Analysis of Electric Vehicle Adoption and CO_2 Emission Patterns

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The widespread adoption of electric vehicles (EVs) marks a significant transformation in transportation and energy systems. Addressing climate change requires an understanding of how EV adoption impacts CO_2 emissions, which is a crucial issue for policymakers, industries, and communities. As one of the largest contributors to global CO_2 emissions, the transportation sector presents an opportunity for emission reduction through the transition to EVs. However, the effectiveness of this transition depends on factors such as energy grid decarbonization, regional adoption trends, and policy support (International Energy Agency [IEA], 2024).

The relationship between EV growth and fossil fuel CO_2 emissions offers valuable insights into the success of current strategies. For example, the global EV charging station market is expected to grow from USD 16.7 billion in 2024 to USD 172.9 billion by 2033, driven by increasing EV adoption, government policies, and technological advancements (IMARC Group, 2024). This growth highlights the importance of infrastructure in supporting the shift to sustainable energy systems.

Examining trends across countries with different levels of EV adoption can identify best practices and challenges. Asia-Pacific leads the EV charging station market due to significant investments in infrastructure and efforts to reduce greenhouse gas emissions (IMARC Group, 2024). Such analyses are essential for creating equitable and effective climate strategies, particularly in regions with limited economic or infrastructure capacity.

This research uses a multi-dimensional approach, analyzing emissions trends, EV adoption patterns, and public sentiment to provide a comprehensive understanding of how societal and technological changes influence CO_2 emissions and sustainability goals (IEA, 2024).

Significance of Findings

- **Policy Development**: This analysis can help refine government incentives for EV adoption and energy grid improvements.
- **Industry Guidance**: Insights can assist the automotive sector in optimizing EV rollout strategies by identifying adoption patterns and regional challenges.
- **Public Awareness**: Demonstrating the impact of EVs on carbon emissions can encourage further consumer adoption.

This study contributes to understanding the global shift toward sustainable transportation and energy systems, addressing critical challenges in the fight against climate change.

Data Sources:

1. IEA Data and Statistics - Provides energy production and consumption metrics, CO_2 emissions data, and trends by country and energy type.
    - https://www.iea.org/data-and-statistics/data-product/global-ev-outlook-2024
2. Electric Vehicle Population (Kaggle) - Contains details about EV models, types, geographical distribution, and trends in EV adoption.
    - https://www.kaggle.com/datasets/willianoliveiragibin/electric-vehicle-population/data
3. Global Fossil CO_2 Emissions by Country (2002–2022) (Kaggle) - Tracks CO_2 emissions by country, with breakdowns by fossil fuel types.
    - https://www.kaggle.com/datasets/thedevastator/global-fossil-co2-emissions-by-country-2002-2022
4. Annual CO_2 emissions 2023 (Global Carbon Budget)- Fossil CO2 emissions', which includes all emissions from the consumption of fossil fuels (from coal, oil, gas and flaring) plus direct industrial emissions from cement.
    - https://ourworldindata.org/explorers/co2?Gas+or+Warming=CO%E2%82%82&Accounting=Territorial&Fuel+or+Land+Use+Change=All+fossil+emissions&Count=Per+country&country=CHN~USA~IND~GBR~OWID_WRL

Data Cleaning and Exploration:

Before conducting the analysis, extensive data cleaning and exploration steps were undertaken to ensure accuracy, reliability, and compatibility across datasets. These steps are critical to maintaining the integrity of the results and minimizing potential biases.

- **Duplicate Removal** - All duplicate entries within and across datasets were identified and removed to prevent overrepresentation of data points and ensure accurate analysis.

- **Handling Missing Values:**
    a. Numerical Columns: Missing values in numerical columns were imputed with median values to maintain consistency without skewing data distributions.
    b. Categorical Columns: Missing values in categorical columns were filled with the placeholder string 'Unknown,' enabling analysis without omitting relevant records.

- **Data Type Validation and Conversion** - Ensured all columns were in appropriate data types (e.g., numerical, categorical, datetime) to facilitate analysis. For instance, date-related fields were converted to datetime format to support time-series analysis.

- **Exploratory Data Analysis (EDA)**
    a. Summary Statistics: Generated summary statistics for key columns to understand central tendencies, distributions, and variability.
    b. Visual Exploration: Created initial plots, such as line and scatter plots, to observe data patterns and identify anomalies.

- **Dataset Merging and Aggregation**

    a. Merged datasets from multiple sources (e.g., IEA and Kaggle) using common keys such as country, year, and fuel type.
    b. Aggregated data by country and year to facilitate temporal and regional analyses.

- **Data Filtering** - Applied filters to include only countries with complete records for both CO_2 emissions and EV adoption rates, ensuring consistency in comparative analyses.

- **Verification of Data Integrity**
    a. Cross-referenced data points to ensure consistency and validate the accuracy of merged datasets.
    b. Sampled random records post-cleaning to verify that preprocessing steps were applied correctly.

By following these steps, the data was prepared for comprehensive analysis, enabling robust evaluations of EV adoption impacts on CO_2 emissions across temporal and geographical dimensions.

Research Questions and Analysis Methods:

- **How has EV adoption influenced CO_2 emissions in various regions?**
    - *Method*: data will be aggregated to compare EV population growth with CO_2 emissions from fossil fuels to identify any trends or reductions in emissions corresponding to EV adoption.
- **Which EV powertrain types are driving adoption globally, and how does their distribution vary by region?**
    - *Method:* explores the dominance of BEVs and the niche roles of PHEVs and FCEVs in different regions.
- **Are there significant differences in emission patterns between countries with high versus low EV adoption rates?**
    - *Method*: Statistical summaries and grouping analyses will allow us to categorize countries based on EV adoption and measure emission differences.

Outputs and Results*:*

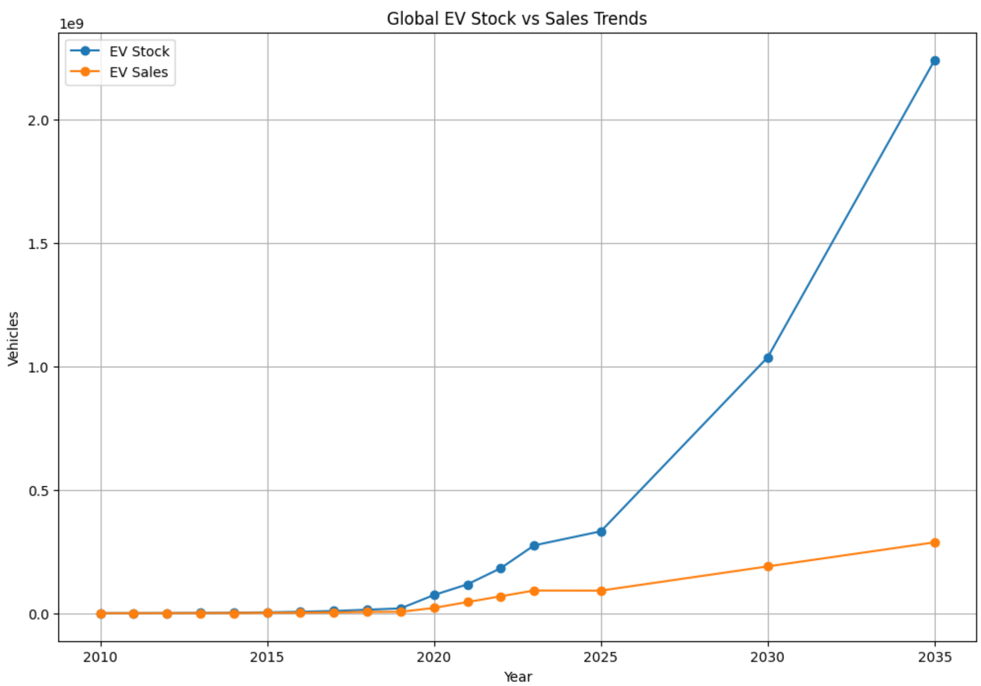
The initial data from IEA Global EV Data 2024.csv was initialized into a Pandas dataframe to be analyzed and cleaned. Missing values and duplicate data were dropped. The data types were also normalized to lowercase string values, integer values, and float values. This new dataframe was saved and the IEA Global EV Data 2024.csv file was overwritten with the cleaned file.

```
Missing Values:
region        0
category      0
parameter     0
mode          0
powertrain    0
year          0
unit          0
value         0
dtype: int64

Cleaned Data Info:
<class 'pandas.core.frame.DataFrame'>
RangeIndex: 12654 entries, 0 to 12653
Data columns (total 8 columns):
 #   Column      Non-Null Count  Dtype
---  ------      --------------  -----
 0   region      12654 non-null  object
 1   category    12654 non-null  object
 2   parameter   12654 non-null  object
 3   mode        12654 non-null  object
 4   powertrain  12654 non-null  object
 5   year        12654 non-null  int64
 6   unit        12654 non-null  object
 7   value       12654 non-null  float64
dtypes: float64(1), int64(1), object(6)
memory usage: 791.0+ KB
None

Cleaned data saved to IEA Global EV Data 2024.csv
```

After cleaning the data, plots were created for data visualization. EV stock and EV sales were filtered from the "parameter" feature and were then plotted, as well as global and regional EV adoption trends. Overall, there is a general rise in EV stock and EV sales in recent years. An example graph shown below displays this global EV stock and EV sales trend.

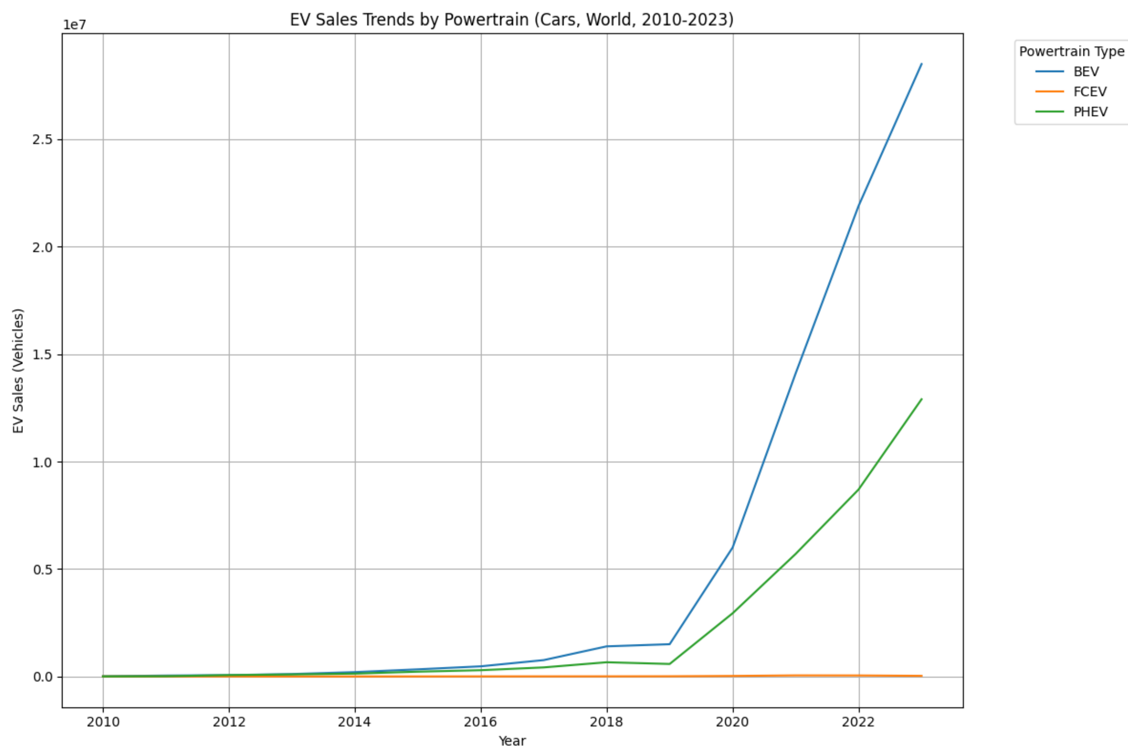


Powertrain Types and Global Sales

Understanding the types of powertrains driving EV adoption is critical for identifying technology preferences and market trends. The primary powertrain types analyzed include:

- **BEV (Battery Electric Vehicles)**: Fully electric vehicles powered by batteries, leading global sales and stock trends.
- **PHEV (Plug-in Hybrid Electric Vehicles)**: Vehicles combining an internal combustion engine with a rechargeable battery, enabling short-distance electric travel.
- **FCEV (Fuel Cell Electric Vehicles)**: Hydrogen-powered electric vehicles, maintaining a niche market presence.

Key Insight: BEVs dominate globally, with exponential growth since 2016, as shown in the second chart below. PHEVs follow as a transitional technology, while FCEVs exhibit limited adoption. This dominance indicates a clear consumer and market preference for fully electric technologies over hybrids or hydrogen fuel cells.



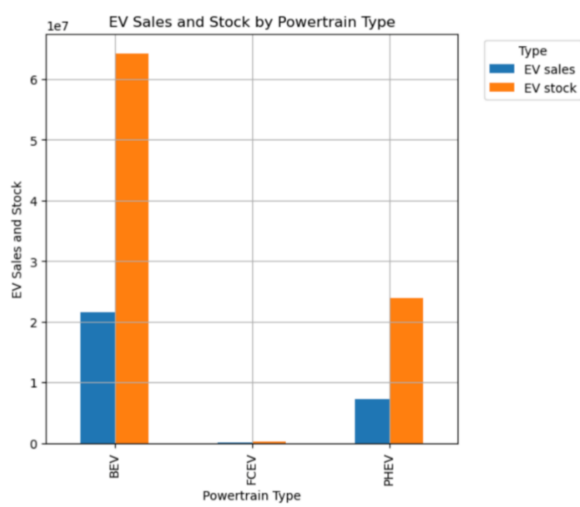
Another dataset was needed to verify these trends and validate the data. Dataframes were created from the GCB2022v27_percapita_flat.csv and IEA Global EV Data 2024-2.csv data files. These dataframes were merged on the “country” and “year” features. After extracting the unique countries in the merged data, a dictionary was created to map countries to specific regions. This simplified the output and allowed us to group multiple countries into a single region. The gas emissions were then compared to the EV sales and EV stocks for different regions.

	region	EV sales	EV stock	total_gas_emissions_per_capita
0	Africa	1962.0	7344.0	9.69
1	Asia	18501280.0	56103456.0	674.07
2	Central America	2331.0	5700.0	0.00
3	Europe	5731763.2	14175029.2	6378.88
4	Middle East	47553.0	89353.0	383.85
5	North America	4545536.2	17747022.8	2768.63
6	Oceania	82009.0	225774.0	464.87
7	South America	27795.0	35203.0	102.13

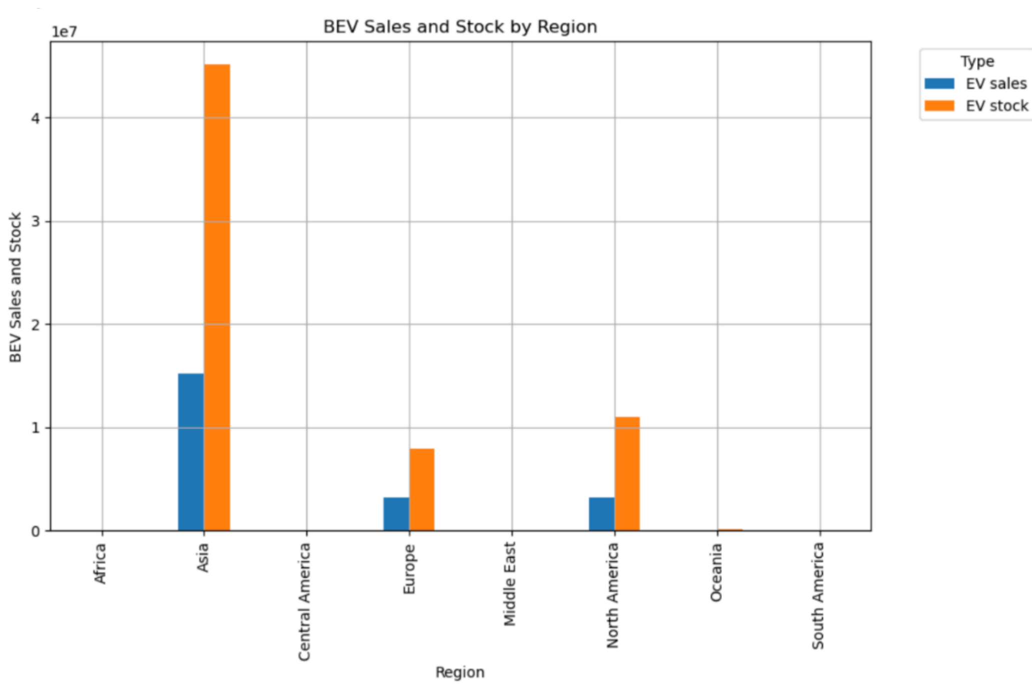
The data reveals clear regional differences in EV adoption and its impact on CO_2 emissions. Asia leads with 18.5 million EV sales and 56.1 million EV stock, which is due to strong manufacturing and government support. Europe (5.7 million sales, 14.2 million stock) and North America (4.5 million sales, 17.7 million stock) follow, which is driven by decarbonization efforts and incentives. In contrast, Africa, South America, and Central America show low adoption due to economic and infrastructure challenges. CO_2 emissions per capita highlight further disparities. Europe and North America have high emissions despite their EV growth, while Asia struggles with emissions due to its coal-heavy energy grid. Africa and Central America, with low EV adoption, have the lowest emissions per capita. These findings highlight the need for tailored strategies, which include cleaner energy grids in high-adoption regions like Asia and better infrastructure support in low-adoption regions like Africa and South America, to maximize the environmental benefits of EVs.

The pivot table and bar graph below help compare the different types of powertrain sales and stock globally:

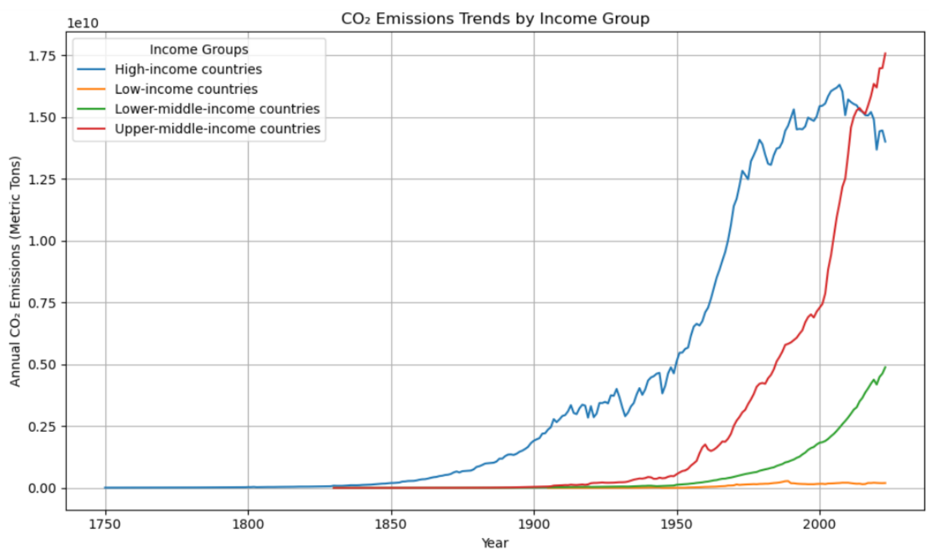
powertrain	EV sales	EV stock
BEV	21624253.2	64306436.8
FCEV	51003.2	169124.2
PHEV	7264973.0	23913321.0



The BEV powertrain is the clear leader globally in both EV sales and EV stock. The bar plots show BEV sales by region as displayed below:



CO_2 Emissions by Income Group at Key Years:



	Year	High-income countries	Low-income countries	Lower-middle-income countries	Upper-middle-income countries
1	1900	1907431000.0		15090113.0	38969628.0
2	1950	5117058000.0	5435304.0	126659900.0	552599300.0
3	2000	15444175000.0	164199840.0	1827241100.0	7286903000.0
4	2023	14014304000.0	196579700.0	4882584600.0	17581070000.0

	Year	Annual CO_2 emissions
count	29137.000000	2.913700e+04
mean	1947.718022	4.156982e+08
std	58.985133	1.945844e+09
min	1750.000000	0.000000e+00
25%	1912.000000	3.737280e+05
50%	1962.000000	4.990392e+06
75%	1994.000000	5.327268e+07
max	2023.000000	3.779157e+10

The data shows clear differences in CO_2 emissions across income groups over time. High-income countries were the largest contributors historically, with emissions rising sharply during industrialization (1850–1950) and peaking around 2000 at over 15 billion metric tons. Since then, their emissions have declined due to cleaner energy technologies and climate policies. Upper-middle-income countries, however, have seen rapid growth, surpassing high-income countries after 2000 as industrialization and economic development accelerated in nations like China and India. Emissions in these countries reached nearly 17.6 billion metric tons in 2023. Lower-middle-income countries show steady growth in emissions as they continue to develop, while low-income countries contribute very little due to limited industrialization and energy use.

From 1750 to 2023, the average annual CO_2 emissions were 415.7 million metric tons, with the highest level recorded at 37.8 billion metric tons in 2023. The graph highlights these trends, with high-income countries reducing emissions, upper-middle-income countries experiencing rapid increases, and lower- and low-income countries contributing smaller amounts. These trends highlight the need for targeted climate strategies: supporting clean growth in middle-income countries, maintaining reductions in high-income nations, and improving energy access for low-income regions.

Conclusion

This study explored how electric vehicle (EV) adoption impacts CO_2 emissions, which powertrain types are driving adoption, and the differences between countries with high and low EV uptake. The findings provide key insights into EVs' role in creating a more sustainable transportation system.

Impact of EV Adoption on CO_2 Emissions
Regions with high EV adoption, such as Europe and North America, show gradual CO_2 emission reductions, especially where energy grids are decarbonized. However, in regions like Asia, the reliance on fossil fuels limits emissions benefits, emphasizing the need for cleaner energy grids.

Key Drivers of EV Adoption
Battery Electric Vehicles (BEVs) dominate global adoption, particularly in Asia, Europe, and North America. Plug-in Hybrid Electric Vehicles (PHEVs) and Fuel Cell Electric Vehicles (FCEVs) have smaller roles, with PHEVs popular in Europe and FCEVs concentrated in Asia and North America. BEVs are clearly leading the global shift toward sustainable transportation.

Differences in Emissions by EV Adoption Levels
High-adoption countries show significant progress in reducing emissions, supported by policies, infrastructure, and clean energy grids. In contrast, low-adoption regions like Africa and South America see minimal changes due to economic and infrastructural barriers.

Key Takeaways

- EV adoption reduces emissions most effectively in regions with decarbonized grids.
- BEVs are driving global adoption, while PHEVs and FCEVs play smaller, regional roles.
- Low-adoption regions need targeted support, including infrastructure investments and economic incentives.

By addressing these challenges, EVs can more effectively contribute to global sustainability goals and create a cleaner, more equitable future for transportation.

References

IMARC Group. (2024). *Electric vehicle charging station market: Global industry trends, share, size, growth, opportunity and forecast 2024-2033*. Retrieved from https://www.imarcgroup.com/electric-vehicle-charging-station-market

International Energy Agency. (2024). *Global EV outlook 2024*. Retrieved from https://www.iea.org/reports/global-ev-outlook-2024