, especially by solar photovoltaics, adds further physical complexities to local distribution infrastructure requirements because of its intermittency and power flowing back onto the wires. Nevertheless, this complexity will have little impact on the need for distribution infrastructure upgrades for unfettered EV charging.

10. This is a consequence of Ohm's Law. As voltage increases, losses decrease by the square of the increase. For example, losses on a 1,000-volt circuit will be 1/100th the losses on a 100-volt circuit.

11. Killian McKenna et al., "Major Drivers of Long-Term Distribution Transformer Demand," NREL/TP-6A40-87653, February 2024 (NREL 2024).

12. WM Warwick et al., "Electricity Distribution System Baseline Report," Battelle Pacific Northwest Laboratory, PNNL-25178, July 2016, Table 2.2.

13. NREL 2024. The report estimates that almost 27 million Level 1 (low voltage) and Level 2 charging ports will be required at single-family and multi-family homes, plus workplaces, by 2030 alone. Given the predicted number of EVs by that year, the 100% EV future envisioned by 2050, in which EVs constitute almost all of the 290 million light-duty vehicle stock, is likely to require 50 million or more charging ports.

14. A study in Norway tracked hundreds of EV owners and their charging habits. See Ase Sorenson et al., "Data Article: Residential Electric Vehicle Charging Datasets from Apartment Buildings," Data in Brief 36 (June 2021), 107105. A 2019 study by Avista Corporation (an electric utility based in Spokane, Washington) found that commuters recharged vehicles 4.9 times per week on average. Peak charging demand took place around 6 pm. See Rendall Farley et al., "Electric Vehicle Supply Requirement Pilot: Final Report," Avista Corporation, Oct. 18, 2019.

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16. A typical home electric stove/oven draws between 20 amps and 60 amps. See Jacob Marsh, "How Many Watts Does an Electric Oven Use? Energy Sage, Dec. 6, 2023.

17. U.S. Census Bureau, Annual Estimates of County Housing Unites for States: 2022 to 2022.

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19. Ibid.

20. Upgrades to distribution lines are discussed in Section III C.

21. The degree to which this will inconvenience EV users is a matter of debate. A recent study prepared by faculty at the Technical University of Denmark uses simulations to claim that EV charging can be controlled without compromising user satisfaction. See Xihai Cao et al., "Distributed Control of Electric Vehicle Clusters for User-Based Power Scheduling," Proceedings of the 2023 IEEE Transportation Electrification Conference and Expo, Asia-Pacific (ITEC-AP 2023), IEEE (Institute of Electrical and Electronics Engineers).

22. Some older distribution lines operate at 4 kV. Distribution voltages generally are defined as those up to 35 kV.

23. For a detailed report on load profiles for the U.S. building stock, see Eric J.H. Wilson et al., "End-Use Load Profiles for the U.S. Building Stock: Methodology and Results of Model Calibration, Validation, and Uncertainty Quantification," National Renewable Energy Laboratory, NREL/TP-5500-80889, March 2022.

24. Ibid.

25. Ibid.

26. NREL 2024.

27. This includes the weight of the oil in the transformer. See Bhagwan Prasad, "Copper and Iron Weight of Content in Transformer," Power Engineering, July 20, 2020.

28. Ibid.

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30. Ibid.

31. The amount of copper used depends on the type and size of battery and the size of the motor. See International Energy Agency (IEA), "The Role of Critical Minerals in Clean Energy Transitions," March 2022.

32. United States Geological Survey (USGS), Mineral Commodity Summaries 2024, Jan. 31, 2024, 64–65.

33. Ibid.

34. Antonia Loibi and Luis Espinoza, "Current Challenges in Copper Recycling: Aligning Insights from Material Flow Analysis with Technological Research Developments and Industry Issues in Europe and North America," *Resources, Conservation, and Recycling* 169 (June 2021), 105462.

35. For a description, see Yasuuki Hayakawa, "Electrical Steels," in *Encyclopedia of Materials, Metals and Alloys*, eds. Goro Miyamoto and Michael C. Gao (New York: Elsevier, 2022), Vol. 2, 208–13.

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37. Lori Lovely, "Electric Grid Steeled for Battle Over Metal Choice," *Electrical Contractor*, July 24, 2023.

38. Sonal Patel, "U.S. Power Sector Trade Groups Flag Critical Electrical Steel Crunch," *Power*, May 25, 2023. See also Bob Tita, "The Paper-Thin Steel Needed to Power Electric Cars Is in Short Supply," *Wall Street Journal*, Mar. 27, 2023.

39. Porchselvan Subramanian, "Electrical Steel Production in US Far from Sufficient to Support OEMs' Electrification Goals," CWIEME Berlin, Nov. 9, 2023.

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41. In January 2024, Congress introduced legislation to prevent the DOE standard from taking effect; see Martin Offutt, "DOE's Proposed

Regulation on Electricity Distribution Transformers," Congressional Research Service, Jan. 3, 2024.

42. Many electric utilities oppose the DOE rule because they fear it will exacerbate supply shortages; see Brian Dabbs, "Meet the Metal that Could Transform the Grid," Energywire, June 22, 2023.

43. See, e.g., Ella Zhou and Trieu Mai, "Electrification Futures Study: Operational Analysis of U.S. Power Systems with Increased Electrification and Demand-Side Flexibility," National Renewable Energy Laboratory, NREL/TP-6A20-79094, 2021.

44. Karl Seyfert, "Fuel Pump Diagnosis: AMP Testing," *Motor*, March 2003.

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74. Dustin Hawley, "How Much Does It Cost to Install an EV Charger?" J.D. Power, Dec. 11, 2022.

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77. U.S. Dept. of Energy (DOE), "Energy Conservation Program: Energy Conservation Standards for Distribution Transformers," Notice of Proposed Rulemaking, Dec. 28, 2022, p. 400, Table VI.2.

78. Kelsey Horowitz et al., "The Cost of Distribution System Upgrades to Accommodate Increasing Penetrations of Distributed Photovoltaic Systems," NREL/TP-6A20-70710, April 2018.

79. U.S. Bureau of Labor Statistics, Producer Price Index, Metals and Metal Products: Copper Wire and Cable, April 2024. This index excludes transformers, which, as discussed previously, have increased even more.

80. MISO (Midcontinent Independent System Operator), "Transmission Cost Estimation Guide for MTEP 24," Jan. 31, 2024, Tables 4.1.1. and 4.1.2. These estimates are for AC circuits. DC circuits are more costly.

81. Ibid, Table 4.2.2.

82. Ibid, Table 5.1.

83. Jonathan Lesser, "Renewable Energy and the Fallacy of 'Green' Jobs," *The Electricity Journal* 23, no. 7 (August/September 2010): 45–53.

84. Mario Loyola, "High Electricity Prices Have Europe Facing Deindustrialization; Don't Let It Happen Here," Heritage Foundation, Feb. 12, 2024. See also Robert Bryce, "The Deindustrialization Of Europe In Five Charts," Feb. 12, 2024. Then again, some researchers suggest Europe "embrace" deindustrialization. See Nikolaus Kurmayer, "Researchers Urge Europe to 'Embrace' Deindustrialization," Euractiv, Apr. 24, 2024.

85. The actual voltages are typically 12.47 kV, 22.9 kV, and 34.5 kV. Some older distribution circuits operate at 4.8 kV.

About the Author

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Lesser is a Senior Fellow at the National Center for Energy Analytics, and President of Continental Economics with over 35 years of experience working and consulting for regulated utilities and government. He has addressed critical economic and regulatory issues affecting the energy industry in the U.S., Canada, and Latin America, including gas and electric utility structure and operations, cost-benefit analysis, mergers and acquisitions, cost allocation and rate design, asset management strategies, cost of capital, depreciation, risk management, incentive regulation, economic impact studies, and general regulatory policy. Jonathan has prepared expert testimony and reports for numerous utility commissions and international regulatory bodies and has testified before Congress and numerous state legislative committees, and also served as arbiter in disputes between regulators and regulated utilities. Jonathan has also designed economic models to value nuclear, fossil fuel, and renewable generating assets. He is the coauthor of three textbooks: *Environmental Economics and Policy* (Addison Wesley Longman, 1997), *Principles of Utility Corporate Finance* (Regulatory Economics Publishing, 2011), and the widely used *Fundamentals of Energy Regulation*, 3d ed. (Regulatory Economics Publishing, 2020), as well as numerous academic and trade press articles. Lesser was previously an Adjunct Fellow with the Manhattan Institute for Policy Research. He is an Editorial Board member for Natural Gas & Electricity. Lesser earned a B.S degree in Mathematics and Economics from the University of New Mexico, and M.A. and Ph.D. degrees in Economics from the University of Washington.

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