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Electric vehicle charging stations at the Bataan Memorial Building in Santa Fe, New Mexico. (Thom Cole/New Mexico General Services Department, via AP)

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Leveraging Charging Strategies to Reduce Grid Impacts of Electric Vehicles

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Electric vehicles (EVs) can challenge or support electricity systems depending on how they are charged. Uncontrolled charging may strain electricity systems, e.g., by increasing peak demand in the evening,[1] which may require cost- and emission-intensive infrastructure investments, such as grid reinforcements and peak generation capacity. In contrast, controlled charging can benefit electricity systems by providing flexibility,[2] e.g., by shifting charging demand away from

1 Gschwendtner, C. et al. The impact of plug-in behavior on the spatial–temporal flexibility of electric vehicle charging load. Sustain. Cities Soc. 88, 104263 (2023), doi.org/10.1016/j.scs.2022.104263

2 Flexibility provision is defined as balancing supply and demand at various time scales, from short-term (starting from milliseconds) to long-term (seasonal). EVs can play a major role in short-term flexibility, from seconds to days.

evening hours. Controlled charging that combines technical solutions with heterogenous EV user behaviors, supported by charging infrastructure at diverse locations, e.g., at work during midday, and incentives, can reduce peak demand to avoid grid constraints and support the integration of renewable energy.

Balancing electricity supply and demand becomes more challenging as the share of variable renewable energy sources and electrification increase. Low-carbon electricity systems likely need more short-term flexibility (on a scale of milliseconds to days) to cope with the fluctuating generation of solar and wind electricity. Growing electrification, including the adoption of EVs, can increase demand peaks, exacerbating the challenge faced by grid operators to always meet electricity demand. The International Energy Agency (IEA), in its Announced Pledges Scenario (APS), estimates that global short-term flexibility needs will double by 2030 and rise 4.5-fold by 2050 compared to today.[3] In the IEA's APS, demand-side flexibility is expected to play a crucial role in fulfilling short-term flexibility needs - meeting one third of needs by 2030 and almost half by 2050.[4]

The increasing relevance of demand-side flexibility represents a paradigm shift in electricity systems: end users actively shifting electricity demand across time and space according to electricity supply, rather than supply following demand. However, to leverage the potential of demand-side flexibility and achieve climate targets, the IEA emphasizes the need for digital technologies, e.g., smart meters, particularly for modernizing distribution grids.[5]

Those digital technologies can support controlled EV charging, which can provide flexibility in a variety of ways, including: automated charging processes that determine when and how fast an EV battery charges during a specified dwell-time; bidirectional charging that allows EVs to feed electricity back into the grid to compensate for shortfalls in renewable electricity generation; changing users' plug-in behavior to shift demand to off-peak hours, e.g., charging during midday when solar PV electricity is available; or some combination of the aforementioned options. Controlled charging can improve the reliability of the electricity grid and provide economic benefits, such as deferring or reducing costly upgrades to grid infrastructure, increasing profits for charging station operators, and reducing charging costs for EV users.

To date, controlled EV charging has primarily focused on technical solutions that assume charging behavior can be fully controlled, e.g., by grid operators. However, the prominent role of end users in demand-side flexibility means that EV charging cannot be fully controlled. Driving patterns,

3 IEA, World Energy Outlook 2023

4 The IEA's APS includes electrolyzers in their estimates for the role of demand-side flexibility.

5 IEA, Electricity Grids and Secure Energy Transitions, 2023

charging behaviors,[6] and willingness to provide flexibility services vary substantially across EV users, and this variability is expected to become more pronounced as EV adoption increases.

Changes in EV users' behaviors could reduce peak demand substantially and thus, potentially required grid reinforcements. Yet the behavioral aspects of EV charging have received little attention compared to technical solutions, which means that some of the flexibility potential of EV charging, and particularly the spatial flexibility, is at risk of remaining untapped.

How can the flexibility of electric vehicle charging be unlocked?

1. **Heterogeneous EV user behaviors can reduce peak demand and their interplay with automated control strategies needs to be considered,** as their combination influences the charging demand and its flexibility.[7] While the plug-in behavior depends on the EV user's decision when and where to connect to a charging station and refers to the temporal and spatial distribution of the charging demand, automated control strategies only refer to the temporal distribution of the demand. Changing users' plug-in behaviors can reduce the charging peak up to 80%.[8] Different plug-in behaviors include charging at home, at work, at any opportunity, or when the state-of-charge of the battery falls below a specific threshold. While changes in the plug-in behavior represent an opportunity to reduce peak demand cost-efficiently, it is more difficult to influence than automated control strategies. Effective incentives can help to untap this potential (see point 4).

2. **Charging infrastructure should be sited at diverse locations to enable heterogeneous plug-in behaviors.**[9] Providing charging infrastructure at different locations, e.g., at workplaces and public spaces, can spatially and temporally diversify the charging demand, thereby reducing electricity peak demand. Since many EVs are not parked at home during the day, charging stations at other locations can shift the charging demand to midday and increase the balance between charging demand and solar electricity supply.

6 Gschwendtner, C. et al. Mind the Goal: Trade-offs between Flexibility Goals for Controlled Electric Vehicle Charging Strategies. iScience 26 (2), 105937 (2023), doi.org/10.1016/j.isci.2023.105937

7 Ibid.

8 Gschwendtner, C. et al. The impact of plug-in behavior on the spatial–temporal flexibility of electric vehicle charging load. Sustain. Cities Soc. 88, 104263 (2023), doi.org/10.1016/j.scs.2022.104263

9 Ibid.

3. **The specific grid context needs to be considered as it determines optimal combinations of behaviors and automated processes.**[10] For instance, in areas with high evening peaks, flattening the charging demand within a charging session can be more effective for reducing peaks than not charging during peak hours as the charging demand is more evenly spread across time and space. Furthermore, the peak charging demand of an average EV is higher in rural areas compared to urban and suburban areas as driving distances, and hence, charging demand, are typically higher in rural areas.[11] At the same time, changes in plug-in behaviors show more potential to reduce peak demand in rural areas, particularly because the charging demand can be distributed across different areas, given longer driving distances.

4. **Effective financial incentives might need to be developed to increase the adoption of optimal charging strategies.** While information might provide enough incentives for early EV-adopters, it is expected that financial incentives are necessary for later adopters.[12] Such incentives should integrate several flexibility goals, such as minimizing transmission and distribution grid challenges, the CO_2-emission intensity of electricity, and energy storage requirements. While incentives should support the most suitable plug-in behaviors and automated control strategies for these goals, the incentives need to be attractive for EV users to ensure acceptability.[13] Electricity tariffs can function as such incentives, e.g., time-of-use pricing, which tends to be more attractive, e.g., compared to real-time pricing, as it results in low risk of unexpected price peaks and acceptable complexity for the users. Despite reduced electricity bills, EV users might be reluctant to provide flexibility due to perceived inconvenience or lack of control.[14] Therefore, experimenting with opt-out mechanisms and support strategies for low-income households who might be unable to shift electricity demand could provide further insights on effective incentive schemes.

5. **Controlled charging strategies should be employed as part of a portfolio of flexibility services.**[15] As EV charging depends on user behavior, the risks of unexpected variations in driving and charging behavior can be reduced by complementing EVs with

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10 Gschwendtner, C. et al. Mind the Goal: Trade-offs between Flexibility Goals for Controlled Electric Vehicle Charging Strategies. iScience 26 (2), 105937 (2023), doi.org/10.1016/j.isci.2023.105937

11 Gschwendtner, C. et al. The impact of plug-in behavior on the spatial–temporal flexibility of electric vehicle charging load. Sustain. Cities Soc. 88, 104263 (2023), doi.org/10.1016/j.scs.2022.104263

12 Gschwendtner, C. et al. Vehicle-to-X (V2X) implementation: An overview of predominate trial configurations and technical, social and regulatory challenges. Renew. Sustain. Energy Rev. 145, 110977 (2021), doi.org/10.1016/j.rser.2021.110977

13 Ibid.

14 M. Muratori, Impact of uncoordinated plug-in electric vehicle charging on residential power demand. Nat. Energy. 3, p. 193–201 (2018), doi.org/10.1038/s41560-017-0074-z

15 Gschwendtner, C. et al. Vehicle-to-X (V2X) implementation: An overview of predominate trial configurations and technical, social and regulatory challenges. Renew. Sustain. Energy Rev. 145, 110977 (2021), doi.org/10.1016/j.rser.2021.110977

other technologies, such as heat pumps and batteries, for demand-side flexibility. In addition, flexibility portfolios should account for different EV use cases. Residential and commercial vehicles exhibit different driving patterns; while residential vehicles are available for charging for longer periods of times, commercial vehicles often follow more predictable charging schedules. Accounting for both types of vehicles can help balance the differences in their availability for flexibility provision. Furthermore, stacking various flexibility services can increase revenue streams for flexibility providers and reduce risks from potentially limited markets, e.g., by providing flexibility at both transmission[16] and distribution grid levels.

Understanding the impact of controlled charging in different grid areas across diverse charging locations is crucial for decision-makers in industry and government. Integrating technical solutions with diverse user behaviors allows for unlocking the flexibility of electric vehicle charging while supporting both electrification and the integration of renewable energy in a cost-efficient way.

16 EVs can participate in frequency services, using vehicle-to-grid technology, as demonstrated in several pilot projects.

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