U.S. DEPARTMENT OF ENERGY | Office of ELECTRICITY

Impact of Electric Vehicles on the Grid

Report to Congress

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Summary

A transition is underway in the Nation's electricity grid, changing grid dynamics from the operational parameters of the past to something nimble, flexible, cleaner, and more resilient. Electric vehicles (EVs) complement many of these advances. The pace and scale of the transition to EVs, driven by customer preference, favorable business economics, and policy incentives, is significant and solutions that integrate EVs with the electricity grid are achievable and well underway.

EVs are more than just another user of energy on the grid to be considered, and determining additional capacity requirements to meet vehicle charging will depend on several variables and the many decisions of stakeholders and customers. EVs' relationship to the grid can be a symbiotic one because they offer flexibility in the time and location where they use energy, they may sit idle for long periods of time, and they store energy in the vehicle battery that could be used for non-transportation applications.

Meeting the energy demand for EV charging will require investments in infrastructure and approaches that take advantage of demand and supply flexibility. Planning, one of the most important arenas in public spending, is crucial to evaluate the engineering aspects, as well as the financial and socio-economic factors. Modeling, analysis, and emerging approaches can inform those planning decisions and de-risk infrastructure investments.

Appropriately planned and designed, the grid can become more flexible and interactive, with better utilization of invested assets. Proactive planning that incorporates a portfolio of options that include infrastructure upgrades, load management approaches to mitigate impacts, and programs that welcome consumers as active participants can balance the growing need for electricity while maintaining affordability and reliability. The Department of Energy (DOE) is dedicated to ensuring a smooth transition, helping stakeholders attain their goals with the help of modeling, tools, data, and analysis.

This report examines the implications that electric vehicle charging will have on the grid and considerations for managing and integrating that load. DOE is committed to — and already is — performing multiple new analyses and is working with stakeholders to navigate the transition.

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I. Legislative Language

This report responds to legislative language set forth in H. Rept. 117-394 – Energy and Water Development and Related Agencies Appropriations Bill, 2023 wherein it is stated:

"The Department [of Energy] is directed to provide to the Committees not later than 180 days after enactment of this Act a report related to the ability of the electric system to meet the demand of new electric vehicle charging infrastructure. The report should anticipate the growth in the use of light duty, medium duty, and heavy-duty electric vehicles and assess how much additional electric generation, transmission, and distribution capacity will need to be added to the electric system to meet demand. For the report and plan, [the Office of Electricity] is directed to coordinate with the Grid Deployment Office, the Vehicle Technologies Office, and the Joint Office of Energy and Transportation."

II. Fast Forward to the Future

To understand the ultimate impact of transportation electrification on the grid, it is important to first fast forward to the future: Gone are electric vehicle (EV) charging anxieties. Against a backdrop of multi-modal transportation options, EV drivers have affordable charging options where they live, work, and pursue their daily lives, so they can drive and charge as they wish. Public charging infrastructure, on-street and enroute, complemented with localized fast- charging options, exists in and around both single-family and multi-family housing, providing charging options for those without garages and/or dedicated parking spaces. Rate structures signal grid conditions that ensure charging occurs at times with available capacity and times of excess renewable generation to minimize operational and economic impacts to the grid.

EVs and chargers that can charge and discharge can take advantage of such rates and contribute to home and grid resilience. A vibrant, competitive EV charging landscape offers options that are aligned with the desires and lifestyles of consumers and communities while also encouraging grid-friendly charging that reduces grid infrastructure and charging costs.

Utility planning practices have evolved to accommodate the accelerated growth, incorporating additional inputs from state, local, and transportation planning activities, building grid infrastructure that is right-sized, safe, resilient, and affordable. Collaboration across entities and between systems occurs because of seamless information sharing agreements and practices that ensure each party has the information necessary for their respective function. Data-privacy policies, as well as technological and economic innovations, have simplified charging, making it convenient and available where needed, while also protecting all parties' confidential information.

As part of the clean generation mix supplying homes and businesses, utility operators coordinate power requirements with local and centralized generation, leveraging the symbiotic nature of driving patterns and renewable generation with the new rhythms of an increasingly decarbonized grid, taking advantage of both distributed and centralized resources. Managed charging, energy storage, and efficiency measures are extensively employed to broaden capacity, flexibility, and resilience in many neighborhoods. Major grid investments are utilized more efficiently and consistently as a result of the flexibility of newly electrified transportation loads, keeping electricity affordable for EV drivers and other consumers alike.

Distribution design standards have adapted to meet the operating characteristics for a system that supports the societal shift to electrify transportation and other sectors. This has rendered certain distribution voltages and circuit layouts obsolete and led to a consolidation and standardization of equipment specifications, resulting in increased manufacturing capacity, shorter lead times, and reduced equipment costs.

Long-haul truckers and middle- and last-mile delivery drivers have cost-effective depot and on- route charging options that match their operational cadences, ensuring that goods are delivered when and where customers need them. Long-distance travelers have reliable, efficient charging options whether enroute, at their destination, or at travel centers that offer charging options for everything from light-duty cars to heavy-duty 18-wheelers. The impacts of load growth and high-intensity charging loads for medium- and heavy-duty vehicles are managed with a combination of innovative rates, collaborative managed and bidirectional charging solutions, and strategic deployment of energy storage.

The coordination and planning that takes place between transportation and electricity has resulted in economic and operational gains, creating additional value and convenience for individuals and businesses. In cities, fleet charging complements parking availability by taking advantage of dual-use opportunities. In rural areas, infrastructure investments to support on- road charging also support electrification of agricultural equipment, non-road transport machinery, and other industrial purposes. In every community, there is an infrastructure convergence to meet societal demands. EVs cooperate and coordinate with the grid, one piece of many that reinforce the resilience of the clean energy future.

III. Changing Grid Dynamics

The electricity sector is — and will remain — in a transitional state, continually responding to emerging technological advances and changing societal and consumer preferences. Electric vehicles are proving a catalyst to the many changes taking place, accelerating and intensifying the implications throughout the system by linking the transportation and electricity sectors, two pillars of American competitiveness. **The vision depicted above is attainable**, and has already sparked the reimagining of long-standing processes, procedures, and practices to achieve value for the customer, the grid, and the Nation as a whole.

The shift to a decentralized system is reshaping grid dynamics to one that is more behaviorally driven, dependent on and responsive to customer decisions. It is expanding customers' relationship with energy beyond the utility. Customers are generating their own energy and offering services in return for compensation with third parties amplifying the customers' voice and broadening the field of who can provide services and value. This evolution entails a more sophisticated approach to how the grid is planned, controlled, and managed, heightening the focus on reliability and resilience.

Determining additional capacity requirements to meet vehicle charging will depend on several variables and the many decisions of stakeholders and customers about how charging is integrated with the grid. EVs are different from many other loads: they can change the time, location, and intensity with which they draw energy, they may sit idle for long periods of time, and they store energy in the vehicle battery that is useable for other non-transportation applications providing value to the EV driver and the grid. No longer solely a temporal factor, energy usage will include spatial and intensity components as customers' mobility patterns are overlaid onto energy usage. These attributes offer tremendous potential from a grid perspective.

Leveraging the flexibility of EVs intensifies the need to integrate social and behavioral sciences in utility planning. While customers purchase vehicles for the primary purpose of transportation, vehicle drive cycles, the amount of time a vehicle is parked, along with the variable battery-charging rates, offer the possibility for time- and location-shifted charging and discharging to match available capacity or renewable generation– all while maintaining drivers' mobility needs. There is potential for the grid to utilize energy from the vehicle battery to support electricity demand and serve as a resource for grid operations, including ancillary grid services. Behavioral science can provide deeper insights into consumer motivations, so customer participation in such programs can be quantified and integrated into utility planning and market design.

Widespread adoption of light-, medium-, and heavy-duty EVs over the coming decades will bring significant new load growth. It will require investments in infrastructure and approaches that take advantage of demand and supply flexibility. It introduces a broader range of considerations and questions regarding the equity implications of decisions and investments. It will necessitate a proactive planning posture, along with responsive actions, to meet the timeframe that customers and businesses demand, because charging infrastructure can be installed much quicker than electric grid infrastructure can be deployed.[1] Proactive planning will allow for a balancing of opportunities and costs to be certain that the energy system meets the desires and preferences of tomorrow's customer, while simultaneously enhancing resilience and reliability and maintaining affordability for all electricity customers.

The relationship between EVs and the power grid will be symbiotic. With judiciously managed transactions, electricity contained in light-, medium-, and heavy-duty EV batteries can serve to support and stabilize the grid during both standard and emergency operations while also increasing asset value to EV owners. Meeting widespread EV adoption will require approaches to infrastructure investment that take advantage of not only the demand, but also of the electricity supply flexibility afforded by EVs.

Embracing these market-driven evolutions can lead to new capabilities that enable innovation, improve efficiencies, and drive benefits for all stakeholders. Leadership and direction from DOE can help navigate the changing dynamics and will drive economic and equitable solutions that benefit customers, the grid, and the Nation as a whole.

IV. Forecasting EV Growth to Determine Grid Impacts

The global rate of adoption of passenger plug-in electric vehicles (PEVs)[2] has increased rapidly since the mid-2010s, and many factors are fueling the growth.[3] The International Energy Association (IEA) reported that global sales of light-duty EVs in 2022 exceeded 10 million and that sales through the first quarter of 2023 outpaced the same period of the previous year by 25% [1]. In the U.S., the market share of PEVs has more than quadrupled from 2020 to 2023 [2], reaching historic peaks of 9.91% in September 2023, for a year-over-year increase for the month of nearly 60% [2].

Consumer preference for EVs has increased [3, 4] as the barriers to EV ownership have decreased. National policy,[4] as well as private investments [5, 6], are expanding the public charging network for light-duty vehicles, and tax incentives and rebates for electric vehicles are reducing the cost to

[1] Timelines for charging infrastructure deployments range from 6 months to more than two years; whereas, electricity distribution upgrades can range up to 2–7 years and transmission upgrades up to 10–15 years [54].

[2] "PEVs" includes plug-in hybrid electric vehicles and full-battery electric vehicles.

[3] The increase in EV adoption is underpinned by three key pillars [9]: Improvements and cost reductions in battery technologies, a wide range of supportive policy actions for clean transportation solutions in major global markets [55], and regulations and standards that support energy-efficient and clean transportation solutions.

[4] The Bipartisan Infrastructure Law invests $7.5 billion to build out the first-ever national network of EV chargers in the United States. Businesses and households that install charging stations can earn up to $100,000 in tax credits through the Alternative Fuel Vehicle Refueling Property Credit (30C) [56].

purchase and operate EVs.[5] Seeking to improve local air quality and reduce greenhouse gas emissions, seventeen states and the District of Columbia have adopted emissions standards set by the State of California through their authority under the Clean Air Act, which will also significantly increase passenger EV sales between now and 2035 [7]. In response to these regulations and increasingly favorable economics for electric vehicles, American auto manufacturers have set ambitious sales goals for the coming years.[6] Related regulations set by the California Air Resources Board (CARB) will drive increasing sales of commercial vehicles nationwide as manufactures develop and build vehicles to the more stringent standards [8].[7] Furthermore, initiatives like the Clean Energy Ministerial's Drive to Zero™ program[8] partners with municipalities and manufacturers across the U.S. to accelerate the transition to global zero-emission commercial vehicles.

Determining how, when, and where EVs' impacts on the electric grid will be felt requires some understanding of how many EVs are expected to be connected. The Department of Energy has worked extensively with National Laboratory partners to develop projections of EV adoption for light-, medium-, and heavy-duty vehicles, although both the speed and ultimate extent of EV adoption remain uncertain [9]. Projecting personally owned light-duty (LD) EV sales is particularly challenging because millions of independent decision-makers value vehicle attributes differently. Adoptions of medium- and heavy-duty (MHD) zero-emission vehicles (ZEV) will be based on technology readiness, regulations, infrastructure availability, and economic assessment, but will also rely on variables that defy precise prediction.[9] Despite the many variables that factor into adoption forecasts, approaches exist for modeling adoption projections. Developing directionally relevant adoption projections with consensus around underlying assumptions can assist utilities, regulators, and other stakeholders as they evaluate infrastructure investment decisions, market design, and load management approaches so that the electricity infrastructure is in place when needed.

Light-Duty PEV Adoption

Studies performed by the National Renewable Energy Laboratory (NREL) utilized three adoption scenarios based on different rates of EV sales growth demonstrating a range of plausible estimates to inform stakeholder planning efforts [10].[10] The results projected a range of 30 million to 42 million LD PEVs on the road by 2030 as shown in Figure 1.

[5] The Clean Vehicle Tax Credit went into effect as part of the Inflation Reduction Act (IRA) of 2022. Additionally, some states are providing credits and other benefits to encourage EV ownership.

[6] A partial example of a long list of manufacturer commitments includes Chrysler seeking to sell only EVs by 2028, Buick and Cadillac planning to achieve the same by 2030, and GM aiming for no later than 2035.

[7] Many global business enterprises, such as Walmart, FedEx, Amazon, and others are developing plans to switch to zero-emissions in the next few years with aggressive ramp-ups [8].

[8] Drive to Zero is an international effort with the aim of zero emissions technology becoming commercially competitive by 2025 and dominant by 2040 in specific vehicle segments and regions.

[9] It is worth noting that adoption of advanced technologies has historically been underestimated in modeling and analysis results [9], which fail to capture rapid technological progress and its impact on sales.

[10] National PEV adoption scenarios were developed using NREL's Transportation Energy & Mobility Pathway Options model, an all-inclusive transportation demand model that covers the entire United States, sponsored by the Office of Energy Efficiency and Renewable Energy.

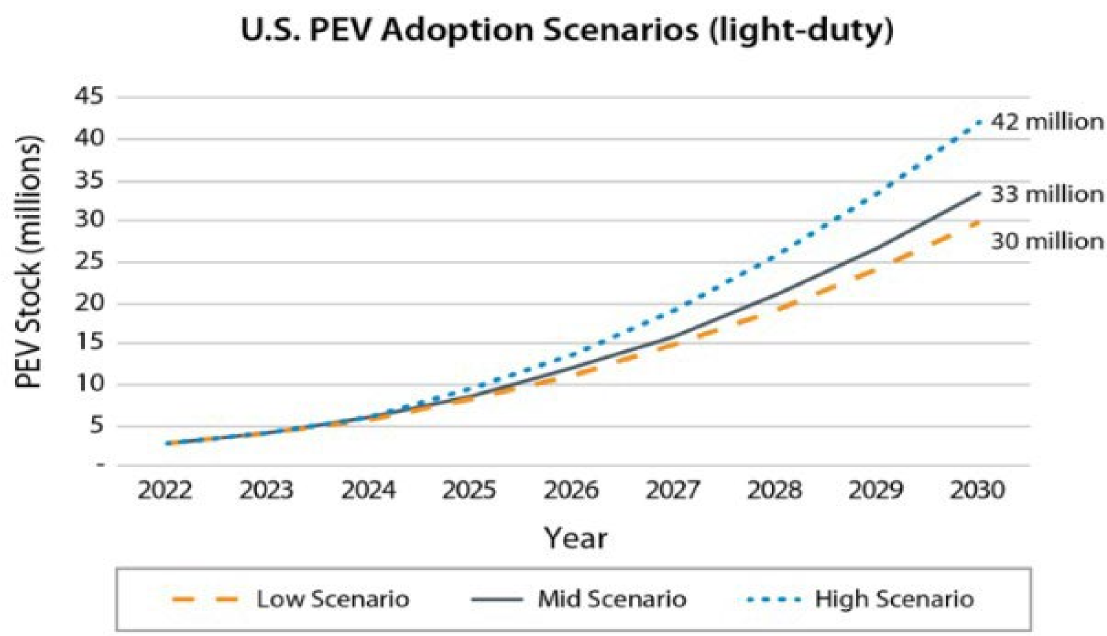


Figure 1: U.S. national light-duty PEV stock under three adoption scenarios used to demonstrate a range of possible futures to inform stakeholder planning. (Total LD vehicle stock is about 270 million vehicles.) [10]

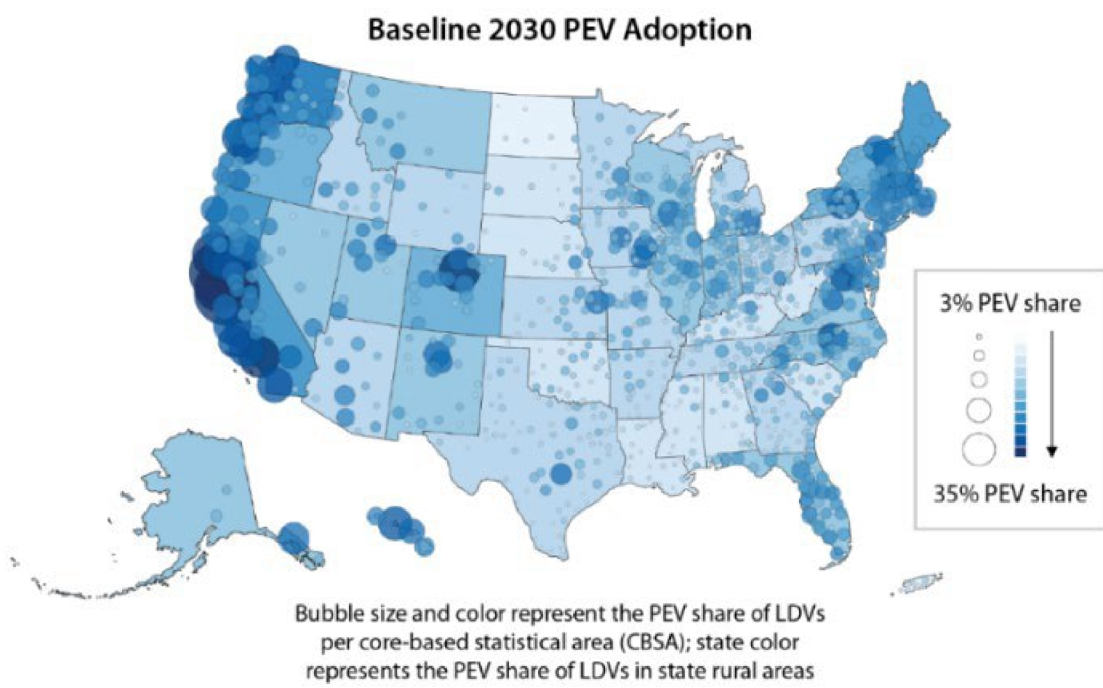
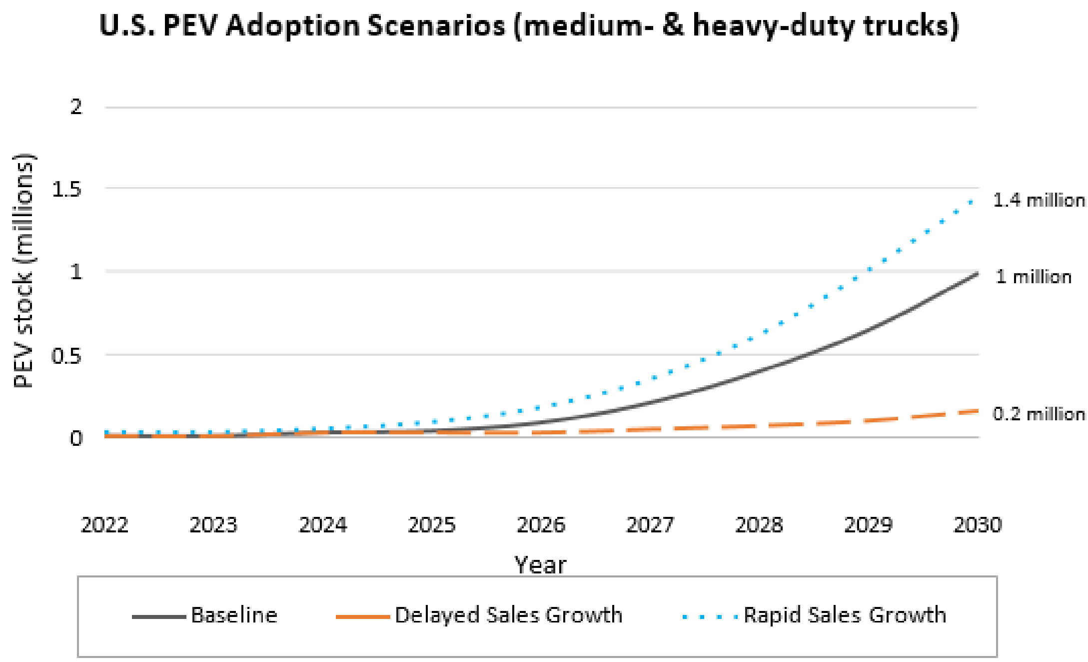


Figure 2: Assumed spatial distribution of 33 million PEVs in 2030 by core-based statistical area and state [10].

The spatial distribution of the 2030 PEV fleet is projected to be proportional to existing PEV and gasoline-hybrid registrations. As visualized in Figure 2, this approach results in the greatest PEV adoption occurring in urban areas, with up to 35% of LD vehicle stock as PEVs in 2030, and the lowest levels of PEV adoption in rural areas, with as low as 3% of LD vehicle stock as PEVs in 2030.

Medium- and Heavy-Duty PEV Adoption

The demand for MHD zero- emission trucks has also grown in recent years due to reductions in cost, increased vehicle model availability, the appeal of reduced fuel (electricity) price volatility [11], and improved vehicle range. As such, nearly 200 public and private fleets have made **c**ommitments to deploy MHD zero-emission trucks, including Amazon, Walmart, FedEx, UPS, PepsiCo, and the United States Postal Service, equating to a greater-than-tenfold increase since 2017 [13, 14]. Commitments cover a broad range of vocations and classes, from step vans all the way up to Class 8 truck tractors.[11]



Includes trucks with a gross vehicle weight rating (GVWR) of 10,000 lbs or greater. Excludes Class 2b (commercial light trucks with GVWR of 8,501 to 9,999 lbs) and buses.

Figure 3: U.S. national medium- and heavy-duty PEV stock under three adoption scenarios. [9]

NREL estimated that ZEV sales in the MHD class could represent 42% of all MHD trucks by 2030 (40% battery electric vehicles and 2% fuel-cell electric vehicles) as shown in Figure 3.[12] Because commercial trucks tend to have longer service lives than personal vehicles, this slow stock turnover and the current market status projects out to only 5% ZEV stock in 2030. In this scenario, ZEV sales reach >99% by 2045, and 80% of the MHD stock transitions to ZEVs by 2050 [12].

Policy and Regulatory Influences

Governmental entities exercise policy and regulatory influences that can accelerate adoptions, but, ultimately, consumers will shape the change to come through their actions, reactions, and willingness to participate. Interplay between these will factor into solutions and outcomes.

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[11] NACFE's Run On Less — *Electric Depot* reported positive results from both of the technology and driver feedback, although two of the ten fleets could not get permanent charging systems in time to participate.

[12] This projection primarily considers smaller vehicles in Classes 3–6 that drive shorter distances (less than 250-mile shipments). Adoption for heavier vehicles (Class 7–8) and vehicles that drive longer distances does not begin in significant numbers until after 2030 in these scenarios. Factors that will affect adoption include technology progress, competitive fuel costs, abundant EV charging infrastructure, and consumer decision-making assumptions.

Local, state, and Federal policies and regulations shape the decision-making landscape through goals, mandates, and incentives. They can create an environment with conditions favorable to accelerate adoptions (e.g., California's Advanced Clean Cars II rule [15] and CARB's Advanced Clean Trucks regulation [16]), as well as conditions that encourage business decisions and market development for innovative products and services (e.g., through data access and sharing policies). These policies and regulations will influence the solutions implemented to achieve key objectives and maximize benefits.

EV planning intersects with numerous independently operating state government agencies that oversee different segments of the economy.[13] EV charging has driven an enhanced level of coordination among agencies and introduces a new complexity to agency roles, such as infrastructure planning done by state departments of transportation, public utility commissions' or utility governing boards' planning of electricity infrastructure, or energy offices' development of energy plans and establishment of climate goals.[14] Decisions made by agencies outside the traditional electricity domain (e.g., state air quality or climate policies, state EV adoption targets, highway right-of-way laws) will now have implications for the electric grid and potentially impact the speed or cost-effectiveness of deploying electricity infrastructure. Alignment across agency policies to improve planning for sufficient electric infrastructure necessary to advance cost-effective, timely progress on regulatory targets has already begun.

Contextualizing Charging Power Requirements

The projections for light-, medium-, and heavy-duty EV adoptions will be an underlying factor as utility, community, regional, and other planners anticipate electricity needs for vehicle charging while addressing changing electricity demand in other market sectors (e.g., residential, commercial, and industrial usage). Extrapolating vehicle adoption into projected energy requirements introduces additional variables. While exact adoption numbers are uncertain, projections point directionally to a growing number of EVs that will connect to — and will impact the grid. In response to projections, **the role of utilities, regulators, and researchers is to develop or design approaches that anticipate needs ahead of demand in a manner that maintains reliable, affordable, and safe electricity for customers**. Even absent proactive approaches to managing EV grid impacts, standard utility load service processes will continue to serve as a mechanism to maintain the reliability of the grid.

EV charging comes in many shapes and sizes. To understand what vehicle charging means for the grid, it is helpful to get an idea of how charging sites equate to traditional utility loads (Figure 4). Power levels for charging vary based on charging type. Charging a single vehicle or powering a single charger — especially at Level 1 or Level 2 charging — may be a minor consideration for a utility. But higher levels of charging in concentrated areas can quickly escalate the demand on the grid. For example, a single charging station with the National Electric Vehicle Infrastructure (NEVI) minimum of four direct-current, fast-charging chargers will require power equivalent to 0.6 megawatts (MW). A large truck stop, on the other hand, could require nearly 20 MW [17].

[13] For example, in California, load forecasts for utility infrastructure planning are developed at the California Energy Commission, infrastructure procurement and utility authorization are decided by the California Public Utilities Commission, and allocation of NEVI funding is the responsibility of the state Department of Transportation.

[14] The roles and activities of State Energy Offices vary by state but are agents of change working together with the private sector, under direction of governors or state legislatures, accelerate energy-related economic development and support state energy goals to address citizens' needs and enhance energy security.

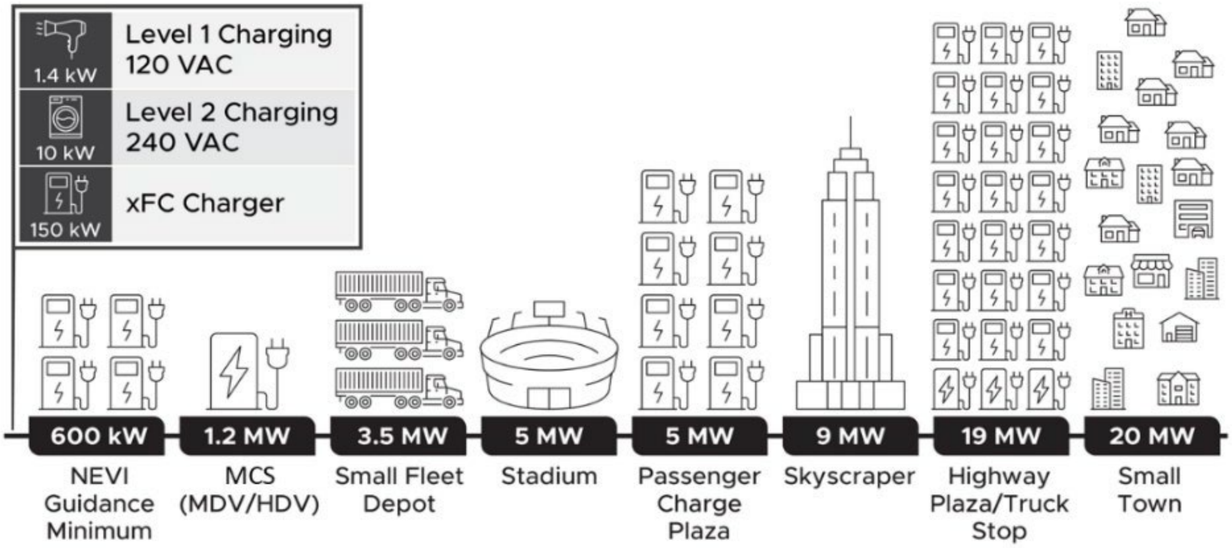
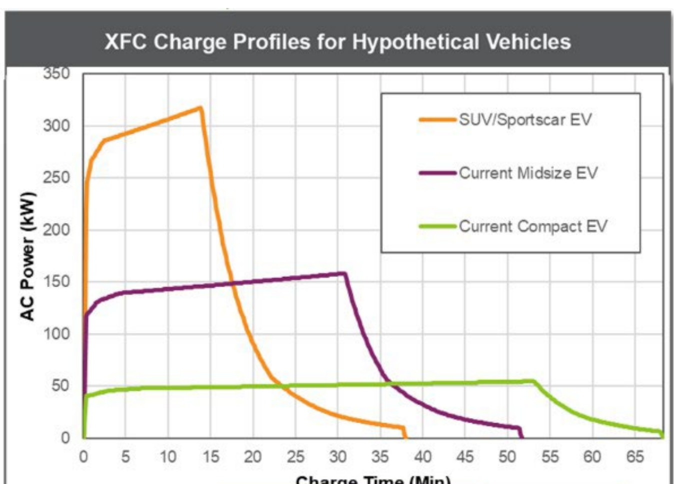


Figure 4: Power levels for EV charging types. (Adapted from National Grid's "Electric Highways" report [17].)

A unique aspect of projecting EV charging load is that the amount of power required depends not only on the charger capacity, but also on the vehicle battery's state of charge when the charging session is initiated, the battery capacity, the charging rate enabled by different vehicles, as well as the vehicle charging profile (Figure 5), which can make it challenging to determine specific load profiles. Understanding these differences helps to bound charging characteristics so that anticipated adoption numbers can be translated into the load forecasts that utilities and regulators need to plan investments in infrastructure and demand flexibility.



	SUV/ Sportscar EV	Current Midsize EV	Current Compact EV
Max Charge Rate (kW)	300	150	50
Vehicle Range (Miles)	250	275	150
Vehicle Resembles	Porsche Taycan	Tesla Model 3	Nissan Leaf

Figure 5: Charging load profiles for different vehicle types [16].

Uncertainty in Understanding the Intensity and Timing of EV Charging on Grid Impacts

Forecasting energy needs, and thus, grid impacts, requires not only an appreciation of the big picture — the overall demand at a macro (or national) level of the grid — but attention to the finer details — at the micro (or circuit) level. Forecasting the impacts from EV charging will be highly localized and requires an understanding of hourly load curves that are a result of several variables (Figure 6). As forecasts become more granular the number of variables increase, introducing greater levels of uncertainty for utility planners and regulators trying to assess infrastructure investment needs. While transmission and generation forecasting each have their own sets of challenges, maintaining reliability and affordability for customers and businesses will hinge on how load is added to the grid neighborhood by neighborhood and business by business. However, novel approaches and new data sets are emerging to model and assess these new variables.

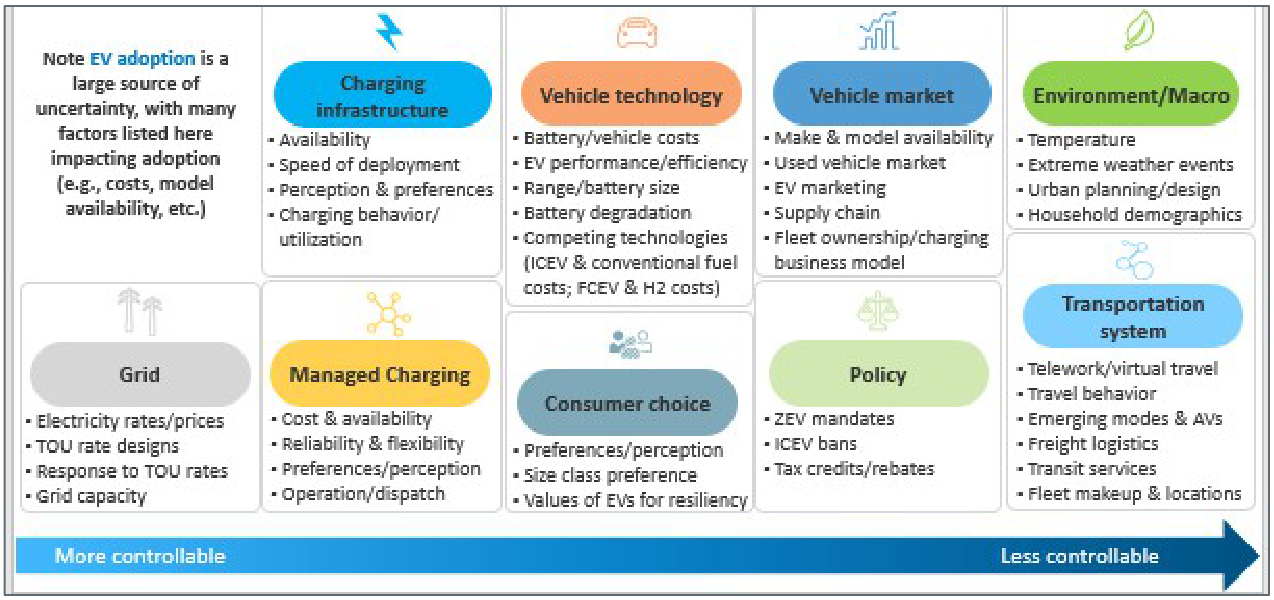


Figure 6: Variables that introduce forecasting uncertainty for decision process.

Load forecasting is a continual exercise that utilities perform to anticipate changing customer demands, and EVs are being integrated into those projections. Using computer models, novel approaches, and new data sets, utilities and other stakeholders can assess and evaluate increasing load from anticipated EV adoptions. Incorporating EVs moves utility forecasting from a deterministic process based on well-established load growth patterns to one that is more stochastic and must incorporate numerous factors, like consumer behavior, travel and freight mobility patterns, and charging infrastructure types, as well as rates or incentive structures that modify charging behavior. The additional number of variables increases the modeling complexity and challenge of gathering and maintaining up-to-date data.[15]

The uncertainty related to forecasting EV loads will change as EVs become more ubiquitous. While uncertainty will remain — because the future is inherently unpredictable — comfort levels will grow as charging behavior becomes better understood and forecasting approaches become more established, using actual charging data. It is also likely that EV charging behavior will diversify as new customer demographics choose electrified transportation. Until then, scenario analysis and directionally relevant adoption projections with consensus around underlying assumptions, robust modeling techniques, and

[15] DOE is working to support the development of the computing resources necessary to model these complex systems, utilizing DOE's Exascale Computing resources.

approaches that help to reduce or bound the uncertainty and de-risk investment decisions can assist with planning decisions. Data sharing between parties and collaboration between stakeholders can enhance the development of EV load forecasts that facilitate near-term decision making.

V. Planning Implications for Anticipating and Addressing Grid Impacts

Planning is **one of the most important arenas in public spending**. Holistic planning evaluates both short- and long-term infrastructure needs, accounting for not only the engineering aspects for deploying infrastructure but also financial and socio-economic factors. Equitable utility system planning balances infrastructure needs with the customer's ability to pay for those investments. Planning occurs at different scales with the inputs and outcomes at one scale cascading to other levels and is affected by data originating from disparate parties across the ecosystem. EVs introduce a new dynamic and new variables to consider as planning for transportation and electricity become inextricably linked. The benefits and risks of closely coupled systems are shared; what originates in one, for better or worse, can propagate into the other sector, sometimes with amplified effect.

Transitioning to electrified transportation will require closer collaboration and coordination between the two sectors. While the level and intensity of that coordination is yet unclear, continuing dialog, research, and cross-sector analysis will reveal the appropriate amount of coordination that is not overly burdensome. Cross-sector analysis and planning can help decision makers, grid designers, and transportation planners to understand and assess the interplay between sectors, revealing options that can mutually strengthen and improve the efficiency of each.

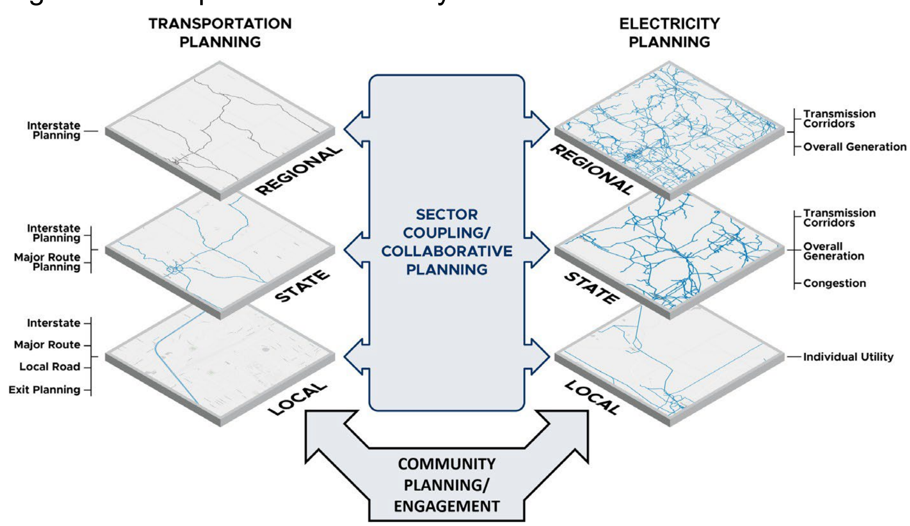


Figure 7: Relationship between transportation, electric, and community planning processes.

Achieving Affordability and Reliability

Legislative mandates and regulations related to utility compensation mechanisms will directly influence electricity affordability and solutions available to customers. Traditional regulatory assessments of utility investment plans balance many factors, including customers' ability to pay, the timing of deployments, and the strategic value of investments. Regulations were designed to **send the right cost-containment signals** through rules, mandates, and direction; however, those rules are based on the energy delivery system of the past century.

An energy system in transition — one that will include distributed energy resources (DERs), two-way power flow, and non-utility assets — will not change the fundamental utility-regulatory construct, but **it**

will require changes to regulatory processes [18] and utility compensation mechanisms[16] [19] to match the needs and pace of changing market and operational dynamics. Mechanisms that compensate capital expenditure may favor traditional infrastructure investments and disincentivize cost-effective solutions that leverage the value of non-utility assets.

Achieving desired results amid a rapidly evolving technology landscape increases the burden on regulators and raises new and more complicated questions. Innovating regulatory processes and involving outside voices can change the conversation around grid infrastructure planning and create a more collaborative, nimble environment that meets customer and community preferences, incorporates socio-economic and equity considerations, increases the implementation of third-party solutions, and expands options and affordability for consumers.

EVs intensify questions about energy access and energy affordability in the face of growing electricity demand. **Maintaining affordable electricity rates will hinge on robust planning that right-sizes grid investments**, balancing infrastructure investments with the customer's appetite for funding those investments. Phased investments that are right-sized and programs that improve asset utilization, coupled with the increased revenue from EV charging, can **economically benefit both ratepayers and investors**.[17] If vehicles are primarily charged off-peak, they will likely reduce electricity costs and prices by improving system utilization. On the other hand, if mechanisms for shifting charging to off-peak and performance metrics fail to send the correct cost-containment strategies, the cost of additional infrastructure would be significant.[18]

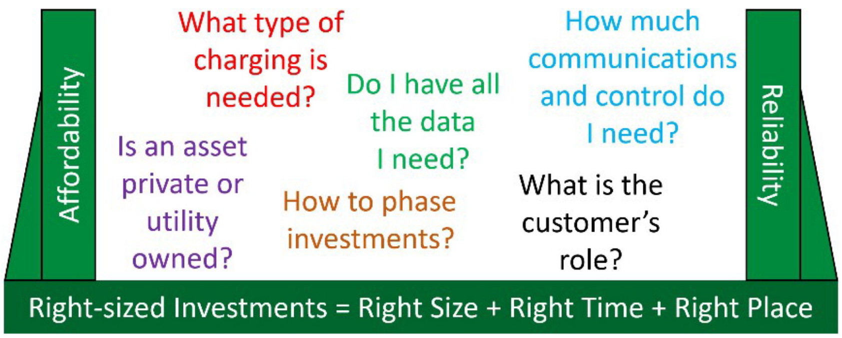


Figure 8: Sample EV investment questions to balance affordability and reliability.

Regulators and utilities weighing investment decisions must consider questions of reliability, resilience, the role of customer or third-party solutions, the timing of investments, and the appropriate allocation of costs to find the sweet spot that maintains reliability without exceeding the customer's near-term ability to pay for those investments.

Strong cost-containment signals for capital investments and the use of emerging compensation mechanisms that reward performance will incentivize innovative rates structures, load management programs, and the incorporation of third-party solutions. Combined with robust, transparent stakeholder planning processes, these signals and mechanisms can create a collaborative environment that enables solutions that minimize rate impacts.

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[16] Performance-based regulation compensates utilities based on performance rather than capital investments in an attempt to align performance with societal goals.

[17] An economic analysis performed by Lawrence Berkeley National Laboratory found that if EVs are deployed with Low Peak Impact (i.e., "managed") charging strategies, ratepayers are always better off because of lower cost impacts suggesting that pricing and programs to encourage noncoincident peak charging are highly beneficial from the ratepayer perspective [40].

[18] A study commissioned by the California Public Utility Commission estimates the potential costs of meeting distribution grid infrastructure needs in California to be approximately $50 billion by 2035 if EV electricity needs are met exclusively with utility distribution assets without considering new real-time dynamic rates and flexible load management strategies [41].

Cross-sector Planning for Converging Sectors

EVs introduce a new interplay between the transportation and electricity sectors, making each more dependent on and influenced by decisions in the other.[19] As the two sectors become more closely linked, **transportation considerations must be integrated into electricity infrastructure planning and vice versa**. Planning will include scalable urban, suburban, and rural planning and land-use solutions, newly defined performance measures, and supporting policies for incorporating environmental justice and equity.

This more dynamic, interdependent environment poses obvious challenges, especially as vehicle charging breaks the norms for traditional electricity planning and operation, which is built on delivering electricity to immobile structures with relatively predictable usage patterns or deviations throughout the day and the year. These changes are taking place at a time when the need for additional electricity for EVs and other beneficial electrification efforts is accelerating. This heightens the need for process changes that incorporate new inputs and linkage points, align planning timeframes, and create pathways for coordination and collaboration that facilitate involvement from a broader range of voices and perspectives.

Additionally, the independent, sector-focused nature of policymaking means that actions in one agency may have unforeseen implications for another sector. For example, **policies from different agencies can reinforce one another, providing a foundation for proactive planning and collaborative transformation at the state, regional, and local levels**; however, if misaligned, policies from different agencies can create confusion that results in missed opportunities and higher costs [20]. Transparent, defined goals at the state level can coalesce stakeholders and provide a basis for decision making that enables cross-agency policy alignment and coordination to bridge knowledge gaps and illuminate interdependencies for greater efficiency.

Regional and State Planning

Regional and state planning processes assess interstate and regional electricity needs to determine resource and infrastructure adequacy. The aim is to evaluate and coordinate infrastructure investments, understand interdependencies, and make sure that regional and state requirements can be met through collaborative planning. They identify strategic opportunities for shared resources and utilize an element of risk science to develop contingency plans and disaster response mechanisms that ensure resilience and enable effective, efficient restoration efforts.

As EV battery technology advances, driving range is increasing. Electricity infrastructure planning at the state and regional level must evaluate vehicle charging options along transportation corridors and destinations to meet the needs of long-distance travelers and long- haul trucking during times of normal operations. Considerations must also be given to evacuations, recovery, mutual aid operations, and disaster relief efforts.

Planning for Blue and Gray Sky Days

EVs amplify electricity risk assessment criteria because, as transportation comes to rely on electricity for powering vehicles, reliability, resilience, and timely restoration options increase in importance. Assessing resource adequacy and sufficient capacity for both blue and gray sky days will be vital for maintaining reliability and resilience as the transportation and electricity sectors become more closely coupled.

[19] In 2022, only 0.15% of the available electricity produced served transportation. If 100% of the 2022 fleet were electrified, this percentage would be expected to grow to 34%, cementing a strongly coupled relationship.

Utilities' distribution and transmission planning processes will rely on the outcomes from regional and state planning processes, which, in turn, will rely on input about electricity infrastructure and available capacity. They will need to include temporary charging solutions in disaster preparedness plans to ensure electricity availability during emergency situations or large-scale outages (e.g., wildfires, tornados, hurricanes, etc.).

Community Planning

Electricity discussions are taking on new dimensions as EV charging is integrated into community and urban planning. It is not only the technology, but the social wellbeing of citizens that factors into decisions. EV charging, and how that is integrated into community development decisions, infuses a new social dimension into the electricity infrastructure planning process.

Communities have varied characteristics and abilities (e.g., affordability, desired services), and their mobility preferences will differ. Solutions and programs that work in one community may not fit the lifestyles and preferences of another. Infrastructure will have to be tailored to meet all the demographics in a community and must reflect and be responsive to the urban planning process. The community will set out the functional requirements that utilities must integrate into their plans so that the community can execute those functions.

Communities themselves — not just the businesses or customers within the community — now become electricity customers because they are deploying vehicle chargers and setting electrification goals, introducing new participants into planning processes. EVs spotlight the need for utility-community communication and partnership to ensure that additional voices are heard and included so that electricity infrastructure and new programs are responsive to community needs and underscore a vibrant, competitive market for services [21].

Grid Infrastructure Planning

Requirements to support EV charging will layer on top of all the other requirements that must be considered in the electricity infrastructure planning process. Uncertainty about the future can breed indecision; but waiting to react to load growth — which, on the surface, can seem prudent — may actually lead to additional costs, inefficiencies, and suboptimal solutions. Continuing with business-as-usual will not be sufficient to meet the charging demands in the timeframe desired by American customers and businesses.

EVs introduce several new factors that grid planners have not needed to consider in the past. Pairing customer and freight mobility patterns on top of energy use patterns will demand a different scale and type of analysis, both in the long term — given the time needed to alter the structures of the electric grid and to understand the interdependencies — and in the near-term — to allow for nimbleness and adaptability that account for unique operating characteristics. **Integrating social and behavioral sciences can provide deeper insight** into customer participation in programs and services, shedding light on ways to offer sufficient value, cement customer buy-in and commitment, and assess the equity implications of decisions and investments.

Electricity infrastructure planning is typically a reactionary process, based on documented load growth and load-minimization principles. Vehicle electrification turns that on its head, especially during the transitional period. The current timeframe required for grid infrastructure planning (months, years, even decades) is mismatched to the timeframe for installing vehicle chargers (months, weeks, even days), and the evolution of planning and companion processes such as interconnection and load service requests must adapt. Successful planning will necessitate mechanisms and frameworks that allow utilities and regulators to proactively plan investments, giving utilities the functionality and capability to manage the system and ensure electricity is available to meet charging needs. Failure to improve planning frameworks will not lead to widespread failure of the electric grid but will instead increase costs and depress EV adoption.

Agile streamlined regulatory processes will be necessary to meet the accelerated pace of vehicle electrification. Streamlining processes and decisions can reduce the burden on regulators and staff while maintaining prudent, deliberate planning to better align regulatory decision making with the pace and scale that the transition to EVs demands. Holistic, integrated transmission, generation, and distribution planning processes with appropriate frameworks, metrics, and incentives enable effective integration of third-party solutions and customer assets that can help defer infrastructure upgrades. Integrating these solutions, offering participation opportunities for a broad range of stakeholders, and balancing non-wires alternatives with traditional utility investments can encourage utility innovation, promote optimal and efficient future outcomes, and enhance grid transparency.

Modeling and other approaches like scenario analysis can reduce uncertainty around investment decisions to enable forward progress. **With appropriate planning,[20] EVs can make the grid more flexible and interactive, with better utilization of invested assets**, thus increasing benefits to all customers.

Investment Risk

Electricity infrastructure investments to meet EV charging demand will need to be made years before the revenue from the increased sale of electricity is recognized. This creates areas of risk for utilities, regulators, and consumers. The timeline misalignment is unique from previous, right-sized load-growth activities, and will require addressing this risk to enable proactive infrastructure build out. Approaches that create areas of certainty[21] and financial mechanisms that bridge the timing misalignment can help to de-risk the investment conversation.

Another factor that contributes to investment risk is the timeframe for utility rate cases. The time between rate cases, which determine whether and how utility investments are recovered from customers, can span several years, but EV forecasts and the adoption and deployment of actual vehicles can change significantly in short order. Infrastructure needs will arise at different speeds in different areas of the country, and these pockets of risk associated with proactive planning will be most acute in the early years of the transition.

VI. Impacts on Grid Operation and Management

EV charging will emerge on the grid in many ways — ranging from a single charger in a home to a highway plaza with dozens of chargers to a fleet depot with chargers for hundreds of trucks. A large number of smaller, dispersed loads may represent the equivalent wattage for a single large load, such as for a fleet or large travel center, but each has different operational considerations and constraints. While meeting the additional requirements for EV charging will require additional infrastructure, EVs together with other grid-edge assets also offer solutions for mitigating impacts and harnessing value.

> In energy or grid services, **aggregation** is the act of combining smaller resources to provide sufficient value or impact. Aggregation can be utility- controlled through a demand response program or a service offered by a third party that combines customer assets in response to a utility signal.

Integrating EVs and other DER (e.g., solar panels and energy storage) has the potential to support rapid electrification while reducing overall infrastructure costs [22] by providing value to customers and

[20] https://www.esig.energy/grid-planning-for-vehicle-electrification/

[21] The National Grid Highway study and Southern California Edison's load forecasting in its 2025 general rate case offer two approaches.

the grid, but will require aggregation.[22] Utilizing customer and third-party assets expands the control surface of the grid and increases the complexity for grid operation and management.

Utilities have a spectrum of approaches available, which range in the amount of control afforded to respond to grid conditions. Some approaches for managing load are long-standing tools that are commonly employed; other approaches are emerging and will need validation and testing to be adopted and accepted; and a few are still under development and require further research. Each range in cost and complexity to implement. At low EV adoption levels, less sophisticated approaches will likely be sufficient for mitigating negative impacts; whereas more complex approaches will likely be necessary as EVs become more prevalent (Figure 9).

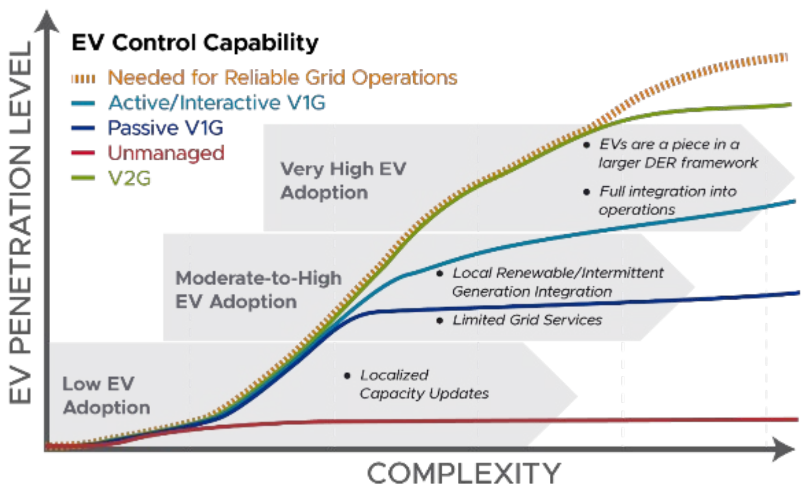

Figure 9: Simple controls will need to evolve to more sophisticated models to sustain reliability

Grid Design Impacts

A major factor in evaluating grid impacts is determining available grid capacity. Assessing grid capacity at a given location requires detailed analysis and depends on numerous variables; it can be difficult to quantify in a snapshot because it varies throughout the day and time of year. Conductor sizing and grid topologies, typically evaluated as part of the utility's asset planning process, are two factors that play a role in the amount of available capacity.

Figure 10 illustrates how various system voltages respond to the volume and magnitude of typical EV charging, and how — given power system design practices — additional load might exceed the limits of available capacity at a specific voltage. As shown, constraints are most pronounced on the distribution system due to their lower voltage levels. Areas on the distribution system that have been upgraded to higher voltage conductors based on past load growth may be better suited to accommodate additional Level 1 and Level 2 charging, but communities with lower voltage wires and aging infrastructure may experience more acute impacts sooner, thereby reducing EV adoption rates or impeding EV participation in underserved communities.

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[22] Virtual Power Plants that aggregate distributed energy resources have the potential to support rapid electrification while reducing overall infrastructure costs [22].

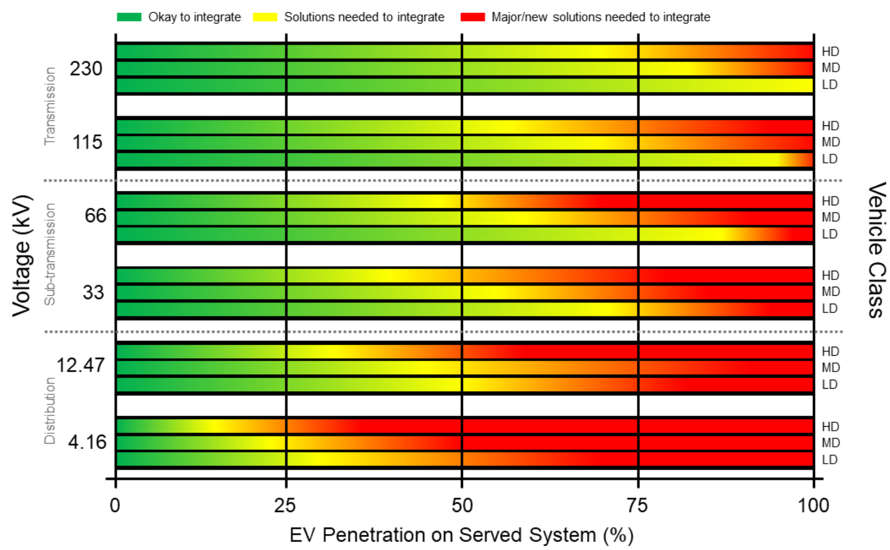

Figure 10: Impacts of EV charging on various system voltages [24, 25, 26, 27, 28].

As electricity requirements grow due to transportation and other electrification efforts, lower classes of voltages may no longer meet the higher power needs of customers. Managed charging can defer infrastructure upgrades as shown in yellow portions of Figure 10. Foresight and planning that phases in higher voltage classes as part of ongoing asset replacement plans can lay the groundwork to easily accommodate load growth from EVs in neighborhoods throughout the country [23].

Some grid designs, such as fixed radial topologies, especially those associated with long rural circuits, may have increased voltage constraints and fewer options for isolating faults or disruptions and may factor into resilience and capacity considerations related to EV charging. Other topologies, like meshed or looped topologies that are often found in core urban networks, provide options for automated feeder switching [24, 25, 26, 27, 28]. This could offer more resilience options and expand available capacity on a circuit for EV charging, though meshed or looped topologies may have additional operational constraints (e.g., reverse flow prevention or protection reconfiguration), especially when integrating DER to support EV charging. These design considerations and more will factor into resilience and capacity considerations when assessing infrastructure needs related to EV charging.

Supply chain shortages can also hinder the pace with which the utility can integrate new load, depending on the need for new equipment to meet capacity constraints. There are approaches that can serve as temporary measures to mitigate site peak demand and reduce the need for upgrades, and efforts are underway to address supply chain shortages. Temporary solutions can include DER-backed charging, mobile charging, and short-term non-firm service for new load.

Impacts of Managing Load and Harnessing Value

The grid has been designed to meet peak load requirements no matter when or for how many minutes during a year that peak occurs. This requirement means that excess capacity exists throughout most of the year. Load management approaches can align vehicle charging with times of available capacity or excess renewable generation, shape load to reduce peaks, and offer options to utilize vehicles for grid services, such as reducing or deferring the need for distribution upgrades.[23] Figure 11 shows how

[23] In California, where electrification and decarbonization are progressing rapidly, analysts estimate that required distribution grid investments may be up to $50 billion by 2035, but could be as low as $15B if measures are taken to manage flexible demand [41]. New York State's projected distribution system upgrade costs due to transportation electrification range from $1.4 billion to $26.8 billion. Upgrade costs were 46-61% lower with managed EV charging [53]. In

load can be managed to meet changing grid conditions.

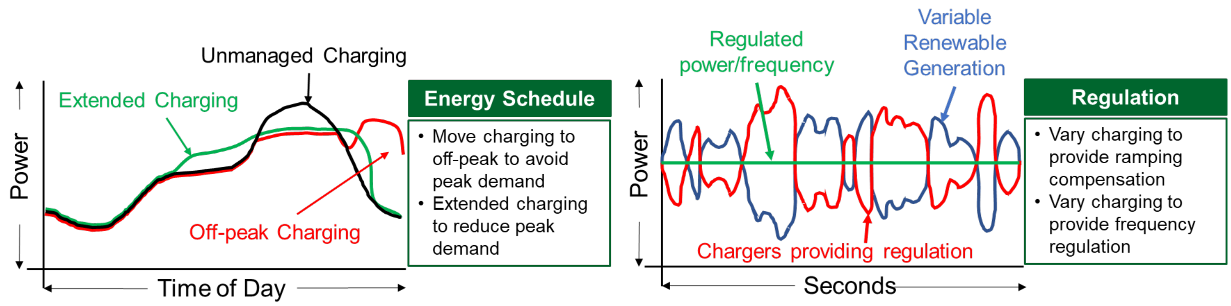

Figure 11: Energy schedule and regulation grid services. (Adapted from DOE VPP Liftoff report [22].)

Shaping consumption to align with decarbonized generation and to meet the needs of growing numbers of electric vehicles will require a portfolio of incentives that respond to differing customer preferences and perceptions of value. Some load management capabilities will be used to address system peaks, also known as coincident peaks, and some will be used to address local distribution constraints, also known as non-coincident peaks. It will require appropriate signals to communicate system conditions and compensation mechanisms that encourage participation [29, 30], as well as distribution grid control capabilities, communications for data transfer and science-based quantitative metrics that characterize behavioral responses.

The collective opportunity for EVs to align charging with grid needs or to provide other services to grid operations is large, but **customers must remain central to load management program development and their transportation needs must be paramount.** Incentives are not one-size- fits-all. No amount of education can prompt participation in an experience that is not seamless, fails to offer value that speaks to different customer segments, or is overly complex for customers to utilize.

Along with differing customer perceptions of value, light-, medium-, and heavy-duty vehicles have distinct usage patterns that must be understood and respected. **The amount of flexibility and the degree to which load can be shifted are highly dependent on the vehicle's use case and the customer's transportation**

What is Managed Charging?

Managing EV charging load, or smart charge management, implements a decision process to start, stop, or modulate vehicle charging based on grid conditions while ensuring that the vehicle is charged when the customer needs it. It leverages the drive cycles and dwell times of electric vehicles while minimizing disruption to the customer to satisfy distribution or transmission grid needs by strategically shaping, shedding, or shifting load or by providing grid services like frequency response.

Managing load or utilizing EVs for grid services can be accomplished through unidirectional charging (electricity from the utility to the vehicle to charge the battery or V1G) or bidirectional charging (electricity flows from utility to the battery, and from the battery to a building or back to the grid, also called Vehicle to X or V2X) [22]. Approaches can either be utility controlled programs, like a demand response program; third party aggregation of grid edge assets (e.g., rooftop solar batteries, EVs) [22]; or approaches on the customer side of the meter, such as automated load management for fleet charging [42]. Any desirable grid service needs to be paired with active or passive incentives or rates to make it a desirable behavior by customers.

Texas, where peak demand grew by 9% from 2018 to 2022, analysis suggests that wider deployment of demand management with smart thermostats, heat pumps, EV charging, water heaters, and other DER could save customers over $150 per year on average by 2030 and achieve more reliable service [22].

requirements.[24] Grid operations must expand beyond traditional power-systems science and other hard sciences to include social, behavioral, and marketing science to understand, appreciate, and measure how consumers respond to different incentive options.

Grid Control Implications

EVs and other DER will expand the control surface of the grid and increase the complexity of grid operations and management. Large, concentrated loads require more advanced planning to supply the megawatts of power in a timely manner and may have a larger potential for voltage fluctuations or thermal overloads than for smaller, dispersed loads. Both types of challenges have solutions based on collaborative behavior and supporting technologies and systems.

On the other hand, large, concentrated loads may pose fewer challenges for managing the load. Coordinating charging of many small, dispersed loads and leveraging them for grid services through third-party aggregation will require more standards for implementation, additional communication pathways, and more entities, which may require more advanced control approaches. But communications for large, concentrated loads (e.g., a fleet operation) are more focused and direct with a single point-of-interconnection, which would limit the impact to the overall feeder and reduce communication pathways and operational challenges (Figure 12).

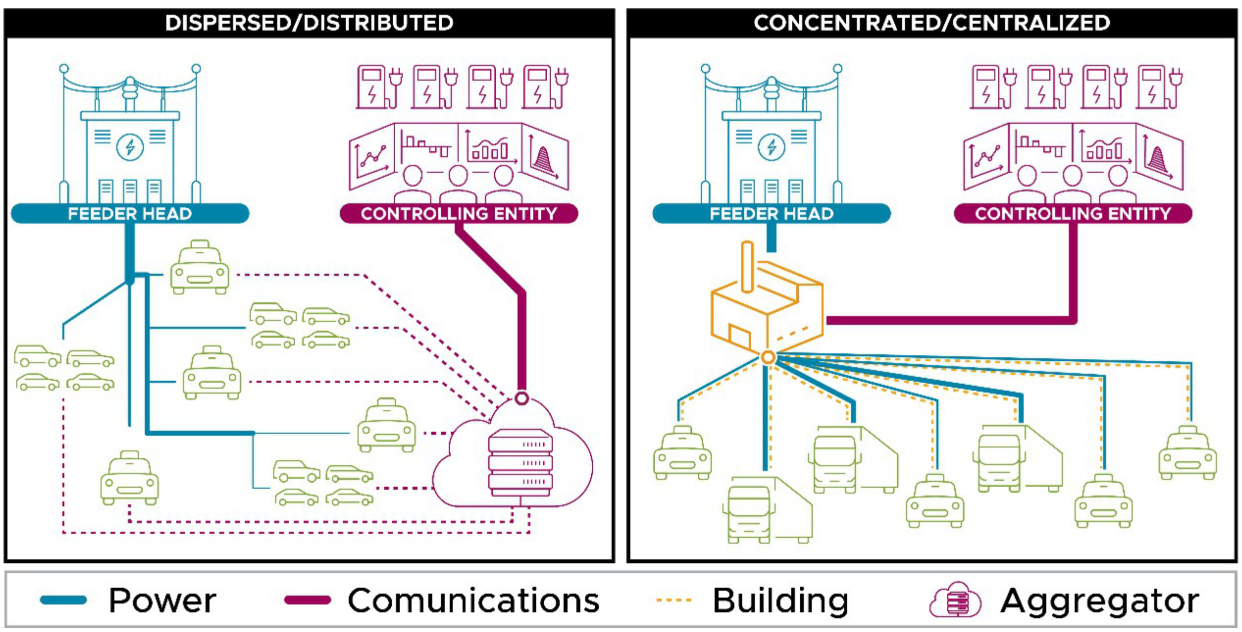

Figure 12: Representation of large, concentrated load versus smaller, dispersed loads.

Advanced grid technologies open avenues for implementation of more sophisticated approaches that can lead to greater value for the customer and the grid. Without them, solutions can be difficult to implement, add additional complexity, and increase overall costs to achieve the same result. Utilities that have advanced distribution control technologies (like advanced distribution management systems and distributed energy resource management systems) and advanced metering infrastructure (AMI) may be better equipped to aggregate distributed resources and implement emerging load management approaches and their accompanying incentive structures.

[24] For example, commercial vehicles do not have as many idle hours as personal vehicles, but their usage patterns are more predictable. Commercial medium- and heavy-duty vehicles will also have larger batteries that offer more capacity, which could provide a larger singular value and call for special incentivization.

Behavioral Interactions that Impact Grid Operations

Customers' relationship with energy has grown beyond a simple commodity transaction in which the utility sends a bill reflecting the amount of energy used. With EVs and other grid edge assets, customers become active participants. This amplifies behavior as a consideration in utility planning — one beyond the utility's control that will contribute to grid performance. Incorporating customer assets (e.g., EVs and other DER) increases complexity and will require rules for participation and accountability for that participation to quantify performance and the risk of non-performance.

Multiple mechanisms are available for ensuring performance from non-utility assets: technical, regulatory, and institutional. Technological approaches that overlay decision science onto behavioral response can bound behavior and enhance the understanding of how solutions contribute to reliability, thereby increasing certainty and helping to quantify the risk of utilizing a given solution. Lacking a degree of certainty, utilities — as the entities singularly responsible and financially accountable for the reliability of the grid — may be reluctant to integrate these solutions, which can hinder implementation or lead to costly technical backstops. Other mechanisms for addressing uncertainty include regulatory rules and mandates and institutional structures that create a favorable environment for incorporating these resources.

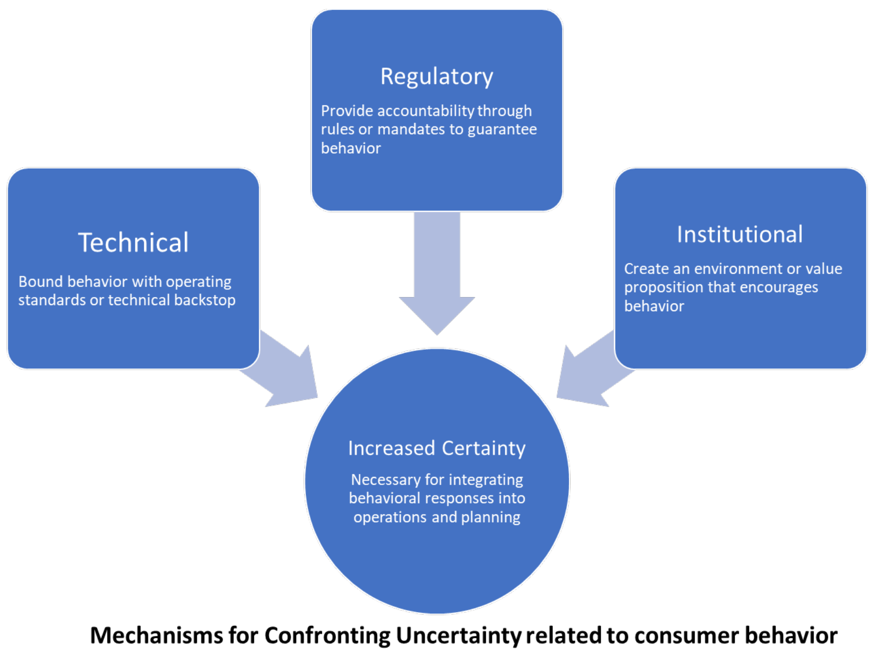

Figure 13: Mechanisms for confronting uncertainty related to consumer behavior.

Each mechanism differs in the amount of influence it has over a desired outcome and its implementation costs. Working in concert, the mechanisms can reduce infrastructure costs by integrating behavioral responses into utility operations to mitigate impacts and contain infrastructure costs.

Interoperability and Cybersecurity Impacts

While the grid delivers electrons, it runs on information and data. Historically, utilities had the data they needed to operate their systems and outside parties had limited interest in that data. Electric vehicles and other DER change this by introducing new devices and entities with which they must interact. There is now data that originates outside the utility that can be valuable for operations and planning. DER increases the pathways for information exchange (Figure 14) and heightens the importance related to data access and sharing — who has what data and who can access it. Additionally, integrating, analyzing, and utilizing DER, AMI, and other data for grid operations and load management will require utility software and operational investments, heightening focus on appropriate compensation mechanisms for utility operational expenses.

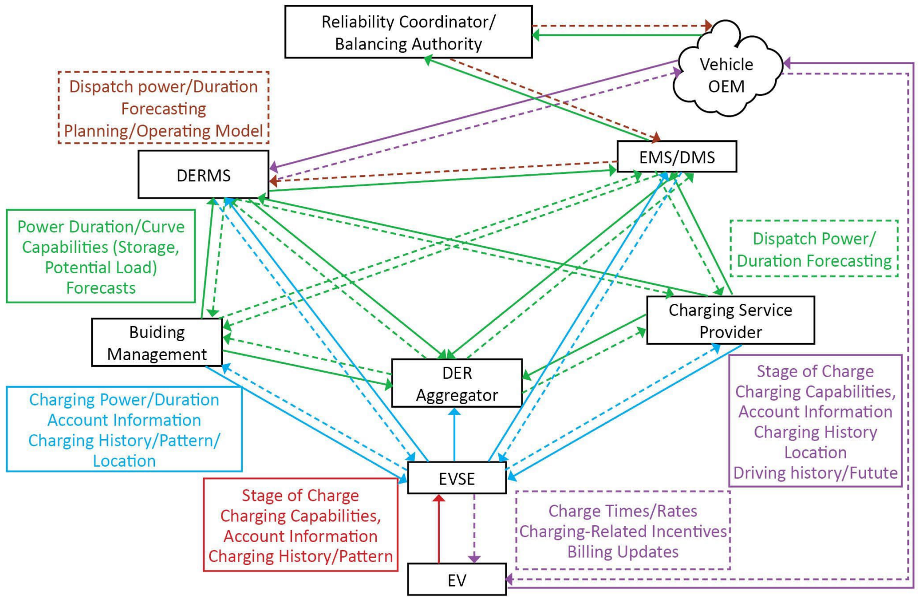

Figure 14: Potential data pathways for information exchange

> Codes, standards, and protocols govern performance and provide certainty of response, laying the foundation for interoperability. They dictate communication and interface requirements between the vehicle, the charging station, and the grid.

Synchronizing numerous decentralized assets can increase grid operational complexity and heighten the need for interoperable, cyber-secure systems. Simplified, streamlined interaction — underpinned by established cybersecurity practices between the grid and those devices — and well-defined, open communication protocols that provide the basis for sending and receiving signals for vehicle charging can facilitate interoperability and reduce the limitations of proprietary solutions that lead to increased costs. The codes, standards, and protocols essential for communications, connectivity, and safety are intertwined with cybersecurity and must be considered in unison. Appropriate cybersecurity protocols must underpin the seamless integration of the grid with electric vehicles and the associated charging infrastructure. Investments in charging infrastructure present a strategic opportunity to proactively build in appropriate cybersecurity protocols to enable a secure interoperable network [31].

VII. Institutional Implications for EV Grid Impacts

Institutional processes currently employed to ensure reliable, safe, resilient electric service will not allow EV charging to occur in a way that would imperil grid operations. However, the pace and magnitude of transportation electrification is leading to efforts to modify and accelerate processes and practices in a way that matches the new system dynamics, meets accelerated timeframes for deploying charging infrastructure in an equitable manner, and integrates EV charging to leverage their unique operational opportunities.

Connecting to the Grid

Traditional operating procedures that assess distribution grid impacts based on maximum operating conditions can overstate EV energy requirements and lead to longer review processes and more expensive upgrades.[25] To meet the time-sensitive and fast-growing interest in deploying and energizing EV charging infrastructure, streamlining the connection (or interconnection in the case of bidirectional electricity flow) process or implementing a flexible interconnection[26] process may help to expand grid capacity to enable vehicle charging connections and alleviate concerns about delays for approving charging infrastructure. Increased transparency about available capacity and other grid characteristics can foster innovative third-party solutions that offer value for customers, the utility, and site owners, and reduce infrastructure upgrades and costs when appropriately balanced by policies and practices that respect confidentiality, privacy, and proprietary operational concerns.

The number of new requests and the accelerated timeframe for energization will have implications for the utility workforce, which must evaluate and assess charger connections' impact on grid operations. Streamlined processes and improved transparency about the ability to host EVs and DERs on the system can reduce the impact on utility workers, shorten approval times, and reduce the cost to connect while maintaining prudent evaluation that ensures system reliability.

Working Together to Build a More Interoperable System

Interoperability is critical for seamless operation of the infrastructure, but achieving an interoperable system goes beyond the technology and standards that allow machines to communicate with each other [32]. Addressing and mitigating impacts to achieve an interoperable system that principally ensures vehicles have the energy they need and enhances value and efficiencies for customers, businesses, and the Nation depends on cohesive relationships and interactions between parties within the system (i.e., how the structures, processes, and stakeholders work together). To illustrate cohesion and preservation of customers' mobility and energy requirements, the standards adopted by the U.S. Department of Transportation for Federal investments in charging infrastructure leverage standard communication protocols [32]. These protocols ensure that smart or bidirectional charging sessions are managed so that drivers' energy needs are met within the time that they are parked and can be further customized with their preferences for reserve energy requirements.

Efforts to ensure interoperability are already underway as the nature of the relationships between players are being reformed to match the changing system dynamics and to solidify synergies across both the transportation and electricity sectors. Even the language and terms of each sector are evolving, and the way businesses interact are transforming to build a reciprocal, collaborative system. Organizations across industries are working to define and harmonize standards across the vehicle-grid interface. Businesses are coalescing to expand charging options to their customers [6, 33]. Public utility commissions are establishing processes that help encourage innovation and speed implementation of innovative ideas for realizing an equitable modern grid [34].

[25] Use of charger nameplate capacity can overstate energy requirements because vehicle charging requirements vary depending on the battery's state of charge and does not remain constant throughout the charge cycle. Energy storage deployed at a site to mitigate demand charges could therefore lead to expensive grid upgrades even though the energy storage device would be used to offset charging during peak times. Even for public charging stations with multiple chargers, each vehicle will likely not initiate charging at the same time or with the same state of charge or with the same charging profile [49].

[26] With flexible interconnection, the concept is to manage the device operation with software-controlled technology to avoid violating grid constraints. Appropriately utilized, technology solutions could allow for additional interconnection without the need for upgrades.

Workforce to Power the Transition

A skilled, dynamic, and retained workforce is at the core of American competitiveness. The energy transition has prompted a surge in the need for workers, and EVs are boosting that demand, not only for electricians and other skilled construction trades workers to install and maintain the EV charging infrastructure, but also for power system engineers and planners, mechanics to repair and maintain EV vehicles, manufacturing workers to build different types of vehicles and related components, and more. These roles require both technical knowledge and employability skills, such as critical thinking, teamwork, and adaptability [35, 36].

While the energy industry is seeing job growth gains across all technologies,[27] energy employers — not unlike employers across many industries — are sometimes unable to find workers with the skills to perform the work on day 1 of the job. Additionally, employers face the challenge of losing talent after workers have gained skills from on-the-job experience, and many are experiencing or anticipate increased turnover as a result of a retiring workforce and increased labor market competition. All of these realities highlight the importance of employers taking bold, intentional steps to recruit, train and retain the workforce needed to power the transition.

Building the pipeline of skilled workers and retaining that workforce to meet the energy demands of tomorrow requires a multi-pronged approach. Such strategies should include:

- intentionally inclusive recruitment that reaches a wide array from the population (e.g., early exposure to energy careers for young people through such activities as youth apprenticeship and career and technical education programs),
- partnerships between often siloed stakeholders to build pathways to energy careers for economically marginalized and under-represented populations (e.g., partnerships with community-based organizations, labor unions, government agencies),
- employer investments in high-quality workforce development with an emphasis on earn-while-you-learn models and industry-valued credentials, and
- programs and services to address common barriers that people face that prevent success in workforce training and in the workforce (e.g., mentorship programs, child care and long-term care assistance, transportation assistance, other forms of financial and non-financial support).

Succeeding in building and retaining the necessary workforce also means prioritizing **the quality of the jobs that are being offered and improving job quality where needed,** such that the jobs are competitive in terms of wage and benefits, and offer career mobility opportunities for the existing workforce.

VIII. Conclusion: Preparing for EVs

A transition is underway in the Nation's electricity grid, changing grid dynamics from the operational parameters of the past to something nimble, flexible, cleaner, and more resilient. Technological advances are driving that evolution, along with changes to how customers live, work, and interact with energy.

Customers have opportunities to be active participants, taking part in innovative programs and services that enhance their daily lives and increase business competitiveness. EVs are a catalyst for the changes underway.

[27] The United States Energy & Employment Report 2023 found that the energy sector added nearly 300,000 jobs from 2021 to 2022, increasing from 7.8 million to more than 8.1 million [37].

Electric vehicles will bring significant new load growth. They introduce new parties and offer opportunities to create additional value for improving efficiency and enhancing resilience. The electric grid will continue to provide safe, resilient, and reliable electricity under the stewardship of the many entities who keep the power flowing, but the rules, practices, and processes that govern the electricity sector are based on the energy delivery system of the past. EVs and other DER introduce new dynamics into that well-established system. Responding to the changing dynamics will require adaptability, flexibility, and creativity — the strength of the American worker — to embrace change and respond with innovative, economical, equitable solutions.

> Electric vehicles are one technology among many contributing to changing electric grid system dynamics. Determining the amount of distribution, transmission, and generation capacity to meet vehicle charging needs will depend on the many decisions of stakeholders and will be determined by the policies, practices, and programs that are implemented.

The pace and scale of the transition to EVs, driven by customer preference, favorable business economics, and policy incentives are significant, but it is achievable and well underway. Meeting the energy needs of EVs while maintaining affordability will require both utility upgrades and demand flexibility through a portfolio of options for both utility operators and customers. Relying on utility assets alone would place too large of a burden on customers and lead to greater costs than necessary until the transition is complete.

Expanding the control surface of the grid to include customer assets will require rethinking how the grid is planned, operated, and managed. It will require proactive planning, utilizing approaches that de-risk investment decisions and balance the appetite and willingness of customers to fund those investments. Customer behavioral responses must be bounded so solutions can be responsibly and economically integrated into utility planning, and utilities will need foundational grid control technologies to provide the visibility and functionality they need to incorporate these new resources. It will require data access and sharing policies and practices that can spur utility and third-party innovations that lead to creative solutions for customers and the grid.

Embracing customers as active participants requires reevaluation of program design. Utility customers do not buy reclosers and voltage regulators; they buy things that matter to them, like cars and homes and on-site generation. Customers will not participate unless they find it valuable for themselves or their business, such as through cost savings, added convenience, or contribution to environmental improvement. Better understanding of behavioral and decision- making science will be crucial to determine what motivates different consumer segments to participate. Options for participation will have to be simple and convenient, making complexity invisible to the customer.

EVs will require adaptation and innovation to drive positive change that leads to increased value and convenience, improved air quality, and better operational efficiencies. Successful vehicle-grid integration can and will enhance synergies and amplify efficiencies as the transportation and electricity sectors become more closely coupled. There will be both short- and long-term solutions that coevolve to adapt to the changing landscape.

Collectively, American businesses and citizens are up for the challenge. DOE is committed to working with stakeholders to navigate the transition whether through deployment of emerging solutions or convenings that reimagine and redefine institutional process, business models, policies, and regulations. Through collaboration and coordination across the many stakeholders, DOE will assist the Nation with the transition to a cleaner, more efficient system that provides value to all.

Appendix A –

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