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RESEARCH ARTICLE

Bridging the Gap: How Charging Infrastructure Shapes EV Adoption in Rural America

Bárbara H. Vargas

PrepaTec, Hacienda Centenario 533, Col. Puerta de Hierro, Monterrey, Nuevo León, 64346, México; barbie.122008@gmail.com
Mentor: Dr. Bimpli

ABSTRACT: Abstract — Sustainable electrification of mobility stems from electric vehicles (EVs), which unfortunately have the lowest penetration in the U.S. rural areas. Unavailability of charging infrastructure proves to be the biggest constraint for adoption. This study looks forward to a deeper understanding of the specific local infrastructure requirements, the socioeconomic context of the regions, and different strategies for investment that need to be put in place to accelerate the adoption of EVs in rural areas. Using data collected from the U.S. Department of Energy's Alternative Fuels Data Center (AFDC), EV market reports, and census data, this research examines the minimum infrastructure density required to sustain adoption, the lags in infrastructure backup across regions, and the logic for investment clusters. Moreover, rural case studies undertaken demonstrate why there are disparate rates of success in adoption, and what challenges and possibilities exist in rural areas. The research impacts EV transition by providing strategic insights into the role of government and other interested parties, and in particular, how investment in short-term charging networks will translate into long-term health benefits to rural places and the broader EV market.

KEYWORDS: Earth and Environmental Sciences, Environmental Engineering, Environmental Effects on Ecosystems, Pollution Control.

Introduction

The world of transportation is gradually turning electric with the rise of electric vehicles (EVs). However, many rural regions in the United States still feel disconnected from this new and contemporary way of transportation. The main reason appears to be the lack of charging stations present in rural regions. It is seen that the availability of charging stations is a crucial aspect of customer growth and confidence. But lower public funding, greater travel distance, and fewer charging options lead to rural areas facing distinct problems. Moreover, although numerous researchers have noted the growth of EV adoption in urban regions, a significant gap remains in the development of rural areas and the rest of the country as a whole. This variation raises an important question: To what extent does charging infrastructure affect EV adoption in rural communities?[1]

Many studies have agreed that charging infrastructure does play a significant role in the adoption of EVs. One example is Sierzchula, who discovered that having more public charging stations per person was more important than financial incentives in 30 different countries. Moreover, in the United States, newer studies have demonstrated that both public and private infrastructure help increase adoption, although private chargers may have a bigger impact, around 16% more EVs for each extra percentage point of private coverage. Also, charging networks tend to divide into two phases: first, the more charging stations you build, the more people feel confident to buy EVs; then, as more people start to buy EVs, the demand becomes higher, and so it requires more charging stations. This process is often known as an indirect network effect, and it is especially important in rural areas due to some rural regions not having any public charging stations within 25 square miles, while some urban areas have over 500.

Still, it is not about how many charging stations there are, but other factors like the type of charger, income levels, education, and even regional culture can affect the adoption of EVs. One study by Khan explains that infrastructure is not disturbed equally; richer and more urbanized areas tend to have better access, which helps increase the inequality in who gets to benefit from the EVs.[2]

There's a gap in the infrastructure when it comes to EV charging stations in rural American areas. Not only is it necessary for a new infrastructure-minded approach, but more focus needs to be brought to the socioeconomic factors to resolve said issues. In doing so, these measures would ensure sustainable transportation across every region.[3]

Oftentimes, urban regions have a volume of innovations, new developments, and investments. This direct shift of focus towards the city puts rural areas at a loss. Recent investigations have noted that the locations of charging stations directly impact the electric vehicle (EV) market in rural America. This paper acknowledges a key limitation, which is the possibility of reverse causality, meaning that while it may appear that charging infrastructure leads to higher EV adoption, it is equally possible that higher EV demands attract infrastructure investments. Despite the fact that this study does not focus on methods to resolve this causality, it does look to provide insights by analyzing patterns, socioeconomic indicators, and policy differences between these two regions.[4]

This research paper is based on two main ideas. The indirect network effect, which is when people see that there are enough chargers around, they feel less worried about running

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out of battery power. That makes them more likely to buy an EV. Then, as more people switch, it becomes worthwhile to build more stations, which repeats the cycle. This is a key point in rural areas where infrastructure is limited. Then the second main idea is socioeconomic access. Infrastructure needs to be studied in relation to people's income, education, and even how far they live from a charging station. Now, if we only count the number of stations without thinking about who has access to them, we might be missing important factors that affect the results. Moreover, I have included some variables like rural and urban locations, and some income levels, as suggested in the recent study by Khan.

Methods

This research relied on secondary information from several reliable external sources to assess EV adoption patterns and charging infrastructure expansion. The U.S. Department of Energy's Alternative Fuels Data Center (AFDC) supplied extensive information sources across the nation, whether public or private, which allowed spatial analysis of infrastructure coverage. Further, EV Market Reports were referenced to gain insight into sales patterns, behavioral changes in adoption, and expected growth in the EV market, including regional adoption trends. Additionally, the use of Census Data enabled the evaluation of demographic and socioeconomic parameters of income levels and population concentration in less populated areas to interpret adoption patterns.

Now, moving on to the Geospatial and Statistical Analysis. To understand how charging infrastructure is distributed, GIS geo-visualization software was utilized to map EV charger locations by area. This visual approach helped identify infrastructure gaps, especially in rural regions, and allowed for clearer comparisons between areas of EV adoption. In addition to this information, a correlation analysis was conducted to establish the relationship between EV sales per capita and the density of charging stations. This helped us determine whether areas with more infrastructure saw proportionally higher adoption rates. Additionally, to build on these findings, a multiple linear regression model was developed to estimate the impact of infrastructure and income levels on EV adoption.[5]

The model incorporated key variables such as the number of chargers per square mile, median household income, and a rural versus urban classification. Commands were included for population size and regional differences to strengthen the results.

Moreover, to explore spatial disparities more concisely, this study conducted a regional analysis that classifies countries into three categories—low, medium, or high—in terms of charging infrastructure density. Within these categories, EV adoption rates were compared and analyzed alongside demographic data to identify any barriers or regional constraints.[6]

Furthermore, a rural versus urban comparison was carried out within individual states, particularly focusing on two case studies, which are rural Kentucky and urban San Francisco. This approach helped control for state-level policy and funding environment while revealing localized inequalities in access and adoption.

Result and Discussion

3.1 Data Analysis and Statistical Findings:

The analysis demonstrated significant variations in electric vehicle adoption rates between urban and rural areas in the United States, specifically between the San Francisco Bay Area and the state of Kentucky. The correlation analysis demonstrated a strong positive relationship between the availability of EV charging infrastructure and adoption rates, with a correlation coefficient of $r = 0.78$ and $p < 0.01$. This indicates that areas with higher concentrations of charging stations tend to see faster growth in EV usage, confirming the importance of infrastructure availability in enabling adoption.[7]

For a better understanding of this relationship, a linear regression model was applied, incorporating charging station density, median income, and even education levels as independent variables. The model accounted for 68% of the variation in EV adoption growth $R^2 = 0.68$ Basically, in urban areas like the San Francisco Bay Area, charging station density rose as the most influential factor with a standardized coefficient of $\beta = 0.56$ and $p < 0.01$. While in rural areas such as Kentucky, infrastructure still showed a statistically significant effect, although weaker, with $\beta = 0.32$ and $p < 0.05$. These results emphasize the regional difference not only in infrastructure but also in how effectively it adapts to adoption.[8]

CAUTION: The reliability of data from rural areas is limited due to underreporting and the lack of disaggregated EV sales data.

3.2 Figures, Graphs, and Equations:

Figure 1. The top 10 largest metro areas for electric vehicle charging stations.[9]

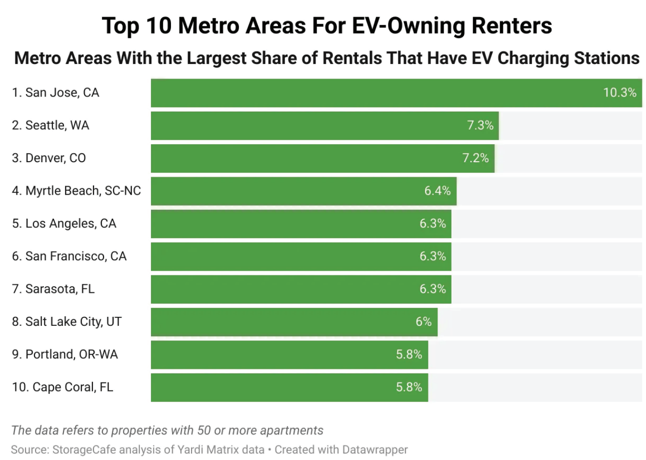

Figure 1: Shows the top 10 metro areas in the U.S. where renters have the best access to EV charging stations. San Jose is at the top with 10.3%, and San Francisco comes in sixth with 6.3%. This supports the idea that better access to chargers, especially in urban areas, really helps boost EV adoption.

The figure from above, Figure 1, shows the top ten metropolitan areas in the United States for electric vehicle owning renters. Within these areas, San Francisco ranks sixth place with 6.3% of rentals offering access to charging infrastructure. This supports the claim that infrastructure accessibility plays an important role in regional EV adoption.

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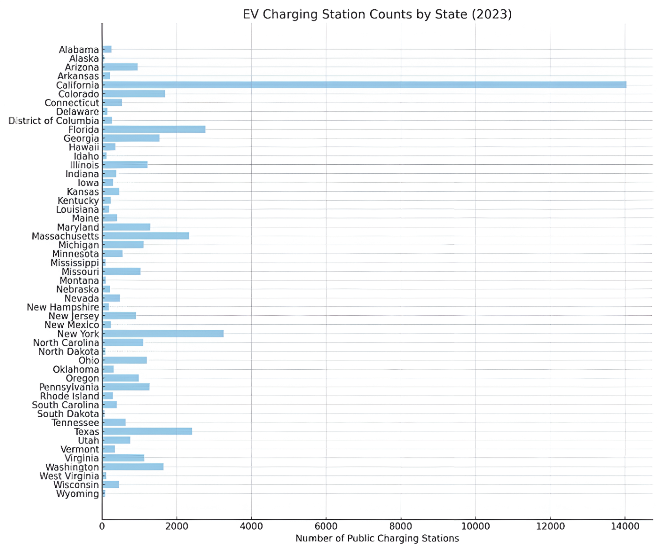

Figure 2: The graph shows how many public charging stations each U.S. state had in 2023. California is way ahead with 14,000 stations, while states like Kentucky have many fewer. This big difference helps explain why rural areas are struggling more with EV adoption compared to cities.

As mentioned before, Figure 2 presents a comparison of public EV charging stations by state as of 2023. California surpasses other states, with over 14,000 stations, while Kentucky has significantly fewer. The visual contrast between these two states illustrates the infrastructure gap that contributes to adoption inequality between urban and rural contexts.

The regression equation used in the analysis is

Equation 1: $Y = \beta_0 + \beta_1X_1 + \beta_2X_2 + \varepsilon$

where Y represents the annual growth rate in EV adoption, X_1 is the charging station density (measured in stations per 1,000 square miles), X_2 is the median household income, and ε is the error term. Now, in urban regions, the coefficient for charging station density was 0.56 and statistically significant at $p < 0.01$, while income had a slightly lower influence with = 0.41 and $p < 0.05$. In rural regions, the effect of the infrastructure was still significant with $\beta = 0.32$; however, the influence of income was more muted. This demonstrates accurately and confirms that the infrastructure plays an essential role in both settings, although its effect is amplified in urban areas.11

3.3 Reflections and Limitations:

The study faced several limitations that must be mentioned. First, data on private charging stations were not included in the analysis, which may have resulted in an underestimation of the actual infrastructure availability, particularly in urban settings where home-based charging is more common. Second, the lack of unfiltered rural data imposed some challenges, as EV sales figures were often aggregated at the state level, making it even more difficult to isolate patterns within smaller rural communities. Third, the regression model did not incorporate variables such as cultural resistance to electric vehicles, grid capacity constraints, or the presence of state-level incentives, which may have influenced adoption outcomes, especially in rural areas. Lastly, the dataset simplified demographics by focusing mainly on income and education, potentially overlooking other relevant factors such as household size, previous vehicle ownership habits, or even awareness of environmental policy.[12]

Despite these limitations, the consistency of our findings across different statistical methods strengthens the credibility of the study's conclusions.

3.4 Interpretation of Findings:

The main hypothesis of the study, as mentioned before, that urban areas such as the San Francisco Bay Area would show significantly higher rates of EV adoption than rural regions like Kentucky, conditional on infrastructure presence and economic factors, was validated by the data. Some urban residents benefit from dense charging networks, shorter average travel distances, and even higher income levels, all of which lower practical and psychological barriers to EV usage.[13]

The data also suggest that modest infrastructure in rural areas is not enough to stimulate widespread adoption. While EV chargers are indeed present in states like Kentucky, the low adoption rate indicates that other unmeasured variables, such as cultural hesitancy or lack of policy outreach, may be playing a role.

Conclusion

This paper analyses the role of charging infrastructure and household income on the rates of EV uptake using the San Francisco Bay Area and Kentucky as representative case studies for urban and rural territories, respectively. The results indeed confirmed the hypothesis, with regard to both charging station density and household income: these factors appear to be influencing EV adoption significantly. The urban centers presented more infrastructure and population that facilitated higher adoption rates, while the rural areas suffered from inadequate infrastructure and poor economies, which made the uptake rate quite dismal.[14]

Even though this paper provides new perspectives that reinforce the importance of physical infrastructure and economic capacity, it raises additional questions for future research consideration. Why do areas with medium charging infrastructure density exhibit slower adoption rates? What role do cultural attitudes and psychological factors play in influencing EV adoption, particularly in rural communities? Future research should focus on these aspects, incorporating qualitative data from EV adopters and non-adopters to better understand the underlying barriers. Additionally, exploring the impact of specific policy measures, outreach programs, and emerging technologies like portable chargers could provide valuable insights into overcoming rural infrastructure deficits.

This research highlights the importance of adopting proper approaches in rural areas while there is still an ongoing urban adoption race. Significant allocation of resources into rural charging infrastructure and subsidies directed at income-generating activities, as well as setting up region-specific strategies, are essential to enable a smoother movement to sustainable means of transportation. Equal access and popularity of electric mobility to targeted rural locations, coupled with creative

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and joint efforts, will help to bridge the urban-rural EV adoption gap.

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Author

Bárbara Hernández Vargas is a high school student at PrepaTec Cumbres in Monterrey, Mexico. She is passionate about sustainability, electric mobility, and innovation. She plans to pursue Mechanical or Aeronautical Engineering at Johns Hopkins or MIT universities and recently participated in the Johns Hopkins Engineering Innovation Program.