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PERSPECTIVE

The shape of electrified transportation

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Transportation is currently the least-diversified energy demand sector, with over 90% of global transportation energy use coming from petroleum products [1]. For more than a century, petroleum fuels have been relied upon to move people and goods within and between towns and cities, and on roads, railways, farms, waterways, and in the air. These energy-dense fuels have unquestionably provided reliable and convenient mobility options to power the modern global economy. However, these benefits have also created challenges associated with geopolitics, energy security, price volatility, and environmental impacts.

Various attempts have been made to diversify the transportation energy mix, but global dependence on petroleum for transport remains [2–7]. For example, since the 1970s, various programs in several countries have been implemented to promote the adoption of compressed natural gas [8], ethanol [9, 10], hydrogen [11, 12], and other alternative fuels, with successes limited to niche applications. After more than a century of petroleum dominance, however, many leading experts anticipate that electric vehicles (EVs, here including battery and plug-in hybrid electric vehicles) could dramatically disrupt the transportation energy demand landscape [13–20]. Light-duty passenger EV cumulative sales passed the 7 million mark in 2019 [19], and annual sales rates are accelerating rapidly in many countries—over 2 million EVs were sold globally in 2019 alone. These trends are mainly driven by recent advances in battery technology and environmental policies [21–23] as well as expanded charging infrastructure and consumer preference for EVs (e.g. greater acceleration and low noise). If these trends continue, electricity—which currently provides a very small share of transportation final energy—could provide an important source of energy for on-road mobility. Such a change could require massive investments in infrastructure and technology (e.g. charging networks [24–27], electric system upgrades [28–30], and vehicle replacement). At the same time, transportation electrification could: remove tailpipe emissions responsible for poor air quality and related health issues, especially in large cities; enable decarbonization of the transportation sector, provided the electricity supply also decarbonizes; reduce energy use by exploiting the efficiency of electric powertrains; diversify the energy mix and reduce dependence on petroleum; and provide more affordable and less cost-volatile transportation solutions.

Extensive electrification of the economy—and particularly of the transportation sector—has become increasingly common in recent energy transformation scenarios, including those designed to achieve climate-change mitigation goals [17, 18, 31, 32]. Previous energy transformation studies (e.g. [33]) relied on greater changes in the energy supply to reduce transportation emissions and petroleum dependency and identified the transportation sector as one of the biggest hurdles to emissions reductions [34–37]. While barriers still exist for widespread EV adoption, more recent studies have highlighted great opportunity to electrify the demand side of several end-use sectors over the next few decades, including prospects for EVs to displace conventional vehicles powered by liquid petroleum fuels [17, 18].

A revealing example of the transportation-electrification nexus is shown in figure 1, which summarizes results from 159 scenarios projected by several models underpinning the *Special Report on Global Warming of 1.5* °C (SR1.5) by the Intergovernmental Panel on Climate Change (IPCC); here we only consider scenarios achieving 1.5 °C or 2 °C warming compared to pre-industrial levels. While transportation currently represents only ∼2% of global electricity demand (with rail responsible for over two-thirds of this total), the role—and impact—of transportation in the power sector may grow significantly in the future. For the median IPCC scenario, electricity provides 18% of all transportation energy needs by 2050, while transportation makes up nearly 10% of annual global electricity consumption. In the more extreme scenarios, these percentages can exceed 40% and 20%, respectively. Qualitatively, these results show that recent models and scenarios consistently project: (a) growing use of electricity in the transportation sector, especially for on-road vehicle electrification; and (b) that the transportation sector will play a much more significant role in future electricity systems.

The potential substantial growth in annual electricity consumption driven by transportation electrification could significantly affect power system planning, operation, and infrastructure investments. However, just as important as the expected load growth (in terms of total megawatt-hours [MWh] consumed) is the *shape* of this new source of power demand. In fact, electricity is an instantaneous commodity that is still expensive to store [38]: electricity supply (generation + storage discharge) must match the demand (including demand response) at each instant. Therefore, understanding the shape of electricity loads is critical for the design, planning, and operation of electricity systems, including projected capacity expansion needed to satisfy demand, sub-hourly dispatch of different production units, and sizing of the transmission and distribution infrastructure.

Still, the shape of EV charging is highly uncertain, dynamically dependent on supply (i.e. due to the intrinsic flexibility in vehicle charging over time and locations and the high potential to engage in demand response), and generally poorly understood—and thus often not well represented in models. Many studies showed that uncoordinated EV charging could introduce challenges for the current power grid [28, 39–44]. Muratori [28], for example, has shown that residential charging of EVs can significantly increase stress on the distribution infrastructure, especially for clustered EV adoption and use of higher-power charging options. At the same time, many opportunities have been highlighted to exploit EV charging flexibility[1] to minimize overall system costs [45–56] and provide ancillary services [57–61]. Zhang *et al* [55], for example, have shown that optimal charging of three million EVs in California in 2030 (responsible for ~4% of total load) could reduce the cost of electricity production up to 7.6% and the costs of EV charging up to 80% by reducing load peak and renewable curtailment, provided that middle-of-the day charging options (e.g. workplace charging) are available.

Despite the growing evidence of the importance of EV charging profiles, the possible effects of transportation electrification on electricity load shapes have often been overlooked in energy transformation analyses. For example, many global- or national-scale energy-economic models, such as those used to generate the scenarios reported in figure 1, characterize EV charging by simply scaling up existing total electricity demand profiles. Many other studies estimate EV charging loads based on average daily driving behavior statistics, without capturing heterogeneities in mobility services and the ability of EVs to provide flexible charging [44, 62]. Sheppard *et al* [63] showed that modeling EV charging profiles 'requires an explicit representation of spatially disaggregated charging infrastructure as well as a more nuanced model of the decision to charge.' Muratori *et al* [64] suggest that modeling future mobility-energy systems requires an integrated approach with increased spatiotemporal fidelity compared to today's models. Some recent studies focusing on electrification opportunities in the United States [17, 18] consider the load-shape aspect of end-use electrification but do not fully assess the impact that EV adoption across different transportation modes could have for different power system applications (e.g. generation, transmission, and distribution). Some studies focused on exploring the impact of EV charging on load shapes and profiles. For example, [62, 65] explore the effects of different charging behaviors on electricity demand profiles, showing that the fleet charging load profile can change shape drastically for different charging scenarios. Both studies rely on travel surveys and are limited to personal light-duty PHEVs, with charging flexibility limited within a single day. Zhang *et al* use the same travel survey data to develop a probabilistic EV charging load simulation model considering users' demographics and social characteristics, showing a significant effect on the magnitude and peak time of the daily charging load within each day [66]. Quia *et al* model EV load shapes stochastically based on retail electricity tariffs and vehicle usage, represented by distribution of average daily travel and simplistic charging assumptions [67].

Overall, studies of EV charging flexibility have usually focused on a single application (e.g. personal light-duty vehicles, buses), single-day average driving statistics that do not capture heterogeneities in mobility needs or the ability of EVs to provide flexible charging across multiple days (i.e. ability to 'reshape' EV charging while guaranteeing mobility requirements are met), and a single value stream application for the power system (e.g. reduce renewable curtailment, reduce system-level peak demand, reduce facility-level peak demand, or align with retail electricity rates). A comprehensive assessment of the value of EV charging flexibility for EV owners and the power system across multiple dimensions and timescales is still missing.

When and *where* EV charging occurs will be as critical as *how much* electricity is needed to meet future electrified transportation demand. For

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[1] EV charging flexibility (or 'smart charging') here is defined as the ability of EVs to change their electricity demand in response to supply-side needs. This implies one-directional interaction: optimally varying the time and/or power level at which an electric vehicle is charged based on dynamic signals from the electricity provider. Bi-directional interactions (i.e. vehicle-to-grid, or V2G) that involve the ability of EVs to supply electricity to the grid can provide additional value.

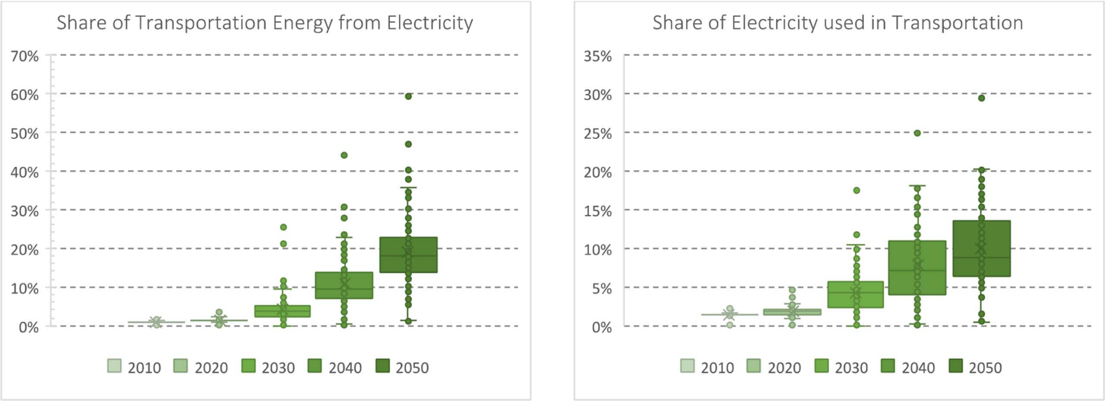

Figure 1. Transportation-electricity nexus in future energy systems scenarios. Data source: Huppmann *et al* (2018).

instance, how electrified transport increases demand peaks will influence resource adequacy considerations in power system capacity planning. More generally, EV charging could alter the potential utilization and economics of different generator types. At the distribution level, the EV charging profiles—and their coincidence across multiple households and buildings—could trigger infrastructure upgrades or impact power quality. Moreover, EV charging management can support reduced charging cost to end-use consumers based on retail electricity tariffs.

These changes in electricity demand complement profound changes happening within electric power supply systems: variable renewables are displacing conventional generation sources; distributed generation is disrupting utility business models; energy storage and other new technologies are emerging; and the traditional system based on the premise that generation is dispatched to match an inelastic demand is evolving to create a system with greater participation in power system planning and operations from traditionally passive consumers. This broader context underscores the importance of understanding how transportation electrification will impact electricity demand, including changes in the load shapes that characterize the system and the opportunity to leverage flexible EV charging to more cost-effectively balance demand and supply.

Moreover, not only will EV charging profiles affect power system planning and operations, but the profiles themselves will likely be influenced by how the power system evolves, including the policies and regulations associated with this evolution, creating a complex dynamic feedback loop. Electricity cost, rate structures including time-varying pricing, and demand response programs will influence EV charging behavior and, in the long run, EV adoption across different market segments.

Futures with major EV and renewable penetrations—which are growing increasingly common in energy-transition scenarios, as well as those designed to meet certain policy objectives—can amplify the interactions between EV charging and power system planning, as well as heighten the enabling role of flexibility in this transition. For example:

- EV charging during the day (i.e. workplace charging) could reduce solar curtailment during the belly of the 'duck curve' [68], and overnight (i.e. home) charging could help reduce wind curtailment. However, charging after the evening commute could further stress ramping needs for systems that already need to manage solar production that rises and sets with the sun.
- EV charging—spread across millions of vehicles—also introduces additional uncertainty for power system operations, including distribution system considerations. This uncertainty, especially coupled with the variability of wind and solar generation and other distributed energy resources, could raise the need for more expensive operating reserves and, possibly, investments in additional generation or storage to meet new or heightened grid requirements.
- At the same time, flexible or 'smart' vehicle charging and vehicle-to-grid (V2G) applications could mitigate these issues and support the grid in several ways. More research is needed to understand the related technical implications (e.g. communication and control systems, impact on battery wear-and-tear and aging), required business models (e.g. retail electricity rates and demand response programs), needed charging infrastructure, the tradeoffs across different value streams that EV could provide, and EV users' willingness to engage in these different charging paradigms.

Figure 2 provides an illustration of possible impacts of EV charging on total electricity load shapes under different paradigms; illustrative non-EV 'Load' is taken from [69] for the peak summer day in the California Independent System Operator (CAISO) system. All cases assume the same number of vehicles

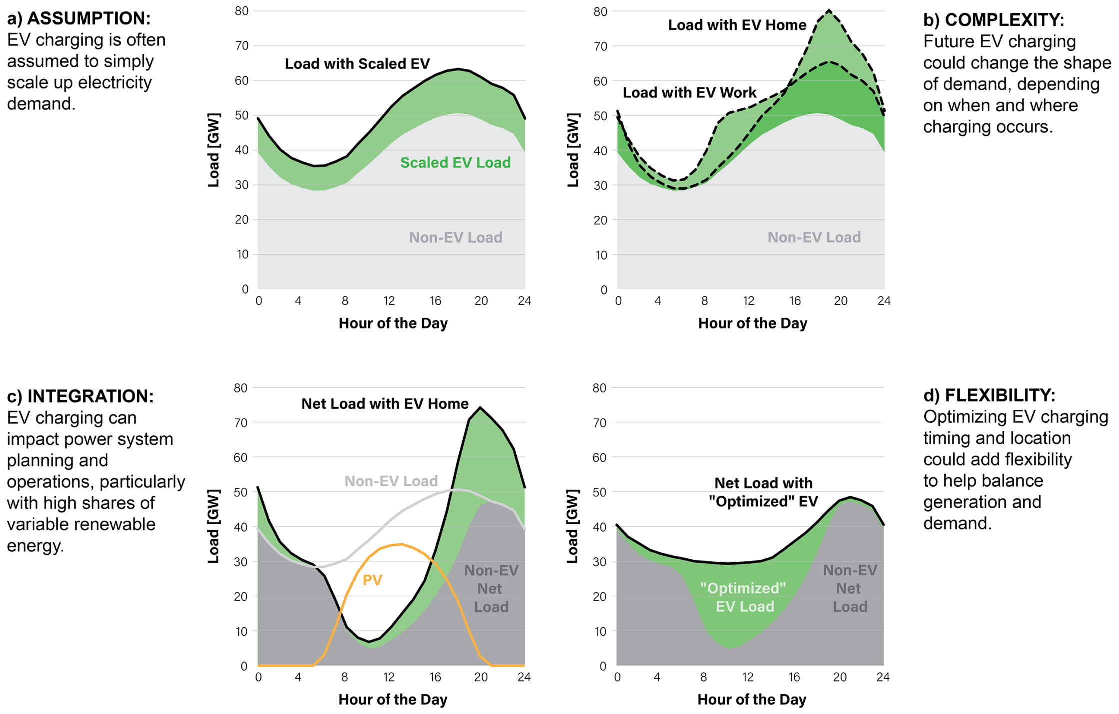

Figure 2. Possible impacts of EV charging on total electricity demand: (a) assuming that EV charging leads to a simple scaling up of current load (current assumption in many models); (b) considering mobility-based modeling of alternative EV charging profiles, leading to two possible total loads that are significantly different; (c) highlighting interaction between EV profiles and variable renewable production; and (d) illustrating the effect of coordinated and optimal EV charging. Load (non-EV) and PV data is from [69] for a summer day in CAISO for a system with 30% annual PV penetration. The different EV charging patterns illustrated in the figure result from different charging strategies, but the green areas (total EV use and charging energy) are the same across all panes.

being driven in the same way but being charged at different times/locations. EV load is assumed to be 25% of total load in this example (in line with results from [18] under a high electrification scenario in 2050). Pane *a* shows the total system load assuming that vehicle electrification would simply scale up current load, without impacting load shapes (the current assumption in many economy-wide or large-scale energy system models). The green areas in Pane *b*, however, illustrate how EV loads, which are characterized by significant uncertainty, might impact total load patterns. Two alternative illustrative EV charging loads shapes for a typical weekday are generated using the EVI-Pro model [24] to represent light-duty vehicle charging mostly performed at home (‘EV Home’) or a case in which significant workplace charging complements residential charging (‘EV Work’). In both cases, public charging is used minimally. Pane *b* illustrates how these loads could impact total load (total load is the sum of ‘Load’ (without EVs) and ‘EV Home’ or ‘EV Work’). EV load from people significantly leveraging workplace charging during the day could create a totally different load shape than people solely charging their vehicles at home—and both lead to a different shape compared to today’s system load (that has very few EVs).

To add to this uncertainty, the growing contribution of renewable generation to the power system (illustrated in Pane *c* using a solar photovoltaic [PV] generation profile from [69] that assumes 30% annual PV generation) also impacts load shapes. Increasing wind generation also has similar implications, but with different net load shapes that are not illustrated in figure 2 for simplicity. In particular, as variable renewables are added to the generation mix, what becomes more important is the net load: the total system load minus the contribution from variable renewables. EV charging could impact net loads in different ways—possibly by further stressing the system by making it ‘peakier’ and more variable. For example, Pane *c* assumes predominant residential EV charging (‘EV Home’) without any sort of charge management, which could exacerbate the ‘duck curve’ challenges introduced by large PV generation, given that EV charging and solar generation are not well aligned in this case. However, EV charging is intrinsically flexible—and with proper charging infrastructure access and demand response programs can greatly help to mitigate the challenges of integrating variable renewable resources by aligning demand with resource availability. For example, ‘optimal’ EV charging (represented in Pane *d* as the green area, an illustration of a possible ‘reshaped’ EV charging load shape to support demand-supply balancing) can decrease the net load ramps and address issues related to local- and system-level peaks in electricity demand or constraints to bulk or electricity distribution systems. Note that achieving this 'optimal' EV charging load shape might require infrastructure investments (e.g. workplace charging options) and business models enabling active consumer participation in electricity markets and proper compensation for the flexibility provided by EV users.

The effects of EV charging occur over several timescales—from multi-year or annual energy use and peak load (e.g. generation capacity requirements, response to extreme events, transmission and distribution system planning), seasonal and monthly scheduling (e.g. hydroelectric power dispatch, maintenance cycles), daily and hourly operations (i.e. commitment and dispatch decisions), and sub-hourly fluctuations (i.e. dispatch, operating reserves, contingency events, power quality). Considerations for integrating flexible loads like EVs over different timescales have some similarities to those for energy storage technologies, which have been deployed at significant scale for applications ranging from fractions of a second to many hours and have been shown to be dependent on the specific structure of the power system (e.g. generation mix) [70, 71]. The effects of EV charging can also differ across regions depending on the local generation mix and details of the transmission and distribution systems—which may impose even more constraints to or, alternatively, offer more benefits associated with flexible vehicle charging.

The potential for EV charging flexibility to provide system benefits has been shown for a variety of power systems applications and timescales, including planning and operations, bulk and distribution systems, and wholesale or retail markets. However, existing studies provide a piecemeal assessment focusing on specific aspects and/or applications rather than a comprehensive analysis of the value of EV charging flexibility across multiple dimensions and timescales. A more nuanced understanding of the impact of EV charging on power systems and of the value of flexible charging or V2G is needed across multiple dimensions and timescales to fill several research gaps.

First, EV charging offers a new source of demand-side flexibility that can respond in real time to system needs (e.g. drops in wind production, one- or bi-directional frequency regulation). But this flexibility is constrained by multiple complex and interacting factors, including mobility needs across multiple transportation segments and applications, vehicle characteristics, charging infrastructure availability, consumer perception and behavior, and markets and policies. Understanding the constraints to and potential for flexibility remains a key research need. V2G, that is, bi-directional power flow, also improves the ability of EVs to provide grid support—but it comes at the expense of potentially degrading vehicle batteries and possibly inconveniencing EV owners, so it requires a careful assessment of these trade-offs. Second, business models and programs have not been established to engage and compensate EV users for providing charging flexibility and proper pricing of different value streams provided by flexible EV charging and V2G, especially for distribution-level aspects that are typically not explicitly reflected in today's electricity pricing. Third, EV charging flexibility could span multiple days, providing the ability to curtail demand in response to critical events (e.g. heat waves) and improve system resilience, but multi-day flexibility has not been considered in most studies. Finally, the trade-offs and interactions among different value streams (e.g. reshaping EV charging to minimize overall system peak or support local distribution systems) have not been fully explored—and competing objectives might lead to different 'optimal' charging solutions.

To conclude, it is clear that vehicle electrification will increase electricity demand, but the *shape* of transportation electricity consumption will be just as influential to the future global energy system as the quantity. Appropriate understanding of electricity demand is essential to inform the optimal design and operation of future electric power systems, including capacity expansion requirements, value of transmission, operation and cost of producing electricity, and design of distribution systems. The ability to accurately model future electrification scenarios across different transportation segments (e.g. personal light-duty vehicles, taxis, vocational commercial vehicles), properly represent vehicle use and charging behavior, and characterize the flexibility of charging scheduling, including its ability to provide grid services, is fundamental to better inform energy system transformation pathways over the 21st century. In particular, a proper assessment of how flexible EV charging can support and optimize electric power system design and operation could support the design and development of future power systems that include appropriate business models and long-term implementation strategies designed to consider mobility and power systems needs simultaneously. More nuanced modeling of the electricity demand from EVs—and of their impact on electricity load shapes and duration curves—has become critical to properly assess energy system transformation pathways, evaluate the potential impacts of different policies, and guide future investments, including informing the energy transition and infrastructure development decisions in a post-COVID-19 world.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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