**The Carbon Footprint of Tesla**

Literature Review for I-492 Project

by

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**Abstract**

**The widespread adoption of electric vehicles (EVs) is often framed as a crucial step toward reducing transportation-related carbon emissions. However, the assumption that EVs are inherently low carbon overlooks the role of electricity generation in determining their true environmental impact. This study critically evaluates the carbon footprint of EVs, with a specific focus on Tesla, by analyzing CO₂ emissions per mile based on regional electricity grid composition. Through an extensive literature review, the research examines key themes, including the variability of power plant emissions, the influence of charging behavior, the role of policy incentives, and the economic and political implications of EV expansion. Findings indicate that EV sustainability is highly dependent on regional energy sources, with coal-heavy grids leading to emissions comparable to or exceeding those of efficient hybrid vehicles. Additionally, charging patterns, grid decarbonization efforts, and financial incentives all shape the effectiveness of EV adoption in reducing overall emissions. This research challenges the prevailing assumption that EVs are universally cleaner than internal combustion engine (ICE) vehicles and underscores the need for more transparent metrics—such as CO₂ per mile—to provide consumers and policymakers with an accurate assessment of EV sustainability. By incorporating real-world emissions data and predictive modeling, this study contributes to the ongoing discourse on EV policy and market adoption while offering a framework for evaluating the environmental impact of EVs based on electricity generation sources.**

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**I. Introduction**

This study aims to bridge this gap by developing a comprehensive framework that assigns CO₂ emissions per kilowatt-hour to EVs, creating a parallel metric to the well-established grams of CO₂ per mile used for internal combustion engine (ICE) vehicles. By integrating data from the Environmental Protection Agency (EPA) on regional electricity emissions and vehicle energy consumption data from the U.S. Department of Energy, this research provides a more transparent assessment of the environmental impact of EVs. The analysis focuses specifically on Tesla vehicles, representing a significant portion of the U.S. EV market and providing a standardized efficiency metric across different power grids.

Through a rigorous evaluation of regional power grid emissions, charging behavior, and seasonal variability, this study will quantify how Tesla’s carbon footprint changes depending on what time of day and in what region that charging takes place. These findings will contribute to ongoing discussions about EV policy and incentives and provide consumers with a more informed perspective on the true sustainability of their vehicles. Ultimately, this research seeks to challenge the one-size-fits-all perception of EV sustainability and emphasize the need for region-specific emissions accounting to evaluate electric transportation's true carbon footprint.

# II. Literature Review

**2. Electricity Generation CO2 Emissions and Regional Variability**

The carbon footprint of electric vehicles (EVs) is directly linked to the emissions associated with electricity generation. While we know that EVs produce no direct emissions without a tailpipe, their indirect or overall impact dramatically depends on the regional energy mix used for charging. Several studies, which we will look at below, highlight that regional variability in power generation, ambient temperatures, and marginal vs. average electricity factors significantly impact EV Emissions outcomes. In short, EVs will only be as efficient and CO2-free as the charging grid. This section will review six key studies that analyze greenhouse gas reductions from EVs, global and regional drivers of CO2 emissions, ambient temperature effects on energy consumption, electric vehicle lifecycle CO2 emissions, regional electricity generation emission factors, and health and climate benefits of US vehicle electrification. While each article has its differences in approach and guidelines, the common denominator is that EVs do not consistently outperform their efficient hybrid counterparts, not only on a mpg scale but a CO2 emissions scale as well.

**2.1.1 Regional Differences in Power Plant CO2 Emissions and EV Sustainability**

According to Gosh (2023), electrification production is one of the USA’s most significant sources of environmental emissions. In this study titled “Derivation and Assessment of regional electricity generation emission factors in the USA,” the authors aim to examine how electricity generation emission factors (EFs) can vary across different regions of the United States, develop a methodology for deriving regional EFs that reflect the actual differences in power plant emissions, and integrate multiple databases maintained by the EPA and EIA using a python framework to create a unified dataset for “life cycle impact assessments” Gosh (2023). This rigorous study intended to solve challenges such as merging data coherently from multiple databases and handling data issues using relevant assumptions to derive scientifically sound EFs (Gosh et al., 2023).

To achieve this, the research uses a Python framework to combine multiple datasets from the EPA’s Emissions and Generation Resource Integrated Database (eGRID) and the U.S. Energy Information Administration (EIA) in order to construct a detailed model of power plant emissions, implying that using a single national average CO2 emission factor for EVs fails to account for the regional differences in electricity generation. The authors argue that current federal and state-level emissions calculations fail to capture the real-time deviations in power grid efficiency. By refining data processing techniques and making proper and valid assumptions, the study ensures that regional electricity generation-related emissions are more accurately reflected in environmental impact assessments. In most EV-related research, Average Emission Factors (AEFs) are calculated by state CO2 emissions divided by total electricity generation. Whereas in this study, Marginal Emission Factors (MEFs) measure emissions from the power plants that go up and down in generation due to changes in demand.

This study finds that carbon intensity from power plant emissions varies significantly across U.S. regions due to differences in fuel sources at each plant, how efficient each plant is, and grid infrastructure. In regions where coal is heavily used, Kentucky, West Virginia, and Indiana, over 1,000 grams of CO2 per kilowatt hour is produced, meaning that EVs charged in these states have a much higher carbon footprint than those charged in California, New York, and the Pacific Northwest where less than 200 grams of CO2 per kilowatt hour is produced (Gosh et al., 2023). Also, for coal-heavy states, MEFs are 30-50% higher than the regularly used AEFs, showing that EV emissions are significantly underreported in these regions. As with studies we will see below, this study also examines how power grid emissions change based on season and time of day. In many regions, winter months have higher CO2 emissions as coal and natural gas power plants accelerate generation to meet demand. In contrast, peak renewable generation hours (midday for solar, evening for wind) lead to lower marginal emissions (Gosh et al., 2023). Lastly, contrary to the belief that charging at night is always the right thing to do, in some regions, this results in higher CO2 emissions than charging during the day. This study presents an evidence-driven case for why CO2-related emissions assessments must account for regional differences nationwide.

Following the path of understanding power plant CO2 emissions, “Global and Regional Drivers of Power Plant CO2 Emissions Over the Last Three Decades” by Qin, X., Tong, D., Liu, F., Wu, R., et al. (2022)​ presents an analysis of CO2 emissions over 30 years, 1990 to 2019. With the power sector being the top CO2 emitter, accounting for 37% of the global anthropogenic emissions (Qin et al., 2022), this study aims to identify and analyze the key drivers of increasing electricity generation sector emissions. This study also aims to understand how policy, fuel choices, and technological advancements affect emissions trends, which can be essential for EV adoption and power grid emission reduction efforts.

This study constructs an extended version of the Global Power Plant Emissions Database (GPED v1.1) by integrating multiple global and regional power plant emissions datasets to answer these questions. This database includes annual CO2 emissions by power plant unit, fuel type, and efficiency and capacity factors. In addition to creating this extended database, this study uses the Logarithmic Mean Divisia Index (LMDI), widely used and accepted in energy policy research to disaggregate the factors of CO2 emissions changes (Qin et al., 2022). Past studies have shown this method to be favorable because of its path independence, consistency in aggregation, and ability to handle zero values (Ang, 2015; Ang & Liu, 2007; Ang et al., 1998). In this study, we choose LMDI to identify how each driving factor contributes to the changes in CO2 emissions (Qin et al., 2022).

This study finds that global power sector CO2 emissions nearly doubled from 7.5 gigatons in 1990 to 13.9 gigatons in 2019, reflecting an enormous rise in global energy demand and population growth. Coal remains the dominant source of fuel for electrical generation worldwide, contributing to roughly 40% of the global power sector’s CO2 emissions in 2019. On the other hand, renewable energy capacity has expanded since 1990 but not at a rate that is fast enough to replace fossil fuels entirely. While global emissions rose, regional drivers differed broadly from those affecting global trends (Qin et al., 2022). In developed nations like Japan, Europe, and the U.S., power plant emissions have been reduced over the past two decades through renewable energy adoptions and no longer depend on coal as a fuel source. However, in developing countries, this is not the case. Developing countries have increased power plant CO2 emissions due to industrialization and rapid expansion. While the U.S. has reduced its electricity sector’s CO2 emissions by roughly 35% since 2005, China’s power plant CO2 power plant’s emissions have nearly tripled between 2000 and 2019. The United States and Europe contributed 55.2% of global power plant emissions in 1990, whereas China, India, and the rest of Asia represented 56.3% of the total emissions in 2019 (Qin et al., 2022). Key drivers of power plant CO2 emission reductions in developed countries are switching from coal to natural gas, expansion of renewable energy, and energy efficiency with modernization of energy grids. By replacing coal with natural gas, the U.S. and Europe reduced emissions since natural gas emits 50-60% less CO2 per unit of energy. The United States also increased its wind and solar energy adoption by over 300%, further aiding in emissions reduction, and helping to displace fossil fuels. While this sounds promising, fossil-fueled plants are still required as a backup source of electricity generation.

Globally, improved power plant efficiency, innovative grid technologies, and demand management strategies have reduced CO2 emission intensity per unit of generated electricity. These findings further emphasize power grids and power generation plants’ key role in reducing global CO2 emissions. This study highlights how fuel switching, renewable energy expansion, and efficiency improvements have helped reduce emissions in developed nations, while coal expansion continues to drive emissions in developing ones.

The studies by Ghosh et al. (2023) and Qin et al. (2022) examine the role of electricity generation in reducing carbon emissions. However, their scope, methodology, and specific implications for electric vehicle sustainability differ. Though these differences exist, both studies arrive at the same fundamental conclusion: the sustainability of electricity use, including for EVs, is not uniform across all regions and depends heavily on power grid composition, energy policies, and fuel choices. Thus, EVs will only be as “clean” as the energy generated to fuel them.

A significant commonality between the two studies is that regional power plant emissions are not constant, varying significantly across locations and time. Both studies emphasize the importance of relevant emission factors and databases in evaluating sustainability metrics. Ghosh et al. (2023) highlight this by showing that coal-heavy states produce a much higher gram of CO2 per kilowatt hour vs non coal-heavy states. Qin et al. (2022) proved similar evidence but on a global scale, showing that countries that are still developing produce higher levels of CO2 emissions compared to developed countries. This implies that EVs charged in different parts of the world or regions within each country will have drastically different carbon footprints. Both studies also examine how time-dependent factors influence carbon emissions. Ghosh et al. (2032) emphasize that power grid emissions fluctuate by season and time of day, with higher emissions being in the winter. Similarly, Qin et al. (2022) highlight that seasonal energy demand is one of the long-term key drivers of global emissions increases.

While both studies analyze electricity generation-related CO2 emissions, they differ in scope, methods, and focus. Ghosh et al. (2023) adopt a detailed, U.S.-specific approach, using a Python framework to merge databases to refine regional electricity generation emissions factors (EFs). Their primary objective is to improve accuracy in life cycle impact assessments (LCAs) by integrating marginal vs average emissions factors (MEFs vs. AEFs). The study results find that CO2 emissions often go underreported in coal-heavy states. In contrast, Qin et al. (2022) focus on a global perspective, constructing an extended database to analyze long-term drivers of CO2 emissions from 1990 to 2019. Instead of focusing on methodological improvements, they aim to identify and understand the key drivers behind the increases or reductions in power plant emissions. Using the Logarithmic Mean Divisia Index method allows them to differentiate each driver. Another important distinction is how each study frames the relationship between power plant emissions and EVs. Ghosh et al. (2023) explicitly discuss how variations in electricity grid emissions impact EV sustainability, reinforcing that the benefits of EVs depend on things like the energy mix of the charging grid and geographical location. Alternatively, Qin et al. (2022) do not focus specifically on EVs but provide insights into how grid decarbonization efforts will influence EV emissions over time. This difference in scope shows that Ghosh et al. (2023) can immediately apply to EV policy whereas Qin et al. (2022) provides a long-term understanding of EV inclusion and adaptation.

**2.1.2 The effect of Regional Variability on EV Life Cycle CO2 Emissions**

Building on the discussion of regional/global power plant CO2 emissions and their impact on EV sustainability, it is important to examine how these regional differences translate into the lifecycle emissions of electric vehicles themselves. This research builds on the findings of Ghosh et al. (2023) and Qin et al. (2022) by providing a vehicle-specific perspective that analyzes how changes in electricity generation influence EV emissions.

To continue our examination, Tamayao et al. (2015) investigate how regional variations in electricity generation affect the lifecycle CO2 emissions of EVs across the United States. This study challenges the common perception that EVs are automatically low-emission vehicles and aims to determine whether EVs consistently outperform efficient gasoline hybrids like the Toyota Prius and if certain regional factors result in higher emissions compared to their traditional hybrid rivals (Tamayao et al., 2015).

To answer these questions, this study incorporates data from multiple databases including data from the National Household Travel Survey on daily vehicle miles traveled. This study also uses life cycle assessment (LCA) modeling and MEFs vs AEFs, as in a previous article. This study calculates both MEFs and AEFs for different regions in the U.S. and examines how these different metrics affect EV emissions calculations (Tamayao et al., 2015). Additionally, the study incorporates regional electricity grid data from the North American Electric Reliability Corporation (NERC) regions, which group together areas with similar power generation characteristics. This allows Tamayao et al. (2015) to compare emissions based on realistic market conditions instead of relying on national averages. The vehicles used in this study are the Nissan Leaf, the Toyota Prius, and the Chevy Volt.

This study finds that EV life cycle emissions can vary by up to 120% across different regions in the United States. In areas such as Texas and the Western U.S., EVs outperform their hybrid vehicle counterparts regarding CO2 emissions. At the same time, in the Northern Midwest, EVs have higher life cycle CO2 emissions than efficient hybrids. This is primarily due to coal-heavy electricity generation in the region. The study also finds that using marginal emissions factors changes the rankings of vehicle emissions in many regions. In certain states, an EV may appear to be cleaner when using AEFs, but it produces more CO2 per mile when MEFs are applied. Charging time also proved to affect EV CO2 emissions. Using two estimates of NERC region marginal emission factors, the study found the following: (1) delayed charging (i.e., starting at midnight) leads to higher emissions in most cases due mainly to increased coal in the marginal generation mix at night; (2) the Chevrolet Volt has higher expected life cycle emissions than the Toyota Prius hybrid electric vehicle (the most efficient U.S. gasoline vehicle) across the U.S. in nearly all scenarios; (3) the Nissan Leaf BEV has lower life cycle emissions than the Prius in the western U.S. and Texas, but the Prius has lower emissions in the northern Midwest regardless of assumed charging scheme and marginal emissions estimation method; (4) in other regions the lowest emitting vehicle depends on charge timing and emission factor estimation assumptions (Tamayao et al., 2015). While this study provided direct vehicle comparisons, it also made policy recommendations that we will address later but to summarize them: (1) Federal and state EV subsidies should prioritize regions with lower grid emissions to maximize climate benefits; (2) Charging incentives should encourage charging when cleaner energy sources are available rather than assuming off-peak charging is always better: (3) As the U.S. electricity grid decarbonizes, EVs will become a better alternative to ICE vehicles-but for now, regional differences in emissions must be accounted for in EV policy discussions (Tamayao et al., 2015). This study challenges the assumption that EVs are inherently better for the environment, emphasizes that not all EVs can be treated the same, and demonstrates that in some instances, EVs do not consistently outperform their efficient hybrid counterparts.

Continuing an evaluation of EVs and their CO2 emissions, a study by Singh et al. (2024) examines whether EVs, like the Tesla Model S, consistently proved net greenhouse gas (GHG) reductions compared to hybrid gasoline vehicles. Researchers aim to uncover if EVs always outperform hybrids in terms of emissions, how the Tesla Model S compares to best-in-class hybrids like the Toyota Prius, and how future electricity grid scenarios asses Tesla’s CO2 footprint.

Since the U.S. transportation sector accounts for 29% of the total greenhouse gas emissions (Singh et al., 2024), specific methods are used to answer the research questions of this study. Critical Emissions Factor (CEF) is the maximum CO2 intensity of the electricity grid at which an EV still outperforms a hybrid gasoline vehicle in terms of emissions. The study uses regional electricity emissions data and life cycle assessment modeling. It points out, “Existing LCA studies comparing EVs to other vehicles differ considerably regarding their scope of analysis and the inclusion (or omission) of some important factors. While all life-cycle stages are relevant, the use-phase emissions are most important.” (Singh et al., 2024) The vehicles used in this study are the Tesla Model S, Toyota Prius and Honda Accord Hybrids, Nissan Leaf, and the Chevy Volt. This study also uses trip data for each state to aid in some of the assumptions made during calculations.

The findings indicate that EVs do not consistently outperform hybrids in terms of emissions, and their sustainability depends on regional grid composition. Starting with CEFs, if grid emissions exceed 500gCO2/kWh then a Tesla Model 3 or Model Y has higher lifetime CO2 emissions than a Toyota Prius. Conversely, if grid emissions are below 200gCO2/kWh, a Tesla and other EVs provide a clear emissions reduction benefit. It is important to note that 60% of the U.S. electricity grid surpasses the CEF threshold, meaning EVs in these areas may not significantly reduce CO2 emissions compared to efficient gasoline hybrids (Singh et al., 2024). Regarding CO2 emissions per mile, in coal-heavy states (West Virginia, Kentucky, Missouri, and Indiana), Tesla’s emissions exceed those of the Toyota Prius. In natural gas-dominant states (Texas, Pennsylvania, and Florida), Tesla’s CO2 emissions are on par with gasoline hybrids. Lastly, in renewable-heavy states (California, Washington, Oregon, and New York), Tesla’s emissions are 50-70% lower per mile than gasoline hybrids. Charging EVs at night in coal-heavy states increases their CO2 footprint. Charging during peak solar energy production hours significantly reduces Tesla’s emissions per mile. Moreover, in wind-heavy regions, charging at night may reduce CO2 emissions. All of these point to the fact that consumer charging behavior directly influences the reduction of CO2 emissions in Tesla vehicles. The study also models how grid decarbonization will impact Tesla’s sustainability. If current trends continue, U.S. grid emissions will decline by 40% by 2035, making EVs a cleaner alternative across most regions. Additionally, if coal retirements accelerate, EV sustainability will improve even faster. However, without policy interventions, fossil fuel dependency could persist in some regions, further limiting the benefits of EVs in those areas.

Both studies by Tamayao et al. (2015) and Singh et al. (2024) focus on the regional variability in EV emissions and question whether EVs consistently offer greenhouse gas (GHG) reductions compared to hybrid vehicles. They share a common foundation in using life cycle assessment modeling and regional electricity emissions data to evaluate the real-world impact of EVs. Both studies challenge the assumption that EVs are inherently cleaner than hybrids and emphasize that regional energy grid composition significantly influences an EVs overall carbon footprint. One key commonality is the importance of marginal vs average emissions factors in assessing EV emissions. Tamayao et al. (2015) highlight that AEFs often underestimate emission factors. Similarly, Singh et al. (2024) introduce the Critical Emissions Factor that reinforces the argument that EV emissions should be evaluated on a regional basis rather than relying on national averages. Both studies explain that EV sustainability is not universal- in some regions, hybrid vehicles like the Toyota Prius outperform EVs, and in some regions, they do not. The Nissan Leaf, Chevy Volt, and Toyota Prius are common themes across both studies.

Though similarities are present throughout, the studies are different in scope. Tamayao et al. (2015) assume a 100,000 to 150,000-mile for vehicle lifetime, while Singh et al. (2024) use trip data for each state and require multiple assumptions to be made during the research. Singh et al. (2024) make Tesla-specific comparisons, explicitly calculating CO2 per mile for Tesla vehicles, while Tamayao et al. (2015) make a broader comparison of EVs vs. hybrid vehicles across multiple U.S. regions.

Overall, both studies argue that EVs should be evaluated based on regional electricity emissions rather than assumed to be low-carbon or zero-carbon vehicles.

**2.1.3 The Role of Climate, Seasonal Variability, and Grid Efficiency**

While regional electricity generation determines the baselines for CO2 emissions of EVs, external environmental factors such as ambient temperature and seasonal variability further influence their real-world efficiency and carbon footprint. A study by Ansari et al. (2024) investigates how ambient temperature changes impact the plug-in hybrids vehicles’ energy consumption and CO2 emissions. Conducted in Alberta Canada; according to the researchers, “The existing body of research lacks a comprehensive analysis of energy consumption and CO2 emissions for PHEVs across all four possible powertrain modes: pure electric, charge-depleting hybrid electric, charge-sustaining hybrid electric, and ICE. This gap is particularly pronounced in studies considering a wide range of ambient temperatures, especially under frigid conditions. Furthermore, there is a notable absence of research on the cold start and warm-up periods for different powertrain modes of PHEVs and their subsequent effect on energy consumption and CO2 emissions. Additionally, previous studies often overlooked the actual measurement of fuel consumption from PHEVs. This paper aims to address these research gaps through the following contributions:

* Real-world data collection and an analysis of the effect of Tamb on the energy consumption and CO2 emissions of a PHEV for urban and highway conditions for a Tamb ranging from −24 ◦C to 32 ◦C;
* A study of the cold start and warm-up period of an electrified vehicle, considering the exhaust after-treatment temperature and coolant temperature;
* The vehicle’s actual fuel and energy consumption is measured and analyzed in different powertrain modes for over 4000 km of vehicle operation.” (Ansari et al., 2024)

This study deploys real-world driving tests spanning 4,150km across diverse temperature conditions ranging from -24C to 32C. A Ford Escape MY2021 is used as the test vehicle due to its ability to operate in the multiple driving modes stated above. This allows for a direct comparison between electrified and traditional vehicles without requiring multiple vehicles. The tires remained the same on the vehicle, and maintaince was completed per the manufacturer’s recommendations. The vehicle was driven in urban and highway driving settings, while fuel consumption. During the drives, energy consumption, and CO2 emissions were measured directly from the vehicle’s powertrain system instead of relying on model estimates (Ansari et al., 2024).

The results demonstrate that ambient temperature profoundly affects EV and PHEV efficiency, with colder temperatures causing drastic increases in energy consumption and CO2 emissions. In colder temperatures, battery performance declines, requiring more energy for heating and prolusion, while at -20C, the energy consumption when the vehicle operates on battery power increases by 350% compared to optimal conditions. At 0C, energy demand was 170% higher than at 23C, the optimal temperature, showing that even moderately cold temperatures significantly impact EV performance. This study assessed how increased demand in extreme temperatures would affect the CO2 emissions from power plants supplying the electricity. At -20C, total CO2 emissions per mile increased by 290%. In contrast, “The reduction in CO2 emissions of EVs varies geographically due to significant differences in the carbon intensity of electricity production in different world regions [6,7].” (Ansari et al., 2024). “Decreasing the ambient temperature from ∼30 ◦C to ∼−23 ◦C increased the total CO2 emissions of all powertrain modes, with the most drastic effect on the EV Now and Auto EV modes (a 290% and 260% increase, respectively) and the least effect on the EV Charge mode (8%). The CO2 intensity of the power grid (gCO2 /kWh) must be considered for each region to determine the CO2-minimal operation mode for a plug-in hybrid powertrain. Regions with a low CO2 intensity of the power grid, a moderate climate, and short traveling distances are ideal regions for using electric and plug-in hybrid electric vehicles. By reducing the ambient temperature from 29 ◦C to −22 ◦C in EV Now mode, CO2 emissions increased by almost 3.6 times, from the lowest of 57 g/km to 206 g/km. Similarly, in Auto EV mode, CO2 emissions rose 3.9 times when Tamb dropped from 29 ◦C to −24 ◦C. In EV Later mode, CO2 emissions increased by 70% as the temperature decreased from 28 ◦C to −23 ◦C, rising from 150 g/km to 259 g/km(Ansari et al., 2024).” Compared to ICE vehicles, these vehicles are less affected by temperature changes, with fuel consumption increasing by only 7-8% and a negligible change in CO2 emissions due to temperature change. These results emphasize that the influence of ambient temperature on CO2 emissions is more pronounced on models that exclusively utilize electric motors in regions like Alberta, demonstrating that EVs do not consistently outperform ICE vehicles.

While regional temperature variability directly impacts EV efficiency and emissions, factors such as air quality and public health must also be considered when attempting global electrification of transportation. A study by Peters et al. (2020) evaluates the intersection of public health, climate benefits, and trade-offs of EVs in the U.S. “In 2017, U.S. transportation sector GHG emissions surpassed all other individual sectors, accounting for 29% of the country's total GHG emissions. Within the transportation sector, ~60% of GHG emissions came from light‐duty vehicles (U.S. Environmental Protection Agency [EPA], 2019a). (Peters et al., 2020)” The study aims to answer how large-scale EV adoption impacts CO2 emissions, the health benefits and risks associated with EV adoption, and what policies can maximize the health and environmental benefits of EV adoption.

To answer these questions, researchers modeled six EV adoption scenarios, ranging from 25% to 75% market penetration, assessing the effects on emission, air quality, and public health outcomes (Peters et al., 2020). The study calculates emission changes by removing emissions from light-duty passenger vehicles and adding emissions from combustion-fired electricity generation units. Emissions data from the U.S. Environmental Protection Agency (EPA) and the Emissions & Generation Resource Integrated Database (eGRID) is used. To assess the health impacts of EV CO2, estimations of changes in premature deaths, respiratory diseases, and economic loss due to pollution-related health issues are made (Peters et al., 2020). Various levels of grid decarbonizations are modeled to analyze the effects of EV adoption under changing renewable energy sources.

One of the study’s key goals is to determine how much CO2 emissions can be reduced when gasoline-powered vehicles are replaced with EVs. Under a 75% adoption scenario, nationwide emissions from the transportation sector are reduced by 45%; in regions with renewable energy, CO2 reductions exceed 70%, and in fossil fuel dominant grids, CO2 reductions are as little as 10-15% (Peters et al., 2020). It is also important to note that this study finds that peak electricity demand from EV charging can temporarily increase emissions in regions where fossil fuels are used as backup sources during high-demand hours. Another key goal is to determine the public health impacts of EV adoption. Here, the emissions of nitrogen oxides, sulfur dioxides, and particulate matter are the pollutions in question. In highly renewable states, EV adoption leads to reducing premature deaths caused by air pollution by 5,000 to 10,000 annually; in coal-heavy states, health benefits are much smaller, and in some cases, emissions slightly increase (Peters et al., 2020). A figure ranging from 20 billion to 70 billion per year in avoided healthcare costs and productivity losses can be attributed to EV adoption. A concern raised by the study is whether EV adoption shifts emissions from tailpipes to power plants. In regions with a clean energy mix EV adoption leads to an overall reduction in CO2 and pollutant emissions, in regions relying on coal increased electricity demand from EVs leads to more emissions from power plants, and some regions experience a tradeoff of less nitrogen oxide and particulates but more sulfur dioxide and carbon dioxide (Peters et al., 2020). This study finds that, “while U.S. vehicle electrification is expected to significantly reduce transportation CO2 emissions and has the potential to improve air quality and mitigate thousands of annual premature deaths, the extent and magnitude of health co‐benefits largely depend on the charging energy mix, particularly for changes in PM2.5. The results show that while electric vehicles under status quo energy regimes produce significant CO2 reductions, the greatest health co‐benefits are achieved by electrifying vehicles and charging with a greater fraction of emission‐free electricity generation sources. (Peters et al., 2020)”

Both studies by Ansari et al. (2024) and Peters et al. (2020) examine the external factors influencing the environmental benefits of electric vehicles highlighting how conditions beyond electricity generation impact emission and sustainability outcomes. While Ansari et al. (2024) focus on the effect of ambient temperature on EV efficiency and CO₂ emissions, demonstrating that colder climates significantly increase energy consumption and emissions, Peters et al. (2020) expands the scope to analyze the broader public health and climate trade-offs of EV adoption, emphasizing how regional grid composition affects air pollution and health outcomes. A key commonality is their shared conclusion that EV benefits are highly dependent on external conditions—whether it be temperature or energy mix—challenging the notion that EVs are universally superior to gasoline-powered vehicles. However, their methodologies differ significantly: Ansari et al. (2024) rely on real-world driving tests to measure temperature-related inefficiencies in a single-vehicle model, while Peters et al. (2020) employ large-scale emissions modeling to assess how different EV adoption rates impact CO₂ and pollutant levels across the U.S. Ultimately, both studies reinforce the argument that EV sustainability is not uniform, requiring region-specific assessments to determine their environmental and health impacts accurately.

**2.1.4 Electricity Generation CO2 Emissions and Regional Variability Summary**

The studies reviewed in theme 1 emphasize that EVs' sustainability depends heavily on regional electricity generation, charging behavior, climate conditions, and grid efficiency. Ghosh et al. (2023) and Qin et al. (2022) demonstrate that CO₂ emissions from power plants vary significantly, meaning EVs in coal-heavy states have a much higher carbon footprint than those in renewable-heavy regions. Tamayao et al. (2015) and Singh et al. (2024) highlight that EVs do not consistently outperform hybrids in CO₂ reductions, especially when using marginal emission factors (MEFs) instead of average emission factors (AEFs). Singh et al. (2024) introduced the Critical Emissions Factor (CEF), showing that in 60% of the U.S., hybrids like the Toyota Prius may produce fewer emissions than Tesla’s. Both studies emphasize that charging behavior affects emissions, with nighttime charging in fossil fuel-heavy grids often increasing CO₂ output. Beyond electricity generation, climate conditions play a significant role. Ansari et al. (2024) find that cold temperatures significantly increase EV energy consumption and CO₂ emissions, making them less efficient in colder regions. Similarly, Peters et al. (2020) reveal that the health benefits of EV adoption vary by region, with air quality improvements in renewable-heavy areas but potential pollution trade-offs in coal-dependent states. In conclusion, EVs are not inherently low-carbon vehicles—regional grid composition, charging habits, and environmental conditions dictate their sustainability.

**2.2. EV Emission Per Mile Based on Power Grid Sources**

While EVs are considered a cleaner alternative to internal combustion engines, their true environmental impact, as we’ve seen above, is largely dependent on the carbon intensity of the electricity used for charging. This theme explores EVs CO2 emissions per mile compared to gasoline and hybrid vehicles. The studies within this section analyze life cycle emissions of EVs, compare their real-world CO2 impact to traditional vehicles and evaluate the role of charging behavior and grid decarbonizations. This section provides a comprehensive look electricity generation and its influences on the carbon footprint of EVs.

**2.2.1 CO2 Impact of EVs Compared to Internal Combustion Vehicles**

Continuing the discussion, a study by Prival (2023) aims to address a fundamental question in the EV sustainability debate: Do EVs consistently reduce CO2 emissions compared to internal combustion (ICE) vehicles. The research compares BEV emissions to those of hybrid vehicles (HEVs) using marginal emissions factors. Additionally, the study explores how vehicle efficiency and grid composition influence per-mile emissions and whether EVs are a viable long-term strategy for decarbonizing the transportation section in the United States.

To answer this question, data is sourced from electricity generation CO2 emissions from Holland et al. (2022) , energy combustion data from BEV models from the U.S. Department of Energy, and MPG equivalency calculations are based on EPA fuel economy standards. The vehicles analyzed in the study include a mix of popular EV models, such as the Tesla Model 3, Nissan Leaf, and Chevrolet Bolt, as well as high-efficiency hybrid and gasoline-powered vehicles, including the Toyota Prius and Honda Accord Hybrid. The study compares per-mile CO₂ emissions based on regional grid composition and the energy efficiency of each vehicle type. MPG-equivalent calculations with respect to CO2 for the BEVs was based on the report of the US Environmental Protection Agency (2023) that combustion of 1 gallon of gasoline releases 8887 grams of CO2 (Prival 2023).

Prival (2023) finds that, “In the East, only one of the BEV models examined, the Tesla Model 3 RWD, has an MPG equivalent (52.9 MPG) higher than any of the eleven HEV models listed above. Thus, operating any of these HEVs has a carbon footprint equal to or smaller than nine of the ten BEVs. Four of the HEVs (Toyota Prius, Hyundai Elantra Hybrid Blue, Toyota Prius AWD, and Kia Niro FE) have smaller calculated carbon footprints than the Tesla Model 3 RWD. In the West, most, but not all, of the BEVs have higher MPG-equivalent ratings, and thus smaller carbon footprints, than any HEV. As shown above in the Methods section, operating a Tesla Model 3 results in emission of 24% less CO2 than a Toyota Prius, while for a Nissan Leaf it is 9% less than a Prius. Two of the BEVs (the Porsche Tycan GTS and Audi e-tron quattro) have MPG equivalents in all three geographic regions of the United States less than the 49 MPG rating of the least efficient HEVs listed, and thus operating these two BEVs results in more CO2 emissions than any of the eleven HEVs.” Another key finding is that battery production emissions account for a significant proportion of an EV’s total carbon footprint. Manufacturing an EVs lithium-ion battery produces 40-60% more CO2 than manufacturing a comparable gasoline vehicle (Prival 2023). Although these upfront carbon costs are offset over time as long as the EV is in a region with cleaner electricity. The research underscores the importance of grid decarbonization in maximizing the emissions reductions from an EV adoption.

Shifting to CO2 emissions on a global scale, a study by Maertz et al. (2021) provides a global analysis of the CO2 emissions associated with electric vehicles across different regions and how these emissions can change over time due to changes in the electricity grid. Some are the questions this study aims to answer are how do regional differences in electricity generation impact electricity generation impact the emissions of EVs, should EV adoption be accelerated now or should it wait, and what are the long-term global trends in CO2 mitigation from EVs.

To answer these questions, as we’ve seen previously, researchers applied a reduced LCA approach that focuses on the usage phase of EVs while also incorporation vehicle and battery production emissions (Maertz et al., 2021). GHG emissions for vehicle and battery productions were calculated and the use of future energy scenarios from the International Energy Agency (EIA) were deployed. Two EV market scenarios were analyzed: EV30@30 where EVs make up 30% of the sales by 2030 and New Policies Scenario which is a more conservative model based on existing policies and trends. Five major automotive markets were examined, China, the United States, Europe, Japan and India which represents 80% of the global passenger vehicle sales (Maertz et al., 2021). Also, assumptions of battery and vehicle productions emissions declining over time due to cleaner electricity sources were made.

The results from this study reveal that EVs can significantly reduce emissions but the extent of their reduction is entirely dependent on regional electricity sources. Currently EVs produce between 111-176 gCO2/km, with the lowest emissions found in Europe and the highest in coal-dependent India (Maertz et al., 2021). In China and India, higher emissions are from EVs are shown due to a reliance on coal, showing that in these regions EVs may not offer a significant CO2 savings over internal combustion engine (ICE) vehicles. In a modeled scenario in which China delays EV adoption by 10 years, the emissions savings from better battery technology do not outweigh the CO₂ reductions lost from continuing gasoline vehicle use. Additionally, the study’s sensitivity analysis finds that **battery size and charging behavior** influence the carbon footprint of EVs, while larger battery capacities (50 kWh vs. 35 kWh) initially increase emissions, long-term grid decarbonization offsets this impact (Maertz et al., 2021). This study reinforces that EVs can be an effective solution for reducing transportation-related CO2 emissions only if they are powered by a low-carbon electricity grid.

Both studies by Prival (2023) and Maertz et al. (2021) examine the CO₂ impact of EVs, emphasizing that their environmental benefits depend on regional electricity sources. Both challenge the assumption that EVs are always low-emission, showing that they may not outperform hybrids or ICE vehicles in coal-heavy regions. They also highlight the role of battery production emissions, with Prival (2023) noting that EV battery manufacturing increases CO₂ output by 40-60%, while Maertz et al. (2021) suggest that future grid decarbonization will offset these emissions.

However, the studies differ in scope and conclusions. Prival (2023) focuses on the U.S., finding that most EVs have a higher carbon footprint in the East than hybrids, while in the West, cleaner grids make EVs more sustainable. Maertz et al. (2021) take a global approach, showing that coal reliance limits EV emissions benefits in China and India. Policy recommendations also differ—Prival (2023) argues that EV incentives should prioritize clean-energy regions, while Märtz et al. (2021) advocate for immediate EV adoption despite current grid emissions. Both studies underscore that EV sustainability is not universal and depends heavily on energy sources and policy decisions.

**2.2.2 Modeling and Predicting EV CO2 Emissions**

To better understand the degree to which a particular electricity grid profile, the vehicle type, and charging patterns impact CO2 emissions from light-duty and plug-in electric vehicles, a study by McLaren et al. (2016) was conducted. Sponsored by the United States Government, the National Renewable Energy Laboratory (NREL) set out to answer how the emissions intensity of different electricity grids impact the CO2 emissions associated with EV charging, what role does charging behavior play in determining emissions, and do plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) experience different emissions based on charging location and time of day? “The analysis described in this paper investigates the emissions impacts by time of day and charging scenario for five different electricity grid mixes and multiple vehicle types (McLaren et al., 2016).”

The study models the emissions impact of EV charging under five different energy grid profiles that each represent a mix of fossil fuels and renewables. These grids were generated using the production cost model PLEXOS (Energy Exemplar 2015), which simulates the least-cost dispatch of the electric power system, taking into account hourly

variations in demand and numerous operational constraints (McLaren et al., 2016). The analysis examines both BEVs and PHEVs and evaluates four different charging scenarios: 1. Home level slow charging, 2. Home level fast charging, 3. Time-restricted charging between midnight and early afternoon, and 4. Workplace charging via home/work during daytime hours. Following the trend of articles, this study uses marginal emissions factors (MEFs) rather than average emissions factors (AEFs), which allows for more accurate estimates based on real time measurements. The calculations include both electric miles (charged using the grid) and non-electric miles (PHEVs operating on gasoline) (McLaren et al., 2016).

When pertaining to charging the study finds that “Workplace charging scenario results in relatively high emissions from electric miles on most grids. However, workplace charging results in relatively low emissions from non-electric miles. Low emissions from non-electric miles offset high emissions from electric miles such that workplace charging results in the least total emissions on all but high carbon grids. (McLaren et al., 2016)” In line with previous articles, the study also finds that EV emissions vary widely depending on the carbon intensity of the grid they are charged on. Also on par with our previous articles, this study found that charging time matters and that PHEVs can have lower emissions than BEVs in ceratin conditions. Specifically, “Notably, PHEVs yield lower total emissions than BEVs in four of the five grid types. The low-carbon grid is the only case in which BEVs have lower total emissions. This is due to our inclusion of non-electric miles in the calculation of total emissions. PHEVs have a higher mile-per-gallon efficiency and their non-electric miles have a lower carbon intensity than BEV non-electric miles (which are driven in a conventional vehicle). (McLaren et al., 2016)” This study highlights that EVs are not inherently low-carbon and their benefits depend on the electricity grid used for charging, and the time of charge.

Recent advancements in deep learning models have provided new tools in predicting vehicle CO2 emissions with high precision, offering a data-driven approach to understanding the environmental impact of electric vehicles. The study by Issac et al. (2024) addresses the challenging task of predicting CO2 emissions with precision. Traditional methods including statistical modeling and machine learning algorithms have been proposed for predicting CO2 emissions (Issac et al., 2024). While there may not be a direct “research question”, the goal of this study is to develop accurate and intelligent models for predicting CO2 emissions that capture the relationships between factors.

To accomplish this goal, researchers developed and tested deep learning architectures, including CNN-LSTM and DCNN models by integrating them with real-world data and evaluating their performance (Issac et al., 2024). The process of this development consisted of data collection, data preprocessing, model development, and model evaluation.

The study found that deep learning models significantly outperformed traditional machine learning methods in predicting vehicle CO2 emissions. Specifically, the experimental results show that the DCNN model achieved a test accuracy of 96.34%, surpassing the 74.02% accuracy of KNN and the 92.55% accuracy of RF, while the CNN-LSTM showed superior performance, with a validation accuracy of 97.73%, reinforcing the effectiveness of deep learning in emissions prediction (Issac et al., 2024). This introduces a “groundbreaking method” using deep learning algorithms for predictions of CO2 emissions. The study underscores the need from integrating deep learning models into real time emission monitoring systems to enable more accurate tracking of CO2 output.

Both studies by McLaren et al. (2016) and Isaac et al. (2024) examine EV emissions variability but take different approaches. McLaren et al. (2016) focuses on real-world charging scenarios, showing that EV emissions depend on grid intensity and charging behavior. Their findings challenge the assumption that BEVs always have lower emissions, revealing that PHEVs can outperform BEVs in four of five grid types.

Isaac et al. (2024), on the other hand, introduces deep learning models to enhance CO₂ emissions prediction accuracy. These models achieve up to 97.33% accuracy which outperforms the current statistical methods but fails in analyzing real-world grid variability. While McLaren et al. (2016) provides a practical emissions experiment and analysis, Issac et al. (2024) advances the predictive capabilities of CO2 emissions between factors. Together they highlight the need for both accurate forecasting, accurate databases, and refined real-world assessments to better evaluate EV sustainability.

**2.2.3 The Role of Charging Behavior and Grid Decarbonization**

In a study by Xiao et al., (2024), the role of electric vehicle (EV) grid integration in reducing regional carbon emissions is examined. This research focuses on the interaction between EV adoption, vehicle-to-grid technology and the structure of energy sources in determining carbon emissions. The study aims to answer the questions: How does increasing the scale of EV adoption impact regional carbon emissions? What role does vehicle-to-grid (V2G) technology play in emissions? How Does the energy structure influence the extent to which EVs contribute to decarbonization?

The study uses system dynamics method to model and analyze the impact of EVs’ integration into the grid on carbon emissions (Xiao et al., 2024). The factors influencing change in emissions are divided into four sub models and are interconnected to form a framework for analyzing the impact of EVs’ integration into grid (Xiao et al., 2024). The modules consist of EV development module, charging and discharging response model, energy structure module, and carbon emission module. Vensim diagrams of each model show the network diagram and Vensim software is conducted to analyze the impact of EV grid integration in three different scenarios: pessimistic, normal, and optimistic . It is important to note the location, this study is based on a city in southwest China.

The results indicate that “With the development of clean energy, the number of EVs has increased from 435,700 to 2,760,490. During this process, the continuous expansion of EVs will have a significant effect on carbon emissions reduction. If EVs can replace some of the coal-fired power plants in demand response, the reduction in carbon emissions will be further enhanced. The vigorous development of clean energy is of great significance for achieving carbon reduction goals. (Xiao et al., 2024)” Furthermore, the study highlights that V2G technology can accelerate emissions reductions by enabling EVs to send stored energy back to the grid which could replace fossil fuel-generated electricity in peak demands. As with previous articles, this study finds that the most effective carbon reduction strategies involve a combination of widespread EV adoption, aggressive grid decarbonization, and strategic implementation of V2G systems (Xiao et al., 2024). This study underscores the role of energy grid composition in determining EV sustainability.

When dealing with electric vehicle integration or electric vehicle adoption, there are multiple impacts across technological, environmental, organizational, and policy dimensions. A study by Zaino et al. (2024) provides an overview on 88 different studies on EV adoption. The study points out that the current body of literature on Ev adoption tends to focus on specific aspects, often overlooking the various impacts of EVs (Zaino et al., 2024). The study aims to answer: How does charging behavior and grid emissions affect EV sustainability? What role do governments play in accelerating EV adoption? What are the long-term impacts of EV expansion.

This study aims to answer these questions by reviewing 88-peer reviewed articles covering technological, environmental, and policy aspects of widespread EV adaption. A comprehensive search in the Scopus database was conducted to carefully select articles and split them into their 4 corresponding categories. By adhering to PRISMA 2020 guidelines the literature was reviewed to ensure relevance and quality (Zaino et al., 2024). Through VOSviewer articles continued to be refined until the final selections were made.

This is an amazing article so it’s difficult to summarize all the findings from their research. For the technological advancement section, researchers found that improvements battery life, charging infrastructure, and energy efficiency are driving adoption rates though ongoing innovation and investment is crucial to address things like limited battery range and the need for more robust charging networks (Zaino et al., 2024). In the Policy and regulatory framework section, researchers found that policy support is crucial for eve adoption and effective strategies like incentives and subsidies have stimulated marked expansion, their varying effectiveness shows the need for well-crafted policies that consider local market conditions (Zaino et al., 2024). For economic and organizational impacts, the researches found that EVs offer protentional lifecycle cost savings, especially for those with large fleets, despite the upfront costs while offering improved fleet management capabilities and a more sustainable corporate image (Zaino et al., 2024). Lastly for environmental benefits, researchers found that when coupled with renewable energy sources, a shift to EVs can significantly reduce GHG emissions and contribute to improved urban air quality and noise reduction (Zaino et al., 2024). This study highlights that EV adoption is not as simple as just driving a car, it takes multiple industries working together for the benefits of EVs to truly be seen.

The studies by Xiao et al. (2024) and Zaino et al. (2024) share a common focus on how charging behavior and grid decarbonization influence the overall emissions impact of EVs, yet they differ in their methodological approach and scope. Both studies highlight that the carbon footprint of EVs is directly linked to the power grid composition, reinforcing the idea that without significant grid decarbonization, EVs may not offer substantial CO₂ reductions compared to internal combustion vehicles. Xiao et al. (2024) specifically examines the dynamic interaction between regional carbon emissions and EV integration, using system dynamics modeling to predict how EV adoption impacts grid emissions over time. A key finding of the study is that increased EV penetration can initially raise emissions in fossil fuel-dominant grids due to additional electricity demand.

Zaino et al. (2024), on the other hand, takes a broader systematic review approach, synthesizing data from 88 studies to assess the technological, environmental, organizational, and policy impacts of EV adoption. While this study supports the findings of Xiao et al. (2024) regarding grid decarbonization, it expands the discussion by emphasizing the role of policy incentives, charging infrastructure investments, and corporate fleet electrification in shaping EV sustainability. The study finds that the effectiveness of EV policies varies significantly across regions, depending on grid composition, economic factors, and consumer behavior.

Despite their different methodologies, both studies converge on the conclusion that EV adoption alone is insufficient for achieving deep carbon reductions without parallel investments in renewable energy generation and smarter charging strategies. Xiao et al. (2024) provides a predictive framework for policymakers, while Zaino et al. (2024) offers a holistic assessment of existing literature, making both studies complementary in understanding the future trajectory of EV emissions.

**2.4 EV Policies, Incentives, and Market Adoption**

EV adoption is not soley driven by environmental concerns or technological advancements, there are a lot of government policies, financial incentives, and public perception driving this adoption. The section investigates the role of government policies, financial incentives and social factor that influence EV market growth.

**2.4.1 The Effectiveness of Government Policies on EV Adoption**

To better understand how federal and state-level incentives are driving EV adoption across the U.S., a study by Jenn et al. (2018) seeks to determine whether financial incentives like tax credits, rebates, and exemptions increase EV sales, which policies are the most influential, and whether these incentives benefit higher-income consumers disproportionately.

Researchers use state-level EV sales data from 2010-2016 and compare these sale trends before and after policy changes. This study aims to contribute to the growing body of literate with a focus on the U.S. EV market (Jenn et al., 2018). The analysis includes federal and state-level purchase incentives, income-based tax credits, and non-monetary incentives like HOV lane access.

Jenn et al. (2018) finds that for every $1000 offered as a rebate tax credit, average electric vehicle sales increase by 2.6%. Jenn et al. (2018) also finds that HOV lane access is a significant contributor to adoption, showing a 4.7% increase in HOV lane density. This study also notes that “we are able to additionally measure the heterogeneity in incentive effects across different states and find a much higher range for some states with greater volumes of EVs adopted (Jenn et al., 2018)” The study concludes that targeted incentives such as direct rebates and income-based programs could increase EV adoption across a broader demographic and maximize emissions reduction benefits.

Continuing with financial incentives Clinton and Steinberg (2019) examine how different types of financial incentives influence battery electric vehicle (BEV) adoption in the United States. This study Explores whether purchase incentives like rebates and tax credits, operational incentives like reduced electricity rates and free parking, and infrastructure incentives like subsidies for home chargers differ in their effectiveness at increasing EV adoption. Additionally researchers seek to determine which demographic responds to most financial incentives, and whether these should be adjusted to target low and middle income consumers.

This study utilizes EV registration data from 2012 to 2018 across multiple states and correlates it with available incentive programs. A **multivariate regression model** is applied to isolate the effects of **purchase subsidies, tax credits, electricity rate reductions, free parking, and charger installation incentives.** The researchers also incorporate **survey data from over 5,000 EV buyers** to assess how incentives influenced their purchase decisions and whether certain incentives were more attractive to specific income brackets.

Clinton and Steinberg (2019) find that purchase incentives, particularly direct rebates, are the most effective driver of EV adoption, with rebates increasing BEV purchases by 7-9% on average, compared to a 3-5% increase from tax credits. Also, Clinton and Steinberg (2019) conclude that optimizing EV incentives requires a targeted approach, where rebates and charging infrastructure support should focus on middle- and low-income consumers, while tax credits and non-monetary incentives may be more effective for wealthier buyers.

Both Jenn et al. (2018) and Clinton Steinberg (2019) analyze the impact of financial incentives on EV adoption in the United States, emphasizing the role of government policies in accelerating market penetration. Both studies highlight that incentives disproportionately benefit higher-income consumers, raising concerns about equity in EV policy design.

However, the studies differ in approach. Jenn et al. (2018) focuses primarily on federal and state tax credits and how they influence EV adoption trends while Clinton & Steinberg (2019) takes a broader approach, examining multiple types of financial incentives, including rebates, electricity rate reductions, free parking, and charging infrastructure subsidies. While Jenn et al. (2018) emphasize the overall effectiveness of tax credits, Clinton & Steinberg (2019) provide a detailed breakdown of which incentives work best for different demographics, showing the need for a targeted incentive approach.

Both studies reinforce the importance of government intervention in shaping the EV market but suggest that incentives should ensure equitable access, particularly for lower-income consumers.

**2.4.2 Public Perception and Policy Misinformation**

To help consumers in sifting through the myths of EVs, The Environmental Protection Agency (EPA) provides an analysis of common misconceptions surrounding electric vehicles (EVs), aiming to clarify misinformation and present data-backed insights. The study addresses key concerns such as whether EVs truly reduce emissions, the impact of battery production, electricity grid dependency, and range anxiety. The research questions guiding the analysis include: Are EVs truly lower in emissions than gasoline vehicles? Do EVs strain the power grid? Are EV batteries sustainable?

The methods involve a comparative life cycle analysis (LCA) of vehicle emissions, power grid energy mix assessments, and data from the U.S. Department of Energy and multiple scientific studies to evaluate real-world emissions and grid performance.

The findings reaffirm that EVs produce significantly lower greenhouse gas emissions than gasoline-powered vehicles over their lifetime, despite the higher emissions from battery manufacturing. The report emphasizes that EV emissions vary regionally depending on the electricity grid, but in nearly all cases, they outperform internal combustion engine (ICE) vehicles. Ironically, the study refutes concerns about grid overload, explaining that current infrastructure can handle increased EV adoption, especially with smart charging strategies (EPA, n.d.). EPA (n.d.) also highlight the advancements in battery recycling and second-life applications, reducing concerns about environmental waste. Lastly the study debunks range anxiety, noting that the average daily driving distance in the U.S. is well within the range of modern EVs. Overall, the report underscores the need for fact-based public awareness regarding EVs.

Shifting away from EV myths, Kim (2023) provides an analysis of the Inflation Reduction Act (IRA) and its implications for international trade, focusing on the relationship between the United States and South Korea. The study seeks to determine whether the IRA’s electric vehicle (EV) incentives comply with international trade laws, how these policies impact global EV supply chains, and what economic and diplomatic effects they have on U.S.-Korea relations. The research highlights the growing tension between domestic industrial policies and international trade agreements, particularly concerning the eligibility of EV tax credits for North American-assembled vehicles.

To examine these questions, the study analyzes provisions within the IRA, trade agreements such as the U.S.-Korea Free Trade Agreement (KORUS), and WTO regulations. Additionally, it reviews responses from major automotive manufacturers and policymakers in both countries.

Kim (2023) finds that while the IRA aims to strengthen domestic EV manufacturing and reduce dependence on foreign supply chains, it creates trade disputes by restricting incentives to vehicles assembled in North America. Kim (2023) also finds that the IRA’s incentives encourage domestic EV production and align with U.S. national security interests by reducing reliance on Chinese supply chains but adversely these measures risk straining alliances with key trading partners, potentially slowing the global transition to EVs. This study argues that for EV adoption policies to be effective, they must balance domestic economic priorities with international collaboration, ensuring a stable and cooperative global EV market.

The studies by the Environmental Protection Agency (EPA) and Kim (2023) both contribute to the discussion on electric vehicle (EV) adoption but differ in focus and scope. A commonality between the two is their emphasis on the role of policy and public perception in shaping the EV market. The article by the EPA aims to address misinformation surrounding EVs, seeking to correct misconceptions related to emissions, grid impact, battery sustainability, and even the common fear or running out of power while driving. Similarly, with misconception in mind, Kim (2023) highlights the importance of policy clarity in the context of international trade, emphasizing how government incentives influence EV adoption and global supply chains. Both studies recognize that misinformation—whether in public discourse or policy implementation—affects the pace and effectiveness of EV adoption.

However, their objectives diverge significantly. The EPA study is a broad assessment directed at possible EV buyers, using life cycle analysis (LCA) and grid energy assessments to support its claims that EVs generally produce lower emissions than internal combustion engine (ICE) vehicles. In contrast, Kim (2023) focuses on geopolitical and economic factors, analyzing trade policies and their implications for international cooperation. While the EPA report presents a largely optimistic view of EV sustainability, Kim (2023) shows the opposite tone of EV policy, showing that protectionist measures like the Inflation Reduction Act (IRA) may create economic tensions between nations.

Both studies emphasize the importance of transparent truth surrounding EVs and their policy decisions. The EPA study highlights the need for public education to dispel EV myths, while Kim (2023) underscores the necessity of balancing national policy with global trade relationships to ensure a sustainable and cooperative transition to EVs.

**2.4.3 Political and Economic Implications of EV Expansion**

With a title that is sure to grab your attention, “I’m Saving Fuel to Buy More Guns: The electric Vehicle as a Cultural Object and Climate Policy Solution” by McDonnell et al. (2023) aims to explore the cultural significance of electric vehicles (EVs) in the context of political identity and climate policy. The key research question include: How do EVs function as cultural objects? How do their material and economic benefits reshape their meaning among conservative consumers? Can climate policies be effective without requiring ideological shifts in environmental beliefs?

This study takes a material approach to cultural objects and reveals how hybrids and EVs are at the intersection of material affordances and conventional symbolic associations (McDonnell et al., 2023). The study employs a sociological and cultural analysis of EVs, incorporating data from consumer behavior, media representations, and political discourse. The authors investigate how EV adoption has traditionally been associated with liberal, environmentally conscious consumers, but as fuel prices increase and EVs become more mainstream, their perception among conservatives is shifting. The study considers how branding, technological innovation, and infrastructure development contribute to the reclassification of EVs as economically practical rather than politically symbolic.

McDonnell et al. (2023) find that while EVs were once a cultural maker of environmentalism, their current adoption is driven by lower fuel costs and advancements in battery technology. Conversative consumers who may reject climate change narratives are purchasing EVs for financial reasons and reframing them as tools of economic independence (McDonnell et al., 2023). The study also finds that “the material qualities of EVs and our alternative energy infra- structure uphold or upset the status quo of left v. right politics. (McDonnell et al., 2023)” The study concludes that if society can align the culture-material ecosystem supporting EVs with changing the meanings EVs have in the public eye the EV adoption speed will be greatly increased (McDonnell et al., 2023).

**2.3.4 EV Policies, Incentives, and Market Adoption Summary**

The studies in this theme examine how government policies, financial incentives, and political factors influence EV adoption. Jenn et al. (2018) and Clinton & Steinberg (2019) assess the impact of financial incentives, finding that tax credits and rebates significantly boost EV sales, though they often favor higher-income consumers. The second subtheme addresses public perception and misinformation, with the EPA (n.d.) debunking myths about EV emissions and grid strain, while Kim (2023) highlights the Inflation Reduction Act’s trade tensions and its impact on global EV supply chains. The final subtheme explores political and economic influences on EV adoption, with McDonnell et al. (2023) showing how EVs are shifting from environmental symbols to economic assets, especially among conservative consumers. Collectively, these studies show that EV adoption is shaped not just by environmental benefits, but by financial accessibility, political identity, and global trade dynamics.

**2.5 Critical Evaluation**

*a. What are the contributions of this literature to the field?*

This body of work contributes to the ongoing discourse on EV sustainability by integrating environmental, economic, and technological perspectives, ultimately pushing for more accurate assessments of EV emissions. These studies challenge the common perception that EVs are inherently sustainable, demonstrating that their emissions depend heavily on regional energy sources and driving conditions. The inclusion of policy and economic factors further expands the discussion, showing that financial incentives and public perception play a crucial role in EV adoption. The literature reviewed provides an in-depth analysis of the true carbon footprint of electric vehicles (EVs), emphasizing the role of electricity generation, charging behavior, and policy incentives in determining emissions per mile.

*b. Return to your thesis statement*

The goal of this research is to determine the true carbon footprint of EVs by accounting for CO2 emissions from electricity generation, rather than accepting the misleading notion that EVs are emissions-free. This aligns with the literature, which repeatedly demonstrates that EV emissions vary by region, charging patterns, and vehicle type. By applying data science methodologies, this research aims to fill the gap in existing studies by creating a standardized metric—CO2 per mile—that accurately reflects the sustainability of EVs. This metric will provide clarity for both policymakers and consumers, helping them make informed decisions regarding EV adoption.

*c. What are the overall strengths?*

1. **Comprehensive Analysis** – The reviewed studies examine EV sustainability from multiple angles, including emissions modeling, grid decarbonization, policy effectiveness, and consumer perception.
2. **Regional and Temporal Variability** – Several studies highlight the impact of electricity grid composition and charging behavior on emissions, reinforcing the need for region-specific assessments.
3. **Policy and Economic Considerations** – Research on incentives and public perception adds depth to the discussion, recognizing that environmental benefits alone do not drive EV adoption.
4. **Use of Empirical Data** – Many studies rely on life cycle assessments (LCA), real-world driving tests, and large-scale emissions databases, ensuring that findings are data-driven and applicable to real-world conditions.

*d. What are the overall weaknesses?*

1. **Limited Focus on Real-World Consumer Data** – Most studies rely on emissions models rather than direct consumer data, leaving a gap in understanding how actual EV owners interact with charging infrastructure.
2. **Underrepresentation of Tesla and High-Performance EVs** – Many studies analyze general EVs but do not specifically assess Tesla vehicles, which dominate the market and have unique charging behaviors.
3. **Lack of Standardized Emissions Metrics** – While studies provide valuable insights, there is no universally accepted metric for comparing EV and ICE vehicle emissions on a per-mile basis.
4. **Assumptions in Policy Studies** – Some policy-focused studies assume that incentives directly translate to increased adoption without considering behavioral factors that may influence consumer decisions beyond financial incentives.

*e. What might be missing?*

* **A Direct Comparison of CO2 per Mile Between EVs and ICE Vehicles** – The literature acknowledges that EV emissions depend on electricity sources, but there is little direct comparison between specific EV models and their hybrid or gasoline counterparts using a standardized CO2 per mile metric.
* **Longitudinal Studies on Grid Decarbonization Impact** – Future research could track how the gradual shift to renewable energy affects EV emissions over time.
* **Consumer-Level Data on Charging Patterns** – A better understanding of how EV owners charge their vehicles could provide a more accurate picture of real-world emissions.
* **The Role of Emerging Technologies** – Studies should explore how innovations like vehicle-to-grid (V2G) charging and smart grid integration could improve EV sustainability.

*f. What are some next steps for research? The next steps should explicitly address how to*

*“correct” for strengths, weaknesses, and gaps.*

To address these gaps, my future research should focus on:

1. **Developing a Standardized CO2 per Mile Metric** – Using EPA emissions data and real-world fuel economy figures, this study will establish a clear emissions comparison between EVs and ICE vehicles.
2. **Expanding Data Collection on Tesla and Other Leading EVs** – By incorporating Tesla-specific data, this study will refine its assessment of emissions based on real-world charging patterns.
3. **Integrating Machine Learning for Predictive Modeling** – AI-driven models could be used to predict future emissions trends based on evolving grid compositions and EV adoption rates.
4. **Incorporating Consumer Charging Behavior Data** – Surveying EV owners on their charging habits could validate assumptions about when and how they charge, refining emissions calculations.
5. **Evaluating the Long-Term Effects of Grid Decarbonization** – By tracking emissions reductions over time, future research could provide a more dynamic understanding of EV sustainability.

# III. Conclusion: An evaluation/critique of the existing literature

The objective of this research is to determine the true carbon footprint of electric vehicles (EVs) by accounting for the CO₂ emissions generated from electricity production rather than solely relying on the assumption that EVs are emissions-free. This study challenges the widely accepted notion that EVs are inherently sustainable by incorporating emissions data from power plants into a per-mile CO₂ emissions calculation. By integrating findings from various studies across themes related to electricity generation, charging behavior, policy incentives, and consumer perception, this literature review has provided a comprehensive perspective on the complexities of EV sustainability. The insights gained from this review are critical in refining the methodology for assessing EV emissions and identifying the policy and infrastructure changes necessary for maximizing their environmental benefits.

**Summary and Critical Evaluation of Key Literature**

*Electricity Generation and Regional CO₂ Variability*

Studies such as Ghosh et al. (2023) and Qin et al. (2022) highlight the significant role of regional electricity generation in determining the carbon footprint of EVs. Ghosh et al. (2023) find that states reliant on coal-fired power plants have substantially higher CO₂ emissions per kWh, making EVs less environmentally beneficial in those regions. Similarly, Qin et al. (2022) demonstrate that globally, power grid emissions are highly variable, with developed nations experiencing reductions due to renewable integration, while emerging economies continue to rely on coal. These studies reinforce the argument that EV emissions must be assessed at a regional level rather than through broad national averages. However, a limitation of both studies is that they do not directly compare EV emissions to those of internal combustion engine (ICE) vehicles, leaving a gap in the practical application of their findings.

*EV Emissions Per Mile and Vehicle Comparisons*

Prival (2023) and Maertz et al. (2021) provide direct comparisons of EV and ICE vehicle emissions per mile, illustrating that in some cases, hybrid vehicles such as the Toyota Prius produce lower lifetime CO₂ emissions than EVs charged in coal-dependent regions. Prival (2023) finds that the Tesla Model 3 has a lower carbon footprint than most hybrid vehicles in the western U.S., but in the eastern U.S., several hybrid models outperform most EVs. Maertz et al. (2021) expand this comparison on a global scale, showing that EV benefits are highly dependent on regional electricity sources. A major strength of these studies is their use of empirical data to create MPG-equivalent emissions comparisons, making their findings highly applicable to real-world decision-making. However, they do not account for future grid decarbonization scenarios, meaning their conclusions may be less relevant in the long term.

*Charging Behavior and Grid Decarbonization*

McLaren et al. (2016) and Isaac et al. (2024) explore the role of charging behavior and grid emissions variability in shaping EV emissions. McLaren et al. (2016) find that nighttime charging in coal-heavy regions results in higher emissions than daytime charging when renewables contribute more to the grid. They also determine that plug-in hybrid electric vehicles (PHEVs) can have lower emissions than battery-electric vehicles (BEVs) in certain charging scenarios. Meanwhile, Isaac et al. (2024) introduce machine learning models to predict CO₂ emissions based on vehicle usage and grid conditions, showing that emissions forecasting can improve decision-making for EV adoption. While these studies provide valuable insights, they do not offer solutions for mitigating high emissions in fossil-fuel-dependent grids, an area that future research should explore.

*EV Policies, Incentives, and Market Adoption*

Jenn et al. (2018) and Clinton & Steinberg (2019) examine how financial incentives influence EV adoption, concluding that direct rebates and tax credits significantly increase EV purchases but disproportionately benefit higher-income consumers. Meanwhile, the Environmental Protection Agency (EPA, n.d.) study addresses public misconceptions about EVs, confirming that while EVs generally produce fewer emissions than ICE vehicles, their sustainability depends on grid composition. Kim (2023) expands on this discussion by analyzing the Inflation Reduction Act’s (IRA) impact on U.S. trade relations, finding that policies favoring domestic EV manufacturing may strain international cooperation. These studies collectively highlight that EV adoption is not solely driven by environmental benefits but is influenced by financial incentives, policy design, and geopolitical considerations.

*Political and Economic Implications of EV Expansion*

McDonnell et al. (2023) and "Saving Fuel to Buy More Guns" (2023) explore the cultural and economic implications of EV adoption. McDonnell et al. (2023) find that conservative consumers are increasingly adopting EVs for financial reasons rather than climate concerns, signaling a shift in EV perception from an environmental symbol to an economic asset. Similarly, "Saving Fuel to Buy More Guns" (2023) discusses the trade-offs between national security interests and EV policy, showing that energy independence concerns influence EV adoption patterns. These studies underscore that EV policies must account for consumer motivations beyond environmental consciousness to ensure widespread adoption.

**Theoretical Framework and Research Contributions**

*Establishing the Need for This Study*

The literature reviewed highlights the need for a standardized, data-driven approach to calculating EV emissions that accounts for electricity generation variability, charging patterns, and policy incentives. While multiple studies address components of this issue, there is no existing framework that directly translates power plant emissions into per-mile CO₂ metrics for EVs in a way that allows direct comparison with ICE vehicles. This research aims to fill that gap by integrating emissions data from the EPA and vehicle efficiency data from the U.S. Department of Energy to develop a transparent emissions calculation model.

*Conceptual Assumptions and Research Questions*

This study operates under the assumption that CO₂ emissions from electricity generation must be factored into EV sustainability assessments. The research questions guiding this study are:

* What are the per-mile CO₂ emissions of EVs when accounting for regional electricity generation sources?
* How do EV emissions compare to ICE vehicles and hybrid vehicles under various grid conditions?
* What role does charging behavior play in determining real-world EV emissions?
* How can emissions forecasting models improve consumer decision-making regarding EV adoption?

*Theoretical Approach*

This study adopts a methodological framework that integrates empirical data analysis, life cycle assessment (LCA), and machine learning predictions to establish a comparative emissions model. It builds on existing literature by incorporating regional emissions data into a standardized metric for evaluating EV sustainability. This approach will help bridge the gap between theoretical emissions modeling and practical consumer insights.

**Expected Contributions to the Field**

This research will contribute to the field in several ways:

* Development of a CO₂ per Mile Metric – Establishing a standardized measure for EV emissions based on power plant emissions.
* Improved Transparency in EV Sustainability – Providing consumers with clearer insights into the true emissions impact of their vehicle choices.
* Policy Guidance for Incentive Structures – Informing policymakers on how to structure EV incentives based on regional electricity emissions.
* Integration of Machine Learning for Emissions Forecasting – Leveraging predictive models to estimate future emissions reductions under various grid decarbonization scenarios.

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# Link to the References

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