An Electric Future: Developing Optimal EV Infrastructure in Urban Areas

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Introduction

When thinking of electric vehicles (EVs), Tesla is most likely the first company that comes to mind. It's without a doubt that Tesla has led the EV market in recent years, but the concept of EVs actually dates back to the late 19th century. In 1890, an Iowan chemist by the name of William Morrison built the first electric car which could hold six passengers and reach a speed of 14 miles per hour. The early 20th century experienced an impressive spike in EV popularity; they made-up about a third of all cars on the road, in fact. However, the rise of the internal combustion engine, discovery of crude oil in Texas, and development of gas-powered vehicles put this craze to a halt (Department of Energy, 2014). Most households didn't have access to electricity and gas stations were much more accessible.

A century later, EVs have made a remarkable comeback, slowly gaining popularity in the automobile market. According to Bloomberg, worldwide battery-electric and plug-in hybrid vehicle unit sales grew from 1.1 million in 2017 to nearly 14 million in 2023. Projections suggest that this number will reach 16.7 million in 2024, with 70% of the cars being fully electric (McKerracher, 2024). This rise in popularity can be explained by the vehicles' environmental friendliness, reduced maintenance costs, better performance, and overall lower fuel cost compared to gasoline. It's without question that EVs can propel global efforts to make sustainable transportation mainstream. However, the rapid influx of EVs brings forth a significant challenge: modern charging infrastructure is insufficient to accommodate the growing demand, posing a risk to urban mobility, sustainability goals, and the market as a whole. Given this reality, it's essential to determine how cities can develop an equitable, efficient, and low-cost EV infrastructure to support growing demand. This is the central question that my thesis will answer. First, I will summarize the research methodology and corresponding findings. I will follow this up with an analysis driven by Actor-Network Theory, ultimately leading into a discussion on what cities should do to solve their problem.

Methods

I used literature review as the core research methodology. The primary sources I examined included academic publications, industry reports, news articles, case studies, consultancy white papers, as well as government reports and policy briefs. I carefully selected each source to offer diverse perspectives on the research question. In identifying the key features of an ideal charging infrastructure, my investigation focused on economic viability, user convenience, ease of integration with existing infrastructure, impact on the power grid, and equity concerns. Determining how governments could promote smart development required me to gather information on existing challenges and strategies, emerging policies and funding initiatives, regulatory frameworks, and even success stories from other countries. Each source had to be relevant, credible, and applicable to the present day, thereby ensuring that the information was as accurate as possible.

I made sure to have a clear and organized process for selecting literature sources. Along with well-reputed digital libraries like Google Scholar and ScienceDirect, I used various key search terms, including “electric vehicles,” “charging stations,” “infrastructure,” “government policy,” and “equity,” to conduct a thorough search. These academic sources offered objective insight, particularly into topics of infrastructure equity and socio-economic barriers to EV adoption. I accessed government reports, policy briefs, and case studies through websites of institutions like the U.S. Department of Transportation, Zero Emissions Transport Association

(ZETA), UC Berkeley School of Law, and The White House. These sources provided clarity on policy directions, funding efforts, infrastructure regulations, and successful development strategies from around the globe. For opinionated perspectives, I selected news articles from magazines like CNBC, MIT News, and Utility Dive. Additionally, I gathered industry-specific insights and policy recommendations from whitepapers written by reputable organizations like McKinsey & Company, C40 Knowledge Hub, and the Harvard Kennedy School.

Actor-Network Theory (ANT) is the primary STS framework that will guide my analysis of EV charging infrastructure. It suggests that human and non-human actors are intertwined in networks, mutually influencing each other through intricate networks to create reality. I selected it for its power to map the complex links between the actors involved, revealing how they shape one another and ultimately influence charging infrastructure implementations. ANT will help me identify the goals, motivations, and strategies of various actors involved in the realm of EV infrastructure, including but not limited to government agencies, car manufacturers, and consumers. In my research, for instance, ANT unveiled how a partnership between governments and small businesses would not only increase charging station numbers but also attract customers to those businesses. This would benefit all parties involved, including the EV owner. I will use ANT in the analysis section to first identify flaws in the current network of actors and then suggest actionable changes to improve its effectiveness.

Results

First and foremost, it’s important to introduce a high-level overview of what cities need to consider during the EV transition. Patricia Morales asserts in her article, featured in Harvard's

Data-Smart City Solutions catalog, that "significant investment in the installation of public charging stations" (Morales, 2023) is critical. She emphasizes the importance of these stations supporting fast charging and being placed in convenient locations. Additionally, given the high-level of stress EVs place on the power grid, Morales notes that cities will need to carefully consider how to best support or even upgrade grid infrastructure. Urban planning is another factor that I must take into account. Morales states, “It will be crucial for cities to incorporate EV charging provisions during the planning and development of residential and commercial areas. This might involve mandating charging stations in parking structures and updating building codes accordingly” (ibid.). Such planning should include existing parking structures as well, as they might have to be redesigned to accommodate charging equipment and dedicated EV spaces. Finally, more EVs on the road will inevitably lead to greater congestion, especially during peak hours. Smart traffic management will be pivotal in ensuring efficient access to charging stations.

In a consultancy article by McKinsey & Company, Phillip Kampschoff and his colleagues (2022) delve into the quantitative outlook for EV-charging infrastructure throughout the United States. In 2023, the Biden administration set the following target: “half of new passenger cars and light trucks sold in 2030 should be ZEVs—a category that includes both battery-electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), which can be recharged with electricity, and fuel-cell electric vehicles (FCEVs), which run on hydrogen” (ibid.). If this is met, there would be over 48 million electric vehicles on the road by 2030, including light commercial vehicles, trucks, and buses. Kampschoff’s models predict that this would increase electricity demand from 11 billion kilowatt-hours (kWh) to 230 billion kWh, necessitating nearly 30 million total chargers across the country. Him and his colleagues also note that while most of these would be in homes, 1.2 million of them would be public chargers, with the cost of hardware, planning, and installation coming to "more than $35 billion over the period to 2030" (ibid.). The recent Bipartisan Infrastructure Law (BIL) invests "$7.5 billion in EV charging, $5 billion of which is for building a "backbone" of high-speed chargers spaced no less than every 50 miles along America's major roads, freeways, and interstates through the National Electric Vehicle Infrastructure (NEVI) program" (ibid.). It must be noted, however, that states must first demonstrate their plans for meeting the federal government's before obtaining access to these funds. Additionally, it's expected that installation and maintenance of public chargers will be done exclusively through private sector contracts.

In an implementation guide, the C40 Cities Climate Leadership Group (2021) dives into the specifics of necessary charger quantities and types, proposes funding models and policies to stimulate investment, and highlights crucial stakeholders to engage with. The group first argues that charger counts in cities should be planned based on a ratio per EV, not a fixed number. In rationalizing this, they emphasize the fact that different cities might have varying requirements: "If more drivers are able to charge their vehicle at their home or workplace, like in Californian cities, fewer public chargers (a higher ratio of EVs per charge point) will be required. If private parking is rare, like in the Netherlands, you will need more public chargers (a lower ratio)" (ibid.). To determine the ratio of slow and fast chargers that need to be installed, the authors urge cities to perform a market analysis of "the types of EV that residents are driving or projected to be driving according to city EV targets" and "where and when they are charging" (ibid.). These two statistics must be understood for the following reasons. First, plug-in hybrid electric vehicles (PHEVs) usually cannot accommodate fast charging. Second, if drivers in a given city primarily charge their vehicles on the road rather than at home, there will be a greater need for fast chargers. In order to minimize construction costs, the group urges cities to minimize the use of single connectors, favor wall-mounted over freestanding stations, build multiple stations in a single area, place charge points in locations where electrical capacity is sufficient, and go for slower, more affordable chargers whenever possible. Financing these projects will require updates to "local policies and incentives to encourage – or require – others to build charging infrastructure" (ibid.). Some proven examples include implementing EV-ready building codes, encouraging investment from local business and EV manufacturers, incentivizing landowners to enable charging on their properties, coordinating with utility companies, and simplifying the permitting process.

The challenge associated with maintainable power grid integration is one that requires significant attention from both policymakers and local energy departments. In her CNBC article, Katie Brigham examines the numbers and points out the harsh reality that "it's not going to be cheap" (Brigham, 2023). To provide an example, she references a state government-backed study where "grid analytics company Kevala forecasts that California alone will have to spend $50 billion by 2035 in distribution grid upgrades to meet its ambitious EV targets" (ibid.). Aram Shumavon, the company's CEO, emphasized the reality that if grid infrastructure doesn't keep up, drivers can expect long charging queues and even blackouts. Brigham argues that the solution to this is to "bring more energy sources online, preferably green ones" (ibid.). Solar and wind sources, however, would typically be located away from metropolitan areas, thus necessitating more high-voltage transmission lines. Currently, the U.S. invests little into expanding transmission line infrastructure, and beginning these projects comes with many obstacles, including but not limited to regulations, permits, and most importantly, time constraints. Brigham states that preventing overload during this construction period requires "residential and solar battery systems" to "help stabilize the grid as customers generate their own power and sell excess electricity back to the grid" (ibid.). Bidirectional charging technology is a prime examples of this and is currently being developed by several car manufacturers. These strategies can also can be combined with dynamic pricing and even constraints on charging times.

David Chandler's MIT News article references multiple research papers to introduce two additional effective strategies for mitigating power grid stress and limiting physical infrastructure costs. He states that better availability of chargers at workplaces is the first step. Not only would it reduce evening peak loads but could also take advantage of solar energy being produced during at midday. This should be combined with delayed home charging, where "each EV charger could be accompanied by a simple app to estimate the time to begin its charging cycle so that it charges just before it is needed the next day" (Chandler, 2023). These two measures would, in theory, both reduce peak electricity demand and satisfy drivers' charging needs. In his opinion article on Utility Dive, Chris Baker, leader of Enel X Way North America, highlights that smart charging is an effective approach to "improve grid flexibility and decrease the risk of outages" (Baker, 2023) while grid improvements take place. The author notes that smart charging would mean that "charging automatically takes place during off-peak times when energy demand is lowest and prices are cheapest, offering much-needed relief for the electric grid and EV owners' wallets alike" (ibid.). For instances where an EV-owner requires immediate refueling and cannot afford to wait long, energy storage mechanisms can be integrated with fast chargers to still provide electricity during peak demand. Baker brings-up solar-plus-storage as an example of this, where "by using solar to power a battery-integrated EV fast charger, excess solar energy can be stored for future use to avoid relying on the grid when the sun isn't shining or demand is high" (ibid.). These are several strategies that cities can adopt to manage power grid stress while longer term infrastructure projects are underway.

Ethan Elkind and colleagues (2022), affiliated with UC Berkeley's Center for Law, Energy, and the Environment, provide case studies describing how different jurisdictions around the world have successfully supported EV infrastructure deployment. California, for instance, used three main tools to fuel its transition: "setting clear targets, investing in advanced technologies needed to meet targets, and driving market certainty through regulatory efforts" (ibid.). Rotterdam, conversely, used early urban planning and policy incentives such as "financial subsidies, technical support, and grants" (ibid.) to encourage private installations. Portugal centered its efforts around creating a user-friendly digital platform to allow EV-owners to access any public charger with just a single card or application. This centralized platform not only enhanced competition among private investors to build charging infrastructure but also increased EV adoption rates through its ease-of-use. Costa Rica set "binding installation targets for charging infrastructure" (ibid.) and focused on electrifying public transportation, thereby increasing public confidence around EV technology. British Columbia, hoping to expand EV adoption among lower and middle class families, offered financial incentives for "EV charger installations in multi-unit residential buildings" (ibid.) and provided rebates. The diverse strategies employed by these cities can assist others in drawing-up productive infrastructure plans and passing smart legislation.

Addressing concerns around social equity is critical. Research by Hopkins et al. (2023) underscores the barriers to equitable EV infrastructure provisioning and reveals the existence of uneven charging station distributions. Social equity challenges in the context of EVs revolve around location, affordability, and useability. Location inequity, for example, entails a "lack of home charging for renters or those with off-street parking" and "less public charging in lower income areas" (ibid. pg 8). Affordability issues include higher public charging costs, exorbitant EV prices (even with incentives), and lack of grants for secondhand vehicles. Inequity concerning infrastructure usability can arise from a "lack of standard specifications" and "poor information on charger availability" (ibid. pg 8). After diving into these issues, the researchers transition into proposing policy-based solutions. For improving EV affordablity, they propose secondhand vehicle loans, battery swapping and extended warrantees, and non-ownership solutions, such as EV car clubs. On the topic of infrastructure, they suggest home charging subsidies for renters and landlords, facilitation of affordable energy tariffs, and setting locally specific targets for public overnight chargers. To improve useability, the paper encourages cities to hire charge point operators, considering them "key players in providing accessible and user-friendly charging points in terms of cables, access, payment method, cost and reliability" (ibid. pg 8). In a 2023 Axios article, Alex Fitzpatrick, Joann Muller, and Erin Davis examine data from S&P Global Mobility and the U.S. Department of Energy, noting that "majority-white tracts are about 1.4 times as likely as majority-non-white tracts to have a charger, while tracts with chargers are about 1.14 times as wealthy as those without them, according to our analysis of the 35 U.S. cities with the highest share of EV sales nationwide" (ibid.). These racial disparities are especially amplified in cities such as Philadelphia, Chicago, and New York, where majority-white areas are 3.9, 2.8, and 2.6 times more likely, respectively, to have a charging station. The successful transition towards green transportation is dependent on the commitment of city officials to proactively support EV infrastructure development within historically marginalized and low-income neighborhoods.

Analysis

As outlined in the Methods section, I use Actor-Network Theory (ANT) to analyze interactions among key actors in EV infrastructure development. These actors include governments, private sector stakeholders, local communities, and the EV technology itself. I specifically chose these actors because they form a strongly interconnected network, which is essential for addressing the central research question of my thesis. My analysis focuses on three important aspects of EV infrastructure: cost, efficiency, and equity.

My findings first reveal the reality that reducing costs associated with EV infrastructure construction requires collaboration between governments and private sector entities. It's clear that federal grants are insufficient to entirely fund the fleet of public chargers most cities require. As a result, incentives are key. By providing subsidies, tax benefits, and grants to automakers, local businesses, and homeowners, governments can spur investment into charging stations. Additionally, collaboration with utility companies can reduce upfront installation and energy costs, potentially facilitating long-term investment from third parties. Another relationship that determines cost is that between governments and EV technology. It was noted earlier that fast chargers, which are typically more expensive than slow chargers, place more stress on the power grid. The C40 Cities Climate Leadership Group highlights that cities are different and have varying infrastructural needs. Recognizing this is important; for that reason, governments should work with local communities to analyze what types of EVs are most common and how typical charging behaviors look like among residents. Once this information is available, governments can then make better estimates of how many public chargers are actually needed. Furthermore, encouraging the installation of workplace charging stations and taking advantage of solar energy could reduce total costs even more. ANT thus reveals the following: cost minimization is not a single-sided task and requires collaboration between city governments, the private sector, and local communities.

The efficiency of EV infrastructure primarily depends on the strategic placement of charging stations and their smooth integration with the power grid. ANT highlights that urban planners, the behaviors of EV owners, and the inherent limitations of EV technology play a crucial role in defining these efficiency metrics. First, by understanding user charging habits, cities can identify high demand areas and collaborate with urban planners to strategically position stations. This would both optimize charging output and prevent unnecessary resource consumption. In addition, partnerships with utility companies and automobile manufacturers can enable city officials to integrate smart charging technologies into infrastructure, thereby reducing power grid stress during peak hours. One effective strategy is delayed home charging, which spreads out electricity consumption overnight, still ensuring vehicles are fully charged by morning – a massive benefit given that most EV charging occurs at night. Improving the mechanism even more, bidirectional charging plugs could allow vehicles to transfer energy back into the grid later in the day, further improving grid resilience. Cities should also encourage daytime charging among users through financial incentives; for instance, dynamic pricing systems would increase charging rates during peak hours and could incentivize drivers to alter their charging habits. This approach would further reduce power grid stress without the need for the immediate completion of larger infrastructure projects. Moreover, as was previously discussed, promoting workplace charging could also limit evening demand. I argue, however, that both local and state governments must acknowledge that these are generally short-term solutions. Continued investment into sustainable energy sources and high-voltage transmission lines is essential for long-term EV adoption.

While strategies to reduce cost and improve the efficiency of EV infrastructure in urban areas is critical, social equity challenges cannot be neglected. It’s the responsibility of government officials to ensure equitable charging station distribution across all communities. Simply lowering the overall cost of EVs, although important, is not sufficient in delivering charging technology to low-income and historically marginalized groups. Without widespread charging infrastructure, the motivation to adopt EVs will inevitably dwindle over time. It’s important to first recognize that many of these overlooked communities lack private charger access, especially in multi-unit buildings where parking access is limited. This is where the relationship between local government and constituent actors must be strengthened, with policymakers mandating the inclusion of EV infrastructure in new development projects. Additionally, partnerships between governments and the private sector could be used to subsidize charging for low-income users, either by making it free or significantly reducing cost. Another strategy to fight this inequity is setting targets for public charger installations in underserved communities, potentially encouraging competition and incentivizing property owners to invest in charger installations. This can go hand-in-hand with increasing accessibility through public awareness campaigns aimed at informing residents about EV technology and its benefits. While these initatives could prove to be effective, policymakers must recognize that active engagement on behalf of the city is essential. Recognizing what works and what doesn’t and adjusting plans in real-time is just as important as delegating the necessary funding. Overall, the evidence shows that EV infrastructure equity is still a major work in progress. It’s critical that we as a society come to understand that a future in green transportation is dependent on everyone having equal access to infrastructural resources.

Discussion

My thesis' core finding is that updating infrastructure to accommodate the surge of electric vehicles is intricate and requires the work of various stakeholders to make it successful in the long run. The key actors include city governments, private sector entities, and local communities, each playing a different role in developing efficient and equitable infrastructure at the lowest cost. On that note, cost reduction hinges on government-private sector partnerships that work to spur competition. To improve efficiency, we need in-depth analysis of local charging habits and city layouts, along with the use of smart charging technologies to support the electric grid. Tackling social inequity around EV infrastructure requires us to not overlook lower-income communities; the answer lies in understanding the struggles they face when it comes to charger access and fuel costs. Ultimately, the current network of EV infrastructure, as showcased by Actor-Network Theory (ANT), doesn't fully follow these principles, proving that cities are still navigating said challenges.

This research is important for several reasons. It proposes strategies to meet the growing demand of EVs, underscoring their role in fighting climate change and reducing greenhouse gas emissions. With improved access to charging infrastructure, urban mobility is bound to flourish as people will become incentivized to adopt these vehicles. The study also details the policy and social initatives governments can adopt to make advancements in both equity and economic growth. Looking ahead, future research in this area should be aimed at technologies that can optimize existing charging systems. Specific examples include swappable batteries and wireless charging roads. In a Stellantis press release, Fernão Silveira and Nathalie Roussel explain, "battery swapping technology allows an EV customer who stops at a battery swapping station to have its depleted EV battery swapped out for a fully charged battery in a matter of minutes"

(Silveira & Roussel, 2023). Similarly, the company Electreon has built a road in Detroit that's a prototype for automatic charging. According to BBC, "the quarter-mile (400m) section of road through the Corktown area of Detroit is a pilot of a wireless technology that is capable of charging vehicles as they drive over it" (Paris, 2024). Unfortunately, these technologies are not only expensive, with a charging road costing over two million dollars per mile, but also still in the early stages and their development, making short-term adoption questionable.

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