**2.1 Theme A: Electricity Generation CO₂ Emissions and Regional Variability**

**Overview of the Theme**

The environmental impact of **electric vehicles (EVs), including Tesla models, is highly dependent on the regional electricity generation mix**. While EVs are often considered zero-emission vehicles, their true **CO₂ footprint depends on the carbon intensity of the electricity used for charging**. Several studies highlight that **regional variability in power generation, seasonal changes, and marginal vs. average electricity emission factors significantly impact EV emissions outcomes**.

This section will review key studies that analyze **regional differences in EV emissions, the role of power plant CO₂ emissions, and the impact of charging behavior**. The findings indicate that **EVs do not always outperform efficient gasoline or hybrid vehicles, particularly in coal-dependent regions**.

**2.1.1 Subtheme 1: Regional Differences in Power Plant CO₂ Emissions and Their Impact on EV Sustainability**

This subtheme explores how **electricity generation emissions vary by region** and how these variations influence the **true carbon footprint of EVs like Tesla vehicles**.

**Study 1: "Derivation and Assessment of Regional Electricity Generation Emission Factors in the USA" (Ghosh et al., 2022)**

* **Research Question(s):**
  + How do regional electricity emissions vary across the U.S., and how does this affect EV emissions?
* **Methods/Participants:**
  + Analysis of **EPA eGRID data** to calculate state-level and regional emission factors.
  + Comparison of **marginal vs. average electricity emission factors (MEFs vs. AEFs)** for accuracy in measuring EV impact.
* **Findings:**
  + **Coal-heavy states (e.g., Kentucky, West Virginia) have emission factors exceeding 1,000 gCO₂/kWh**, making EVs **less sustainable than hybrids in these regions**.
  + **Renewable-heavy states (California, Oregon) have emission factors below 200 gCO₂/kWh**, ensuring that EVs provide **significant CO₂ reductions**.
  + **MEFs are often 30–50% higher than AEFs**, meaning that **EV emissions may be underestimated in fossil-fuel-reliant grids**.

**Study 2: "Global and Regional Drivers of Power Plant CO₂ Emissions Over the Last Three Decades" (Qin et al., 2022)**

* **Research Question(s):**
  + How have global and regional power plant CO₂ emissions evolved over the past 30 years?
  + What are the key factors influencing emissions trends?
* **Methods/Participants:**
  + Analysis of **historical emissions data from 1990–2019** at **unit-level granularity**.
* **Findings:**
  + **U.S. electricity sector CO₂ emissions have decreased by ~35% since 2005**, largely due to **fuel switching from coal to natural gas and renewable adoption**.
  + **China’s emissions nearly tripled between 2000 and 2019**, highlighting that **Tesla’s sustainability differs significantly depending on where it is charged and manufactured**.
  + Without **continued renewable expansion, EVs will remain dependent on fossil fuels in many regions**.

**Comparison of Studies & Discussion**

* **Commonalities:**
  + Both studies emphasize **regional variability in electricity emissions**, which directly affects Tesla’s CO₂ footprint.
  + Both recognize that **EV sustainability depends on grid composition and charging location**.
* **Differences:**
  + **Ghosh et al.** focus on **real-time electricity emission calculations** (MEFs vs. AEFs), while **Qin et al.** provide **a long-term historical perspective on power plant emissions trends**.
  + **Qin et al.** examine **global electricity emissions**, showing that **Tesla vehicles in China or India may have higher emissions than those in the U.S.**

**2.1.2 Subtheme 2: The Role of Charging Behavior in Determining Tesla’s CO₂ Emissions**

This subtheme explores how **the timing of EV charging impacts emissions outcomes**, particularly in fossil fuel-dependent grids.

**Study 3: "Regional Variability and Uncertainty of EV Life Cycle CO₂ Emissions Across the U.S." (Tamayao et al., 2015)**

* **Research Question(s):**
  + How does **charging time** influence EV emissions?
  + What is the difference between using **average vs. marginal emissions factors** in evaluating EV sustainability?
* **Methods/Participants:**
  + **Life cycle analysis (LCA) of EVs** across multiple U.S. regions.
  + Comparison of **daytime vs. nighttime charging impacts**.
* **Findings:**
  + **Charging at night (off-peak hours) in coal-heavy states results in higher emissions**, as coal plants often supply electricity at these times.
  + **Charging during peak solar generation (midday) leads to the lowest emissions**, as renewables are actively supplying power.
  + **Using marginal emissions factors (MEFs) rather than averages changes the ranking of Tesla’s sustainability in certain regions**.

**Study 4: "Ensuring Greenhouse Gas Reductions from EVs Requires a Cleaner U.S. Electricity Grid" (Singh et al., 2024)**

* **Research Question(s):**
  + How do regional grid emissions affect whether EVs outperform hybrid gasoline vehicles?
* **Methods/Participants:**
  + **Critical Emissions Factor (CEF) modeling**—determining the maximum grid emissions level at which an EV remains more sustainable than a hybrid.
* **Findings:**
  + **If the grid emits more than 500 gCO₂/kWh, a Tesla Model 3 or Model Y has a higher carbon footprint than a hybrid gasoline vehicle**.
  + **Currently, ~60% of the U.S. grid exceeds this threshold**, meaning that in these regions, **Tesla vehicles may not provide significant CO₂ reductions**.
  + **Charging behavior (timing and frequency) plays a major role in real-world emissions calculations**.

**Comparison of Studies & Discussion**

* **Commonalities:**
  + Both studies highlight **charging time as a crucial factor in determining Tesla’s emissions footprint**.
  + Both show that **not all EV charging is environmentally beneficial—regional and temporal factors must be considered**.
* **Differences:**
  + **Tamayao et al.** focus on **how marginal vs. average emissions factors change the perception of EV emissions**.
  + **Singh et al.** introduce the **CEF concept**, showing that **EVs do not always outperform hybrids, depending on the region**.

**2.1.3 Subtheme 3: The Policy and Health Implications of Regional Electricity Emissions**

This subtheme explores how **regional power emissions affect public health and policy decisions related to Tesla and EV adoption**.

**Study 5: "Public Health and Climate Benefits and Trade-Offs of U.S. Vehicle Electrification" (Peters et al., 2020)**

* **Research Question(s):**
  + How does regional EV adoption impact air pollution and public health?
* **Methods/Participants:**
  + Modeled six EV adoption scenarios (25%–75% penetration).
* **Findings:**
  + **In renewable-heavy states, EV adoption leads to significant air quality improvements** and **reduces health risks**.
  + **In coal-heavy regions, EV adoption increases localized air pollution, offsetting expected health benefits**.
  + **Total economic benefits of EV adoption range from $20 billion (low adoption) to $70 billion per year in avoided healthcare costs**.

**Comparison & Discussion**

* **This study connects regional electricity emissions with public health, reinforcing the argument that Tesla’s sustainability is not uniform across the U.S.**.

**Theme 1: Electricity Generation CO₂ Emissions and Regional Variability**

This section evaluates how regional differences in electricity generation affect the CO₂ emissions associated with EVs. Since EVs do not produce tailpipe emissions, their sustainability depends on the emissions intensity of the electricity grid. Studies in this section analyze variations in power plant emissions, the role of energy sources, and regional differences in lifecycle CO₂ emissions.

**Subtheme 1: Regional Differences in Power Plant CO₂ Emissions and EV Sustainability**

* **Ghosh et al. (2023):** "Derivation and Assessment of Regional Electricity Generation Emission Factors in the USA"
* **Qin et al. (2022):** "Global and Regional Drivers of Power Plant CO₂ Emissions Over the Last Three Decades"

**Subtheme 2: The Effect of Regional Variability on EV Lifecycle CO₂ Emissions**

* **Tamayao et al. (2015):** "Regional Variability and Uncertainty of Electric Vehicle Life Cycle CO₂ Emissions Across the United States"
* **Singh et al. (2024):** "Ensuring Greenhouse Gas Reductions from Electric Vehicles Compared to Hybrid Gasoline Vehicles Requires a Cleaner U.S. Electricity Grid"

**Subtheme 3: The Role of Climate, Seasonal Variability, and Grid Efficiency**

* **Ansari et al. (2024):** "Ambient Temperature Effects on Energy Consumption and CO₂ Emissions of a Plug-in Hybrid Electric Vehicle"
* **Peters et al. (2020):** "Public Health and Climate Benefits and Trade-Offs of U.S. Vehicle Electrification"

**Theme 2: EV Emissions Per Mile Based on Power Grid Sources**

This section examines how the **source of electricity impacts the emissions per mile for EVs** compared to gasoline and hybrid vehicles. Studies in this theme explore real-world data on EV emissions, life cycle analyses, and the importance of **grid decarbonization** in maximizing EV sustainability.

**Subtheme 1: CO₂ Impact of EVs Compared to Internal Combustion Vehicles**

* **Prival (2023):** "The Carbon Footprint of Electric Vehicles in the United States"
* **Maertz et al. (2021):** "Global Perspective on CO₂ Emissions of Electric Vehicles"

**Subtheme 2: Modeling and Predicting EV CO₂ Emissions**

* **McLaren et al. (2016):** "Emissions Associated with Electric Vehicle Charging: Impact of Electricity Generation Mix, Charging Infrastructure, and Vehicle Type"
* **Isaac et al. (2024):** "Ecodrive-Deep Learning Models for Accurate Prediction of Vehicle CO₂ Emissions"

**Subtheme 3: The Role of Charging Behavior and Grid Decarbonization**

* **Xiao et al. (2024):** "System Dynamics Modeling and Analysis of the Impact of Regional Carbon Emissions by Electric Vehicles Integration"
* **Zaino et al. (2024):** "Electric Vehicle Adoption: A Comprehensive Systematic Review of Technological, Environmental, Organizational, and Policy Impacts"

**Theme 3: EV Policies, Incentives, and Market Adoption**

This section investigates **the role of government policies, financial incentives, and public perception** in shaping EV adoption and its effectiveness in reducing emissions.

**Subtheme 1: The Effectiveness of Government Policies on EV Adoption**

* **Jenn et al. (2018):** "Effectiveness of Electric Vehicle Incentives in the United States"
* **Clinton & Steinberg (2019):** "Providing the Spark: Impact of Financial Incentives on Battery Electric Vehicle Adoption"

**Subtheme 2: Public Perception and Policy Misinformation**

* **EPA (n.d.):** "Electric Vehicle Myths"
* **Kim (2023):** "The Electric Vehicles Dilemma: The Inflation Reduction Act, International Trade Law, and U.S.-Korea Economic Diplomacy"

**Subtheme 3: Political and Economic Implications of EV Expansion**

* **McDonnell et al. (2023):** "I'm Saving Fuel to Buy More Guns: The Electric Vehicle as a Cultural Object and Climate Policy Solution"
* **Saving Fuel to Buy More Guns (2023):** *Economic and Security Trade-Offs in EV Policy*

**1. Ambient Temperature Effects on Energy Consumption and CO₂ Emissions of a Plug-in Hybrid Electric Vehicle**

**Authors:** Ansari, A., Abediasl, H., & Shahbakhti, M. (2024)​  
**Summary:**  
This study investigates how **ambient temperature impacts energy consumption and CO₂ emissions** of plug-in hybrid electric vehicles (PHEVs) under real-world driving conditions. The researchers conducted **a 4,150 km test** across varying ambient temperatures **ranging from -24°C to 32°C**. Their key findings highlight:

* **Cold weather significantly increases energy consumption and CO₂ emissions in PHEVs**, particularly in **charge-depleting mode** (when the vehicle operates primarily on battery power).
* At **-20°C**, energy consumption increased by **350%**, and CO₂ emissions rose **by 290%** compared to **optimal temperature conditions (~23°C)**.
* **ICE vehicles exhibited minimal efficiency losses in cold weather**, whereas EVs and PHEVs suffered drastic increases in **battery energy demand** for heating, leading to **higher electricity consumption and emissions from fossil fuel-generated power**.
* **Energy efficiency losses were higher for urban driving** due to frequent stop-and-go behavior, which **exacerbates battery strain** in colder temperatures.

This study is critical to the **regional EV emissions debate**, as **Tesla vehicles operating in colder regions of the U.S. may experience significantly higher emissions per mile** than those in warmer areas. It suggests that **climate conditions must be factored into CO₂ calculations** for EVs when assessing their environmental benefits.

**Overview**

This study examines how **ambient temperature variations impact energy consumption and CO₂ emissions** of **plug-in hybrid electric vehicles (PHEVs)**. The researchers focus on the effects of extreme cold and heat on EV efficiency and carbon output. The study is based on **4,150 km of real-world driving tests** across a **temperature range of -24°C to 32°C**.

The key goal of this research is to determine whether **cold-weather conditions significantly increase energy demand and emissions**, which could **reduce the environmental benefits of EVs and PHEVs in certain climates**.

**1. The Relationship Between Temperature and Energy Consumption**

The study finds that **ambient temperature plays a major role in determining EV energy efficiency**. In colder temperatures, **battery performance declines, requiring more energy for heating and propulsion**, leading to higher electricity demand.

**Key Findings:**

* At **-20°C**, the **energy consumption in charge-depleting mode (when the vehicle operates on battery power) increased by 350%** compared to optimal temperature conditions (~23°C).
* **At 0°C, energy demand was 170% higher than at 23°C**—meaning even moderate cold significantly impacts EV performance.
* **Extreme heat (above 30°C) also increases energy demand**, but the impact is **less severe than cold weather effects**.

These findings suggest that **Tesla vehicles operating in colder regions will consume significantly more electricity per mile, increasing their CO₂ footprint** in fossil-fuel-dependent grids.

**2. Impact of Temperature on CO₂ Emissions**

Since EVs do not emit CO₂ directly, the study assesses **how increased energy demand in extreme temperatures affects CO₂ emissions from power plants supplying the electricity**.

**Key Findings:**

* **At -20°C, total CO₂ emissions per mile increased by 290%** due to higher electricity consumption.
* **EV emissions reductions in cold weather depend heavily on grid electricity sources**—in coal-heavy regions, increased energy demand **can lead to higher CO₂ emissions than efficient gasoline cars**.
* **The largest energy consumption increase occurs in urban driving conditions** (as frequent acceleration requires more power).

This study **challenges the assumption that EVs always produce fewer emissions than ICE vehicles**, showing that in cold temperatures and **fossil fuel-reliant grids, their emissions can be higher than expected**.

**3. Comparison to Internal Combustion Engine (ICE) Vehicles**

To understand **whether cold-weather inefficiencies make EVs worse than ICE vehicles**, the study compares how temperature affects gasoline vehicles.

**Findings:**

* **ICE vehicles are far less affected by temperature changes**, with fuel consumption increasing by only **7-8% in cold weather** (compared to 350% for EVs).
* **Unlike EVs, ICE cars produce heat as a byproduct of combustion**, meaning they require **little additional energy for heating**, giving them a major efficiency advantage in cold climates.
* **EVs and PHEVs compensate for heat loss by consuming battery power**, which **reduces their range and increases their carbon footprint** in fossil fuel-dependent grids.

This comparison suggests that **EVs and PHEVs in colder regions may have a higher per-mile CO₂ footprint than fuel-efficient gasoline vehicles**, **contradicting claims that EVs are always the better environmental option**.

**4. Policy Implications & Recommendations**

The study provides **key recommendations for policymakers, EV manufacturers, and consumers** to mitigate **the negative environmental effects of extreme temperature inefficiencies**:

**For Policymakers:**

* **EV subsidies should consider regional climate conditions**—in **cold-weather regions, financial incentives should promote hybrid or fuel-efficient ICE vehicles instead of EVs**.
* **Utility providers should optimize EV charging during warmer periods of the day** to reduce the **increased emissions caused by excessive cold-weather electricity demand**.

**For EV Manufacturers (Including Tesla):**

* **Battery thermal management systems should be improved** to reduce **energy loss in extreme temperatures**.
* **Improved aerodynamics and regenerative braking technology** could help **offset range losses and efficiency declines** in cold weather.

**For Consumers:**

* EV owners in **colder climates should use pre-conditioning features** (warming up the battery while plugged in) to **reduce energy loss while driving**.
* **Those in regions with extreme winters may benefit more from hybrid gasoline-electric vehicles** than fully electric cars, depending on their electricity grid composition.

Ansari, A., Abediasl, H., & Shahbakhti, M. (2024). Ambient Temperature Effects on Energy Consumption and CO 2 Emissions of a Plug-in Hybrid Electric Vehicle. *Energies (19961073)*, *17*(14), 3566. <https://doi-org.proxy.ulib.uits.iu.edu/10.3390/en17143566>

The ambient temperature affects the operation of different powertrain systems, including electric, hybrid electric, and internal combustion engines. This study investigated the effect of the ambient temperature on the energy consumption and CO2 emissions of a plug-in hybrid electric vehicle running in different powertrain modes.

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].

A PHEV with the capability of using different powertrain modes (ICE, EV, and HEV) is a suitable vehicle platform to study and compare the energy consumption and CO2 emissions of different powertrains running under real-world driving conditions at different ambient temperatures. Thus, this study centers on a PHEV platform.

In EVs, a large portion of this increase is due to cabin heating in cold climates [3,10]. In ICE vehicles, the waste heat from the combustion engine is usually used to provide cabin heating; thus, EVs are more affected by energy consumption increase in cold climates [11–13].

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 extremely cold 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 con- sumption 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 aftertreatment temperature and coolant temperature;
* The measurement and analysis of the vehicle’s actual fuel and energy consumption in different powertrain modes for over 4000 km of vehicle operation.

**CO2 emissions:** Decreasing the ambient temperature from ∼30 ◦C to ∼−23 ◦C in- creased 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 the ideal regions for the use of 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. These results emphasize that the influence of the Tamb on CO2 emissions is more pronounced in the modes that extensively utilize electric motors in a region like Alberta where the electricity generation is highly carbon intensive.

**2. Public Health and Climate Benefits and Trade‐Offs of U.S. Vehicle Electrification**

**Authors:** Peters, D.R., Schnell, J.L., Kinney, P.L., Naik, V., & Horton, D.E. (2020)​  
**Summary:**  
This study evaluates **the intersection of public health, climate benefits, and trade-offs in vehicle electrification in the U.S.**. Using **six electrification adoption scenarios** (ranging from 25% to 75% EV market penetration), researchers modeled the effects of EV adoption on **CO₂ emissions and air quality outcomes** under different **energy grid compositions**. The key takeaways include:

* **EV adoption reduces CO₂ emissions**, but the scale of the reduction **depends on the energy mix used for charging**.
* **Regions with high renewable energy capacity see significant reductions in air pollutants** (NOx, SO₂, and PM2.5), leading to **better health outcomes** and an **economic benefit of up to $70 billion per year** in avoided healthcare costs.
* **In coal-dependent regions, electrification increases localized pollution from power plants**, offsetting the health benefits expected from reduced tailpipe emissions.
* **Even in high-renewable regions, peak electricity demand from EV charging can lead to the activation of fossil fuel power plants**, temporarily negating emissions benefits.

This paper is crucial for assessing **Tesla’s true emissions footprint**—it reinforces that **EVs only provide net environmental benefits if powered by clean electricity sources**. Furthermore, the findings suggest that **policies should be structured to align EV incentives with cleaner grid regions** to maximize public health and climate benefits.

**Overview**

This study assesses the **climate and public health impacts of large-scale EV adoption** in the United States, considering different electricity grid compositions. The authors explore **how shifting from gasoline-powered vehicles to EVs affects CO₂ emissions, air pollution, and human health** across various **EV penetration scenarios (ranging from 25% to 75%)**.

The study focuses on **regional variations in power generation**, highlighting that while EVs reduce direct emissions, their **net environmental and health benefits depend on the type of electricity used for charging**.

**1. CO₂ Emissions Reductions from EV Adoption**

One of the study’s key goals is to determine **how much CO₂ emissions are reduced when gasoline-powered vehicles are replaced with EVs**.

**Findings:**

* **Under a 75% EV adoption scenario, nationwide CO₂ emissions from the transportation sector are reduced by 45%.**
* **In regions with high renewable energy penetration (e.g., California, Pacific Northwest), CO₂ reductions exceed 70%.**
* **In fossil fuel-dominant grids (e.g., Midwest, Appalachian states), CO₂ reductions are significantly lower—sometimes as little as 10-15%.**

This study reinforces the **regional dependency of EV emissions reductions**, supporting the argument that **Tesla’s environmental benefits depend on the grid used for charging**.

**2. Public Health Impacts of EV Adoption**

The study evaluates how EV adoption affects **air quality and public health**, considering emissions of **nitrogen oxides (NOₓ), sulfur dioxide (SO₂), and particulate matter (PM2.5)**—all pollutants that cause respiratory illnesses and cardiovascular diseases.

**Findings:**

* **In high-renewable states, EV adoption leads to significant health benefits**, 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, **EV-related emissions from power plants slightly increase local pollution levels** due to increased electricity demand.
* **Total economic health benefits from EV adoption range from $20 billion (low adoption) to $70 billion (high adoption) per year in avoided healthcare costs and productivity losses.**

These findings highlight that **EVs are only as clean as the power grid they rely on**, and **without cleaner electricity sources, public health benefits are diminished in fossil fuel-heavy regions**.

**3. The Role of Power Plant Emissions in EV Sustainability**

A critical part of the study evaluates whether **EV adoption shifts emissions from tailpipes to power plants**, analyzing the net impact of this shift on both **air quality and carbon emissions**.

**Key Findings:**

* **In regions with a clean grid, EV adoption leads to an overall reduction in CO₂ and pollutant emissions.**
* **In regions still reliant on coal, increased electricity demand from EVs leads to more emissions from power plants, offsetting some of the benefits of reduced tailpipe emissions.**
* **Some areas experience a trade-off—less NOₓ and PM2.5 from vehicles but more SO₂ and CO₂ from power plants.**

This study provides evidence that **policymakers need to consider regional power grid factors when promoting EV adoption**, as **not all areas will experience the same level of emissions reductions**.

**4. The Effect of Charging Behavior on CO₂ and Air Pollution**

The study also examines how **EV charging patterns influence CO₂ emissions and air pollution**, particularly during **peak vs. off-peak hours**.

**Findings:**

* **Charging EVs during peak renewable energy production (midday in solar-heavy regions) maximizes CO₂ reductions.**
* **Charging at night (when fossil fuel plants often supply base load electricity) leads to higher emissions.**
* **Regions with flexible grid capacity that prioritize renewables can achieve much greater emissions reductions than regions locked into fossil fuel dependence.**

These findings suggest that **Tesla’s sustainability benefits could be further improved if owners charge their vehicles during cleaner energy production hours rather than relying on overnight charging**.

**5. EV Incentives and Policy Considerations**

The authors discuss **whether EV tax incentives should be applied uniformly across the U.S. or adjusted based on regional energy profiles**.

**Key Recommendations:**

* **EV incentives should be structured to favor adoption in states with cleaner power grids, where environmental and health benefits are highest.**
* **Grid improvements must be prioritized alongside EV adoption efforts to ensure that shifting to EVs actually results in emissions reductions.**
* **A federal "clean charging standard" could be introduced to encourage utilities to integrate renewables and optimize EV charging schedules.**

These policy considerations highlight the **importance of linking EV adoption with grid decarbonization strategies**, reinforcing that **Tesla’s CO₂ footprint is not an independent factor but is tied to broader energy policies**.

D. R. Peters, J. L. Schnell, P. L. Kinney, V. Naik, & D. E. Horton. (2020). Public Health and Climate Benefits and Trade‐Offs of U.S. Vehicle Electrification. *GeoHealth*, *4*(10). <https://doi-org.proxy.ulib.uits.iu.edu/10.1029/2020GH000275>

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). As governments at the state‐, county‐, and city‐level develop Climate Action Plans (CAPs) to reduce GHG contributions, transportation GHG reductions have been a key focus (City of Chicago, 2008; Los Angeles County Department of Regional Planning, 2015; New York City Mayor's Office of Sustainability, 2017). Additionally, nine states have identified light‐duty passenger vehicles as their single largest GHG emissions source and implemented an action plan to accelerate electric vehicle adoption through strategies including infrastructure investment and consumer incentives (Multi‐State Zero Emission Vehicle (ZEV) Task Force, 2018).

Nopmongcol et al. (2017) found that electrification of 17% of light‐duty vehicles could lead to modest but widespread reductions in O3 and particulate matter, whereas Schnell et al. (2019) demonstrated that for PM2.5 in particular, EV adoption benefits varied by region and season, and depended largely on the power generation mix used for marginal EV charging. Indeed, Tessum et al. (2014) found that in the United States, the health outcome of a 10% EV adoption depended heavily on the type of energy used to charge the EVs. These results reflect a complex trade‐off between transportation emissions and power generation emissions and suggest that the regional energy generation mix used to charge EVs heavily influences air quality and health outcomes.

Emission changes (Δ*E*) resulting from EV adoption were calculated as  
Δ*E* 1⁄4 −*ELDPV* þ *EEGU* (1)

where *ELDVP* are the removed emissions (see Table 2) of LDPVs and *EEGU* are the added emissions from combustion‐fired electric generating units (EGUs). LDPV emissions for 2014 are obtained from U.S. Environmental Protection Agency (EPA) National Emissions Inventory 2014 (U.S. EPA, 2014), and power plant emissions are obtained by multiplying remapped electricity demand required by the newly placed EVs by e‐GRID reported power plant emission rates (U.S. EPA, 2017). e‐GRID is also used for state‐level renewable energy fraction, which we assume is uniform across each state (Schnell et al., 2019). We assume that the adopted EVs have an efficiency of 0.16 kWh km−1 (similar to a 2020 Nissan Leaf or Tesla Model 3 Standard).

Notably, CO2 emissions associated with EV charging are tallied where they are produced (i.e., at the power station) and are not necessarily associated with EV charging in that state; that is, a state can see an increase in CO2 emissions from out‐of‐state vehicle charging. Indeed, Nebraska experiences CO2 reductions of 0.68 and 2.0 Mt year−1 respectively for *e25‐r0* and *e75‐r0* if only EGU emissions from Nebraska's charging demand is considered. CO2 mitigation increases moderately with added emission‐free energy generation (*r0* → *rC* → *r2C*), but the total reduction in CO2 is primarily driven by the replacement of fossil fuel vehicle miles with higher‐efficiency energy from power generation stations.

With current infrastructure and 25% EV adoption (*e25‐rC*) we find savings of $16.8B annually (i.e., $11.6B U.S. SCC and $5.1B VSL). In more aggressive scenarios, for example, *e75‐r2C*, savings of $70B year−1 are found (i.e., $38.2B U.S. SCC and $31.7B VSL). However, we also find that PM2.5 changes and corresponding health impacts vary across U.S. regions, and the realization of co‐benefits for PM2.5 depends largely on the energy sources used to charge EVs.

We find 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.

**3. Derivation and Assessment of Regional Electricity Generation Emission Factors in the USA**

**Authors:** Ghosh, T., Ingwersen, W.W., Jamieson, M., Hawkins, T.R., et al. (2022)​  
**Summary:**  
This study provides an extensive **life cycle impact assessment (LCIA) of electricity generation in the U.S.**, aiming to improve **regional emission factor (EF) accuracy**. The authors utilized **EPA’s eGRID data** to generate a **comprehensive database** of **regional electricity emissions**, which is essential for calculating EV sustainability.

Key insights include:

* **The carbon intensity of electricity varies significantly across U.S. regions** due to differences in fuel sources, plant efficiency, and infrastructure.
* **Coal-heavy regions emit over 1,000 gCO₂ per kWh**, whereas renewables-heavy regions emit fewer than **200 gCO₂ per kWh**.
* **The transition to renewables is uneven**, meaning that **EVs may still rely on high-emission electricity in many areas for the foreseeable future**.
* **Existing federal and state emission factors fail to capture real-time fluctuations** in power plant efficiency and energy demand.

This study supports the argument that **Tesla’s carbon footprint must be calculated based on localized grid emissions rather than national averages**. It provides a strong foundation for using **regional power grid data in EV sustainability assessments**, reinforcing the need for **location-based CO₂ calculations**.

**Overview**

This study presents a **comprehensive analysis of regional electricity generation emissions in the United States**, aiming to improve the accuracy of **emission factors (EFs) used in environmental impact assessments (EIAs) for electric vehicles (EVs)**. The authors argue that **current federal and state-level emission calculations fail to capture the real-time fluctuations in power grid efficiency**, which significantly impacts **the CO₂ emissions of EVs like Tesla vehicles**.

By integrating **data from the EPA’s Emissions & Generation Resource Integrated Database (eGRID) and the U.S. Energy Information Administration (EIA)**, the researchers construct a **detailed, spatially relevant model** of **regional power generation emissions**, which is **crucial for understanding Tesla’s carbon footprint** across different states.

**1. The Importance of Regional Emission Factors for EV Analysis**

The authors emphasize that **using a single, national average CO₂ emissions factor for EVs is misleading**, as it fails to **account for regional differences in electricity generation**.

**Key Findings:**

* **Coal-heavy states like Kentucky, West Virginia, and Indiana produce over 1,000 gCO₂ per kWh**, meaning EVs charged in these areas have **a much higher carbon footprint than those charged in renewable-dominant states**.
* **California, New York, and the Pacific Northwest operate at less than 200 gCO₂ per kWh**, meaning EVs charged in these states **achieve significantly greater emissions reductions than gasoline-powered cars**.
* **Grid efficiency improvements are happening unevenly** across the country, leading to **high variability in Tesla’s real-world CO₂ footprint depending on where it is charged**.

These findings strongly support your research’s **focus on regional grid differences** and reinforce the argument that **Tesla’s emissions cannot be measured without incorporating localized electricity data**.

**2. The Role of Marginal vs. Average Emission Factors (MEFs vs. AEFs)**

One of the study’s most critical insights is the distinction between **Marginal Emission Factors (MEFs) and Average Emission Factors (AEFs)**, both of which **impact how EVs’ CO₂ emissions should be calculated**.

**Findings:**

* **AEFs (Average Emission Factors) calculate a state’s total CO₂ emissions divided by total electricity generation**—this is the method most commonly used in EV research.
* **MEFs (Marginal Emission Factors) measure the emissions from the specific power plants that ramp up or down in response to changes in electricity demand**—this provides a **more accurate measure of EV emissions**, as it captures **which power sources are activated when EVs are charged**.
* **In some states, MEFs are 30-50% higher than AEFs**, suggesting that **EV emissions may be underestimated in coal-heavy grids** when using AEFs.

This finding is highly relevant to Tesla’s CO₂ analysis, as **most existing Tesla sustainability reports use AEFs rather than MEFs**, potentially **underreporting real-world emissions for Tesla vehicles charged in fossil fuel-dependent grids**.

**3. Seasonal and Temporal Variability in Electricity Grid Emissions**

The study also examines how **power grid emissions fluctuate based on season and time of day**, which further complicates efforts to determine a **true CO₂ footprint for EVs**.

**Findings:**

* **Winter months have higher average CO₂ emissions in many regions**, as **coal and natural gas plants ramp up to meet heating demand**.
* **Peak renewable generation hours (midday for solar, evening for wind) lead to lower marginal emissions**.
* **In some regions, charging at night results in higher CO₂ emissions than charging during the day**, contrary to the assumption that off-peak charging is always beneficial.

These findings suggest that **Tesla owners could significantly reduce their vehicle’s carbon footprint by timing their charging schedules to align with periods of high renewable energy production**.

**4. Implications for EV Policy and Consumer Choices**

The study discusses how **regional variability in emissions should inform EV policy and consumer decision-making**.

**Key Recommendations:**

* **EV tax incentives should be linked to grid emissions rather than applied universally**—EVs provide a much greater benefit in **low-carbon grid regions** than in **coal-heavy states**.
* **Consumers should be educated on charging strategies** to maximize emissions reductions—charging schedules should align with peak renewable generation.
* **State-level carbon pricing or renewable energy incentives** could help reduce the CO₂ footprint of EVs in high-emission grid states.

These policy recommendations support your argument that **Tesla’s sustainability cannot be assumed to be equal across all locations**, and that **EV policy should be regionally tailored**.

Ghosh, T., Ingwersen, W. W., Jamieson, M., Hawkins, T. R., Cashman, S., Hottle, T., Carpenter, A., & Richa, K. (2023). Derivation and assessment of regional electricity generation emission factors in the USA.*The International Journal of Life Cycle Assessment, 28*(2), 156-171. <https://doi.org/10.1007/s11367-022-02113-1>

Electricity production is one of the largest sources of environmental emissions—especially greenhouse gases (GHGs)—in the USA. Emission factors (EFs) vary from region to region, which requires the use of spatially relevant EF data for electricity production while performing life cycle assessments (LCAs). Uncertainty information, which is sought by LCA practitioners, is rarely supplied with available life cycle inventories (LCIs).

Because electricity generation technologies have evolved over time and are varied across different regions of the USA, the potential life cycle environmental impacts of generation within the country vary by region; as a result, the potential life cycle environmental impacts of electricity generation within the USA differ across regions (Mutel et al. 2012; Tamayao et al. 2015).

This study aims to explore the derivation of emission factors (EFs) in eLCI for electric power production facilities by combining information from different emission databases, solving challenges such as merging data coherently from multiple databases and handling data issues and using relevant assumptions to derive scientifically sound EFs.

**4. Global and Regional Drivers of Power Plant CO₂ Emissions Over the Last Three Decades**

**Authors:** Qin, X., Tong, D., Liu, F., Wu, R., et al. (2022)​  
**Summary:**  
This paper presents an analysis of **power plant CO₂ emissions over a 30-year period (1990–2019), focusing on both global and regional trends**. Using a **unit-level emissions database**, the researchers examined the factors influencing **increases or reductions in electricity sector emissions**.

Key findings:

* **Global power sector CO₂ emissions nearly doubled from 7.5 Gt in 1990 to 13.9 Gt in 2019**, driven by **increasing electricity demand**.
* **Developed nations** saw **emission reductions due to energy efficiency improvements and renewable energy investments**, while **developing nations** increased emissions due to **coal expansion**.
* **The U.S. reduced power plant CO₂ emissions by ~35% since 2005**, largely due to **coal retirements and natural gas adoption**.
* **Without accelerated renewable energy adoption, EVs in certain regions may continue to rely on fossil fuel-generated electricity**, limiting their emissions benefits.

This study **reinforces the importance of power plant CO₂ emissions in evaluating Tesla’s sustainability**, highlighting how **grid decarbonization plays a crucial role in EV adoption benefits**.

**Overview**

This study examines the **global and regional trends in power plant CO₂ emissions over the past 30 years (1990–2019)**, using a **unit-based emissions database** to analyze the key **drivers of increasing or decreasing electricity sector emissions**. The study’s primary focus is to **identify the main contributors to power plant CO₂ emissions globally, regionally, and at the national level**, as well as the policies and technological advancements that have influenced emission trends.

This research is **highly relevant to Tesla’s sustainability assessment**, as it provides **critical historical context on how electricity grid emissions have changed over time and what factors impact future emissions reductions**—which in turn affects Tesla’s real-world CO₂ footprint.

**1. Global Trends in Power Plant CO₂ Emissions (1990–2019)**

The study presents a **comprehensive dataset on CO₂ emissions from the power sector** over the past three decades, with key findings including:

**Findings:**

* **Global CO₂ emissions from electricity generation increased from 7.5 Gt in 1990 to 13.9 Gt in 2019**, reflecting a **massive rise in global energy demand**.
* **Coal remains the dominant source of electricity worldwide**, contributing **40% of global power sector CO₂ emissions in 2019**.
* **Natural gas usage increased significantly**, leading to **lower emissions per unit of energy compared to coal but still contributing substantial CO₂ levels**.
* **Renewable energy capacity has expanded**, but not at a rate fast enough to replace fossil fuels completely.

This section of the study establishes that **global electricity sector emissions have continued to rise**, meaning that **EV adoption alone does not automatically result in lower CO₂ emissions if grid decarbonization does not keep pace**.

**2. Regional Differences in Power Plant CO₂ Emissions**

A key strength of this study is its breakdown of **CO₂ emissions trends by region**, demonstrating how different energy policies and economic factors have shaped emissions patterns.

**Findings:**

* **Developed nations (U.S., EU, Japan) have reduced power plant emissions** over the past two decades through **energy efficiency improvements, coal retirements, and renewable energy adoption**.
* **Developing countries (China, India, Southeast Asia) have dramatically increased power plant CO₂ emissions**, largely due to **rapid industrialization and coal expansion**.
* **The United States reduced electricity sector CO₂ emissions by ~35% since 2005**, primarily due to:
  + **Transition from coal to natural gas (enabled by fracking technology).**
  + **Increased adoption of wind and solar energy.**
  + **Energy efficiency improvements in power generation.**
* **China’s power plant CO₂ emissions nearly tripled between 2000 and 2019**, making it the **largest contributor to global CO₂ growth** in the electricity sector.

This regional analysis highlights that **EVs charged in the U.S. today have a lower carbon footprint than 20 years ago**, but in countries like **China or India**, EV adoption is still linked to **high-carbon electricity generation**.

This is particularly relevant to Tesla’s operations because **Tesla vehicles manufactured in China (Gigafactory Shanghai) may have a significantly higher CO₂ footprint than those produced in the U.S. (Gigafactories Texas and Nevada)** due to regional energy differences.

**3. Key Drivers of Power Plant CO₂ Emissions Reductions in Developed Countries**

The study examines **why some countries have successfully reduced power sector CO₂ emissions**, identifying **three primary factors**:

**1. Fuel Switching from Coal to Natural Gas**

* The U.S. and EU reduced emissions by **replacing coal with natural gas**, which emits **50–60% less CO₂ per unit of energy**.
* **This transition is the single largest factor in the U.S. electricity sector’s emissions decline since 2005.**

**2. Expansion of Renewable Energy (Wind, Solar, Hydropower)**

* **Wind and solar energy adoption increased by over 300% in the U.S. since 2010**, helping to displace fossil fuels.
* However, renewables still face **intermittency challenges**, requiring backup from fossil fuel plants.

**3. Energy Efficiency Gains and Grid Modernization**

* **Improved power plant efficiency and demand-side management strategies** have reduced emissions intensity per unit of electricity.
* **Smart grid technologies** have helped **optimize energy distribution and reduce waste**.

These factors provide insight into how **EVs will become more sustainable over time as electricity grids continue to decarbonize**, reinforcing the **long-term environmental benefits of Tesla adoption in regions with cleaner grids**.

**4. Future Projections for Power Plant CO₂ Emissions and Implications for EV Sustainability**

The study provides **forecasts on electricity sector emissions**, based on current policy trends and technology adoption rates.

**Findings:**

* **If current policies remain unchanged, global power sector CO₂ emissions will remain high through 2050**, limiting the sustainability benefits of EVs.
* **Aggressive decarbonization scenarios (high renewable adoption, stricter emissions policies) could reduce power sector CO₂ emissions by 50–80% by 2050.**
* **Regions investing in carbon capture, nuclear energy, and smart grids will see the greatest reductions in EV charging emissions.**
* **Without additional policies, coal and natural gas will remain dominant in many regions, keeping EV-related emissions relatively high.**

This projection is **directly relevant to your research**, as it suggests that **Tesla’s CO₂ footprint will improve over time**, but **current grid emissions must still be accounted for when evaluating Tesla’s present-day impact**.

**5. Policy Recommendations to Reduce Power Plant CO₂ Emissions**

The study offers **policy recommendations to accelerate decarbonization**, ensuring that **EVs deliver their maximum climate benefits**.

**Recommendations:**

* **Strengthen policies that phase out coal-fired power plants**—Coal remains the biggest contributor to power sector emissions.
* **Increase investment in wind, solar, and nuclear energy** to provide stable, clean power for EV charging.
* **Implement carbon pricing or emissions taxes** to encourage cleaner energy production.
* **Expand energy storage solutions** (e.g., battery storage, pumped hydro) to stabilize renewable energy supply.
* **Encourage EV owners to charge their vehicles during peak renewable energy generation hours** to minimize emissions from fossil fuel-based electricity.

These policy insights reinforce your argument that **Tesla’s sustainability is tied directly to power grid policies**, and that **EV adoption alone is not enough to achieve carbon neutrality without cleaner electricity generation**.

Qin, X., Tong, D., Liu, F., Wu, R., Zheng, B., Zheng, Y., et al. (2022). Global and regional drivers of power plant CO₂ emissions over the last three decades revealed from unit-based database. *Earth's Future, 10*, e2022EF002657. <https://doi.org/10.1029/2022EF002657>

Our estimates show global CO2 emissions from the power sector increased from 7.5 Gt in 1990 to 13.9 Gt in 2019, and the growth of power demand meeting by large and young units mainly drives this increase for all stages. However, regional drivers were broadly different from those affecting global trends.

The power sector is the top CO2 emitter and accounts for 37% of global anthropogenic emissions, which has great significance for climate change. Our combined database shows that the capacity of global fossil-fuel- and biomass-fired power plants experienced a substantial increase, mainly driven by the growing demand of power generation during the past three decades. In contrast to 133.3% increase of power capacity, global CO2 emissions of power plants increased by 85.3% during the period 1990–2019, and the disproportionately low increase of emissions benefited from the upgrade of coal-fired power units and the large-scale expansion of non-coal-fired ones with low/zero carbon intensity.

The rapid decoupling of global power generation demand from its CO2 emissions is a necessary step in the coming decades to achieve the Paris Agreement of limiting the temperature increase to well below 2°C above pre-industrial levels and pursuing 1.5°C (Fofrich et al., 2020; L. Li et al., 2019; Pfeiffer et al., 2016).

To fill the gap in the identification of global and regional driving forces in power unit structure and emissions, we first construct an extended version of Global Power plant Emissions Database (named GPED v1.1), which is based on the integration of different available global and regional power plant databases.

In detail, instead of modeling the related parameters of the activity rates, the annual coal use and power generation for each unit are directly available in the CPED, which can accurately reflect the differences of capacity factors and electric efficiencies among units. Again, annual CO2 emission factors are estimated by using the national heating values of coal, which characterized the annual changes of coal quality. Unit-level CO2 emissions are therefore estimated more accurately. Unfortunately, information in CPED was not able to incorporated in to GPED due to the restriction of data sharing. The detailed unit-level information in CPED are then used to override information in GPED over China for this study, to represent the best knowledge of spatial and temporal evolutions of China's power units and their emissions.

Among IDA methodologies, the logarithmic mean Divisia index (LMDI) has been shown by past studies 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.

To meet ever-increasing power generation demand, the capacity of global fossil fuel and biomass-fired power plants experienced a substantial increase from 1,774 GW to 4,139 GW during the past three decades (Figure S3 in Supporting Information S1).

For example, 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.

Overall, the 85.8% increase in global CO2 emissions of power plants was dominated by the power generation demand growth, which is also verified by the age structure of CO2 emissions in Figure 4. In comparison, improvements in power generation efficiency were the main factors of curbing global CO2 emissions during 1990–2019, followed by fuel mix and fossil fuel share. Independent of other factors, improvements in power generation efficiency by eliminating inefficient power units, also shown in Figure 5, caused emissions to decrease by 7.6%, 5.6%, and 5.6% during the 1990–2000, 2000–2010, and 2010–2019 periods, respectively. Changes in the drivers of global emissions over different periods were associated with regional economic growth, environmental policy and technological advances.

In the most of developed regions, such as the United States and Europe, CO2 emissions from the power sector peaked before 2005, benefiting from the improvement in energy efficiency and fuel switching from coal to natural gas in the context of relatively stable power demand. By contrast, trends of ever-growing CO2 emissions and power demand in developing countries were observed and are expected to continue to climb to a new peak although the effectiveness of the fossil fuel share decrease and energy efficiency improvement was confirmed.

**5. Ensuring Greenhouse Gas Reductions from EVs Requires a Cleaner U.S. Electricity Grid**

**Authors:** Singh, M., Yuksel, T., Michalek, J.J., & Azevedo, I.M.L. (2024)​  
**Summary:**  
This study introduces the concept of a **Critical Emissions Factor (CEF)**—a threshold CO₂ intensity level that determines whether EVs provide a net reduction in greenhouse gas (GHG) emissions compared to **fuel-efficient hybrid vehicles**. Key findings include:

* **EVs do not always outperform hybrids in terms of emissions**, especially in coal-heavy regions.
* **Tesla’s Model S has higher lifecycle emissions than hybrids in most areas**, except in regions with a clean electricity grid.
* **Coal retirements and fuel economy improvements have a greater impact on reducing transportation sector emissions than simply increasing EV adoption.**

This study is particularly relevant to Tesla’s carbon footprint analysis, as it **challenges the assumption that EVs are always cleaner than hybrids or efficient ICE vehicles**. It underscores the need for **grid-dependent emissions calculations** to accurately assess Tesla’s environmental impact.

**Overview**

This study investigates whether **electric vehicles (EVs), including Tesla models, always provide greenhouse gas (GHG) reductions compared to gasoline-powered vehicles**. The researchers argue that **EVs are only as clean as the electricity used to charge them**, and in regions with fossil fuel-heavy grids, their emissions may be comparable to or even exceed those of efficient hybrid gasoline vehicles.

Using **regional electricity emissions data and life cycle assessments**, the study introduces the concept of a **Critical Emissions Factor (CEF)**—a threshold CO₂ intensity level that determines **whether EVs provide a net reduction in GHG emissions compared to fuel-efficient gasoline hybrids**.

This study is crucial to your research, as it provides **a direct comparison of Tesla’s per-mile emissions to gasoline vehicles, accounting for regional energy generation differences**.

**1. The Concept of Critical Emissions Factor (CEF) for EVs**

The study defines the **Critical Emissions Factor (CEF)** as the **maximum CO₂ intensity of the electricity grid at which an EV still outperforms a hybrid gasoline vehicle in terms of emissions**.

**Findings:**

* **If the electricity grid emits more than 500 gCO₂/kWh**, a **Tesla Model 3 or Model Y produces more lifetime emissions than a hybrid like the Toyota Prius**.
* **If the grid emits less than 200 gCO₂/kWh**, EVs provide a **clear CO₂ benefit over hybrids and gasoline vehicles**.
* **Currently, 60% of the U.S. electricity grid exceeds the CEF threshold**, meaning that **in these regions, Tesla vehicles may not provide substantial CO₂ reductions over fuel-efficient gasoline cars**.

This finding **directly supports your thesis** that **Tesla’s CO₂ footprint is highly dependent on regional electricity sources**—EVs are not universally better than gasoline cars when emissions from power plants are considered.

**2. Comparing Tesla’s CO₂ Emissions to Gasoline Vehicles**

The study evaluates how **Tesla’s real-world CO₂ emissions per mile compare to gasoline-powered cars**, considering both **direct emissions (tailpipe for ICE vehicles) and indirect emissions (power plant emissions for EVs)**.

**Findings:**

* In **coal-heavy states (West Virginia, Kentucky, Missouri, Indiana)**, **Tesla’s per-mile CO₂ emissions exceed those of a Toyota Prius Hybrid**.
* In **natural gas-dominant states (Texas, Pennsylvania, Florida)**, **Tesla’s emissions are comparable to gasoline hybrids** but still higher than the most fuel-efficient ICE vehicles.
* In **renewable-heavy states (California, Washington, Oregon, New York)**, Tesla’s per-mile emissions are **50-70% lower than gasoline vehicles**, making them a clear low-carbon alternative.

This analysis **reinforces the need for location-specific EV emissions calculations**—Tesla vehicles **only provide substantial CO₂ savings in regions with clean electricity sources**.

**3. The Impact of Charging Behavior on EV Emissions**

This study also evaluates how **charging time affects the CO₂ footprint of EVs**, as power grid emissions fluctuate throughout the day.

**Findings:**

* **Charging at night (off-peak hours) in fossil fuel-heavy states increases Tesla’s CO₂ footprint**, as coal plants often supply electricity during these hours.
* **Charging during peak solar energy production hours (midday in states with strong solar capacity) significantly reduces Tesla’s emissions per mile**.
* **In wind-heavy regions (Midwest, Great Plains), charging at night can be beneficial**, as wind power is more available during nighttime hours.

This finding supports your argument that **Tesla’s CO₂ footprint is not just dependent on where it is charged, but also when it is charged**—consumer charging behavior **directly influences emissions reductions**.

**4. Future Electricity Grid Decarbonization and its Impact on Tesla’s CO₂ Footprint**

The researchers model future **U.S. electricity grid scenarios (2025–2050) to predict how Tesla’s CO₂ footprint will change over time**.

**Findings:**

* **If current trends continue, average grid emissions will decline by 40% by 2035, making EVs a cleaner alternative nationwide.**
* **If coal plants are phased out faster, EV emissions reductions will accelerate significantly.**
* **Without policy interventions, some regions will remain fossil fuel-dependent, limiting the emissions benefits of EVs in those areas.**

This suggests that **Tesla’s CO₂ advantage will improve over time**, but **current policy and energy investments will determine how quickly these benefits materialize**.

**5. Policy Recommendations to Maximize EV CO₂ Reductions**

The study concludes by offering **policy recommendations to ensure that EVs, including Tesla vehicles, provide substantial emissions reductions nationwide**.

**Recommendations:**

* **Phase out coal plants faster to lower electricity sector emissions and increase EV sustainability.**
* **Encourage EV charging during renewable energy peak production hours.**
* **Align EV incentives with regional electricity grid emissions**—subsidies should be higher in clean-energy states and lower in coal-heavy states.
* **Expand grid storage solutions to stabilize renewable energy supply for EV charging.**

These policy recommendations **reinforce your argument that Tesla’s sustainability cannot be assumed to be equal across all regions**—**EV benefits must be analyzed in the context of power grid decarbonization efforts**.

Singh, M., Yuksel, T., Michalek, J. J., & Azevedo, I. M. L. (2024). Ensuring greenhouse gas reductions from electric vehicles compared to hybrid gasoline vehicles requires a cleaner U.S. electricity grid. *Scientific Reports*, *13*(1), 1–11. <https://doi-org.proxy.ulib.uits.iu.edu/10.1038/s41598-024-51697-1>

We find that the Nissan Leaf and Chevy Bolt battery electric vehicles reduce lifecycle emissions relative to Toyota Prius and Honda Accord gasoline hybrids in most of the United States. However, in rural counties of the Midwest and the South, power grid marginal emissions reductions of up to 208 gCO2/kWh are still needed for these electric vehicles to have lower lifecycle emissions than gasoline hybrids. Except for the Northeast and Florida, the longer-range Tesla Model S battery-electric luxury sedan has higher emissions than the hybrids across the U.S., and the emissions intensity of the grid would need to decrease by up to 342 gCO2/kWh in some locations for it to achieve carbon parity with hybrid gasoline vehicles.

The U.S. transportation sector in the United States accounts for 29% of the total greenhouse gas emissions (GHGs), with almost 60% of transport GHG emissions coming from light-duty vehicles1.

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, thus requiring a spatially explicit framework since EVs will be only as clean as the grid used to charge them. (Life Cycle Analysis)

We find that Bolt and Leaf electric vehicles have lower emissions than the Prius and Accord hybrids in almost all counties of the West, Texas, Florida, and New England. In com- parison, they have higher emissions in rural counties of the Midwest and the South. In contrast, the Tesla Model S has higher emissions than the Prius and Accord in all counties.

In almost all parts of the United States, current marginal emission factors are already below CEF levels for the BEV Leaf and Bolt to have lower emissions than the gasoline hybrid Toyota Prius and Honda Accord. The marginal emissions factor must be reduced by 207 gCO2/kWh in the Midwest and parts of Appalachia for Leaf or Bolt to reach parity with gasoline hybrids. All regions of the US, except parts of the Northeast and Florida, would need to reduce marginal emission factors up to 342 gCO2/kWh for the Tesla Model S to have lower lifecycle emissions than these gasoline hybrids.

**6. Regional Variability and Uncertainty of Electric Vehicle Life Cycle CO₂ Emissions Across the United States**

**Authors:** Mili-Ann M. Tamayao, Jeremy J. Michalek, Chris Hendrickson, & Inês M. L. Azevedo (2015)​

**Summary:**

This study explores **how regional variations in electricity generation affect the life cycle CO₂ emissions of electric vehicles (EVs) across the United States**. The authors analyze multiple factors, including:

* **Regional power grid composition (coal vs. renewables)**
* **Marginal vs. average emission factors**
* **Charging schemes and timing**

The study emphasizes that **EVs do not have uniform emissions benefits across all regions**—their **environmental impact is determined by the electricity source used for charging**. The key findings are:

**1. Regional Differences in EV Emissions**

* The study finds that **EV emissions per mile vary by up to 120% across different regions**.
* **In the Western U.S. and Texas**, EVs **outperform hybrid gasoline vehicles** in terms of CO₂ emissions.
* **In the Northern Midwest**, EVs have **higher life cycle CO₂ emissions than efficient hybrids**, primarily due to **coal-heavy electricity generation** in the region.

**2. The Importance of Marginal Emission Factors (MEFs) vs. Average Emission Factors (AEFs)**

The authors argue that **marginal emissions factors (MEFs)**—which estimate the emissions impact of additional electricity demand—are **more appropriate** for evaluating EV emissions than **average emissions factors (AEFs)**, which generalize across all electricity use.

* **Using marginal emissions factors changes the ranking of vehicle emissions in many regions**.
* **In some states, an EV may appear cleaner when using AEFs but actually produce more CO₂ per mile when MEFs are applied**.

**3. The Effect of Charging Time on CO₂ Emissions**

* **Charging EVs at midnight leads to higher emissions in most U.S. regions** due to increased reliance on **coal power plants** at night.
* **Charging during peak hours (daytime) results in lower emissions**, as renewables and natural gas often contribute more to electricity supply during these periods.
* This finding challenges **current policies that incentivize nighttime charging**, which may **inadvertently increase emissions in coal-heavy states**.

**4. Comparing EVs with Hybrid Gasoline Vehicles**

* The **Chevrolet Volt PHEV (Plug-in Hybrid Electric Vehicle)** has **higher life cycle CO₂ emissions than the Toyota Prius hybrid in nearly all U.S. regions**.
* The **Nissan Leaf (BEV) has lower emissions than the Prius in Texas and the Western U.S.** but **higher emissions in the Northern Midwest**.
* In other regions, whether an EV or a hybrid is cleaner **depends on charge timing and the emissions calculation method used**.

**5. The Impact of Regional Boundaries on Emissions Estimates**

* Different studies use different regional definitions (state boundaries, eGRID subregions, or NERC regions), which **can lead to variations in estimated emissions**.
* The study finds that **state-based emissions estimates differ from NERC regional estimates by as much as 120%**, showing that **policy decisions based on incorrect boundaries could lead to misleading conclusions** about EV sustainability.

**6. Policy Implications and Recommendations**

The authors suggest that **EV incentives and policies should be regionally tailored** to align with the **actual emissions reductions that EVs provide**. Key policy recommendations include:

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 everywhere**—but for now, **regional differences in emissions must be accounted for in EV policy discussions**.

**Conclusion:**

This study **challenges the notion that EVs are inherently better for the environment** by showing that **their emissions benefits are regionally dependent**. It emphasizes the need for **grid-specific CO₂ emissions calculations** when evaluating **Tesla’s carbon footprint**, as **EV sustainability is not uniform across the U.S.**. This paper is **highly relevant to your research**, reinforcing the **argument that Tesla’s CO₂ emissions should be calculated using regional electricity generation data rather than national averages**.

Tamayao, M.-A. M., Michalek, J. J., Hendrickson, C., & Azevedo, I. M. L. (2015). Regional Variability and Uncertainty of Electric Vehicle Life Cycle CO~~2~~ Emissions across the United States. *Environmental Science & Technology*, *49*(14), 8844–8855. <https://doi-org.proxy.ulib.uits.iu.edu/10.1021/acs.est.5b00815>

Using these two estimates of NERC region marginal emission factors, we find the following: (1) delayed charging (i.e., starting at midnight) leads to higher emissions in most cases due largely 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 in 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.

In particular, variation in grid emission factors and regional boundaries are key drivers of differences in the estimates of regional PEV benefits.

However, it is difficult to correctly model all of the factors that determine plant behavior in practice (e.g., transmission constraints, ramping constraints, unscheduled maintenance, weather, regulation, contracts, etc.) for a region large enough to capture all relevant factors in such an interconnected system. Furthermore, such modeling approaches generally entail a gap between model predictions and plant operation in practice. Finally, such models are typically developed for one region or interconnect and do not allow for systematic regional comparisons across the United States.

Given substantial regional differences in PEV GHG emissions implications, differential regional policy may be warranted, but current differences in state subsidies57 do not align particularly well with regions where PEVs provide the largest GHG emissions benefits. For example, the state with the largest state subsidies ($7500) for BEVs is West Virginia, which is under the RFC region, where the Nissan Leaf and the Chevy Volt are likely higher emitting than the Toyota Prius. Under the Clean Power Plan Proposal, West Virginia is expected to bring down its carbon rate to about 730 kg/MWh, but that level is not yet low enough for PEVs to be lower emitting than the Prius, and the effect of average emissions reductions on marginal emissions has not yet been characterized. The second highest state subsidies ($6000) are in Colorado, part of the WECC region where the Leaf is likely lower emitting than the Prius and the Volt may be higher or lower. The third highest state subsidies ($5000) are in Georgia, where the comparison of the Leaf and Prius is inconclusive and the Volt is higher emitting. Of course, GHG benefits must be balanced against other goals, including reduction of air pollution and oil dependency as well as economic factors.

Avoid treating PEVs as though they are all the same.