WHITE PAPER

Leveraging Locational and Temporal Flexibility in Transportation Electrification to Benefit Power Systems

By Jennifer Chen, World Resources Institute

Electric vehicles (EVs) that charge where and when electricity is cheaper on the bulk power system can help lower system costs, improve the grid's ability to incorporate affordable renewable generation, and help to meet grid reliability needs. To enable and encourage EVs to provide these benefits, charging station siting and rates could factor in locational and temporal values of electricity. In organized wholesale electricity markets, locational marginal prices provide some of this information. Charging station rates could track locational marginal prices and include a price on greenhouse gas emissions. This would allow drivers to react to EV charging prices similarly to how consumers react to gasoline prices today. Adding bi-directional capabilities could enable EVs to also provide services back to the grid, which would be valuable during scarcity. To the extent possible, charging stations along interstate highways and EV fleet charging could be sited away from congested distribution grids and account for transmission bottlenecks to reduce infrastructure needs.

This paper examines how locationally flexible demand can be used to address grid needs. It considers potential use cases and their challenges, identifies key questions around designing incentives, and offers ideas for regulators and policymakers as they develop policies, act on proposals, and disburse funding to support electric transport infrastructure.

A White Paper from the Energy Systems Integration Group's Retail Pricing Task Force

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About ESIG

The Energy Systems Integration Group is a nonprofit organization that marshals the expertise of the electricity industry's technical community to support grid transformation and energy systems integration and operation. More information is available at https://www.esig.energy.

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Potential for Transportation Electrification to Offer Locationally and Temporally Flexible Grid Services

Well-managed electrification across the distribution and transmission systems can reduce overall costs and emissions, improve equity outcomes, and help smooth variability in wind and solar generation (Szinai et al., 2020). Transportation is on the leading edge of electrification, and electric vehicles (EVs) could represent up to 27 percent of global demand by 2050 (McKerracher, 2022). However, EVs are not usually exposed to incentives to promote efficient resource use and do not generally have access to appropriately sited infrastructure that can facilitate this (Myers et al., 2019; Kubli, 2022; Tomich, 2022). This paper examines how to leverage locational as well as temporal flexibility of new load to benefit customers and the grid, paying particular attention to early holistic infrastructure planning and enabling market prices to inform electricity customer behavior.

Transmission and distribution system investments needed to support electrification could cumulatively reach hundreds of billions of dollars over the next few decades (Weiss, Hagerty, and Castañer, 2019; Larson et al., 2021). These costs will depend on how electrified end uses are managed and informed by grid conditions. Uncontrolled EV charging can overload transformers and transmission lines, force early replacement of equipment or require upgrades, and worsen power quality (Powell et al., 2022).[1] Expectations of future uncontrolled charging can lead to overbuilding power plants to meet load added at peak times.[2] But studies show that managed EV charging significantly reduces distribution system impacts (Brockway, Callaway, and Elmallah, 2022; Szinai et al., 2020). EVs can also provide grid services, such as frequency regulation and ramping (Powell et al., 2022), when given the appropriate signals and incentives.

“Flexibility” for demand-side resources normally refers to the ability to shift time of use, but mobile loads like EVs can also offer a degree of locational flexibility.

Customer load that is flexible in charging or siting will increase as transportation and industry electrify. Leveraging this demand-side flexibility is critical to optimizing the benefits and costs of electrification. “Flexibility” for demand-side resources normally refers to the ability to shift time of use, but mobile loads like EVs can also offer a degree of locational flexibility. This potential grows as more mobile batteries hit the roads. Where and when customers choose to charge will impact overall cost and emissions savings and will depend on the incentives and information provided, as well as available charging infrastructure locations. For example, EV charging station siting could be planned to avoid congested distribution networks and offer rates that track wholesale electricity prices to help relieve transmission bottlenecks and absorb surplus renewable generation.

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[1] See also National Grid ESO (2022a), p. 208, and Venkataraman and Speckman (2022), p. 42, for visualizations of the stark differences between managed and unmanaged charging.

[2] For example, PJM’s latest long-term load forecast informs capacity market procurement that includes EV charging adding to peak demand due to insufficient retail rate reforms (Howland, 2022); see also PJM (2022), p. 27.

EV charging behavior can be helpfully guided by market prices and retail rates that accurately reflect the full costs of electricity generation as well as the appropriate siting of charging infrastructure. Organized wholesale market prices transparently convey bulk power grid conditions through granular locational marginal prices (LMPs) that account for transmission constraints and marginal costs of supplying electricity every five minutes.[3] End-use electricity customers can participate in these markets and react to prices, including as part of an aggregation if each consumer load is small.[4] These markets are also starting to provide emissions data with the same granularity as their real-time electricity markets (Gledhill, 2021).[5] However, for EVs to contribute to both locational and temporal grid flexibility and provide grid services, charging station siting as well as charging rates must account for grid needs.

> **EV charging behavior can be helpfully guided by market prices and retail rates that accurately reflect the full costs of electricity generation as well as the appropriate siting of charging infrastructure.**

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[3] See https://www.iso-ne.com/participate/support/faq/lmp.

[4] See U.S. Federal Energy Regulatory Commission (FERC) Order 719, Wholesale Competition in Regions with Organized Electric Markets 2008, https://www.ferc.gov/media/order-no-719; FERC Order 745 Demand Response Compensation in Organized Wholesale Energy Markets, https://www.ferc.gov/media/order-no-745; and FERC Order 2222 Participation of Distributed Energy Resource Aggregations in Markets Operated by Regional Transmission Organizations and Independent System Operators, 2020, https://www.ferc.gov/sites/default/files/2020-09/E-1_0.pdf.

[5] See https://insidelines.pjm.com/marginal-emission-rates-added-to-data-miner-tool/ and https://insidelines.pjm.com/pjm-emission-data-sparks-innovative-approach-to-reduce-carbon-footprint/. For more on the potential role of regional transmission organizations in a high electrification future, see Chen (2022). Also, the Infrastructure Investment and Jobs Act mandates that the Energy Information Administration collect and publish spatially and temporally granular electricity emissions rate data. See https://www.rff.org/publications/reports/options-for-eia-to-publish-co2-emissions-rates-for-electricity/.

The Value of Locationally Flexible Demand

Flexible resources can be characterized as having a temporal component, a locational component, or both. Temporal flexibility has received more attention, from seasonal storage to resources capable of providing fast frequency response. Stationary resources mostly offer a temporally flexible service; however, in conjunction with a grid connecting them to other producers and consumers elsewhere, these temporally flexible resources can also help improve the spatial flexibility of the overall system. An example is the ability of demand response to increase the system's ability to absorb high levels of remote variable wind and solar generation within the same balancing area.

Locationally flexible resources add another value stream, particularly when the grid has constraints that limit the ability of temporally flexible stationary resources to serve grid participants located elsewhere. These could include hydrogen and ammonia fuels and mobile batteries.

This paper focuses on locationally flexible demand. Strategically siting flexible demand, such as EV charging, can help the system avoid transmission and distribution system upgrades and provide EV owners access to non-emitting, lower-cost energy resources. Bi-directional chargers could also enable EVs to offer grid services. In addition, signaling EVs to charge at locations with greater supply can avoid the need for additional generation capacity or ramping resources to serve peak needs. This enables EVs to contribute to system flexibility, which can benefit grid resilience and help integrate more renewable resources onto the grid. This paper looks at different categories of benefits and cost estimates that are available but does not systematically quantify them.

Some of the locational flexibility benefits of mobile batteries are like those of transmission. Managed EV charging and discharging may be able to alleviate problems associated with too little transmission capacity, particularly in densely populated areas where vehicular traffic is heavier and transmission is harder to site. While the locational flexibility benefits of mobile batteries will not displace the need to modernize the transmission system, good planning for EV charging infrastructure accounting for grid needs may help to inform efficient transmission investment.

Managed EV charging and discharging may be able to alleviate problems associated with too little transmission capacity, particularly in densely populated areas where vehicular traffic is heavier and transmission is harder to site.

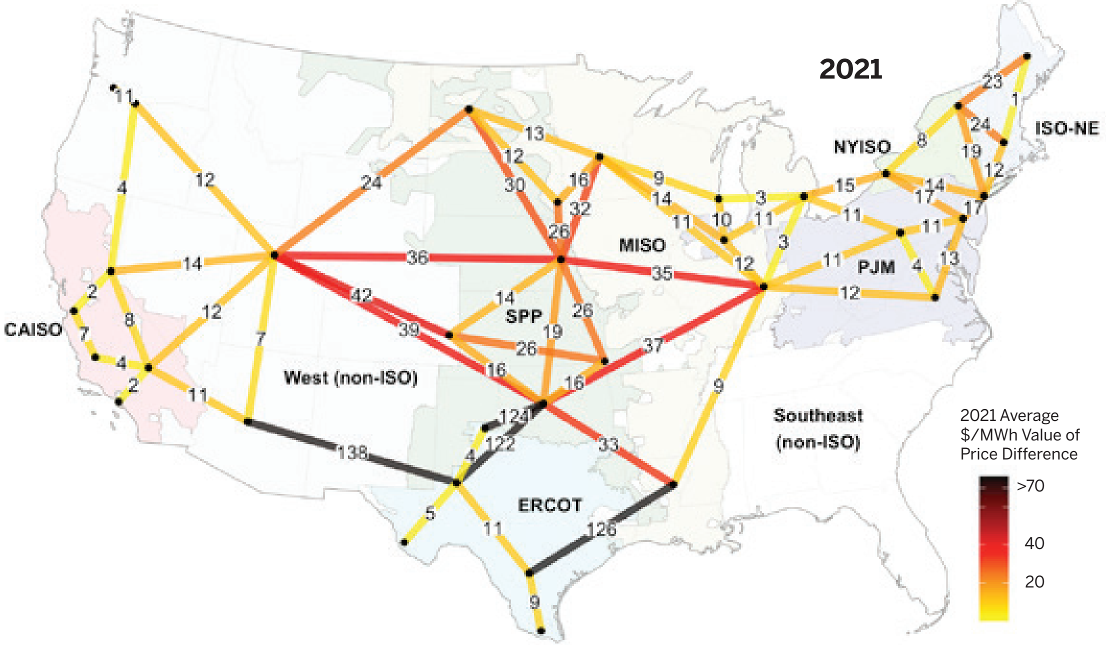
Congestion Relief and Renewable Integration Benefits

Congestion on the power grid bottles up low-cost generation, particularly renewables sited far from demand. This causes higher prices for electricity customers and lower and potentially negative prices for generators. Congestion can be seen in wholesale energy market price differentials across geographic nodes. Some of these differentials are stable over time, so that solutions addressing these constraints can predictably and consistently offer value (Millstein et al., 2022).

As more EVs hit the roads, they can add to or relieve congestion depending on where they charge. Mobile batteries could help relieve congestion impeding generation from reaching load and thereby help equalize prices.

FIGURE 1

Average Hourly Price Differences Across Selected Wholesale Pricing Hubs and Zones



This map shows select locational marginal pricing nodes and average price differentials between them due to transmission or market constraints. Some of these differentials between nodes can be substantial and persistent, which indicates that solutions addressing constraints preventing supply from reaching demand can consistently create value. Transmission is one solution that studies focus on, but mobile batteries charging at stations accounting for grid congestion can provide similar kinds of benefits. While the nodes shown in this map are far apart, some disparate pricing nodes need not be (see Figure 3 on p. 6), so EV drivers may be able to access lower-priced energy if charging stations are strategically sited.

Source: Millstein et al. (2022). © The Regents of the University of California, Lawrence Berkeley National Laboratory.

The map in Figure 1 estimates some of the potential value that congestion relief solutions like mobile batteries could offer in 2021. Using 2022 data, the updated analysis saw even higher average price differences across the same pairs of points pictured: the mean price difference was $25 per MWh, with a median price difference of $22 per MWh (Millstein et al., 2023).

For reference, chargers for a 500-mile-range EV truck will be about a MW.[6] Two hypothetical EV stations with a $25 per MWh difference in rates charging one truck each at all hours of one year would incur a cost difference of nearly $220,000. Siting chargers where long-haul freight and road trippers can charge at lower-priced nodes could help them save on charging and reduce grid congestion.

As seen in Figure 1 for 2021 and in the same analysis for 2022, the cost differential patterns arising from transmission congestion is heavily influenced by extreme weather: Winter Storm Uri in 2021 and Winter Storm Elliot in 2022 (Millstein et al., 2022; Millstein et al., 2023). While extreme weather may pose hazards to EVs driving, anticipating and preparing for these emergencies could include positioning charged batteries in advance of these events, and thereby reduce congestion.

LMPs from temporary transmission constraints can inform efficient charging if this information is transmitted to drivers. As seen in Figure 2 (p. 5), a two-hour drive along Interstate 95 between Baltimore and Philadelphia on a summer afternoon can traverse zones priced at $150-$200/MWh and $0-$20/MWh.

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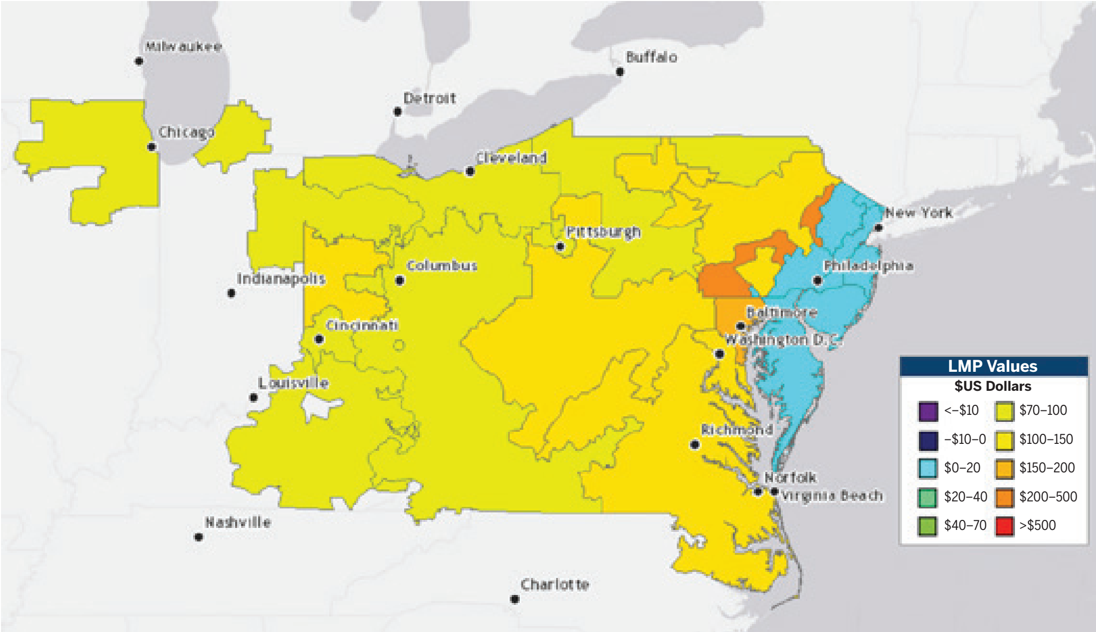
[6] See https://www.notateslaapp.com/tesla-reference/963/everything-we-know-about-the-tesla-semi.

FIGURE 2

Real-Time Locational Marginal Pricing Map for PJM at 1:00 PM Eastern Time on August 25, 2022



This contour map visualizes various ranges of LMPs for real-time energy every five minutes in PJM at 1:00 PM on August 25, 2022. A two-hour drive along Interstate 95 between Baltimore and Philadelphia on a summer afternoon can traverse zones priced at $150-$200/MWh and $0-$20/MWh. Similarly, there is significant price variation on I-76 from Pittsburgh to Philadelphia including a zone with prices of $200-$500/MWh, which could be avoided to the east or west.

Source: PJM (https://www.pjm.com/library/maps/lmp-map.aspx, accessed on August 25, 2022).

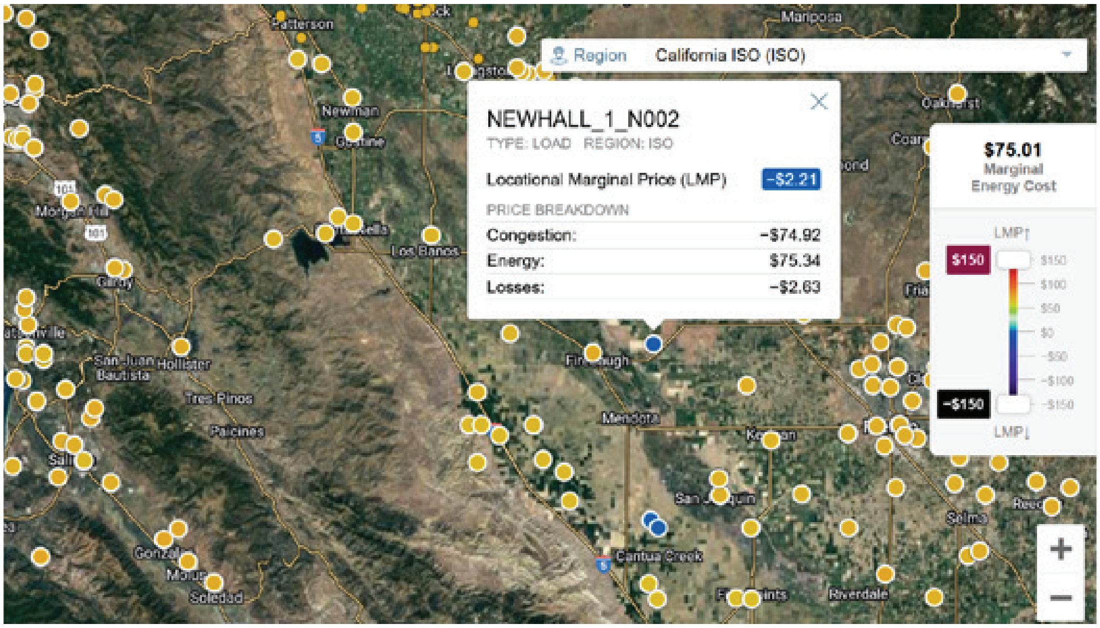
Nodes with negative and positive price differentials need not be far from one another, as seen in Figure 3 (p. 6) zooming into a region near Interstate 5 operated by the California Independent System Operator (CAISO). The proximity of disparate pricing nodes, some negative, indicates that drivers could opt for less expensive charging if stations are sited factoring in congestion patterns and if variable pricing information is conveniently transmitted to customers.

The real-time energy market operated by the Electric Reliability Council of Texas (ERCOT) can accurately reflect grid conditions in prices, including growing transmission constraints as wind and solar levels rise (Kleckner, 2020). This information can inform efficient electricity use. As seen in Figure 4 (p. 7), wholesale prices differ by more than $30/MWh in Houston and surrounding areas on an example day at noon in late August; Austin and San Antonio also see significant differentials. (Further below, Figure 7 (p. 12) shows that many cities and highways form major trucking routes and hubs.) Other cities with similar differentials as Houston could also benefit from strategic charger siting.

In avoiding congested areas and charging where supply is relatively high, including renewable generation, EV charging can also help reduce renewable curtailment (Szinai et al., 2020), ramping needs, and negative pricing. The renewable integration benefits of stationary storage and responsive demand are well recognized—they can shift consumption in time to match renewable generation. Mobile batteries offer an additional advantage of arbitraging across space, for example, by charging in lower-cost renewable-rich regions and transporting energy to where supply is relatively scarce. This could be useful if transmission lines are down or insufficient to transport renewable generation from low or negatively priced regions.

FIGURE 3

Real-Time Locational Marginal Pricing Map for Part of CAISO Around 10:00 AM Pacific Time on August 25, 2022



Region California ISO (ISO)

NEWHALL_1_N002

TYPE: LOAD REGION: ISO

Locational Marginal Price (LMP) -$2.21

PRICE BREAKDOWN

Congestion:	-$74.92
Energy:	$75.34
Losses:	-$2.63

$75.01 Marginal Energy Cost

This more detailed map shows LMPs at various nodes for real-time energy every five minutes in CAISO around 10:00 AM on August 25, 2022. Here, the blue dots denote negative LMPs, while the surrounding yellow dots signify LMPs of more than $50/MWh.

Notes: CAISO = California Independent System Operator; LMP = locational marginal price.

Source: California Independent System Operator (https://www.caiso.com/PriceMap/Pages/default.aspx, accessed August 25, 2022). Licensed with permission from the California ISO. Any statements, conclusions, summaries or other commentaries expressed herein do not reflect the opinions or endorsement of the California ISO.

An interesting possibility could be to install in-road, dynamic charging systems (Ott Zehnder et al., 2022) in regions where congestion and renewable curtailment typically occur and enable free charging to passing EVs when renewables would otherwise be curtailed.

Avoided Distribution and Transmission System Impacts

Siting charging stations away from the main distribution grid would help to avoid costs from infrastructure upgrades or additional congestion on the distribution system, which studies indicate would be significant.

- New York State's distribution system capital upgrade costs due to transportation electrification could be up to $26.8 billion by 2050 (net present value) in the unmanaged EV charging high-distribution system impact case (Venkataraman and Speckman, 2022).[7]
- In another study, projected total avoided distribution upgrade costs help justify transmission upgrade costs of building larger DC fast-charging stations and interconnecting them directly to the transmission system. This is the case in New York, where government policies include plans for ambitious electrification of transportation (Katsh et al., 2022).
- A University of California, Berkeley study on residential and EV electrification impacts estimates that distribution circuit and substation upgrades will add at least $1 billion and potentially over $10 billion to

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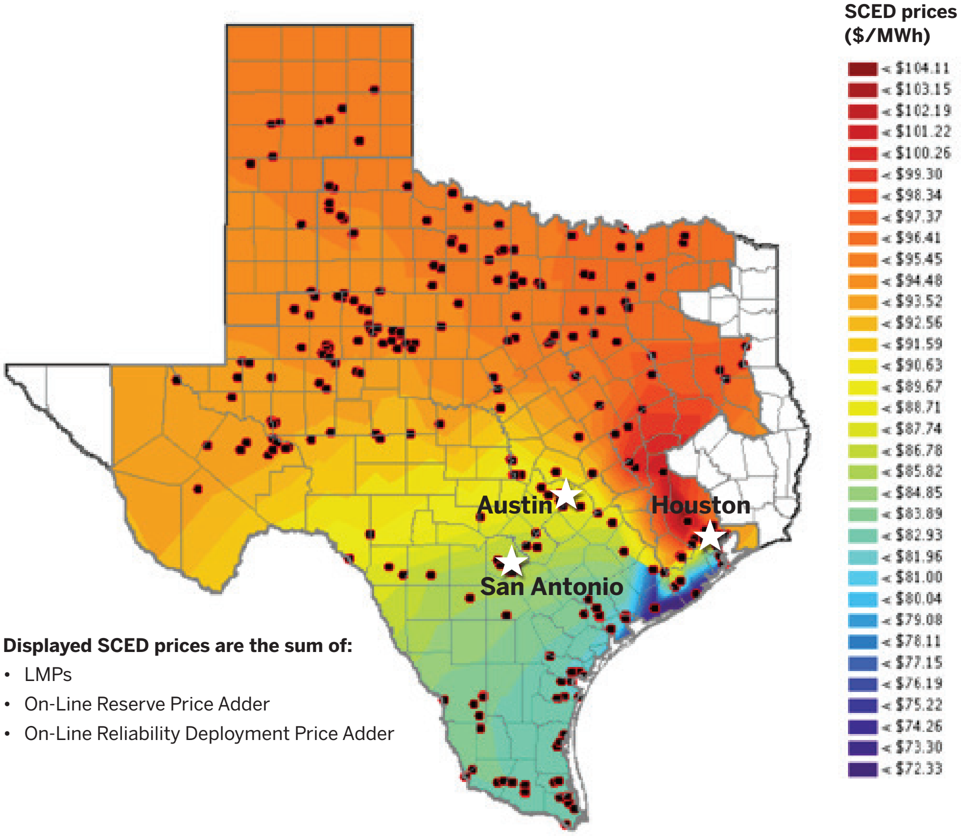
[7] These costs can include upgrading or adding new circuits, transformer banks, and substations; upgrades to distribution system components downstream from the distribution substation and the main feeder leaving the substation; voltage regulation equipment; and the replacement of distribution transformers (Venkataraman and Speckman, 2022, 41–43).

FIGURE 4

Real-Time Locational Marginal Pricing Map for ERCOT at 12:05 PM Central Time on August 25, 2022



Displayed SCED prices are the sum of:

- LMPs
- On-Line Reserve Price Adder
- On-Line Reliability Deployment Price Adder

This gradient map shows real-time LMPs ($/MWh) with reserve and reliability adders for ERCOT at 12:05 PM on August 25, 2022, shows how drivers may traverse regions with different pricing. The areas surrounding Houston, Austin, and San Antonio can have significant differentials in wholesale prices. SCED, or security-constrained economic dispatch, is the process of selecting and deploying energy resources every five minutes based on offer prices and transmission constraints.

Notes: LMP = locational marginal price; SCED = security-constrained economic dispatch.

Source: Electric Reliability Council of Texas (https://www.ercot.com/content/cdr/contours/rtmLmpHg.html, accessed August 25, 2022).

Pacific Gas & Electric's rate base by 2050 (Brockway, Callaway, and Elmallah, 2022). Timing and location influence total capacity additions: uncontrolled nighttime residential EV charging could have significantly larger impacts than daytime or managed nighttime residential charging.

Transmission investments could be optimized if long-term load forecasting and transmission planning account for the responsiveness of EV charging as well as other locationally flexible loads.[8] While forecasting is done at the utility or regional grid operator level, the U.S. Federal Energy Regulatory Commission (FERC) is currently undergoing transmission planning reforms to better anticipate how supply and demand will evolve decades into the future (U.S. FERC, 2021, 2022). Future demand could include newly electrified loads, such as building heating, ventilation, and air conditioning; industrial processes; and chargers for EVs. It could also include new loads, such as data centers, cryptomining, and indoor agriculture.[9] If loads are sited without regard for grid impacts, even more transmission will need to be built to accommodate them. But co-optimizing planning

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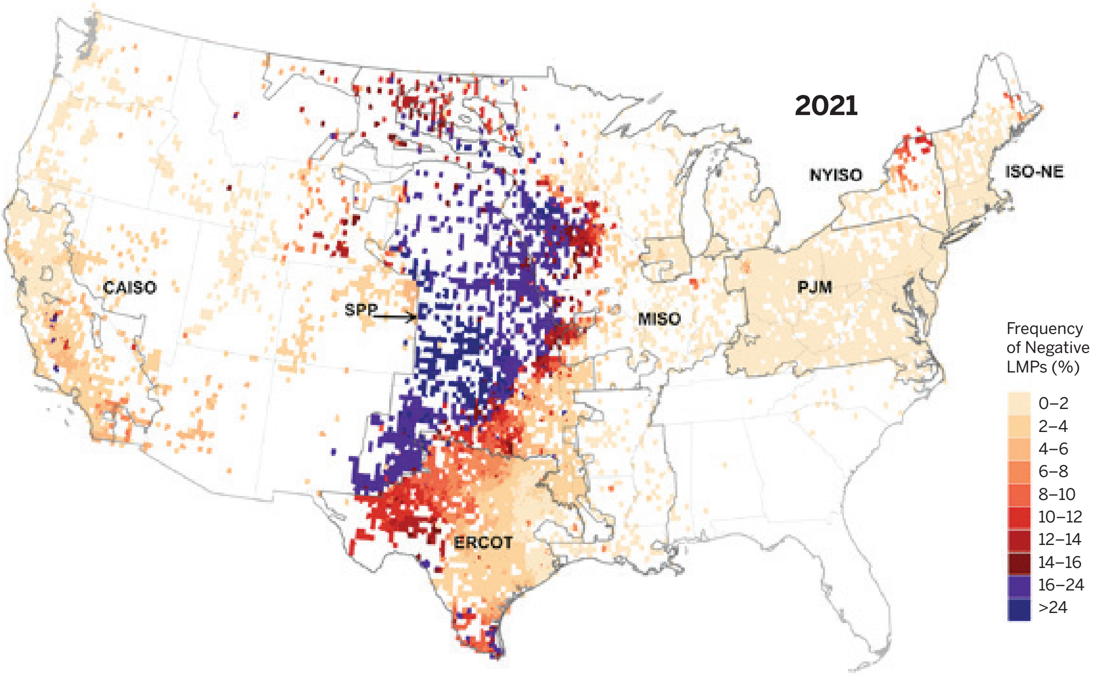
[8] In addition to mobile EV loads, locationally flexible loads could include facilities that have some flexibility in siting, such as cryptomining (Glinton, 2022) and other electricity-intensive facilities. However, once sited, these facilities lose locational flexibility.

[9] PJM projects new data centers to contribute two and one-half times the load growth of light-duty EVs every year (Gledhill, 2021).

FIGURE 5

Frequency of Negative Locational Marginal Prices, 2021



Negative electricity prices result from congestion of the transmission system leading supply to exceed demand locally. Excess supply can come from limited ramping flexibility, out-of-market commitments from some thermal generators, and production incentives enabling negative bids. Negative prices predominantly correlate with high wind production compared to demand.

Notes: CAISO = California Independent System Operator; SPP = Southwest Power Pool; ERCOT = Electric Reliability Council of Texas; MISO = Midcontinent Independent System Operator ; NYISO = New York Independent System Operator; ISO-NE = Independent System Operator of New England.

Source: Seel et al. (2021). © The Regents of the University of California, Lawrence Berkeley National Laboratory.

for transmission, generation, and locationally flexible loads could help reduce needed investments.[10]

Avoided Retail Costs in Charging

Locationally flexible EV use can include long distance drivers who can stop at various charging stations or some fleet charging that can be sited on the outskirts of densely populated cities. If charging stations sited away from main distribution grids can allow EVs to charge at prices near wholesale, there is an opportunity to avoid some retail costs. This can be significant, as wholesale prices can be about half of retail or less, depending on the region (see Figure 6, p. 9).[11]

Co-optimizing planning for transmission, generation, and locationally flexible loads could help reduce needed investments.

Retail costs can include a broad range of distribution investments that normally may be socialized among all ratepayers. However, some of these costs are not caused by newly electrified loads if they are not taking service from the main distribution network, which would be the case for transmission-connected EV charging stations. Excluding some costs from EV charging rates could

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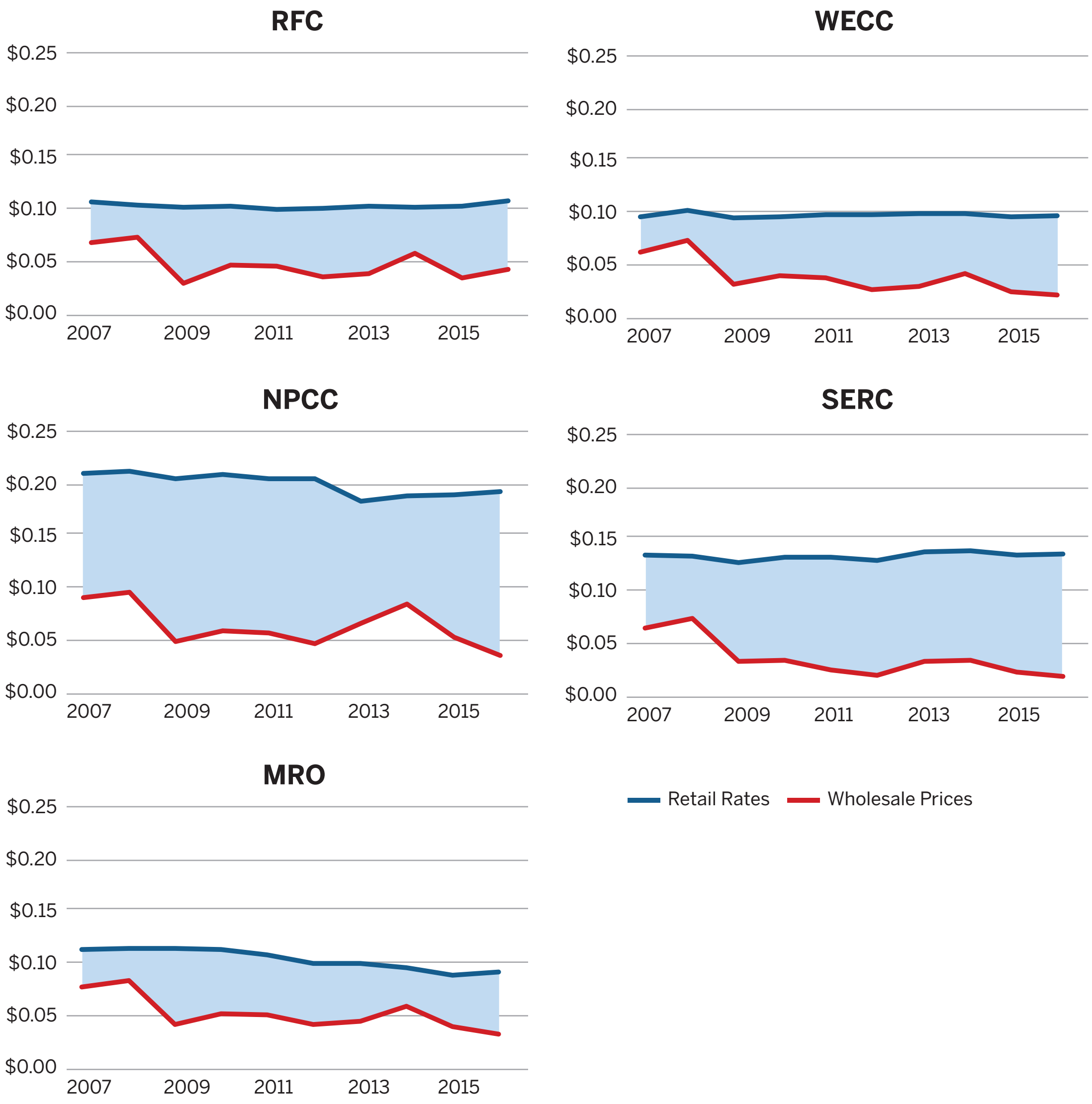
[10] See https://pubs.naruc.org/pub/536D834A-2354-D714-51D6-AE55F431E2AA.

[11] See https://www.regrid.net/home/the-current-blog/wholesale-market-studies.

FIGURE 6

Retail and Wholesale Rates in Various NERC Regions



Retail rates are the blue lines and wholesale prices are red lines (2016$/kWh). Depending on the region and fuel prices, wholesale prices can be half or less of the total retail rate, which means that avoiding some of the retail costs can produce significant savings. Note that retail electricity rates tend to blunt wholesale price signals in comparison to gasoline prices (see Figure 10 on page 15).

Notes: NERC = North American Electric Reliability Corporation. NPCC (Northeast Power Coordinating Council) is New York and New England combined. RFC (ReliabilityFirst Corporation) here includes the northern part of PJM. SERC (SERC Reliability Corporation) here includes the southeastern United States and utilities that are now part of PJM and MISO (Midcontinent Independent System Operator) but not the Florida peninsula. MRO (Midwest Reliability Organization) roughly corresponds to the northern part of MISO. WECC is the Western Electricity Coordinating Council.

Source: Cappers and Murphy (2019). © The Regents of the University of California, Lawrence Berkeley National Laboratory.

thus be justified. It could also be warranted from a policy perspective if these retail costs are discouraging drivers from choosing electricity over fossil fuels. Charging installations connected directly to the transmission system (stepped down in voltage) could make that separation from distribution cost causation clearer.

This separation can also enable rate design to better reflect power system conditions. As seen in Figure 6 (p. 9), current retail electricity rates on average do not follow wholesale price trends that reflect grid conditions. Insufficient electricity price signals impede responsive charging. In comparison, Figure 10 (p. 15) shows that retail gasoline prices more closely track wholesale prices and can encourage smart consumption.

Avoided Costs for Additional Generation Capacity and Dedicated Storage

EV charging that is responsive to LMPs can reduce projected generation capacity needs as well as dedicated storage procured to modulate capacity charges. Grid operators are projecting generation capacity requirements based on anticipated customer response to retail rates, but response to wholesale prices can be much more visible to grid operators. For example, PJM estimates that light-duty EVs will account for 0.1 percent of load growth per year (Gledhill, 2021, 33) by assuming that retail time-of-use rates designed to push EVs to charge off-peak are successful at cutting each EV's peak impact in half by 2036 (PJM, 2023, 27). However, if these EVs directly interact with the bulk power system and respond to market incentives, grid operators could refine their forecasts to account for their flexibility more accurately.

Dedicated stationary storage is often used to integrate renewables, particularly where transmission capacity is insufficient. Well-managed EV charging can reduce the amount of that storage needed and provide savings from avoiding those costs.

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Locationally Flexible Use Cases

Customer load that is flexible in charging or siting will increase as transportation and other sectors electrify. EVs could be flexible as to where they charge, especially if they travel for long distances, which would be useful in avoiding transmission and distribution constraints (and their costs) and accessing bottled-up, lower-cost wind and solar generation. EVs exposed to prices tracking LMPs could charge where and when prices are low and renewable generation is high—and potentially discharge where prices are high.[12]

EV fleet charging depots that have locational flexibility could factor in average prices and congestion when making siting decisions.[13] EV charging for delivery fleets might be co-located with companies' warehouses, manufacturing facilities, logistic centers, and transportation hubs and ports. Renewable generators could also co-locate EV charging stations to sell or perhaps give away energy when prices are low or dip below zero. These use cases could interact with wholesale prices and avoid overloading distribution system components by tapping the transmission system. Where EVs are parked, charging could be programmed to occur when the prices are forecasted to be lowest over the dwell period.

The ease of aggregation will also inform EV ability to respond to wholesale prices or provide grid services, such as energy injection, frequency regulation, or capacity. FERC Order No. 2222 allows EVs and other distributed energy resources to aggregate to participate in organized wholesale electricity markets and obtain supply-side revenue streams. Large charging hubs could aggregate predictable load; for example, park-and-ride commuters, and large EV fleets are well situated to aggregate their demand to respond to electricity prices. Charging station and fleet owners could participate in these markets directly or engage third-party aggregators to manage grid services for a share of the profit.

> **EVs exposed to prices tracking LMPs could charge where and when prices are low and renewable generation is high—and potentially discharge where prices are high.**

However, current incentives and infrastructure planning are not taking advantage of locational flexibility. Charging stations are mostly sited on distribution systems, typically without accounting for broader grid needs (WattEV, 2021a; WattEV, 2021b).[14] Charging stations in urban environments are installed as needed and allowed, and some utilities socialize the cost of grid-side upgrades needed for new charging stations to all ratepayers. Fast charging is typically provided through flat rates. These actions tend to insulate cost causers by socializing costs more broadly, leading to less efficient behavior and contributing to higher total costs of electrification.

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[12] To benefit from wholesale market access and transparent wholesale locational marginal prices, charging station operators may want to participate in markets operated by regional transmission organizations and independent system operators.

[13] See Lazar, Chernick, and Marcus (2020) for the suggestion of transmission-connected heavy-duty EV fleet charging.

[14] WattEV's 110-acre truck stop near Amazon and Walmart fulfillment centers by Highway 65 will be powered by 25 MW solar with storage and energy from Pacific Gas & Electric (WattEV, 2021a). WattEV is also partnering with Southern California Edison to build charging plazas at the Port of Long Beach (Bloomberg, 2022). Portland General Electric and Daimler Trucks have opened a 5 MW EV charging hub near I-5 for the West Coast Clean Transit Corridor Initiative to electrify 1,300 miles of I-5 to provide public charging for freight and delivery trucks (HDT, 2021).

The following subsections suggest some use cases that could particularly benefit from early considerations in planning and siting to leverage EVs' locational flexibility.

Charging Superhubs Along Highways for Light- and Heavy-Duty EVs

Fast charging could be flexible in time and place of charge, particularly for long-distance routes. Major trucking routes crisscross the United States, with increased traffic in areas where population density is greater and transmission is more challenging to site (Figure 7). EVs traveling along some of these corridors could charge where the prices are lower, which can help relieve bottled-up wind and solar, thus reducing renewable curtailments and transmission congestion.

New EV trucks constitute significant electrical loads, with ranges of 500 miles per charge, batteries greater than 1 MWh, and requiring MW-power chargers.[15] These trucks thus could help alleviate grid congestion or add to it, depending on where and when they charge. For perspective, a typical big box store requires up to 1 MW and a distribution substation could be 15 to 20 MW (Schroeder, 2022).

FIGURE 7

Estimated Average Daily Volumes for Trucks on National Highway System, 2017

This map provides a rough proxy for what EV trucking traffic might eventually look like based on historical patterns. The line thickness indicates the density of trucks for specified types of freight in aggregate (flows include 42 different commodities). Major flows include freight moving by truck on highway segments with more than 25 Freight Analysis Framework trucks per day and between places typically more than 50 miles apart. Truck traffic is greater in regions where new transmission can be more difficult to site.

Source: U.S. Department of Transportation (2017).

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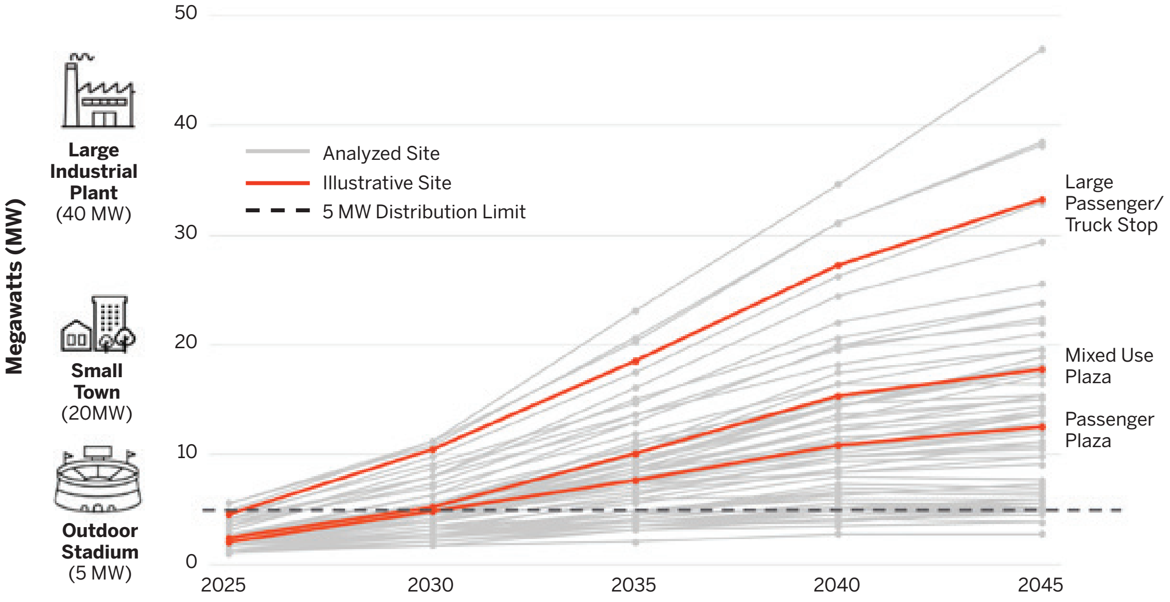
[15] See https://www.cnbc.com/2017/11/16/tesla-semi-truck-has-a-500-mile-range-ceo-elon-musk-reveals.html.

FIGURE 8

Capacity Required to Meet Annual Peak Demand at Each EV Charging Site Compared to Other Large Energy Users



A comparison of anticipated charging station capacities, needed as electrification scales up, with large electricity consumers.

Source: Katsh et al. (2022).

States are currently planning for fast charging stations along highways, spurred through the $5 billion federal assistance National Electric Vehicle Infrastructure (NEVI) program (Figure 9, p. 14).[16] These plans typically consider factors such as land use, equity, traffic congestion, and emergency evacuation.[17] States have not expressed much near-term concern about overall grid capacity (Zukowski, 2022), but they are also not including grid impacts in station siting planning (Texas DOT, 2022).[18]

To leverage EV flexibility, charging superhubs with sufficiently large loads could feed directly from the transmission system, stepped down in voltage. Hubs could offer fast charging with prices tracking LMPs. Charging stations could co-locate with other loads to scale up enough to justify connecting with the transmission system and transacting at wholesale. These could include services and facilities that enhance the convenience and comfort of a charging station, such as restaurants, lodging, and recreational facilities, which can also generate revenues.[19] These facilities could offer slow charging for customers staying longer, who could also provide grid services for compensation.

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[16] See https://www.fhwa.dot.gov/bipartisan-infrastructure-law/nevi_formula_program.cfm.

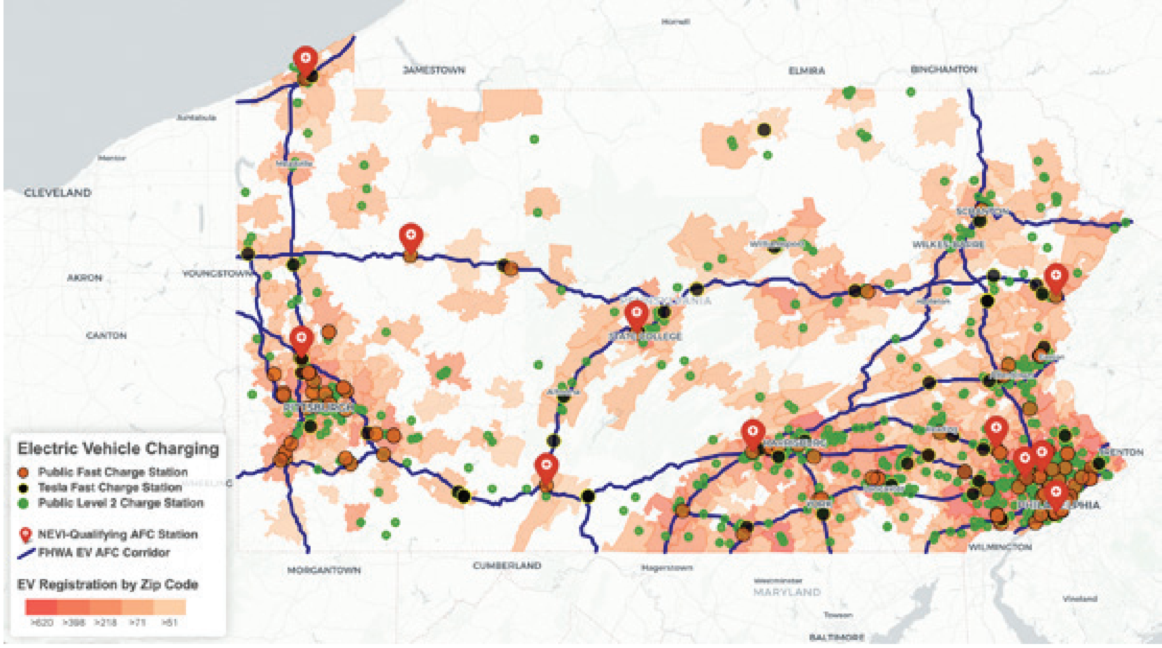
[17] See https://ftp.txdot.gov/pub/txdot/get-involved/statewide/EV%20Charging%20Plan/TexasElectricVehicleChargingPlan.pdf.

[18] See, for example, Texas's plan: "If all DC and Level II charging stations in this plan were utilized at the same time at their max rate, they would consume 666.7 MW of electricity from the grid. The Electric Reliability Council of Texas hosts an assortment of dashboards displaying near real-time grid conditions. On May 3rd Operating Reserves ranged from 3,751 MW to 6,066 MW. The potential impact on the overall statewide grid appears minimal for the type and quantity of EV Chargers outlined in this plan" (Texas Department of Transportation, 2022, 37). Germany, however, has reached a point where EVs are contributing to distribution grid stress. See https://www.netzerowatch.com/german-electricity-to-be-rationed-as-evs-and-heat-pumps-threaten-collapse-of-local-power-grids/.

[19] See, for example, the conceptual sketch of a high-voltage grid-connected charging hub by EcoFactor: https://ecofactor.eu/hub.

FIGURE 9

Pennsylvania’s National Electric Vehicle Infrastructure Plan



This map of Pennsylvania’s initial National Electric Vehicle Infrastructure plan indicates where new stations will be sited in relation to existing charging infrastructure and EV registrations. It would be informative to overlap this map with maps of LMPs over time to see whether proposed sites could take advantage of lower prices.

Notes: EV = electric vehicle; LMP = locational marginal price.

Source: Pennsylvania Department of Transportation (2022).

Customer Price Responsiveness for Transportation

Consumers have shown more responsiveness to gas prices at the pump than electricity consumption, in general. Retail gas prices can vary in time and location, determined by wholesale gas prices as seen in Figure 10 (p. 15). Gas prices per gallon are prominently displayed at stations and the total cost is tallied in real time. Customers can see how gas prices change over time and whether a gas station farther away is less expensive. Customers may also choose lower-cost, membership-based gas stations, such as Costco, or fuel up before entering large metropolitan areas where prices will be higher. In contrast, retail electricity prices usually are not designed to be variable, and costs are generally not visible in real time; thus customers have no information or incentives to consume differently.

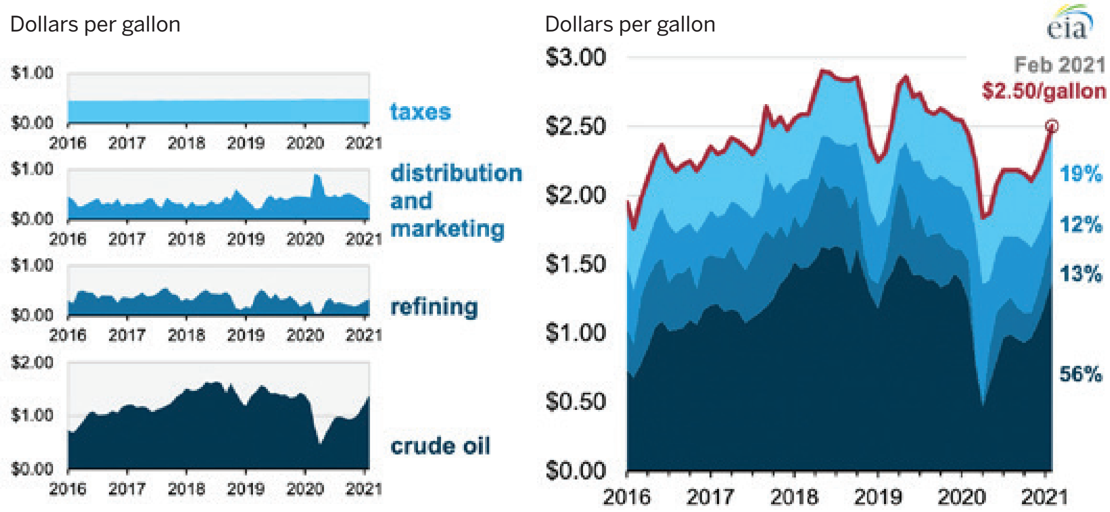
Customer price responsiveness to gasoline prices at the pump could translate well to EV charging.

Customer price responsiveness at the pump could translate well to EV charging. Gas prices are posted on Google Maps today, the same could be done for charging station prices (Figure 11, p. 16).

Locational marginal emissions information could be provided in addition to charging prices at each stop. Smart EV dashboards could help optimize where and when to charge along a route given time constraints, costs, greenhouse gas footprint, and other preferences. In addition to real-time pricing, these stations and customer apps could receive critical event notifications that could inform conservation efforts during emergencies.

FIGURE 10

Estimated Components of U.S. Average Retail Gasoline Price, January 2016–February 2021



Compared to retail electricity prices, retail gasoline prices better track wholesale prices. Gasoline prices in the United States are primarily driven by crude oil prices, refining costs, retail distribution and marketing costs, and taxes. Because gasoline taxes and retail distribution costs generally remain stable, retail gasoline prices change with variations in crude oil prices and refining costs. Compare this with Figure 6 on p. 9, where retail electricity rates are mostly flat over time and do not closely track wholesale prices.

Source: U.S. Energy Information Administration (2021).

> Locational marginal emissions information could be provided in addition to charging prices at each stop. Smart EV dashboards could help optimize where and when to charge along a route given time constraints, costs, greenhouse gas footprint, and other preferences.

Examples of Transmission-Connected Charging Stations

Most existing charging stations are connected to distribution systems, but there are at least two examples of initial forays into stand-alone charging stations connected to the transmission system. These stations were set up for high-reliability access to fast charging and to avoid burdening the distribution system but are not yet in position to exploit locational flexibility from EV charging. Both examples are in Europe, where electricity market prices are not as sensitive to location as U.S. nodal markets. More stations would need to be sited accounting for grid constraints, and nodal electricity market prices would need to be developed that granularly reflect locational in addition to temporal values.

In one example, Redes Energéticas Nacionais piloted SPEED-E, supplying high-power EV charging stations directly from a 220 kV switching station on the periphery of Lisbon, Portugal. SPEED-E's brochure emphasizes cost-effective and scalable access to fast charging from the transmission system, with applications to highway, fleet, military, and other heavy EV charging.[20]

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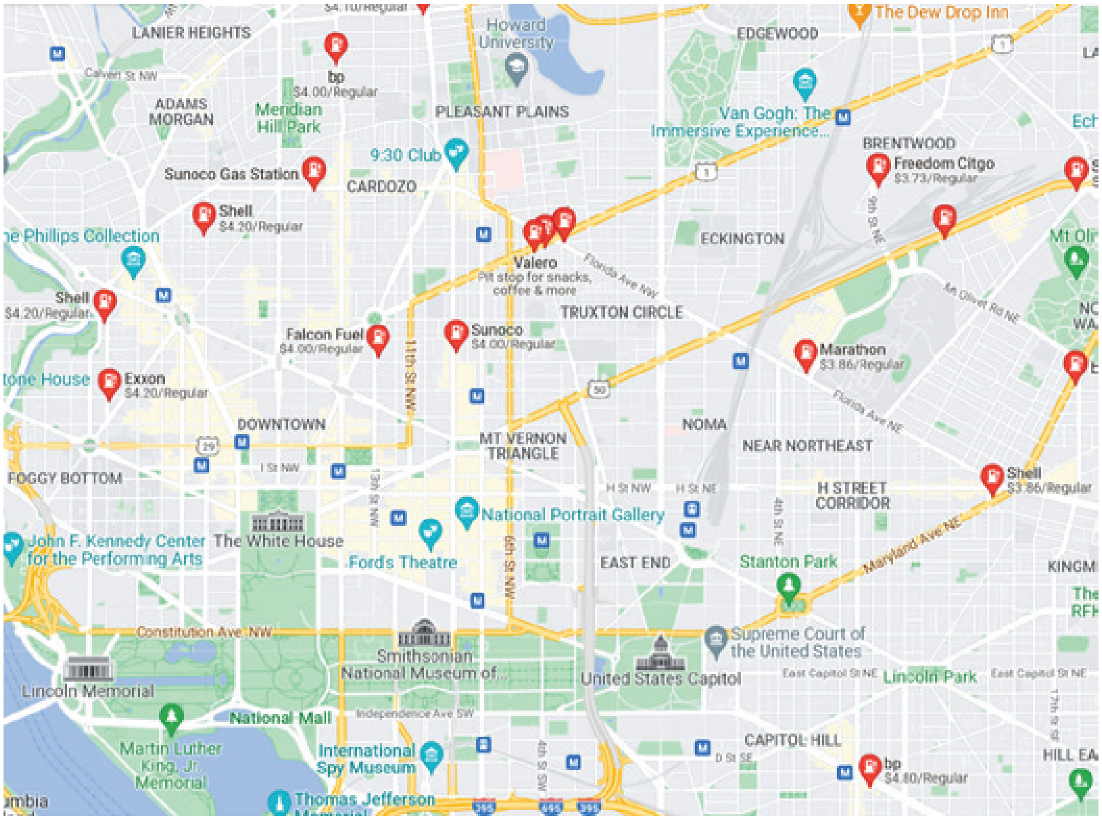
[20] See https://www.hannovermesse.de/apollo/hannover_messe_2022/obs/Binary/A1163810/RENPRO%20Mini%20Brochura%20Speed-e.pdf.

FIGURE 11

Gas Station Locations and Prices as Displayed by Google Maps



Google Maps displays locations and prices at nearby gas stations, making it easier for customers to decide where to fuel up.

Source: Google Maps (accessed August 25, 2022).

In another example, Oxford's Redbridge Park and Ride Superhub in the UK is a new charging hub directly connected to National Grid's high-voltage transmission network via a four-mile high-voltage DC underground cable delivering 10 MW of power (Oxford City Council, 2022). The hub provides fast charging for 42 EVs. Commuters can charge their cars while taking public transport into Oxford. There is currently no nodal market with LMPs in the UK (National Grid, 2022b), but the press release does note the benefit of avoiding additional strain on the distribution network by direct connection to transmission.

Connecting to the transmission system is more cost-effective if a charging hub exceeds a certain minimum size to benefit from scale and justify the large cost of a substation.

Connecting to the transmission system is more cost-effective if a charging hub exceeds a certain minimum size to benefit from scale and justify the large cost of a substation. In Oxford's case, the hub was able to avoid building its own substation by taking advantage of a tertiary winding on one of the double circuits at an existing substation that could provide up to about 50 MW.

Pivot Power, acquired by Électricité de France (EDF, 2022), developed the network and has plans to grow a nationwide network of hubs that will combine transmission-connected batteries and EV charging (Hanley, 2022b). The impetus for the project was to develop additional revenue streams for batteries that would provide voltage control, frequency regulation, and ride through. As the desire is to keep these batteries partially charged, the EVs and their chargers help by providing arbitrage.

EV Fleet Charging

EV fleet depots could also site to minimize distribution system impacts and take advantage of wholesale electricity prices. These depots could include fleets of buses, delivery trucks, solid waste vehicles, rental cars, U.S. Postal Service trucks (Sharp, 2022), and other fleets with electrification plans and significant fuel costs. These EV fleets could flexibly charge while idle and offer grid services at these stations to offset charging costs. Their grid-interactive batteries could help mitigate interconnection costs by flattening their load profiles and spreading out fixed costs. Co-locating with solar generation could also be beneficial.

Currently, charging depots for EV fleets do not appear to be sited in a way that accounts for locational grid needs (Hanley, 2022a).[21] These depots can be large; for example, electric school bus fleets could reach over 300 buses per depot (Lewis, 2022).[22] Charging depots are typically sited on distribution grids, but there may be some unexploited locational flexibility. These fleets typically have predictable schedules, have overnight dwell times, and are suitable for flexible charging and providing grid services (Chen et al., 2022).

Fleet charging could be co-located with warehouses and other facilities. Some industrial and commercial customers directly participate in wholesale markets and could extend that direct procurement to charge their EV fleets at wholesale prices.

Fleet charging could be co-located with warehouses and other facilities.[23] Some industrial and commercial customers directly participate in wholesale markets and could extend that direct procurement to charge their EV fleets at wholesale prices. Idle times may offer flexible charging and vehicle-to-grid services. Depot siting would likely need to be close to the facility, but there could be some locational flexibility if the facility is yet to be sited. This can be particularly important if there are plans to electrify other processes there. Potential co-locating facilities include:

- **Large industrial wholesale electricity customers** already purchasing directly from organized wholesale markets, as they would already have the physical connections and expertise to participate in markets and manage variable pricing. This type of customer typically produces goods in need of transport, which could make co-locating with heavy-duty EV charging mutually beneficial. For example, PJM's end-use customer sector includes steel, grain, paper, dairy, and chemicals operations.[24] These types of industries are also good candidates for electrification to reduce emissions (Hasanbeigi, Kirshbaum, and Collision, 2021).

- **Large distribution centers/warehouses** that are wholesale customers, which may have affiliated delivery fleets that electrify. These include Albertson's, Walmart, and Amazon, among others.

- **Ports for air, rail, and water transport** that need to transfer cargo to trucks, particularly if these ports electrify ships, airport shuttles, and trains. Some shipping ports in California (Los Angeles and Oakland) have limited EV charging, and others have plans to install chargers. There is some concern that chargers

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[21] E.g., Amazon is building an EV charging station for 760 vehicles (Hanley, 2022a).

[22] According to industry experts, existing electric school bus depots are sited on the distribution system. Buses in some cases are contractually bound to stay in the school district, and some drivers have indicated that they will quit if depots are moved. Even if contracts are not long term, contractual arrangements are difficult to change.

[23] For example, Albertsons, a direct access customer of the California Independent System Operator, piloted an e-transportation refrigeration unit project at its distribution center. See https://cadmusgroup.com/wp-content/uploads/2021/06/CA-TE-Priority-Review-Project-Evaluation-Report-Public-Version.pdf#page=366.

[24] See https://www.pjm.com/about-pjm/member-services/member-list.aspx.

> **If charging hubs for co-located facilities can accommodate vehicles from different companies, networks of businesses could offer reciprocal agreements for charging service. Charging could be for the companies' own fleets, open to a network, or open to the public.**

take up space and encourage truck idling near ports, but these problems can be addressed. In a similar vein, the New York City Metropolitan Transportation Authority subway runs off of the high-tension system and is seeking to electrify its buses on the same retail tariff.

- **Variable renewable generation plants** (before stepping up to the high-voltage system).[25] If wind and solar generators offer co-located EV charging at LMP, this could encourage mobile batteries to charge at these sites and thus mitigate curtailment and negative pricing. These could be sited near highways through windy and congested areas frequently traveled by truckers or other long-distance drivers.

If charging hubs for co-located facilities can accommodate vehicles from different companies, networks of businesses could offer reciprocal agreements for charging service. Charging could be for the companies' own fleets, open to a network, or open to the public.

Residential, Business, or Workplace Charging

Residential, business, or workplace EV charging patterns may have workday or overnight idle time that allows for temporal and locational flexibility. Workplace daytime charging and home vehicle-to-grid discharge could help balance solar generation profiles and avoid grid impacts, with appropriate incentives. Flexibility will depend in part on whether bi-directional chargers are installed and whether shared charging capacity has enough headroom so plugged in EVs can shift charging temporally without denying other EVs the ability to charge.

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[25] Consistent with the NextGen Highway concept (NGI, 2020), using highways' rights of way for transmission to interconnect renewables could make charging hubs near them more accessible.

Policy Considerations

Decisionmakers interested in cost-effective electrification to facilitate clean energy policy could consider at least four categories of recommendations to enable EVs to act as grid resources:

- Charger siting planning could better forecast and factor in grid impacts and future needs.
- Targeted financial incentives could mitigate higher upfront infrastructure costs that deter more efficient investments in larger transmission-connected charger stations compared to incrementally adding chargers to distribution grids.
- Pricing to encourage responsive demand could reflect real-time conditions to better inform charging behavior. Allocating costs of avoidable generation capacity and infrastructure additions to those causing them could motivate customer response and encourage siting to account for these investment costs.
- Regulatory treatment could encourage third-party and utility business models to build infrastructure needed for EV fast-charging stations while offering pricing incentives that align with public policy, such as reducing greenhouse gas emissions and improving grid resilience.

Comprehensive Planning for Charging Stations

Strategically planning and siting infrastructure and structuring business models to efficiently encourage EV demand flexibility could help alleviate transmission and distribution system upgrade costs, as well as coordination issues across the high- and lower-voltage systems. If there is sufficient aggregated EV or co-located load, charging stations could tap more directly from the transmission system. Connecting locationally flexible load to the edge of the distribution grid or stepped down from the transmission system could avoid some distribution impacts as broader electrification solutions for all customers are being worked out.

Targeted financial incentives could mitigate higher upfront infrastructure costs that deter more efficient investments in larger transmission-connected charger stations compared to incrementally adding chargers to distribution grids.

However, there is currently little consideration for how to leverage the locational flexibility of EVs and planning for charger siting accounting for grid needs:

- Charging station companies have so far sited where they can in urban areas, and some utilities will upgrade the distribution grid for charging stations where the customer chooses to site while spreading the upgrade costs to all customers.
- EV fleet depot charging is being sited at existing depots where traditional vehicle fleets are parked, which may be burdensome for the distribution system. Some of this inertia is due to contractual or labor arrangements.
- Initial state National Electric Vehicle Infrastructure (NEVI) plans are not factoring in grid needs as part of their siting criteria. Understandably, certain other factors will be primary, such as convenience, traffic patterns, land use, existing depot locations, equity,

and emergency evacuation (Texas DOT, 2022), as well as the basic NEVI criteria for minimum separation between stations and distance to nearest highway exits.

To optimally enable EVs to boost grid flexibility and resilience where needed and reduce the costs of integrating new supply and electrified demand, charging site planning should consider transmission and distribution constraints and locations where customers can take advantage of lower power prices. Other types of locationally flexible demand could benefit from comprehensive planning as well. While some congestion patterns are stable (Millstein et al., 2022), others may change over time. Optimization algorithms could use average LMPs and LMP volatility to help determine siting. Planning and siting could also consider hosting capacity analysis of transmission and distribution systems, optimizing existing land used for utility infrastructure and relationships with landowners.

Transmission planning processes should holistically co-optimize transmission, generation, and demand, including charging stations.

In the absence of managed EV charging, transmission constraints could be eventually addressed through transmission planning and expansion factoring in locations of highways, rest stops, transmission capacity, and chronic transmission-constrained high-generation pockets. However, this process would result in higher costs compared to one that accounts for how flexible locational demand could reduce transmission needs. Ideally, transmission planning processes should holistically co-optimize transmission, generation, and demand, including charging stations.

Overcoming Higher Upfront Costs to Achieve a More Efficient Outcome

EV charging stations will scale up as transportation electrifies. It may be more cost effective to build larger DC fast-charging stations and interconnect them directly to the transmission system than to make a series of distribution upgrades (Katsh et al., 2022). The current practice of incrementally building chargers on the distribution system may be due to insufficient capital to cover the large upfront investment in transmission-connected charging stations. Key questions for regulators and stakeholders include:

- How can we optimize the infrastructure needed to enable EVs to both cost-efficiently charge at desired speeds and provide grid services?
- In what circumstances should we continue to incrementally add EV charging stations to the distribution system versus forecasting and planning for larger stations that are transmission-connected?
- If building larger charging stations stepped down from the transmission system is more economically efficient, who should build the grid upgrades and charging infrastructure, and how would they recover the costs of these investments? How can these entities be incentivized to build efficiently and account for grid needs?

The costs to build or expand the relevant infrastructure for charging hubs on the transmission system can include substations and high-voltage cables. The costs to add a new substation and tap of a transmission line to support about 100 MW of charging can range from $15 to $20 million (Katsh et al., 2022). There are also North American Electric Reliability Corporation (NERC) and FERC compliance costs associated with owning transmission equipment, but these may remain with the transmission-owning utility. Costs may also include operations and maintenance, equipment, installation, networking, permitting, and inspection, but some of these may be incurred regardless of where the chargers are sited. The costs can vary by region and regulatory structure.[26] Third-party charging companies can avoid triggering utility status and regulatory costs associated with reselling electricity by selling DC fast-charging services that cannot be used to charge or power other electric devices.

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[26] See https://afdc.energy.gov/fuels/electricity_infrastructure_development.html. A study on reforming electricity rates to enable economically competitive electric trucking modeled customers as transmission-connected with access to wholesale prices across three scenarios (Phadke, McCall, and Rajagopal, 2019, 27).

It is possible for a transmission utility to build and own the needed transmission equipment and for a third party to build and operate the charging station. Companies like Applegreen Electric can lease a site and build EV hubs with facilities for customers to use while their cars are charging. In the Oxford Superhub example discussed above, chargers were installed by Fastnd, Wenea, and Tesla. A utility building the transmission infrastructure may seek to rate base the investment. While rate basing is one way of overcoming high upfront costs for infrastructure that can benefit all customers, care is needed to ensure that costs are not allocated unfairly and do not burden vulnerable customers.

Overcoming high initial infrastructure cost hurdles to otherwise efficient projects benefiting the broader public could be a good use of federal EV infrastructure funding made available through the Infrastructure Investment and Jobs Act (or Bipartisan Infrastructure Law).[27]

Strengthening Price Signals to Encourage Efficient Responsive Demand

EV charging costs have variable and fixed components: setting prices at full societal marginal cost can incentivize efficient behavior that adjusts to variable grid conditions, but fixed costs can dilute these price signals. With siting that enables locationally flexible resources to benefit from low-cost energy price pockets, variable costs should reflect these real-time energy savings. Marginal costs could track LMPs plus variable costs associated with operating an EV station and costs reflective of externalities.[28]

A significant component of customers' retail bills are fixed costs in the short run but variable over longer time horizons over which investments are made. These include infrastructure and generation capacity investments. If these costs are allocated to those who cause them, they could influence and be influenced by customer response over longer time horizons (Wood et al., 2016).[29]

A key question is how to enable fixed-cost recovery while exposing variable pricing that incentivizes efficient customer behavior:

- With price-responsive demand and siting that accounts for grid needs, some of these fixed costs related to longer-term generation capacity needs could be reduced. Capacity charges for using the system should incentivize efficient use, but price volatility resulting from current insufficiently granular cost allocation schemes have been a challenge (NACS, 2022).
- Where there are societal benefits to charging stations, public funding could be offered to defray upfront capital costs. To further societal goals, there could be funding eligibility requirements for charging sites to optimally locate and price accounting for grid needs, as well as display locational marginal emissions information or price in greenhouse gas emissions and other externalities. This upfront assistance could also help diminish the fixed cost component, which may dilute variable prices and thus better expose price signals.

Upfront financial assistance could help diminish the fixed cost component, which may dilute variable prices and thus better expose price signals.

Charging stations may offer options to address customers' sensitivity to price volatility. EV drivers who are not as locationally or temporally flexible and are more sensitive to the risk of variable pricing could pay for a subscription for simple, flat rates. Some charging stations owners may also choose to physically hedge by co-locating batteries to modulate peak load to control capacity costs. Like insurance, these hedges may result in higher payments over time but more price certainty. A potentially more cost-effective solution could be swappable batteries for EVs. A bank of swappable EV batteries at the station

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[27] See https://www.congress.gov/bill/117th-congress/house-bill/3684/text.

[28] For example, there could be a price on greenhouse gas emissions, or the charging station could have a program for offsetting emissions.

[29] See also the summary of demand charge issues at https://cadmusgroup.com/wp-content/uploads/2021/06/CA-TE-Priority-Review-Project-Evaluation-Report-Public-Version.pdf#page=366, pp. 32-35. Fixed costs could be better designed to optimize customer behavior and build needed grid infrastructure and generation capacity efficiently. See the California Public Utilities Commission staff's proposed "Dynamic Capacity Charges" (Madduri, Foudeh, and Phillips, 2022, 52).

could help mitigate high LMPs by charging during low-price hours or providing other grid services. They could replace what presumably would be more expensive dedicated stationary batteries.

Regulatory Implications

Purchasing and reselling electricity at wholesale and owning high-voltage transmission equipment entail regulatory obligations with which EV charging companies likely have little experience. However, large energy consumers participating in wholesale markets are familiar with this regulatory space, and a chain of fast-charging EV stations could use a new business model that blends that of traditional gasoline stations and truck stops with large electricity customers. Large industrial and commercial electricity customers can create separate legal entities to resell electricity to their own businesses.

The success of this business model for third-party charging stations may depend on whether a charging station is deemed to be reselling electricity, which can subject it to regulatory costs. Some states have exempted third-party charging from being a regulated party reselling electricity from public utility commission jurisdiction. For example, the Pennsylvania Public Utility Commission adopted a policy considering that third-party EV charging is providing a service and is not considered resale/redistribution under Section 1313 of the Public Utility Code.[30] The reasoning for these types of exclusions is that EV DC fast-charging companies are altering AC power to provide a DC charging service, and their chargers cannot charge any devices other than EVs. Thus, they are not reselling electricity and are not regulated as a utility. In some states, pricing by the minute instead of by the kWh helps avoid triggering utility status.

Large energy consumers participating in wholesale markets are familiar with this regulatory space, and a chain of fast-charging EV stations could use a new business model that blends that of traditional gasoline stations and truck stops with large electricity customers.

Alternatives to a fully private third-party model include utilities owning all grid and station infrastructure or owning just the grid infrastructure. If the utility owns the station infrastructure, it could also lease space to third-party EV charging companies. One caveat with utility ownership is that they are state public utilities commission–regulated entities. What rates utilities can charge and how legacy investments across the system are recovered may impact the amount of fixed costs that could dilute variable price signals. Compared to a private third-party enterprise, a utility typically has costs embedded in its rates that are associated with existing distribution system infrastructure; utilities thus may need to seek exclusion of some of these fixed costs to offer a clearer price signal to guide charging behavior. This rate exclusion could be justified on cost causation grounds if the new EV charging load is sited away from distribution grids.

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[30] See, for example, https://www.puc.pa.gov/press-release/2018/puc-adopts-final-policy-statement-on-third-party-electric-vehicle-charging-reduces-regulatory-uncertainty-promotes-new-investment.

Now Is the Time to Consider Locationally Flexible Resources

Even though EV shares are currently low, decisions made now will influence the future trajectory of how these loads help to avoid or put additional stress on the grid. Because of path dependencies and the high costs of scaling up the current practice of incrementally adding charger stations, there are advantages to planning and starting on a more efficient track.

Siting Decisions Are Being Made Now That Will Lock in Grid Impacts

There are currently federal funding opportunities for charging infrastructure in new legislation: the Bipartisan Infrastructure Law has already spurred states to submit their initial NEVI plans. The Inflation Reduction Act extends tax credits for commercial and residential chargers.[31] It also allocates funds for electrifying the Post Office fleet as well as state and local heavy-duty vehicles, which will drive up the need for new charging stations.[32]

Regional grid planners considering light-duty EV impacts are making decisions assuming these EVs will add to peak load (Howland, 2022) and/or will not provide vehicle-to-grid services. However, decisions that do not sufficiently factor in flexible demand will encourage overbuilding generation capacity to meet peak or ramping needs—some of which will prolong dependence on fossil fuels.

While newer research is starting to emphasize the importance of reflecting generation-level impacts in utility rates (Powell et al., 2022) and promoting a shift from home to daytime workplace charging, broader considerations of charger siting and use cases beyond residential light-duty EVs are needed to help reduce grid impacts.

Because of path dependencies and the high costs of scaling up the current practice of incrementally adding charger stations, there are advantages to planning and starting on a more efficient track.

Sticky Customer Habits Are Being Shaped Now

Engaging flexible demand is recognized as a cost-effective means of addressing grid flexibility and reliability. However, customers can be relatively insensitive to or unaware of how they consume electricity due to several factors. Rate structures with large fixed costs can dilute variable price signals, dynamic rate structures and real-time consumption information may be lacking, or the right business model and apps don't yet exist to exchange needed information and incentivize customers to help the grid.

As the transportation sector electrifies, customers' price responsiveness to gasoline prices could translate to price-responsive demand in EV fast charging. Dashboard apps could optimize routes and charging stops depending on customer preferences on travel time, cost, and emissions

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[31] See https://www.electrificationcoalition.org/work/federal-ev-policy/inflation-reduction-act/.

[32] See https://www.jdsupra.com/legalnews/ira-clean-energy-incentives-and-2812316/.

savings. At present, however, most EV fast-charging rates are flat to encourage EV uptake.[33] Some in a handful of states may factor in time of use,[34] but these rates generally do not dynamically consider grid needs. At the currently low shares of EVs, the lack of incentives for responsive charging has not yet created grid problems, but customer habits and expectations about charging and rates can be hard to change once set.

In addition, once set, customers get comfortable with existing practice. Physical, contractual, and regulatory inertia associated with changing charging siting is already making it difficult to move traditional fleet parking areas as vehicles convert to electric. Businesses used to public utilities commissions' regulatory regimes worry about unfamiliar FERC/NERC regulation and compliance, which could be triggered with owning bulk power equipment. Overcoming this hurdle in siting fleet charging areas will require rate incentives and assistance with understanding alternatives.

Conclusions

As electrification scales up and more EVs hit the road, a set of use cases for these mobile batteries can offer locational and temporal flexibility if charging station siting and rates are planned and designed to leverage these resources. Managed charging in time and place can mitigate the cost impacts of electrification and improve power system flexibility and resilience. This paper identifies potential locationally flexible use cases, benefits, challenges, and key questions, and offers some policy and regulatory considerations for decisionmakers looking to support beneficial electrification.

Some of the benefits of mobile batteries that are locationally flexible in charging/discharging resemble those of transmission, with EV charging stations acting like nodes and endpoints of lines. Planning for EV charging, when it exists, like transmission planning, may be too incremental, myopic, and missing considerations of key grid benefits. Local, state, and federal entities could work with utilities and third-party charging companies to determine optimal siting locations given power system needs, policy goals, and transportation electrification plans.

Local, state, and federal entities could work with utilities and third-party charging companies to determine optimal siting locations given power system needs, policy goals, and transportation electrification plans.

Customers' response to electricity prices is an under-tapped resource despite recognized benefits of flexible demand. However, customers react to prices at the gasoline pump. Ensuring that these habits translate to EV charging/discharging that is responsive to price, emissions, and grid emergency information should be a key policy goal.

As with large infrastructure projects, insufficiently comprehensive planning and upfront capital requirements can deter efficient investments for electrification. Public funding could defray high start-up costs for projects with significant public benefits and encourage charging stations to provide incentives and information so that EV owners and aggregators can charge efficiently and in a way that creates broader grid and societal benefits.

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[33] E.g., Electrify America has two different kinds of rates for DC fast charging—per kWh or per minute—but the rate structures are the same for each class across states. For example, California and Delaware have a rate of $0.43/kWh, while Alabama and Texas have rates of $0.16/min (for 1 to 90 kW) and $0.32/min (for 1 to 350 kW) (https://www.electrifyamerica.com/pricing/). Aside from flat and simple rates, EV uptake can be encouraged through other means that would not eliminate price signals for charging, such as tax credits (U.S. Department of the Treasury, 2022) and rebates.

[34] These states are Arizona, New Jersey, Ohio, Pennsylvania, Utah, and California. See https://www.evgo.com/pricing/.

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By Jennifer Chen, World Resources Institute

A White Paper from the Energy Systems Integration Group's Retail Pricing Task Force

This white paper is available at https://www.esig.energy/aligning-retail-pricing-with-grid-needs.

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