Powering the future: electric vehicle charging profile impact on California's future energy storage needs

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***Abstract*— This research investigates the implications of light-duty electric vehicle charging patterns on energy storage requirements for California. The study examines three plausible EV charging profiles and incorporates energy storage technologies with 4-, 8-, and 12-hour durations. Results show that charging in the evening increases the new infrastructure for power and energy storage capacity to meet the electric vehicle load by approximately 50 to 80% relative to the case when the load peaks at noon, depending on the storage duration. Remarkably, the relative differences in the amount of the added storage among the three cases decrease as the model switches to deploy longer-duration instead of 4-hour storage, suggesting the potential to reduce the impact of different load patterns and a reduced necessity for investments in public charging station infrastructure. Specifically, 8-hour storage provides a good trade-off between the needed power and energy storage capacity and establishing extensive public charging infrastructure.**

Keywords—electric vehicles charging profile, load shifting, long-duration energy storage, lithium batteries, public charging infrastructure

I. INTRODUCTION

As we stand at the point of a transportation revolution, electric vehicles (EVs) are expected to become a dominant means of transportation in California. According to executive order N-79-20 [1], all sales of new light-duty passenger vehicles in California must be zero-emission vehicles (including battery and fuel cell electric vehicles) by 2035. With the shift from conventional fossil fuel-based vehicles to electric vehicles, the electricity demand is anticipated to rise significantly, predicting that around 10% of the total California Independent System Operator (CAISO) electricity load will be associated with light-duty electric vehicles in 2045 [2].

For grids with high renewables penetration, energy storage is a critical element that absorbs the excess renewable generation during off-peak times and supplies it when the demand exceeds generation. In other words, it mitigates the misalignment between renewable generation and load demand. Adding the EV charging load to the grid could affect this misalignment. As it is a flexible load, the rise of EVs has significant implications for the electric grid, particularly in load management and energy storage requirements. The timing of EV charging influences the load profile on the grid, which, in turn, can impact the necessity and configuration of energy storage [3].

Wald et al. [3] showed that optimizing the load shifting of flexible loads (including EVs) could reduce the need for utility-scale battery storage systems. More specifically for the EVs, Forrest et al. [4] showed that transitioning from immediate to intelligent charging strategies allows for better alignment of renewable generation and load profiles, resulting in reduced power- and energy-storage-capacity requirements of the storage system. Consequently, it is assumed that shifting the EV charging load to the middle of the day for a solar-dominated grid such as California will reduce the total need for storage systems.

However, the analysis of Moon et al. [5] on consumer preferences and charging patterns indicates that consumers mainly prefer charging their EVs during the evening. Moreover, according to a study by Deb, et al. [6], extensive use of EVs will result in challenges with locating charging stations in terms of the adequacy of the chargers and infrastructure to deliver the electricity to the chargers, especially when fast charging is used. An optimal grid design could charge EVs during the day while parked underneath solar panels, thereby aligning both the location and time of charging with the electricity source, reducing the need for storage. However, for days when a car is not parked in a solar-covered parking lot, charging at home will still be desired requiring duplicative charging infrastructure. Thus, it is anticipated that developing infrastructure to charge all EVs during the day may reduce the grid's need for storage, but will increase the charging infrastructure needed.

Similarly, shifting the EV charging load to the middle of the day in California has benefits associated with a lower need for storage, lower misalignment with renewables generation, and lower solar curtailment. On the other hand, it will result in increased need for charging infrastructure. Therefore, this study examines a tradeoff between these by analyzing three light-duty EV charging profiles and investigating how the storage characteristics, such as duration and cost, will affect the total amount of storage under each charging load pattern.

II. ANALYTICAL MODELING

In the execution of this study, the RESOLVE publicly accessible capacity expansion model was adopted [7], which was designed and developed by Energy and Environmental Economics (E3) [8]. To do the simulations, the Critical Time Step (CTS) technique was used, which provides an excellent tradeoff between the accuracy of the results and the computational intensity, especially for the grids with a high penetration of solar power in the total operational power such as California [9][1].

[1] The article is under the final review for publication in Energy Journal. We plan to update this reference in the current manuscript in the final submission.

The model considered batteries with a 4-hour duration and 85% efficiency, reflecting the currently observed efficiencies in California's energy storage power plants [10]. Also, two technologies with durations of 8 and 12 hours were considered by the model, each having the same 85% efficiency. Additional storage technologies could be considered [11] but were omitted to focus on the effects of three diurnal load profiles that were assumed to apply consistently every day of the year.

This study investigates three cases [12] for future light-duty-EV load profiles within California's power grid in 2045 and analyzes how varying charging behaviors might influence the demand for energy storage systems. As Fig. 1 shows, in the first case, called 'High-Residential-Access,' 95% of vehicles are assumed to have access to home charging and the EVs are programmed to start charging at midnight. This is based on current time-of-use rates whereby the EV owner pays less for the electricity during nighttime hours. In this situation, the load on the electric grid would peak at midnight and gradually decline throughout the day. The second case, labeled 'Unconstrained' in Fig. 1, reflects a more spontaneous charging behavior, assuming no controlled charging patterns or economic incentives. Here, the charging peak is postulated to occur during the evening when people typically return home from work and charge their EVs using their private charging systems. Lastly, the 'Happy Hour' case models two distinct periods of high load: one in the middle of the day and another at midnight. This load profile is built on the premise that, despite the lower electricity rates available at midnight, there would be a significant increase in charging during the day, possibly due to the presence of workplace charging stations.

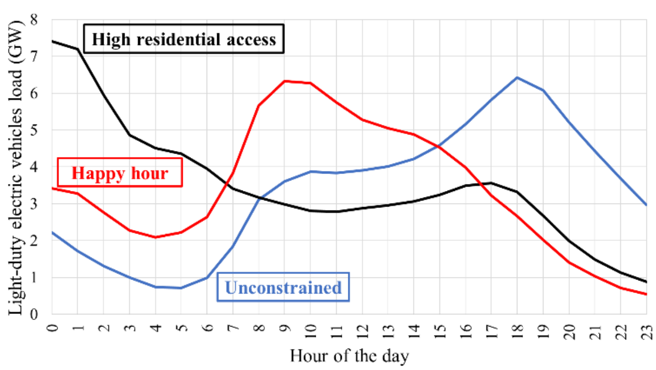

Figure 1. Light-duty electric vehicles load (GW) versus the hour of the day for the three cases [12]

III. RESULTS AND DISCUSSION

Figs. 2 and 3 plot the selected buildout of 4-hour vs 8-hour storage versus the cost ratio of 8-hour to 4-hour storage with equivalent energy capacity. These figures show results for the three load profiles, as well as a case in which no light-duty EV is deployed (labeled as "Zero_EV"). It is apparent that at elevated cost ratios (right sides of the graphs), where the model exclusively selects 4-hour storage, the total energy buildout (Fig. 2) is lower while the total power buildout (Fig. 3) is higher. This is the opposite to situations with lower cost ratios where the model exclusively selects 8-hour storage (left sides of the graphs). This outcome occurs because the installed number of 4-hour storage exceeds the number of 8-hour storage units, although it does not reach double the quantity.

Figs. 2 and 3 show that when the relative cost of 8-hour compared to 4-hour storage with the same energy capacity surpasses 96%, the energy and power storage contributed by 4-hour storage exceed that offered by 8-hour storage. Interestingly, this transition point remains fairly constant across the three cases, suggesting that load shifting of light-duty EVs does not significantly influence the cost threshold required for 8-hour storage to compete with 4-hour storage.

According to Figs. 2 and 3, shifting the loads to the middle of the day in the Happy Hour case decreases the need for energy and power storage in the entire system by around 10.2% compared to the High Residential Access case, when the model only selects 4-hour storage (at the high cost ratios). This number is around 7.9% at low cost ratios when the model only selects the 8-hour storage, suggesting that by shifting the peak of the light-duty-EV's load to the middle of the day, the total need for energy storage could be reduced significantly.

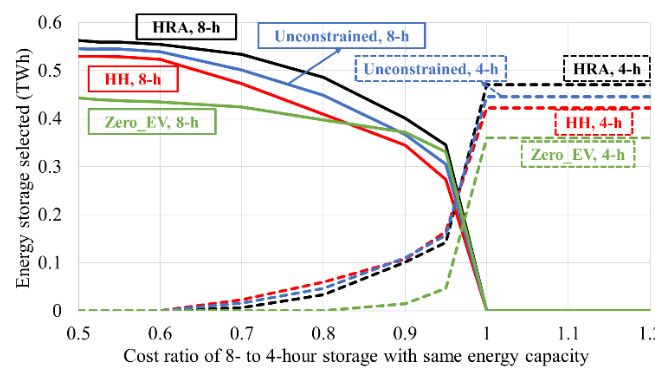

Figure 2. 4- and 8-hour storage energy build for different cost ratios of 8-to 4-hour storage for the three load profiles of Unconstrained, High Residential Access (HRA), and Happy Hour (HH), and the case of zero light-duty electric vehicles

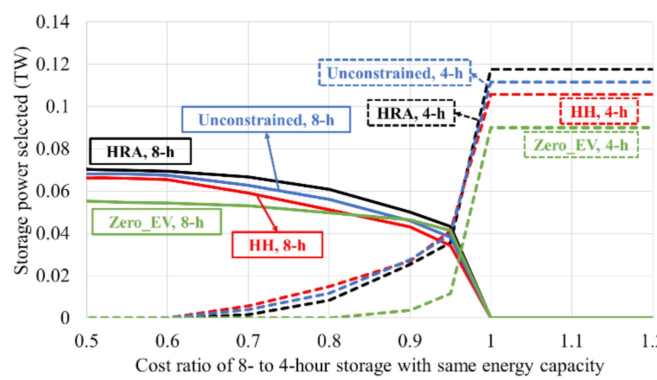

Figure 3. 4- and 8-hour storage power build for different cost ratios of 8-to 4-hour storage for the three load profiles of Unconstrained, High Residential Access (HRA), and Happy Hour (HH), and the case of zero light-duty electric vehicles

Figs 4 and 5 show similar data, but this time the storage technology is chosen to last for 12 hours. Similar conclusions could be reached as shown for the 8-hour duration in Figs. 2 and 3, but this time, the transition cost target from 12- to 4-hour storage is lower and approximately around 70%. Again, the transition point remains fairly constant across the three cases implying that the cost threshold is roughly independent of the load profiles for light-duty EVs. Figs. 4 and 5 exhibit that at low cost ratios, when the model only selects 12-hour storage, shifting the loads to the middle of the day in the Happy Hour case will reduce the total amount of needed power and energy storage by approximately 7.7% with respect to the High Residential Access case.

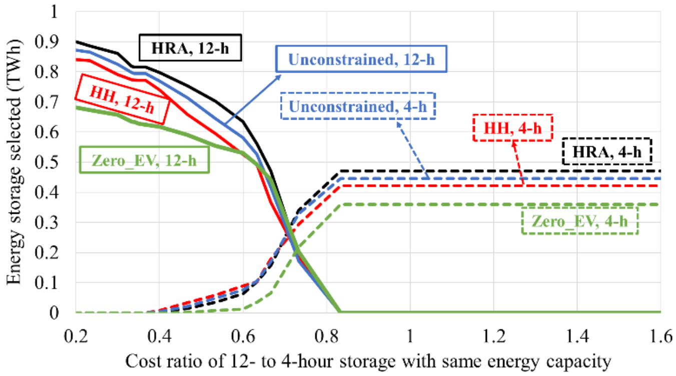

Figure 4. 4- and 12-hour storage energy build for different cost ratios of 12- to 4-hour storage for the three load profiles of Unconstrained, High Residential Access (HRA), and Happy Hour (HH), and the case of zero light-duty electric vehicles

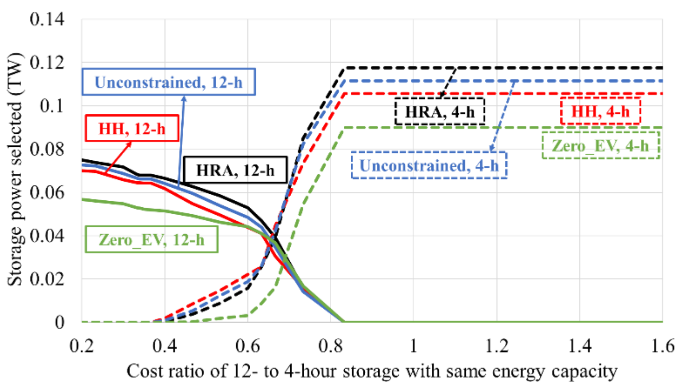

Figure 5. 4- and 12-hour storage power build for different cost ratios of 12-to 4-hour storage for the three load profiles of Unconstrained, High Residential Access (HRA), and Happy Hour (HH), and the case of zero light-duty electric vehicles

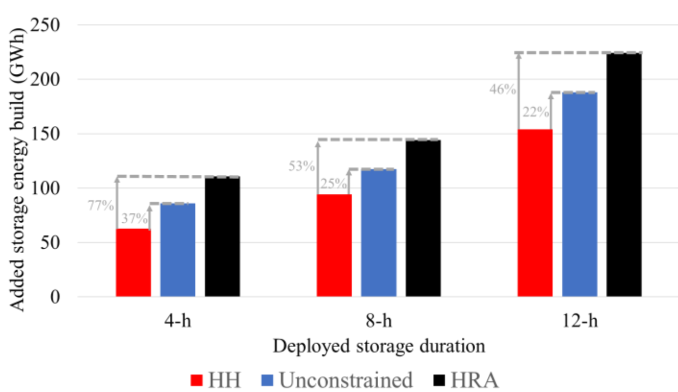

Figure 6. The amount of added storage energy relative to the case without EVs deployment for each load profile and storage duration

To better understand new infrastructure that will be needed to accommodate EV charging in a solar-driven grid, Figs. 6 and 7 show the storage needed relative to the case with no light-duty EV charging. These are constructed to provide enhanced insights into how load shifting, within the three examined cases, influences the need for new storage with durations of 4, 8, and 12 hours. These figures represent the added storage quantities with respect to the Zero_EV case for each specific load profile and storage duration. As the figures show, charging in the evening as for the High Residential Access case increases the need for new storage by approximately 76, 65, and 45% relative to the Happy Hour case for 4-, 8-, and 12-hour storage, respectively.

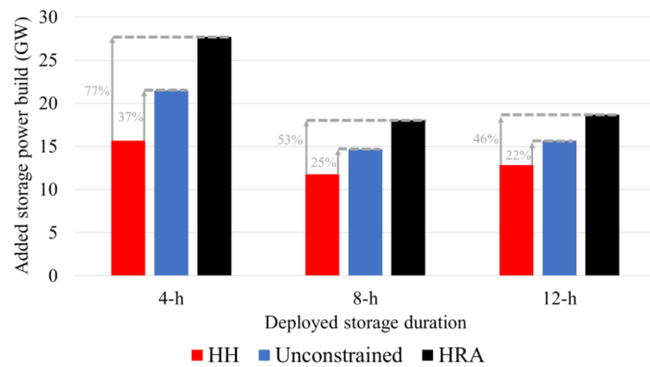

Figure 7. The amount of added storage power relative to the case without EV deployment for each load profile and storage duration

Fig. 6 exhibits that as the storage duration lengthens, the added energy buildout correspondingly grows. However, a comprehensive embrace of 12-hour storage necessitates a lower cost ratio in comparison to the 8-hour storage. This requirement may potentially make the extensive use of 12-hour storage less feasible.

Contrarily, Fig. 7 reveals an inverse trend. The buildout of power storage substantially reduces from 4- to 8-hour storage, but it generally remains steady for more extended durations. One key observation from Fig. 7 is that the relative differences among the three cases decrease as the longer-duration storage is deployed. This suggests that the utilization of extended-duration storage to satisfy the charging load of light-duty EVs could reduce the impact of different load profiles, implying that investments geared toward constructing public charging station infrastructure could be reduced by utilizing longer-duration storage. More specifically, according to Figs. 6 and 7, dedicating 8-hour storage to meeting the EVs' charging loads not only reduces the need for power and energy storage capacities but also reduces the effect of charging profiles substantially compared to the 4-hour storage.

IV. CONCLUSIONS

This study elucidates the implications of varying light-duty electric vehicle charging patterns on the energy storage requirements for California's power grid in 2045. Three plausible electric vehicle (EV) charging profiles, High Residential Access, Unconstrained, and Happy Hour, were explored, each with unique attributes and implications for energy storage infrastructure. In the High Residential Access profile, the charging load peaks at midnight, and in the Unconstrained profile, most people charge their vehicles around sunset when they return home from work, and finally, in the Happy Hour profile, the charging load peaks in the middle of the day when there is excess renewables generation. These cases collectively aim to provide a comprehensive view of the potential load on the electric grid in the context of the rising use of EVs. These insights help to identify potential challenges and opportunities for managing grid capacity and inform the development of future strategies and policies for energy storage systems.

Results indicate that continuing utilities' current policy of offering "EV rates" that reduce the price of electricity during the night will result in the need for more storage as solar electricity is stored during the day to charge vehicles during the night. While this 'High Residential Access' case was found to be the most expensive to implement from the perspective of delivering the electricity from the grid, it may reduce the requirements for investment in public infrastructure with the private sector shouldering the majority of the responsibility for creating "charge-at-home" infrastructure. On the other hand, if EVs are charged mostly during the day when the sun is shining ('Happy Hour' case), the storage needed to support the EVs may be halved. Evaluation of the trade off between added public investment in charging infrastructure wherever cars are parked during the day and the reduced need for storage will be useful. Furthermore, it was noted that the difference in storage needs among the three cases decreased when the model was switched to use longer-duration energy storage technologies instead of 4-hour storage. This outcome implies reducing the impact of varied load profiles, potentially diminishing the need for extensive investments in public charging station infrastructure.

Remarkably, the analysis also presented an interesting trade-off with the 8-hour energy storage technology. This storage duration emerged as an appealing middle-ground, balancing power- and energy-storage-capacity requirements against the need for a large-scale public charging infrastructure.

Consequently, the adoption of light-duty EVs without adding additional emissions of carbon dioxide in California is expected to require 11-27 GW and 60-200 GWh of storage beyond what would be needed without the EVs. The investment in charging infrastructure that would enable the EVs to be charged during the day could reduce the needed storage by about a factor of two relative to continuing current practices, especially when 4-h storage is used. While the cost of infrastructure to enable charging during the day will reduce the value of the reduced need for storage, about half of the benefit could be achieved by simply revising the EV rates that encourage nighttime charging. The use of 12-h storage instead of 4-h storage reduces the sensitivity to the charging profile. However, it appears that 8-h storage is better than 4-h and 12-h storage in providing the needed storage without over building the power or energy components of the storage. The choice between investing in more and longer-duration storage versus the large reduction in storage that could be achieved with daytime charging of EVs is informed by this study, but will require additional analysis.

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