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GROUP PROJECT

Final Report

FOUNDATIONS OF DATA SCIENCE, DATA 5100

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ABSTRACT

This project investigates whether counties with higher renewable energy shares in electricity tend to emit less carbon dioxide (CO_2) emissions. Using a panel dataset from 2010-2024 across multiple countries and regions, we analyze the relationship between these renewable energy shares, GDP per capita, and CO_2 emissions. Through our analysis, we gather consistent evidence that greater renewable energy adoption is associated with lower CO_2 emissions per capita. Additional analysis shows that renewable energy can reduce emissions even when economies continue to grow. These findings provide real-world insight into how renewable energy transitions can decouple economic growth from carbon emissions.

INTRODUCTION

Global carbon dioxide (CO_2) emissions have continued to rise despite record levels of investment in renewable energy technologies. According to the International Energy Agency (IEA, 2025), energy-related CO_2 emissions reached an all-time high in 2024, driven by growth in total energy demand. Previous research shows that renewable energy expansion can help reduce carbon emissions intensity, but results vary by region and economic structure (Wang & Zhao, 2023; Ozturk & Acaravci, 2013). Other studies note that investment alone may not lead to immediate reductions, as infrastructure transitions and fossil fuel dependencies can delay impacts (Bölük & Mert, 2014).

This raises a critical question: Do higher levels of renewable energy shares translate into measurable reductions in carbon dioxide (CO_2) emissions? Understanding this relationship is important for evaluating whether clean energy transitions are successfully addressing climate change.

Our investigation focuses on the problem:

"Is higher share of renewable energy in total energy supply associated with lower per-capita CO_2 emissions?"

We used the following data sources in the analysis:

1. **Global Carbon Atlas**. (2025). Global Carbon Atlas Database: CO_2 Emissions by Country. https://globalcarbonatlas.org: Provides annual country-level carbon dioxide emissions (total, per capita, and per GDP) spanning several decades.
2. **World Bank**. (2025). World Development Indicators (WDI). The World Bank Group. https://databank.worldbank.org/source/world-development-indicators: Supplies complementary data on renewable electricity share (% of total electricity generation), GDP, and population.
3. **Energy Institute**. (2025). Statistical Review of World Energy 2025. Energy Institute. https://www.energyinst.org/statistical-review: Provided by the Energy Institute, this can offer us some insight into the demand for energy supply by fuel, region, etc.

This project seeks to quantify these effects using real-world data. We are confident that these sources are sufficient as they provide consistent data for many countries over several decades. Preprocessing has been completed—including merging datasets by **year** and **country**; handling missing values; and normalizing variable scales by **converting emissions to metric tons per capita**.

THEORETICAL BACKGROUND

At a fundamental level, electricity generation is a major contributor to global CO_2 emissions, especially in countries that rely heavily on coal, oil, or natural gas. The idea driving this analysis is that shifting this energy mix toward renewable energy sources such as hydroelectric, wind, solar, or geothermal should, in theory, separate energy production from CO_2 emissions. Renewable energy sources can produce electricity with significantly lower direct CO_2 emissions; however, the extent of this reduction likely depends on displacement. Just adding renewable energy to a country's infrastructure may not be enough; instead, there is likely a need for a country to replace existing fossil fuel generation to lower total emissions.

This process is not immediate, and the extent of this reduction likely depends on how quickly renewable energy sources replace fossil fuel generation and how long those energy systems take to integrate into a country's infrastructure. Complex dynamics such as gradual transitions, long investment cycles, and slow retirement of fossil fuel systems suggest that the effects of renewable adoption may unfold over multiple years. Due to this, a meaningful analysis should look at these changes over time, instead of in a single snapshot.

Economic conditions may also play an important role. As an economy grows, energy demand typically increases, which can lead to an increase in CO_2 emissions unless renewable adoption can keep pace. This creates the possibility that renewable adoption may help moderate CO_2 emissions even in countries with expanding economies. If a country can increase its renewable share faster than its energy demand grows, it is possible it could have economic growth without a significant increase in CO_2 emissions.

METHODOLOGY

We conducted a comparative observational study using quantitative, correlational analysis to examine the relationship between **carbon emissions** and the **share of renewable energy** in national electricity generation from 2010-2024. Our analysis uses a country-year panel dataset, containing annual observations from multiple countries, to examine how renewable energy shares and CO_2 emissions change over time.

Our variables of interest include:

- CO_2 emissions per capita
- Renewable energy share
- GDP per capita
- Country/Regional population
- Country/Regional identifiers
- Timeframe identifiers

Our analysis steps were as follows:

1. Initial analysis of baseline relationships between key variables.
2. Top 10 and Bottom 10 – Compare global renewable share levels across regions in 2010-2024.
3. Analyze the relationships between renewable energy share per capita, CO_2 emissions per capita, and GDP per capita in 2010-2024 (Panel Regression Model).
4. Analyze whether renewable energy reduces carbon emissions immediately, or whether the benefits show up over time (Lag Analysis)
5. Check whether our main findings are reliable and don't disappear when we change assumptions, model structure, or variable definitions (Robustness Testing)
6. Analyze whether renewable energy shares reduce emissions even while economies grow (Expansion Analysis).

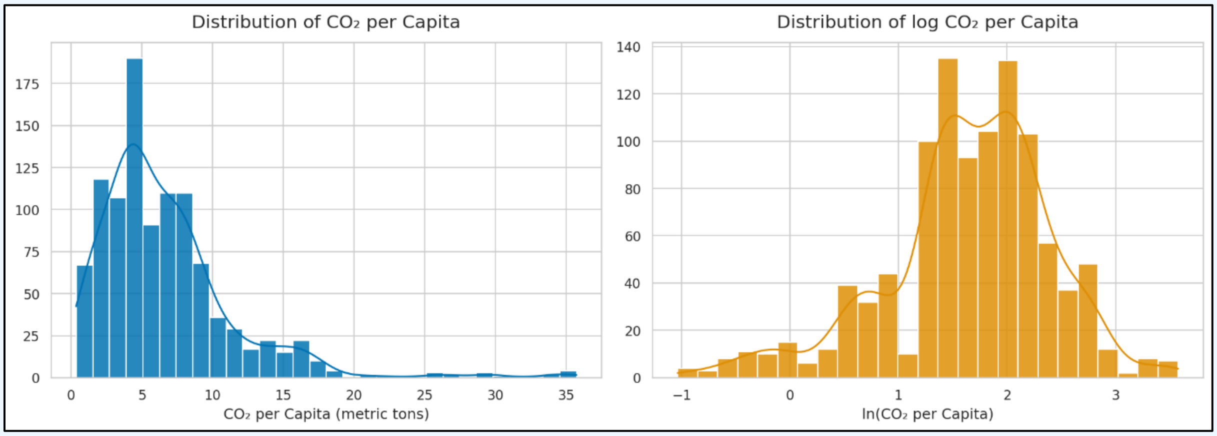
SOLUTIONS TECHNOLOGY

Processing and exploratory analyses has been done in Python as the primary language, specifically: pandas and NumPy for data wrangling and merging; matplotlib and seaborn for visualization; stats models and scikit-learn for regression and exploratory modeling; and Data Processing Notebook in Google Colab for reproducible analysis and documentation.

COMPUTATIONAL RESULTS

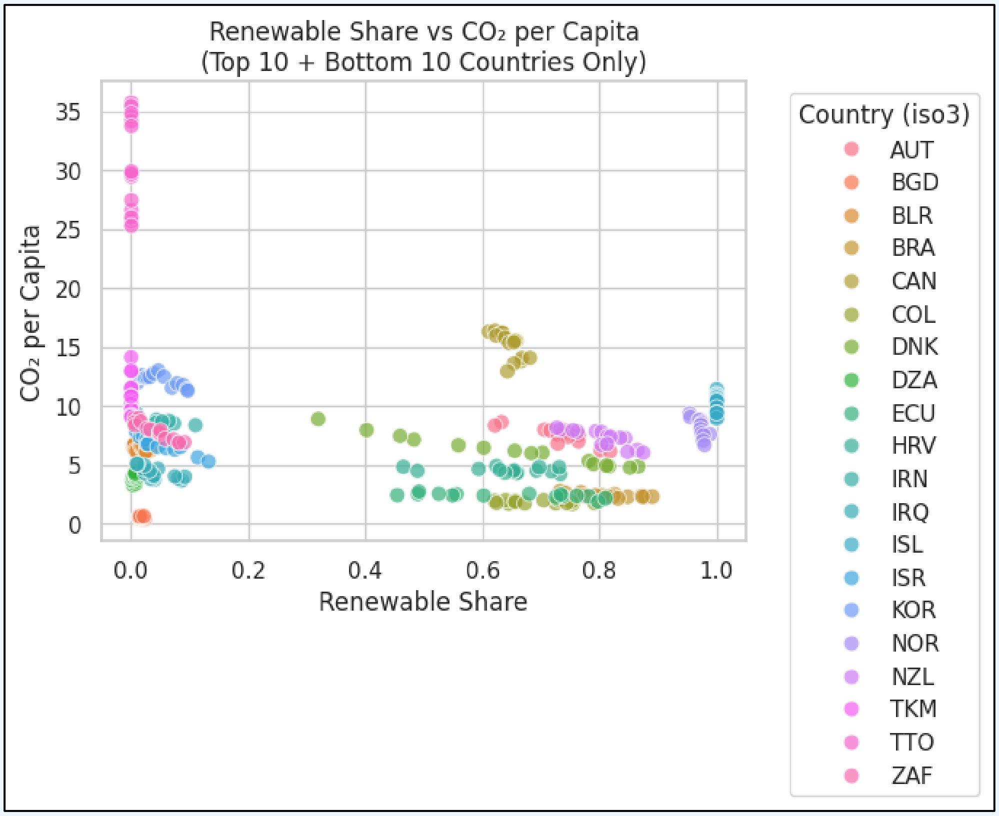
Exploratory Data Analysis:

We began our exploratory data analysis (EDA) by looking at the distribution, trends, and pairwise relationships among CO_2 per capita, renewable energy share, and economic indicators from 2010 to 2024. Before we began modeling, we investigated how these variables behaved over time and across regions in addition to their initial pairwise relationships.



Countries showed a wide variation in renewable energy adoption and emissions levels, with renewable energy share ranging from under 1% to over 98%. The CO_2 emissions per capita were heavily right skewed, with industrialized countries and oil exporting countries showing the highest values. The GDP per capita showed significant variation which may reflect overall global economic inequality. Because these variables were highly skewed, we applied log transformations to stabilize variance and improve linearity for regression modeling.

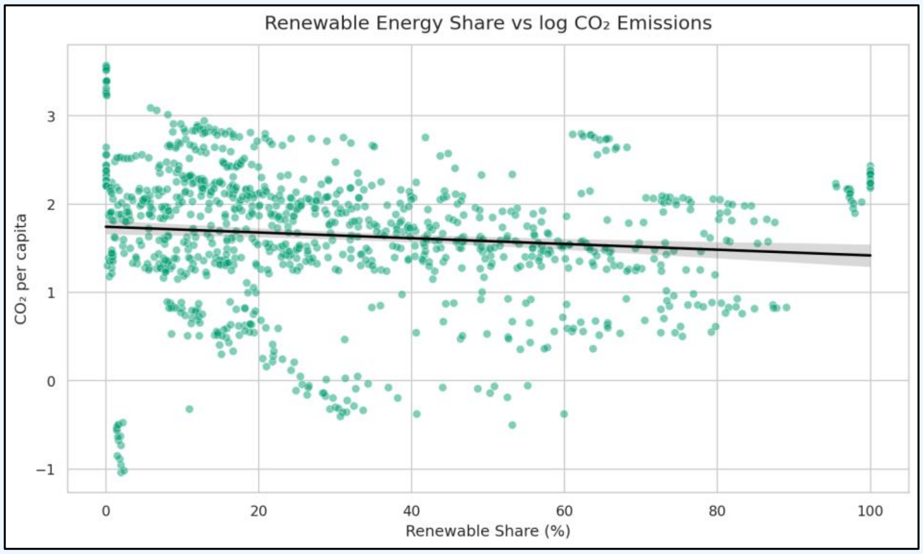
To understand the differences in renewable energy globally, we found the ten countries with the highest and lowest renewable electricity shares within our dataset.



As seen in the display above, countries with the highest renewable share tended to have an abundance of natural resources. Leaders included Iceland (ISL, 99.99%), Norway (NOR, 97.92%), and Brazil (BRA, 87.33%) with the following 7 countries still being above 72% renewable share. The Countries with the lowest renewable shares were Turkmenistan (TKM, 0.03%), Trinidad and Tobago (TTO, 0.07%), Algeria (DAZ, 0.74%), and Iraq (IRQ, 1.04%) with the next 6 being below 12%, these countries seemed to be fossil fuel intensive or resource constrained.

Our Comparison of renewable energy share and CO_2 emissions per capita indicates a generally negative relationship: countries with more renewable electricity tend to have lower CO_2 emissions. This relationship, however, is more complex with the data showing significant variation: countries with similar renewable energy shares often show different CO_2 emissions per capita. This finding prompted further analysis into economic growth.

Lag Effects:



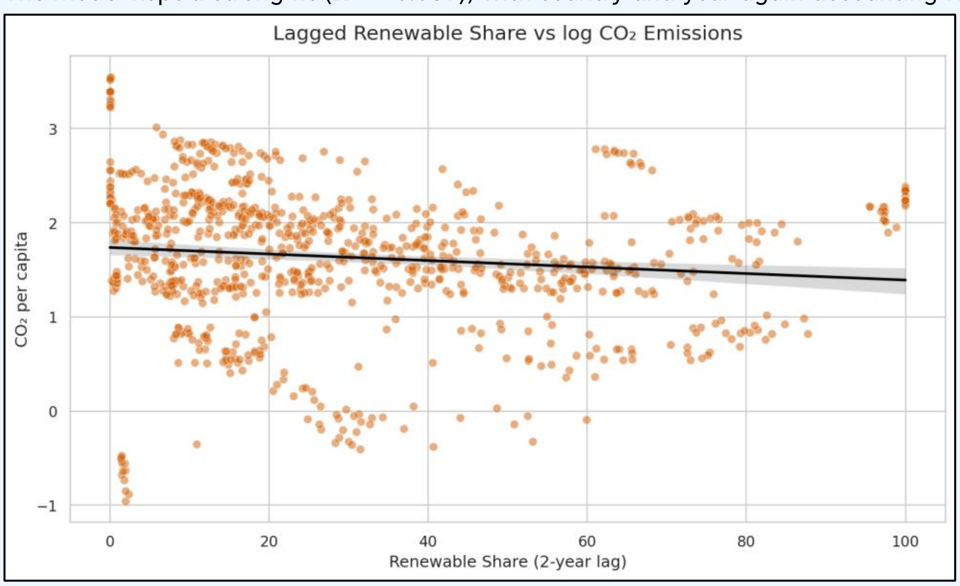
To determine if the impact of renewable energy adoption is seen immediately or develops over time, we estimated two fixed effects panel regression models: the first includes a one-year lag of renewable share, and the second includes a one year and two-year lag. These models show us how changes in renewable electricity share influence emissions not only in the current year, but also in the years that follow.

The single lag model suggests that higher renewable energy adoption is associated with lower CO_2 emissions. The R^2 = 0.986N = 965), with country and year fixed effects accounting for most of the variation in emissions. In particular, the renewable share of electricity showed a statistically significant, negative relationship with emissions per capita (β = -0.0095, p < 0.001). This implies that a 1% increase in renewable share is associated with roughly 0.95% decrease in CO_2

Additionally, this relationship seems to continue over time. The lagged renewable share was also negative and significant (β = -0.0022, p = 0.032), suggesting that an additional 0.22% reduction in emissions may occur one year later. GDP per capita remained positively correlated with emissions (β = 0.208), but the negative coefficients for the renewable variables support the view that adopting renewable energy is linked to reduced CO2 emissions per capita independent of a country's economic status.

The single year lagged coefficient displayed above shows statistical significance (β = -0.0019, p < 0.010), which suggests that the reduction in CO_2 emissions per capita continues into the following year with an additional 0.19% drop. However, the two-year lagged coefficient was found to not be statistically significant (β = -0.0014, p = 0.140). This result suggests that while the impact of renewable adoption is immediate and continued for a year, the measurable effect on emissions *may* fade after that.

The two-year lag model suggests that the benefits of renewable energy adoption are strongest in the short term. The model kept a strong fit (R^2 = 0.987), with country and year again accounting for most of the variation. The current year renewable share remained negative and significant (β = -0.0088, p < 0.001), which implies that a 1% increase in renewable share is associated with an immediate 0.88% decrease in CO2 emissions per capita.

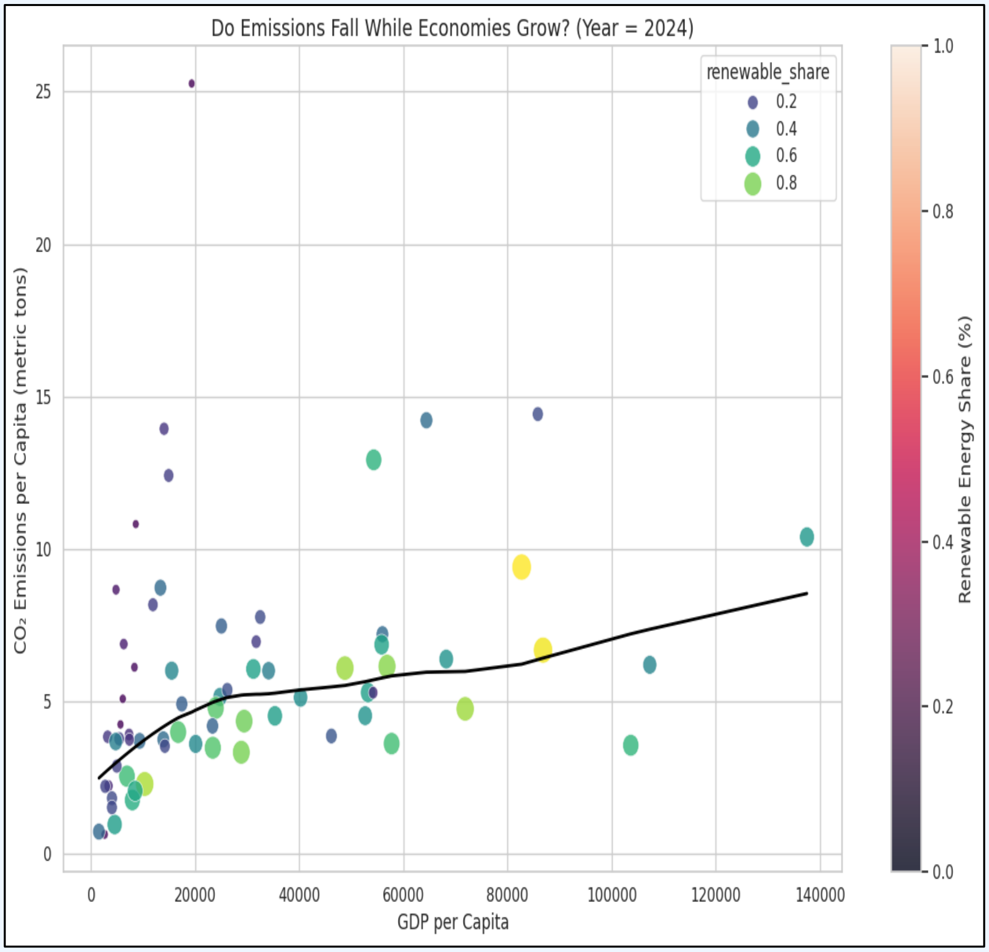


Robustness Testing:

To check whether our findings are sensitive to extreme values or model assumptions, we performed a robustness analysis by re-estimating the lagged effects model after removing outliers. The results stayed highly consistent: the coefficients for renewable energy share stayed negative and stable, which again suggests that higher renewable adoption is associated with lower CO_2 emissions per capita even when outliers are removed.

Expansion Analysis:

We also investigated whether countries could reduce CO_2 emissions while their economies continue to grow. We incorporated GDP per capita into our fixed effects models and analyzed whether the negative relationship between renewable energy share and CO_2 emissions continued after accounting for economic growth.



The graph above displays the relationship between GDP per capita (economic output) and CO_2 emissions per capita in the most recent year of our data (2024); each point representing a country. Countries with a higher renewable share (lighter/larger points) tend to have lower emissions, even at similar GDP levels. The black trend line shows that at economic output levels (GDP per capita) carbon dioxide emissions do not always keep rising and can even decline, consistent with the idea of partially “decoupling” the expected correlation between economic growth and increases in CO_2 emissions.

This suggests that, although CO_2 emissions are reported to increase as countries become wealthier, they do not have to. If renewable energy adoption is high enough, CO_2 emissions per capita can level off or even go down while GDP continues to increase.

DISCUSSION

The results of our analysis suggest a consistent association between higher renewable energy share in electricity generation and lower CO_2 emissions per capita within countries over time. Across all fixed-effect models, increases in renewable electricity share were linked to reductions in CO_2 emissions, even when accounting for economic growth. Because the fixed effect models control variables that do not change over time, these findings indicate that changes in renewable adoption within a country correspond to changes in its emissions profile.

The lag analysis offers greater insight into the timing of these CO_2 emission reductions. Negative coefficients on one-year lagged renewable share show that the benefits of renewable adoption are not confined to the same year. Instead, emissions continue to fall in the year following renewable adoption, possibly reflecting the time needed for grid integration, renewable expansion, or fossil fuel displacement to take full effect. Effects beyond two years were weaker and not statistically significant, suggesting that the majority of emissions benefits occur within the first year or two of renewable deployment.

Robustness testing confirms that this relationship is not driven by extreme values. After removing outliers, the direction and magnitude of the renewable share effects remained stable, indicating that the association holds across both high and low-emitting countries. This increases confidence that the findings reflect general global patterns rather than the influence of a small set of unique economies.

Finally, our expansion analysis examined whether CO_2 emission reductions continue even during periods of economic growth. GDP per capita remained positively associated with emissions overall, consistent with global trends in energy demand. Yet, the renewable share coefficient remained negative and significant in all models that included economic conditions. This suggests that renewables help weaken — and in some economies, reverse — the long-standing link between income growth (increased GDP per capita) and rising carbon emissions. In other words, economic expansion does not necessarily *have* to correlate to higher CO_2 emissions when renewable energy becomes a larger part of the electricity mix. This finding supports the emerging concept of “green growth,” under which economic development can occur alongside stable or declining carbon emissions.

CONCLUSION

Global carbon dioxide (CO_2) emissions have continued to rise despite record levels of investment in renewable energy technologies. In this project, we set out to evaluate whether increasing the share of renewable energy in national electricity generation is meaningfully linked to reductions in carbon dioxide (CO_2) emissions. Using an international panel dataset from 2010 to 2024, our analysis consistently showed that countries with higher renewable electricity shares have lower CO_2 emissions per person.

Importantly, these reductions are observed to persist even when accounting for economic expansion, demonstrating that cleaner energy systems can indeed support climate progress without halting economic growth.

The results also suggest that the benefits of renewable shares are not limited to the year they are adopted. Evidence from our lag analysis indicates that emissions continue to decline in the years following increases in renewable electricity production. While GPD per capita remained positively associated with emissions overall, the negative and statistically significant relationship between renewable adoption and CO_2 emissions per capita shows that renewable energy helps weaken the historic link between a population's growth (GDP per capita) and pollution (carbon emissions) – a key observation made that can support advocating for more aggressive transitions towards sustainable development, such as increasing renewable energy shares in electricity.

Because this study uses observational data, we cannot make definitive casual claims. However, our findings align closely with policy goals across the globe that aim to target net-zero CO_2 emissions. As countries continue to modernize their energy systems, our results provide encouraging evidence that increasing renewable energy is a practical and effective strategy for reducing carbon emissions while still encouraging economic growth and opportunity.

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Sources:

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