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Exploring resource access in electric vehicle-induced power distribution grid upgrades

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ABSTRACT

The transition to a decarbonized energy system is reshaping electricity distribution grids particularly with the rapid uptake of electric vehicles (EVs). This study examines spatial disparities in distribution grid upgrade needs and utilization across various communities in California, using real-world grid data and simulations of light-, medium-, and heavy-duty EV charging. By 2035, high-density residential areas are projected to see a larger share of feeders requiring upgrades. Communities with higher CalEnviroScreen scores—indicating greater environmental and socioeconomic burdens—tend to exhibit lower EV adoption rates, yet face a higher fraction of feeders needing upgrades, though of smaller average size. Despite these differences, the costs and benefits of upgrades remain roughly proportional across communities: high-burden areas incur lower upgrade costs in line with lower utilization, while less burdened communities both drive and benefit more from expanded grid resources.

1. Introduction

The energy system is going through an unprecedented evolution towards decarbonization. However, the benefits of this transition may not be distributed in a balanced manner, and the costs or burdens might be borne by only the "frontline" communities. A growing body of literature has begun to discuss the topic of energy equity under various transitions in the power system, such as renewable generation deployment and fossil fuel phase out, distributed energy resources, and transportation electrification. Understanding and addressing these equity dimensions is essential for designing effective policies that ensure the energy transition benefits all communities rather than exacerbating existing disparities.

On the bulk generation level of the electricity grid, increased renewable energy penetration generally comes with a more uniform distribution of social benefits [1]through emission reduction and health benefits. But there are also discussions on the negative externalities borne by the communities located next to the renewable power plants, such as noise from wind turbines [2]. The decentralization of power generation accompanies renewable integration and gives rise to various new challenges in the electric distribution grid, including discussions on the resulting distribution of benefits and harms on the end-use side of the power system [3]. Rooftop solar, as one of the major distributed energy resources, has raised concerns about cross-subsidization – the burden of fixed cost recovery from the utilities is shifted towards the ratepayers without rooftop solar, since the solar adopters get to offset a part of their electricity bills with solar generation [4]. The circuit capacity available for rooftop solar installation is also distributed inequitably, with the disadvantaged communities having less access to grid resources [5]. Studies have discussed possible methodologies to deploy distributed energy resources to help the communities with energy insecurity [6], as well as different electricity tariff designs to distribute cost recovery in a more equitable manner [7,8].

The rapid uptake of electric vehicles (EV) is another essential revolution in the distribution grid, which raises similar distributional issues as rooftop solar. Various studies have explored technical aspects of integrating EVs into distribution networks, such as optimization algorithm for operation and planning of the grid and charging infrastructure [9,10]. Discussions on the distributional impacts of the technology, on the other hand, usually cover aspects such as emissions, supply chain, and resource access. While electric vehicles are expected to reduce tailpipe emissions and benefit public health, there are concerns about possible emission increases from electricity generation, if the grid is not "clean" enough, and hence affecting the communities near the power generation plants [11]. EV battery manufacturing significantly increases the demand for lithium and cobalt, and these minerals are associated

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with severe injustices, including child labor [12] and health risks [13] at both upstream communities at extraction sites and downstream communities at waste disposal. However, the majority of these discussions are focused on technology access. Studies have shown disparities in EV adoption across different communities [14]. Participation in EV incentive programs is also shown to lean towards the higher-income households, which are not the communities that need this subsidy the most [15–17].

Many studies examine the accessibility of existing EV charging infrastructure and evaluate the spatial disparities related to social-economic factors [18–20]. Others explore the equity in electrical grid resource availability for potential EV charger installation in the future, by evaluating the access to electrical outlets near parking spaces [21], or the circuit hosting capacity [5]. Unfortunately, studies that combine grid resource availability and EV charging demand projections are lacking in the field of equal distribution of opportunity and access. Steinbach and Blaschke [22] estimate the grid reinforcement costs for EV owner groups with different incomes, using power flow simulation on hypothetical distribution grid feeder models. In this study, we use real-world distribution grid network data, combined with EV adoption model and empirical EV charging data, to estimate distribution grid upgrade needs in different communities. This analysis covers over 5000 distribution feeders all over California, where ambitious EV policies are enacted. Additionally, we use separate models to project light-duty passenger EV and medium- and heavy-duty EV charging demands, which is not covered in previous studies. We explore not only the physical access to grid assets, but also the utilization of these resources, and discuss the differences across communities.

The remainder of the paper is structured as follows: Section 2 describes the methodology and data sources used in this study. Section 3 presents the results of distribution circuit upgrade needs caused by EV uptake across different communities. And in Section 4, we conclude with a discussion on the major implications and outlook of our work.

2. Methods and data

The general framework of this study can be seen in Fig. 1. We utilize spatial and temporal data at the feeder level from both the grid and the EV side to project the hourly EV charging load and baseload profile by feeder in the future. These results are then compared with the feeder capacities to determine the upgrade need of each feeder resulting from EV uptake. Lastly, we categorize the type of community that each feeder belongs to and analyze the equity of grid resource access in different communities.

In Section 2.1, we describe the distribution grid data that we use. In section 2.2, we explain how the light-duty EV travel and charging behavior are simulated. And in Section 2.3, the simulation of medium- and heavy-duty EV travel demand and charging profile is shown. Finally, in Section 2.4, we describe the datasets used for community categorization.

2.1. Distribution grid data

The baseload and capacity of each circuit in the distribution system are obtained from the Integration Capacity Analysis (ICA) maps of the three major IOUs in California: Pacific Gas & Electric (PG&E) [23], Southern California Edison (SCE) [24], and San Diego Gas & Electric (SDG&E) [25]. The dataset contains information on distribution network patterns, hourly load profiles per feeder, as well as both thermal and voltage load thresholds of each feeder on an hourly basis. Table 2 shows statistics of the ICA dataset for different communities. Categorization of communities will be explained in Section 2.4.

The cost of upgrading distribution grid infrastructure is derived from PG&E's Distribution Investment Deferral Framework (DIDF) map. The distribution grid upgrade projects are grouped by different scales of upgrade size, in order to address the economies of scale of grid upgrade cost. Then the per-kW investment of each project is calculated. In each scale group, we use the 25th, 50th, and 75th percentiles of the per-kW costs to calculate future upgrade costs in the same scale range.

2.2. Light-duty EV charging load simulation

We first use the California Statewide Travel Demand Model (CSTDM) [26] to simulate the number of light duty vehicle trips traveled to each

Table 1
Charger power range of different medium- and heavy-duty EV classes in HEVI-LOAD model.

	Public Charging	Depot Charging
Light-Heavy-Duty (LHD) Trucks	350 kW	20 kW – 150 kW
Class 4–6	350 kW	20 kW – 150 kW
Class 7	350 kW – 1 MW	20 kW – 150 kW
Class 8	350 kW – 1.5 MW	20 kW – 150 kW

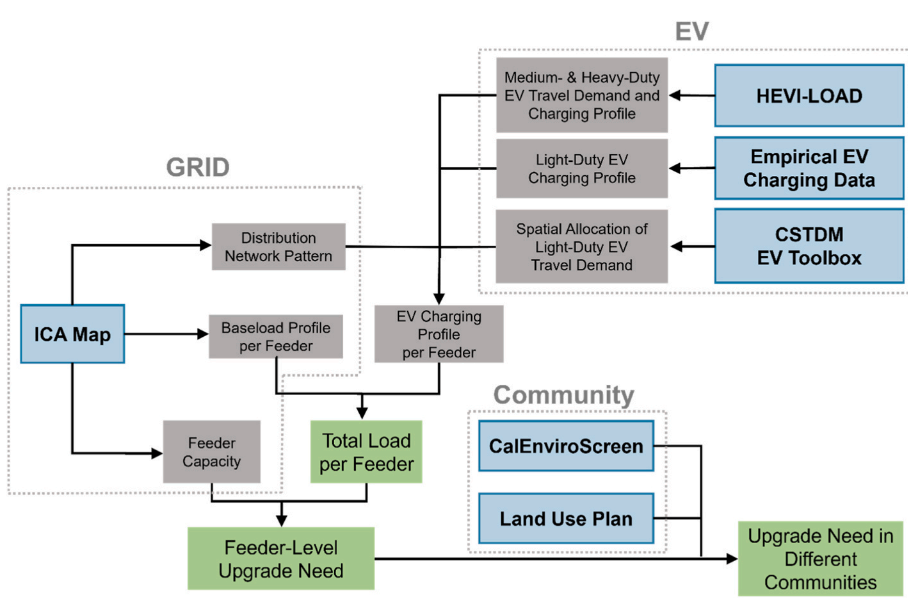

Fig. 1. Data sources (blue), intermediate data (gray), and outputs (green) in the general research framework.

Table 2
ICA data statistics in communities with different CalEnviroScreen percentiles.

CalEnviroScreen Percentile Bin	Number of Feeders	Average Capacity per Feeder (MW)	Average Peak Baseload per Feeder (MW)
[0,10)	614	10.39	6.55
[10,20)	633	10.71	6.68
[20,30)	606	10.52	6.40
[30,40)	573	10.60	6.64
[40,50)	598	10.82	6.57
[50,60)	558	10.06	6.17
[60,70)	507	10.49	6.63
[70,80)	512	10.35	6.52
[80,90)	481	9.61	6.21
[90,100]	470	9.37	5.88

area, as well as the purpose of each trip, which can be categorized into three major types: "home", "workplace", and "public". Then, to determine which of these trips are made by EVs, we adopt the EV Toolbox [27,28] to project future light-duty EV adoption in each area. The EV Toolbox is based on regression and diffusion of innovations model, and we calibrate it to make sure that the growth in EV sales meets the Advanced Clean Cars II regulations in California [29], which requires up to 100% EVs within all new light-duty vehicles sold in 2035.

Then, to simulate EV charging load from the EV trips, we need to determine where the EVs choose to charge during the trips. Short-distance and long-distance trips are treated separately. For short-distance trips, the CSTDM indicates which trips belong to the same tour, and we assume that EV owners charge after certain trips in each tour. The major types of charging locations (home, workplace, and public charging) correspond to the trip purposes, and we bootstrap

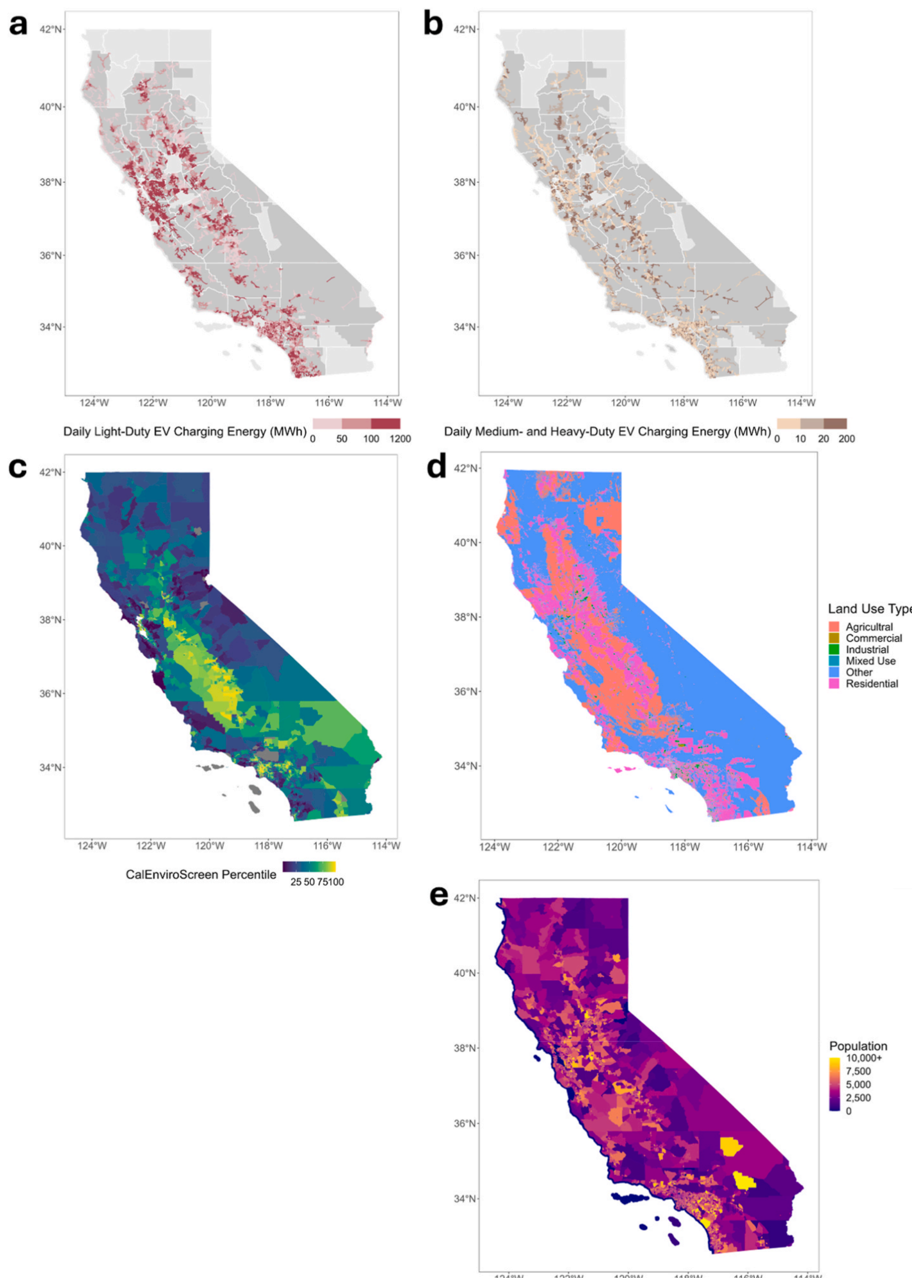

Fig. 2. Spatial distributions of: a) Light duty EV daily charging energy by feeder in 2035. Areas in darker gray are the territories of the three major IOUs in California; b) Medium- and heavy-duty EV daily charging energy by feeder in 2035; c) CalEnviroScreen percentile by census tract; d) Parcel-level land use pattern; e) Population by census tract.

people's choice of charging locations in each tour from the eVMT survey data [30]. For long-distance trips, we assume that public charging would take place in the middle of the trip, and each EV would charge at the destination as well. The demand of each charging event equals the split of travel distance within the corresponding tour or trip.

Finally, we simulate the charging profiles by bootstrapping from empirical charging session records. For each charging event, a charging session is sampled from the pool of the same charging location (home, workplace, or public) and with a similar charging energy demand. The charging session includes charging start and end times and charger power. By adding up the total charging power in each hour on each feeder, we derive the light-duty EV charging profile by feeder. Spatial distribution of light-duty EV charging energy on an average day in 2035 is depicted in Fig. 2a by feeder. It can be observed that population dense areas (shown in Fig. 2e) are more likely to have higher charging energy. More details about the light-duty EV charging load simulation process and data can be found in a previous paper by the authors [31]. Results of this methodology generally align with other papers on the same topic [32,33].

2.3. Medium- and heavy-duty EV load simulation

We adopt the Medium and Heavy-Duty Electric Vehicle Infrastructure – Load Operations and Deployment (HEVI-LOAD) modeling tool [34,35] to simulate future medium- and heavy-duty EV charging load at high granularity. This model performs agent-based simulation on the travel and charging behavior of each individual medium- and heavy-duty EV along the road network in California, at the time segment of every 10 min. Vehicle classes that are simulated include: Light-Heavy Duty (LHD, 10,001 – 14,000 lbs), Class 4-6 (Medium-Heavy Duty: 14, 001 – 26,000 lbs), Class 7 (Medium-Heavy Duty, 26,001 – 33,000 lbs), Class 8 (Heavy-Heavy Duty, > 33,001 lbs). HEVI-LOAD adopts an optimistic scenario of fleet electrification assumptions, which is shown in Fig. 3.

Medium- and heavy-duty EV charging is expected to be a lot faster than that of light-duty EVs. Table 1 shows HEVI-LOAD's assumptions on the charger power level [36]. In our light-duty EV load simulation (Section 2.2), the maximum charging power is 100 kW in public DC fast charging. But in the HEVI-LOAD model, depot charging can already go up to 150 kW. The model assumes that public charging for medium- and heavy-duty EVs should be faster than depot charging, with a charging power of at least 350 kW, in order to save the on-route charging time for commercial fleets. Class 7 and 8 EVs have lower energy efficiency and would need even higher charger power, which can go up to MWs. We map each charging event to the nearest distribution feeder, and aggregate the hourly charging power on each feeder to obtain the medium- and heavy-duty EV charging profiles at the feeder level. Spatial distribution of medium- and heavy-duty EV charging energy on an average day in 2035 is depicted in Fig. 2b by feeder. It can be observed that, compared to Fig. 2a, the distribution pattern of higher charging energy areas is quite different from that of the light-duty EV charging energy.

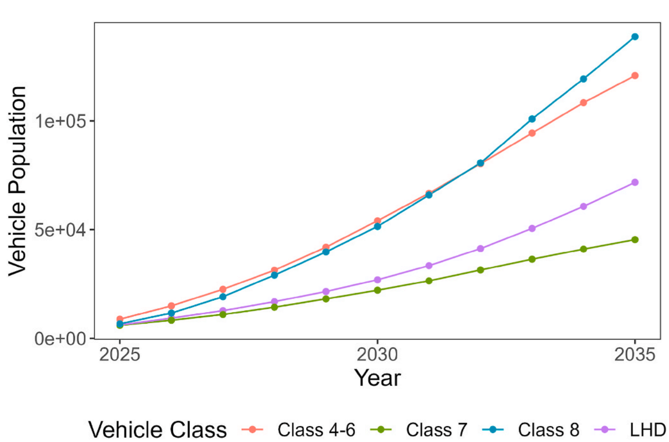

Fig. 3. The growth of medium- and heavy-duty EV adoption in different vehicle classes over the years in the HEVI-LOAD model.

2.4. Community categorization

We categorize the communities in California in two different ways. The first is using land use plan [37]. This parcel-level statewide Geographic Information System (GIS) dataset is an integration of all county and some city general plans in California, standardizing the zoning patterns into thirteen land use classifications, including agricultural, industrial, water, etc., as well as commercial and residential areas in multiple different levels of density. The spatial distribution of six combined land use categories is depicted in Fig. 2d. The 'Other' category covers the lands that are not developed, such as water and open space.

The other categorization method that we use is the CalEnviroScreen tool [38]; California Office of Environmental Health Hazard Assessment [39,40]. CalEnviroScreen is a science-based screening tool developed by the California Environmental Protection Agency to identify communities disproportionately burdened by multiple sources of pollution while accounting for population vulnerabilities. The tool employs 21 statewide indicators organized into four components: (1) Pollution Burden - Exposures (including air quality, drinking water contaminants, pesticide use, toxic releases, and traffic impacts), (2) Pollution Burden - Environmental Effects (including cleanup sites, groundwater threats, hazardous waste, and impaired water bodies), (3) Population Characteristics - Sensitive Populations (asthma, cardiovascular disease, low birth weight), and (4) Population Characteristics - Socioeconomic Factors (educational attainment, linguistic isolation, poverty, unemployment, and housing burden). Based on these indicators, the tool generates census tract-level scores that represent the relative ranking of statewide communities. The higher the score, the higher the pollution burdens and population sensitivities in this area. The census tracts with the highest 25 percent of overall CalEnviroScreen scores are designated as disadvantaged communities by the California Environmental Protection Agency (CalEPA) for Senate Bill 535 (California Office of Environmental Health Hazard Assessment (OEHHA), n.d.). Since its initial release in 2013, CalEnviroScreen has been widely adopted as a "gold standard" geospatial screening tool and has guided significant public investments and policy decisions aimed at addressing environmental justice in California. The tool has also influenced the development of similar screening tools in other states and informed the U.S. EPA's EJScreen tool. Spatial distribution of each census tract's percentile of CalEnviroScreen score among all census tracts is shown in Fig. 2c. We use the percentiles as a reference for the categorization of communities in our analysis.

3. Results and discussion

We run the models from 2022 to 2035, and determine the upgrade need of each feeder based on the size of the maximum overload value in the year. Then we categorize each feeder based on the area that overlaps the most with it, under the two different sets of area categorization described in Section 2.4. In this way, we investigate distribution grid access and upgrade needs caused by EV adoption in different communities.

In Section 3.1, we analyze the distribution grid access and congestion conditions in different residential density areas. In Section 3.2, we discuss the impact of EV uptake in communities with different CalEnviroScreen percentiles, with special attention on the disadvantaged communities.

3.1. Distribution grid congestion in different residential density areas

The community design and distribution grid planning can be significantly different in residential areas with different densities. The higher-density residential areas have more dwellings per acre on average, and thus have more multi-unit dwellings. After categorizing each feeder by the land use type that overlaps the most with it, we calculate the population served by each feeder according to the census blocks that are nearest to this feeder, with the population data from the American Community Survey (ACS) [41]. As shown in the purple bars in Fig. 4 (left), the higher the residential density, the more population served per feeder on average. While more population does not necessarily translate into more electricity consumption, this difference in the population density of feeders can still affect the grid infrastructure access and availability in different communities. The orange bars, which depict the average charging energy per feeder among the communities, show a different trend. In high-density residential areas, while each feeder serves the most people compared to other residential areas, access to home charging can be limited in multi-unit dwellings, which leads to a lower charging demand on average.

We calculate the remaining capacity left in each feeder, excluding baseload in 2022 (the electricity load before further growth of EV charging load), which is referred to as headroom. The average headroom per feeder in different residential density areas is depicted by the green bars in Fig. 4 (right), and it shows that generally, less headroom is left in the higher density residential areas. This contributes to the reverse trend in the red bars, which represent the fraction of overloaded feeders within all feeders under each residential density category, after adding the projected EV load in 2035 to the current feeder capacities. This implies that a higher percentage of feeders will need upgrading in higher-density residential areas to accommodate future EV uptake.

3.2. Distribution grid upgrade need in disadvantaged communities

We first examine the EV adoption in census tracts with different CalEnviroScreen scores, results of which are shown in Fig. 5. The EV ownership per capita in 2022 is obtained from the EMission FACtor (EMFAC) Fleet Database [29,42], developed by the California Air Resources Board (CARB), based on vehicle registration data from the California Department of Motor Vehicles. And the EV per capita in 2035 is projected by the EV Toolbox, which is used in the light-duty EV charging load simulation in this study, as described in Section 2.2. It can be observed that in both current EV adoption and future projections, the higher the CalEnviroScreen percentile of a community, the lower the EV ownership in general. So the disadvantaged communities have less EV adoption compared to other communities.

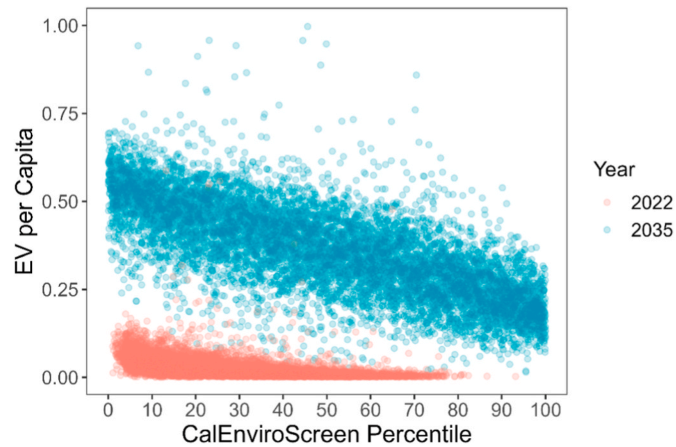

Fig. 5. EV adoption per capita in 2022 and 2035 in areas with different CalEnviroScreen scores. The higher the CalEnviroScreen percentile of a community, the lower the EV ownership.

Then, how does the travel and charging behavior differ in different communities? In Fig. 6a, the percentage of various EV charging load types is shown in communities with different CalEnviroScreen scores. We examine the load contribution to the peak load of each feeder, which is what determines the size of the capacity upgrade needed. Communities with a higher score tend to have more public and workplace charging from light-duty EVs, as well as slightly more depot charging from medium- and heavy-duty EVs. This is related to the planning of different communities. Fig. 6b shows the area share of different land use types in different communities. It is clear that communities under 80% percentile (representing more privileged communities) have substantially more areas that are categorized as 'Other', which are the lands that are not developed, such as water and open space. The top 20% communities (representing more disadvantaged communities), on the other hand, have a much higher utilization rate of their lands, with higher shares of agricultural, commercial, and industrial areas, which contribute to the higher pollution exposure in these communities, as well as the higher share of public, workplace, and depot charging demand.

The distribution grid upgrade need is a result of both existing infrastructure availability and the growing EV charging demand. The green bars in Fig. 7 show that in the communities with higher CalEnviroScreen scores, especially the top 20% percentile, less capacity

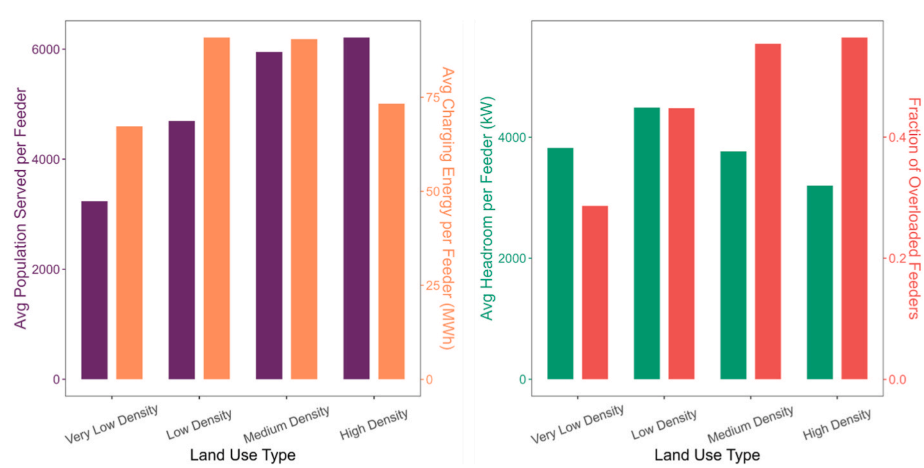

Fig. 4. Average population served per feeder (left in purple), average charging energy per feeder (left in orange), average capacity headroom left (remaining capacity excluding baseload) per feeder in 2022 under different residential densities (right in green), and fraction of overloaded feeders due to the growth of EV charging load in 2035 in different residential density areas (right in red). High-density residential areas are expected to have a higher fraction of feeders that will need an upgrade.

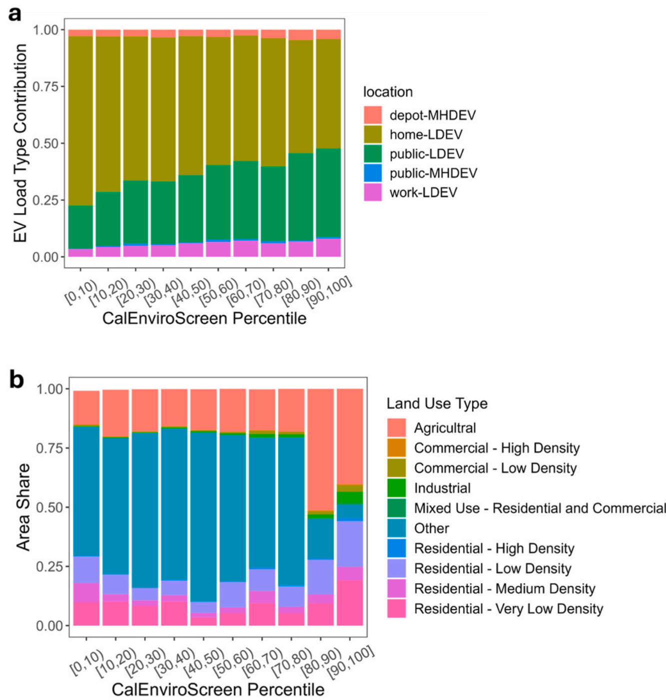

Fig. 6. Contribution of different EV load types at peak load in 2035 (a), and area share of different land use types (b) in communities with different CalEnviroScreen scores. Communities with a higher score tend to have a higher land utilization rate, as well as a higher share of public, workplace, and depot charging.

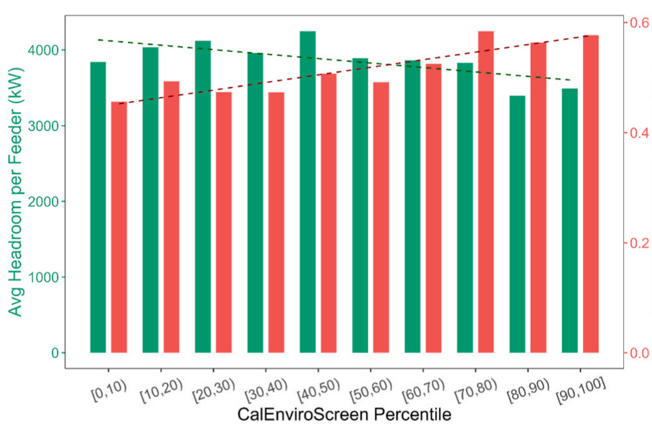

Fig. 7. Average capacity headroom left (remaining capacity excluding baseload) per feeder in 2022 (green), and fraction of overloaded feeders due to the growth of EV charging load in 2035 (red) in areas with different CalEnviroScreen scores. Dashed lines represent the regressed trend of the bars. In the top 20% disadvantaged communities, less capacity headroom is left when feeders are built, and a higher fraction of feeders would need upgrade.

headroom is left in the feeders in 2022. This is likely because utilities anticipated lower demand growth in these areas during infrastructure planning, and thus built feeders with limited spare capacity. However, even though absolute EV adoption remains lower in disadvantaged communities compared to other area (as shown in Fig. 5), the actual EV load growth can exceed the limited capacity headroom that was originally designed based on those lower growth expectations. This mismatch between planned capacity and actual demand leads to a higher fraction of feeders that need upgrading, as is shown in the red bars of Fig. 7. While the share of feeders that need upgrade is higher, the average size of upgrade needed per feeder tends to be lower in these communities, which can be observed in the blue bars of Fig. 8. This is related to the lower EV adoption in the higher-score communities overall, which results in lower charging demand intensity on average in the disadvantaged communities, as indicated by the yellow bars in Fig. 8.

Finally, to evaluate the grid access benefits versus costs for the EV owners in different communities, we estimate the total rate base increment (i.e., feeder upgrade cost) and the rate base payment (part of the electricity bills) on each feeder. The range of total upgrade cost by 2035 is calculated for each feeder as described in Section 2.2, which is expected to be added to the current distribution grid rate base [43]. The rate base payment per kWh is calculated by assuming a 7.5% annual rate of return [44] and dividing it by the total load of a whole year. This price is calculated separately for each IOU territory. For each feeder, the annual total rate base payment is the price times the annual total load on this feeder projected in 2035. The average cost and payment per feeder in each community group of different CalEnviroScreen percentiles are presented in Fig. 9. The rate base increment represents the cost of ensuring grid resource access, and the rate base payment indicates the utilization of these infrastructures, which is the benefits that consumers get out of the distribution grid resources.

Generally, the cost and utilization of upgraded grid resources are rather proportional. In Fig. 9, communities with more upgrade in the distribution grid also utilize it more in the meantime, due to the growth in total electricity consumption. The top 20% disadvantaged communities need less upgrade than other communities and utilize less as well. There are some communities that have slightly higher resource utilization rates, such as those within 10%-20% and 30%-40% percentiles. The rate base payments in these communities, to some extent, subsidize the distribution grid upgrades in other communities.

4. Conclusion

This study highlights the critical intersection between resource access and the evolving electricity distribution grid under the influence of the rapidly accelerating EV uptake. By leveraging real-world distribution grid data and detailed simulations of light-duty, medium-duty, and heavy-duty EV charging behaviors, we have provided a comprehensive analysis of the distribution grid infrastructure upgrade needs and resource access implications across different communities in California.

Our results show spatial disparities in distribution grid resource need and utilization across different communities. Residential areas of different density levels are expected to have significantly different levels of congestion. The distribution feeders in the higher-density residential areas are currently left with less capacity headroom, leading to a higher percentage of feeders requiring upgrades to support future EV uptake.

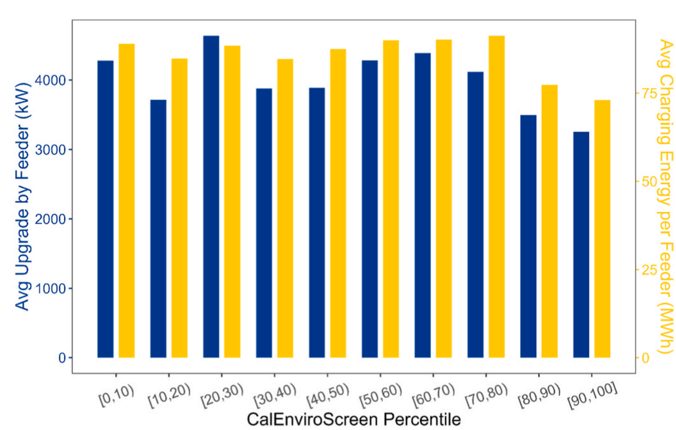

Fig. 8. Average upgrade needed per feeder (blue) and average total charging energy per feeder (yellow) in 2035 in areas with different CalEnviroScreen scores. In the top 20% disadvantaged communities, charging energy intensity is lower, and a smaller size of feeder upgrade is needed on average.

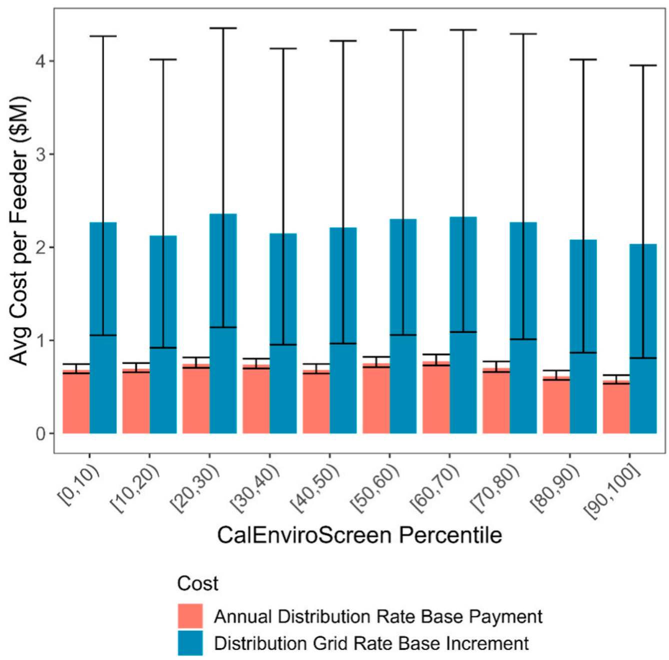

Fig. 9. Average distribution grid rate base increment (upgrade cost) and annual rate base payment (through electricity bills) per feeder in 2035 in areas with different CalEnviroScreen scores, where the bars are calculated using the median of reported costs, and the upper and lower edges of the whiskers are calculated with the 75th and 25th percentile of reported costs. The cost versus utilization of the upgraded distribution grid resources is quite proportional among different communities.

Communities with higher CalEnviroScreen scores, indicating higher pollution and socioeconomic burdens, often have a higher utilization rate of their lands, especially more agricultural, industrial, and commercial land use, contributing to increased public, workplace, and depot charging demands. The higher-score communities exhibit lower EV adoption rates both currently and in future projections. Distribution feeders in the higher-score communities are generally left with less capacity headroom currently, due to the lower expectation in electricity load growth when the grid infrastructure is built. These spatial disparities in EV adoption and capacity access result in a higher share of feeders needing upgrade in the future in the top 20% disadvantaged communities, with a lower average upgrade size compared to other communities. This implies an under-expectation of electricity load growth in the disadvantaged communities, and indicates that utilities should re-evaluate end-use load growth with respect to EV uptake to ensure sufficient grid reinforcement, with potential prioritization of resource distribution on disadvantaged communities accordingly.

Despite the difference in capacity upgrade needs among different communities, the costs versus benefits of the upgraded distribution grid resources are expected to be quite proportional among different communities. While the top 20% disadvantaged communities utilize the grid resources less than other communities, attributed to lower charging demand, the associated costs for infrastructure upgrades in these areas are also comparatively lower. Some of the more prosperous communities have a slightly higher utilization rate, which indicates their compensation to other communities' distribution resource reinforcement. The three major IOUs in California recently proposed to convert part of consumers' electricity bills to a flat rate based on their income [45]. According to our study, income-based electricity charges might not be equitable, since our results do not show higher-income households (more likely to be located in the more privileged communities) paying disproportionally less in rate base recovery. Setting the flat rate in proportion to the fixed costs of the grid resources that the household has access to (such as the local distribution network) might be a more equitable means.

This study evaluates the spatial disparities in distribution grid resource costs and benefits generated from future EV charging demand growth. The findings, of course, should be interpreted with consideration of certain limitations. For instance, this analysis relies on aggregate indicators to categorize communities, so caution is warranted when discussing the relationship between disparities and individual factors such as pollution exposure, education levels, etc. Additionally, this study does not account for changes in the baseload, such as the effect of electrification, energy efficiency programs, or rooftop solar installation. The spatial distribution of these factors may differ from EV load growth across communities, which could affect distribution grid upgrade needs as well. Furthermore, the context-specific nature of this analysis - including California's unique distribution grid characteristics, state-specific EV policies and mandates, and the California-focused CalEnviroScreen tool - requires careful consideration when generalizing these results to other regions, as distribution grids are spatially heterogeneous and policy landscapes vary considerably across jurisdictions. Nevertheless, the analytical framework developed in this study can be adapted to other contexts using region-appropriate community vulnerability indicators and local grid data to assess equity implications. And the findings of this work contribute to the broader body of research examining infrastructure transition impacts on "frontline" communities.

The inequities highlighted in this study could be addressed through targeted measures, such as incentives to promote EV adoption in disadvantaged communities, strategic allocation of charging infrastructure to ensure equitable access to grid resources, and well-designed EV charging tariffs to guide charging behavior and alleviate grid congestion. These topics remain to be explored by future studies.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Alan Jenn reports financial support was provided by State of California. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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