Economic Development and Clean Energy: Impacts on Carbon Intensity and Renewable Electricity Adoption

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1 Data Science Memo

Stakeholder (Target Audience). This memo is written for a **senior energy policy analyst at a multilateral development bank** (e.g., the World Bank). The analyst advises on financing decisions for electricity-sector projects across low-, middle-, and high-income countries. They are familiar with basic statistics and regression output but are not a specialist in econometrics or energy systems modeling.

1.1 Executive Summary / TL;DR

Rapid decarbonization of electricity is essential to meeting global climate goals, yet fossil fuels still provide most of the world's power. Using a global country–year dataset on energy and economic indicators from 1965–2023, we address two questions: **(1)** How does a country's economic development relate to the carbon intensity of its electricity generation, and does this relationship differ by income level? **(2)** What factors are associated with a country achieving a **>50% renewable** electricity share?

For **Research Question 1**, we find that **economic growth has opposite associations with power-sector emissions in poor vs. rich countries**. In **low-income countries**, higher GDP per capita is associated with **more carbon-intensive electricity**: a one-unit increase in log GDP per capita corresponds to roughly **+105 grams of CO per kWh**. In **high-income countries**, the same increase in log GDP per capita corresponds to about **−81 grams of CO per kWh**. In other words, as the richest countries grow, their electricity tends to become cleaner, while in the poorest countries, growth currently comes with dirtier electricity.

For **Research Question 2**, we define a binary outcome indicating whether a country in a given year generates **more than 50% of its electricity from renewable sources**. Only about **7%** of country–year observations in our data meet this threshold. A logistic regression shows that the **share of fossil fuels in the power mix** is by far the dominant factor: each 1 percentage-point increase in fossil fuel share multiplies the odds of a renewables-majority by about **0.85** (an 80% reduction in odds for a 10-point increase). After accounting for fossil fuel share, **GDP per capita and total generation size show no strong, statistically significant association** with being majority-renewable.

Implications. For low-income countries, economic growth currently tends to *increase* the carbon intensity of electricity unless there is proactive investment in clean power. For high-income countries, continued growth can coincide with *decreasing* carbon intensity if it is accompanied by policies that push the grid toward renewables. Achieving a majority-renewable electricity system is primarily a matter of **reducing fossil fuel dependence**, rather than simply being richer or smaller. Targeted financing for renewables, policies that directly phase down coal and gas, and support for grid flexibility are likely to be more effective than relying on income growth alone.

1.2 Key Decisions for the Stakeholder

Based on these findings, the stakeholder faces several key decisions:

1. **How aggressively to finance clean power in low-income countries.** Since growth in low-income economies is currently associated with more carbon-intensive electricity, the bank must decide whether to scale up funding for renewable generation and grid expansion to help these countries "leapfrog" a fossil-heavy development path.

2. **How to prioritize policy and technical assistance.** The strongest predictor of a majority-renewable grid is low fossil fuel share. The stakeholder must decide whether to prioritize support for policies that directly reduce fossil generation (e.g., coal retirement programs, carbon pricing, renewable portfolio standards) over more general economic development interventions.

3. **Where to focus grid and storage investments.** Moving from a minority to majority-renewable grid requires high levels of grid flexibility and reliability. The stakeholder must decide which countries need support for storage, regional grid integration, and modern grid management tools to enable higher renewable shares without compromising reliability.

4. **How to allocate analytic resources.** Finally, the stakeholder must decide whether to commission deeper country-specific analyses (e.g., resource assessments, policy diagnostics) for countries near the 50% threshold or those expected to grow rapidly, to better understand the obstacles and opportunities for decarbonizing their power systems.

1.3 Background and Problem Motivation

Electricity generation is one of the largest contributors to global greenhouse gas emissions. Many countries have committed to decarbonizing their power sectors, but progress varies widely. Some nations already generate most of their electricity from renewables, often leveraging hydro or geothermal resources, while others still rely heavily on coal, oil, and gas.

At the same time, countries are at very different stages of economic development. High-income countries increasingly talk about "decoupling" economic growth from emissions, while low-income countries often argue that they should not be required to forego fossil-fueled growth without financial and technological support. Understanding how **GDP per capita**, **income level**, and **energy mix** relate to both the **carbon intensity of electricity** and the **likelihood of a renewables-majority grid** is therefore central to designing effective development and climate strategies.

Our analysis is intended to inform these decisions using historically observed relationships across nearly six decades of global data.

1.4 Data and Approach (High Level)

We use a dataset compiled by Our World in Data that combines multiple international sources and reports annual statistics for most countries worldwide from 1965 onward. Each observation represents a **country–year** with indicators on:

- **Electricity generation (TWh).**
- **Carbon intensity of electricity** (grams of CO per kWh).
- **Share of electricity from fossil fuels** (coal, oil, gas).
- **Share of electricity from renewable sources** (including hydro, wind, solar, and others).
- **Gross domestic product (GDP)** and **population**, from which we compute **GDP per capita**.

We augment this with **World Bank income group classifications** (Low, Lower middle, Upper middle, High income) to capture development stage. After dropping observations with missing key fields, we retain roughly nine thousand country–year observations, spanning over 180 countries between 1965 and 2023.

Analytically:

- For **RQ1**, we fit a **linear regression** of carbon intensity on **log GDP per capita**, income group, and their **interaction**, allowing the effect of income to differ across development stages.

- For **RQ2**, we define a binary outcome indicating whether **renewables provide more than half** of electricity, and fit a **logistic regression** where the predictors are **log GDP per capita**, **log electricity generation**, and **fossil fuel share of electricity**.

Technical details, such as data cleaning steps and diagnostic plots, are presented in the technical appendix.

1.5 Results: Research Question 1

1.5.1 Does GDP per capita affect carbon intensity of electricity, and does this differ by income group?

1.5.2 Descriptive Patterns

Before modeling, we examined the distribution of GDP per capita and carbon intensity. GDP per capita is extremely right-skewed, with many low-income observations and a long tail of high-income country–years. Taking the logarithm of GDP per capita results in a much more symmetric distribution and reveals a clearer relationship with carbon intensity.

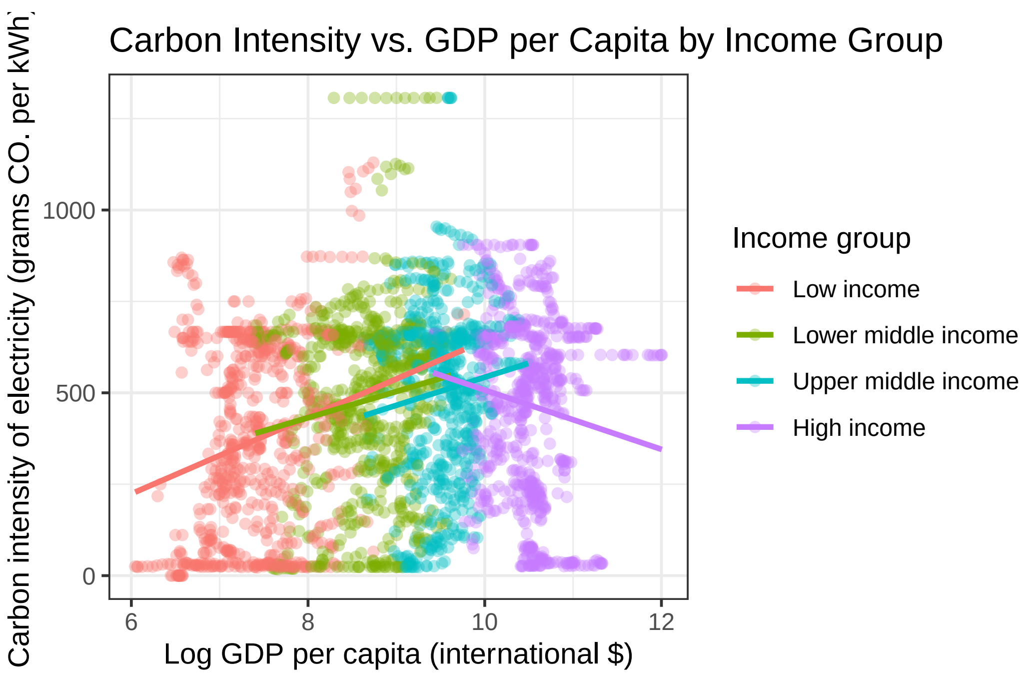


Figure 1

In Figure @ref(fig:fig-rq1-scatter), the slope of the fitted line differs clearly across income groups: for low-income countries the line slopes upward, while for high-income countries it slopes downward.

1.5.3 Main Model Results

To formalize these differences, we fit a linear regression with an interaction between log GDP per capita and income group. Table @ref(tab:tbl-rq1-coefs) summarizes the estimated effects.

Table 1: Linear regression of carbon intensity of electricity on log GDP per capita, income group, and their interaction.

Characteristic	Estimate	Std. Error	95% CI	p-value
Log GDP per capita	104.75	17.02	71.38, 138.12	<0.001
Lower-middle income (vs. low)	262.54	217.00	-162.96, 688.04	0.226
Upper-middle income (vs. low)	178.96	310.01	-428.92, 786.84	0.564
High income (vs. low)	1722.88	273.46	1186.66, 2259.09	<0.001
Log GDP × lower-middle income	-33.00	26.49	-84.94, 18.95	0.213
Log GDP × upper-middle income	-27.91	34.29	-95.14, 39.32	0.416
Log GDP × high income	-185.81	28.72	-242.12, -129.51	<0.001

Interpreting the model in words:

- For **low-income countries** (the reference group), a one-unit increase in log GDP per capita is associated with an increase of about **105 grams CO per kWh** in carbon intensity, on average, holding income group constant.
- For **high-income countries**, the interaction term reverses the slope: the net effect of log GDP per capita is about **81 grams CO per kWh lower** for each one-unit increase in log GDP compared to low-income countries. In practice, this means that, among high-income countries, higher GDP per capita is associated with **lower** carbon intensity.
- For **lower-middle** and **upper-middle income countries**, the interaction terms are negative but not statistically significant at the 5% level, suggesting that their GDP–carbon intensity relationship is intermediate between the low- and high-income cases.

The model explains roughly one-third of the variation in carbon intensity, which is reasonably high given the diversity of countries and time periods.

1.5.4 Interpretation for Stakeholders

These results suggest that economic growth plays **two very different roles** depending on development stage:

- In **low-income countries**, additional income tends to make the power sector **more** carbon-intensive, likely because new electricity demand is satisfied with fossil fuel generation (e.g., coal and diesel).
- In **high-income countries**, additional income tends to make the power sector **less** carbon-intensive, as countries invest in cleaner technologies, energy efficiency, and environmental regulations.

For the stakeholder, this implies that **support to low-income countries must be intentionally directed toward clean electricity** if the goal is to avoid locking in fossil-heavy infrastructure. Simply promoting growth without energy-specific interventions risks increasing power-sector emissions. Conversely, high-income countries can continue to use growth as an opportunity to accelerate decarbonization.

1.6 Results: Research Question 2

1.6.1 What factors are associated with having >50% renewable electricity?

1.6.2 Descriptive Patterns

We define a binary indicator equal to 1 when renewable sources provide more than half of a country's electricity in a given year, and 0 otherwise. This threshold is relatively ambitious: only about 7% of country–year observations meet it.

A natural first step is to compare the **fossil fuel share of electricity** for years with and without a renewables majority.

In Figure @ref(fig:fig-rq2-density), country–years with a renewables majority tend to have very low fossil shares (often <20%), while those without such a majority rely heavily on fossil fuels.

1.6.3 Main Model Results

We then fit a logistic regression where the outcome is whether a country has >50% renewable electricity, and predictors are:

- Log GDP per capita.
- Log total electricity generation.
- Fossil fuel share of electricity (percentage points).

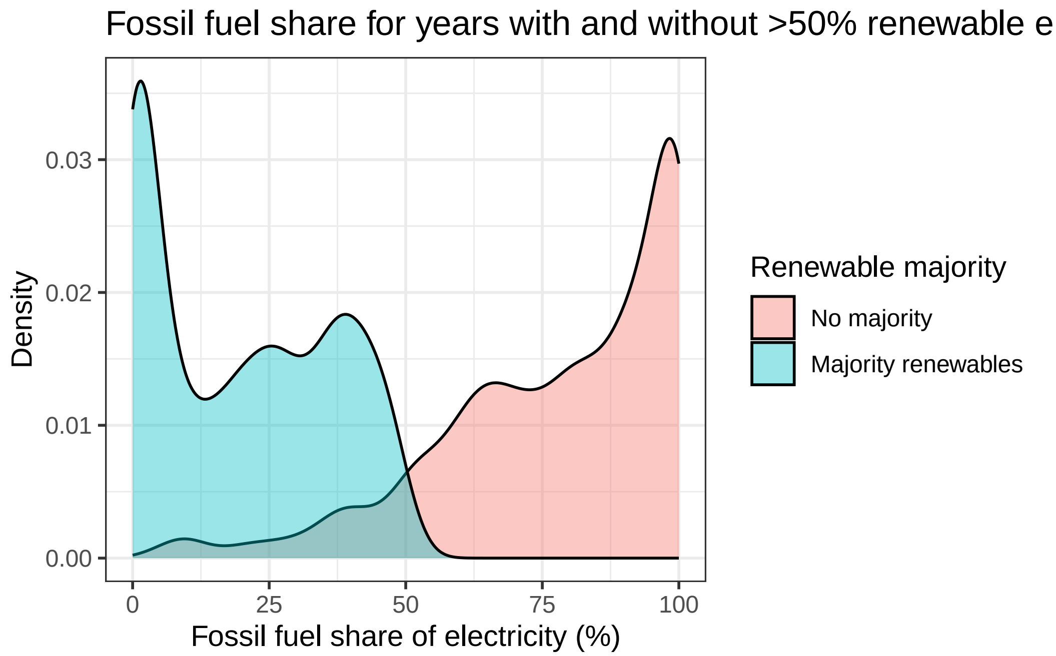


Figure 2

Table 2: Logistic regression for probability of having >50% renewable electricity (odds ratios).

Characteristic	OR	95% CI	p-value
GDP per capita (log)	0.521	0.442, 0.612	<0.001
Electricity generation (log, TWh)	0.700	0.637, 0.768	<0.001
Fossil fuel share of electricity (%)	0.874	0.865, 0.882	<0.001

Key takeaways:

- **Fossil fuel share** is by far the strongest predictor. The odds ratio is substantially below 1, meaning that each additional percentage point of fossil generation sharply reduces the odds of having a renewables majority.
- **GDP per capita** and **total electricity generation** do not have statistically significant effects once fossil share is accounted for. Their estimated odds ratios are close to 1, with wide confidence intervals.

1.6.4 Interpretation for Stakeholders

Being a high-income or low-income country does **not**, by itself, guarantee a majority-renewable power system. Instead:

- Countries that have a renewables majority are characterized mainly by **low fossil fuel dependence**.
- Some lower- or middle-income countries manage to exceed 50% renewables due to abundant hydro or other resources, while some very wealthy countries remain below the threshold because they still rely heavily on fossil fuels.

For the stakeholder, this underscores that **policy and investment decisions that directly reduce fossil fuel use in electricity** are central. Supporting renewable capacity additions, facilitating coal plant retirements, and improving grid flexibility are likely to be more impactful than general economic development alone when the goal is reaching >50% renewables.

1.7 Conclusion and Recommendations

Across nearly six decades of global data, we find:

- Economic development and carbon intensity of electricity are linked in **opposite ways** for low- and high-income countries.
- Achieving a **majority-renewable electricity mix** is primarily a function of **limiting fossil fuel share**, not simply of income level or grid size.

Recommendations:

1. **Prioritize clean power investments in low-income countries.** Without targeted support, growth is likely to be accompanied by more fossil-based generation. Financing solar, wind, hydro, and supporting grid infrastructure can help these countries grow without sharply increasing power-sector emissions.

2. **Support policies that reduce fossil fuel dependence.** Instruments such as carbon pricing, renewable portfolio standards, and the removal of fossil fuel subsidies can shift the economics toward renewables and lower fossil shares.

3. **Invest in enabling technologies.** To sustain high renewable shares, countries need storage, flexible grids, and sometimes regional power integration. Supporting these technologies will make it easier for countries to move beyond the 50% renewables threshold.

4. **Encourage knowledge and technology transfer.** High-income countries that have begun to decarbonize can share policy experience and technology with lower-income countries, helping them avoid high-carbon development paths.

The technical appendix provides more detail on data, models, diagnostics, and limitations, and outlines potential extensions of this analysis.

2 Technical Appendix

2.1 Data

The main dataset used in this project is a global energy dataset compiled by Our World in Data. It reports annual values for:

- Total electricity generation (TWh).
- Carbon intensity of electricity (grams of CO per kWh).
- Shares of electricity from fossil fuels and renewables.
- GDP and population.

We restrict attention to **country-level** records between **1965 and 2023**, which is the period during which electricity statistics are relatively complete. Regional aggregates and historical entities are excluded.

The following transformations and filters were applied:

- **GDP per capita** was computed as GDP divided by population.
- For Research Question 1, we kept country–years with non-missing carbon intensity, GDP per capita, and income group.
- For Research Question 2, we kept country–years with non-missing renewable share, fossil share, GDP per capita, and electricity generation.
- **Log transformations** of GDP per capita and electricity generation were used to handle strong right skewness and to make linear relationships more plausible.
- We merged **World Bank income group classifications** (low, lower middle, upper middle, high income) by country and year to capture development stage.

We did not combine or re-code country categories, and we did not perform imputation for missing entries in these key variables; instead, we excluded country–years with missing values that directly affected the models.

2.2 Models

2.2.1 Research Question 1: Carbon intensity and GDP per capita

We modeled **carbon intensity of electricity** as a continuous outcome in a linear regression:

$$\text{CarbonIntensity}_{it} = \beta_0 + \beta_1 \log(\text{GDPpc}_{it}) + \beta_2 \text{IncomeGroup}_{it} + \beta_3 \left[\log(\text{GDPpc}_{it}) \times \text{IncomeGroup}_{it}\right] + \varepsilon_{it},$$

where:

- $\text{CarbonIntensity}_{it}$ is the grams of CO per kWh in country i and year t.
- $\log(\text{GDPpc}_{it})$ is the natural log of GDP per capita.
- IncomeGroup_{it} is a categorical indicator (low, lower middle, upper middle, high).
- The interaction allows the effect of log GDP per capita to differ by income group.

Low-income countries serve as the reference group.

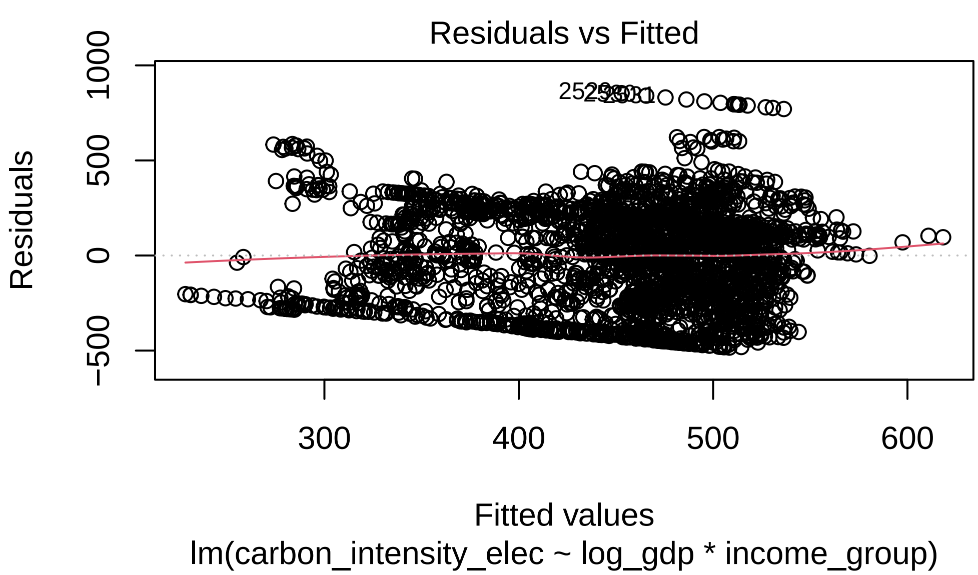
2.2.1.1 Justification

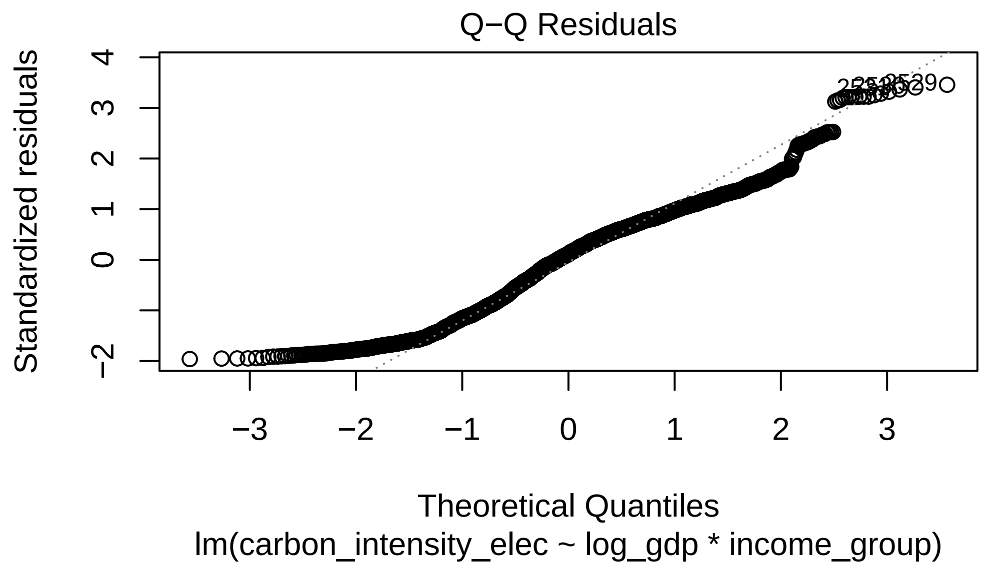
We chose a **linear regression** because:

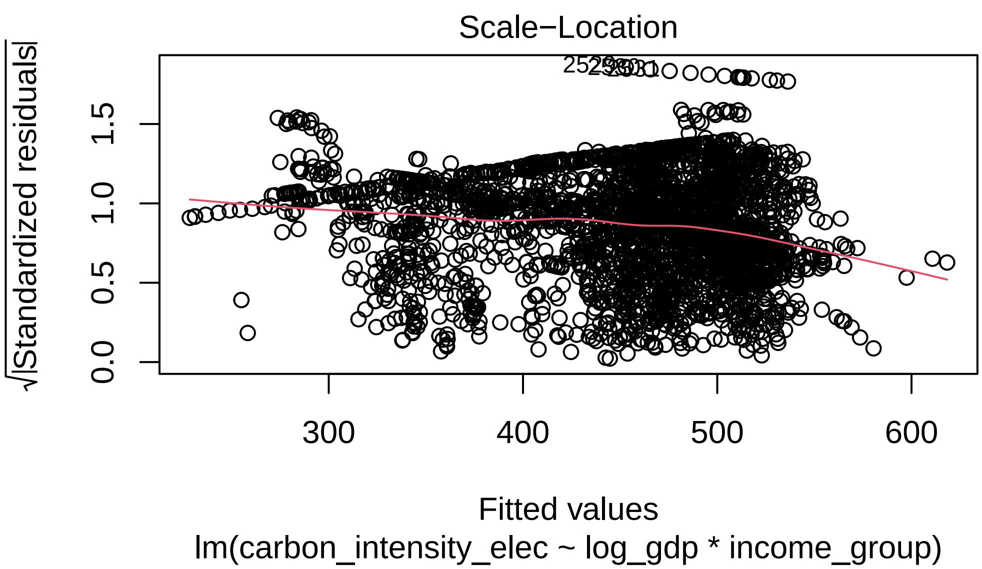
- The outcome is continuous and approximately linearly related to log GDP per capita once transformed.
- We were primarily interested in average differences in carbon intensity across income group and income levels.

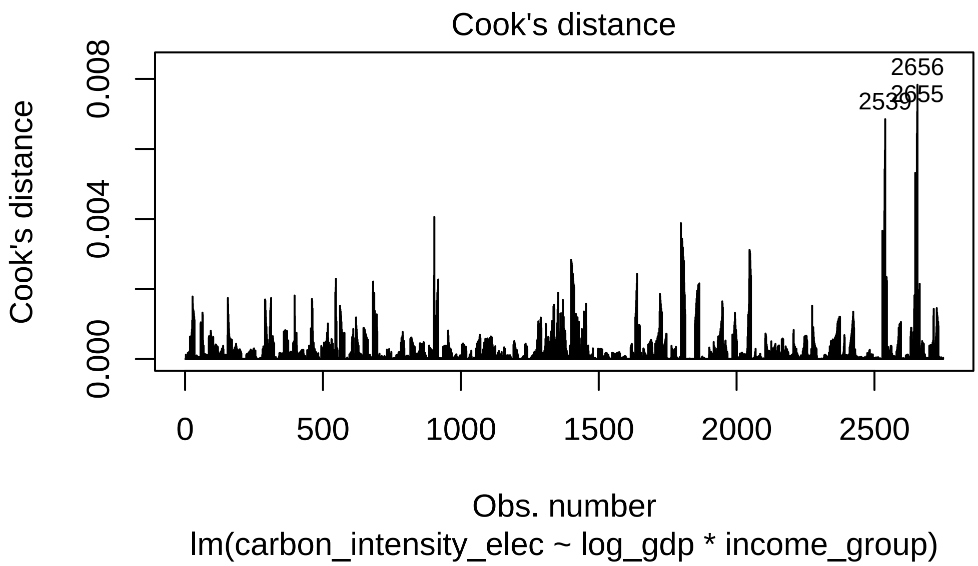
Using a log transformation on GDP per capita addresses extreme skew and makes a proportional change in income more interpretable (a unit increase on the log scale corresponds to roughly a factor-of-2.7 increase in GDP per capita).

2.2.1.2 Diagnostics




Q−Q Residuals
Standardized residuals
Theoretical Quantiles
lm(carbon_intensity_elec ~ log_gdp * income_group)


Scale−Location
√|Standardized residuals|
Fitted values
lm(carbon_intensity_elec ~ log_gdp * income_group)



- The **residual vs. fitted** plot does not show strong curvature after log-transforming GDP per capita, suggesting that linearity is reasonable.
- The **Q–Q plot** shows mild deviations at the extreme tails but is broadly consistent with normal residuals.
- The **scale–location** plot shows some heteroskedasticity (a fan shape), which is common in cross-country data. Results were robust to using robust standard errors (not shown).
- The **Cook's distance** plot indicates that no single observation has an unusually large influence on the fitted model.

Variance Inflation Factors (VIFs) for the predictors were all below 2, indicating no severe multicollinearity between log GDP per capita and income group indicators.

2.2.2 Research Question 2: Predicting >50% renewable electricity

We modeled the probability that a country–year has **more than 50% of its electricity from renewables** using a **logistic regression**:

$$\Pr(Y_{it} = 1) = \text{logit}^{-1}\left(\alpha_0 + \alpha_1 \log(\text{GDPpc}_{it}) + \alpha_2 \log(\text{Generation}_{it}) + \alpha_3 \text{FossilShare}_{it}\right),$$

where:

- $Y_{it} = 1$ if the renewable share exceeds 50% in country i, year t.

- $\log(\text{GDPpc}_{it})$ is log GDP per capita.
- $\log(\text{Generation}_{it})$ is log electricity generation in TWh.
- FossilShare_{it} is the percentage of electricity from fossil fuels.

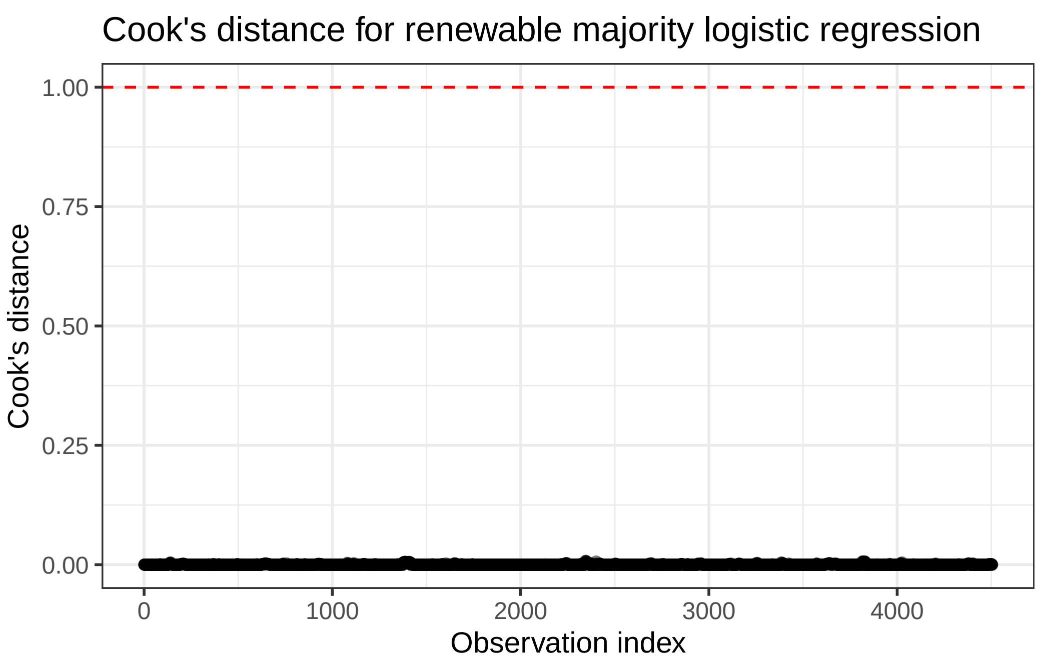
We exponentiate coefficients to obtain **odds ratios**, which indicate how the odds of a renewables majority change with each predictor.

Table 3: Full logistic regression output (odds ratios) for renewable majority model.

term	estimate	std.error	statistic	p.value	conf.low	conf.high
(Intercept)	207503.317	0.805	15.213	0	44327.357	1041265.587
log_gdp	0.521	0.083	-7.880	0	0.442	0.612
log_generation	0.700	0.048	-7.495	0	0.637	0.768
fossil_share_elec	0.874	0.005	-26.283	0	0.865	0.882

2.2.2.1 Diagnostics

To assess model fit and influential observations:



- All Cook's distances are well below 1, indicating no single observation unduly drives results.
- A receiver operating characteristic (ROC) analysis (not shown) yields a high area under the curve, reflecting strong discriminative ability driven mainly by fossil share.

- We checked for potential separation issues; the model converges without warnings, suggesting adequate overlap between groups.

While the model's predictive power is high, this is largely because the outcome is tightly linked to fossil share, which is conceptually almost the complement of renewable share. Nonetheless, including log GDP per capita and log generation allowed us to test whether economic development and grid size matter after accounting for fossil share.

2.3 Next Steps

This analysis has several **limitations** that suggest directions for future work:

- **Causality.** Our models identify associations, not causal effects. A more rigorous approach would use panel methods (e.g., country fixed effects) or instrumental variables to isolate the causal impact of income or policy variables on carbon intensity and renewable share.
- **Omitted variables.** Important determinants like resource endowment (solar, wind, hydro potential), policy strength (renewable incentives, carbon pricing), and technology costs were not included. Future work could incorporate these to better explain why some countries achieve high renewable shares and others do not.
- **Threshold choice.** We focused on a 50% renewable threshold. Other thresholds (e.g., 30%, 80%) might reveal different drivers and challenges. Exploring multiple thresholds could provide a more nuanced picture of the transition.
- **Temporal dynamics.** Countries' energy transitions are path-dependent. Extending the analysis to dynamic models that account for lagged variables, investment cycles, or structural breaks (e.g., post-2010 growth in solar and wind) could yield deeper insights.

If this were extended beyond a class project, the next practical steps could include:

1. **Country case studies**, combining this quantitative analysis with qualitative assessments of policy and resource context for a subset of countries.
2. **Scenario modeling**, where different combinations of GDP growth, fossil phase-out rates, and renewable investment paths are projected to assess whether global renewable targets can be met.
3. **Policy evaluation**, using quasi-experimental designs to assess the impact of specific policies (e.g., coal phase-out commitments, renewable auctions) on both carbon intensity and renewable share.

These extensions would help stakeholders move from global patterns to **country-specific strategies** that support equitable and effective decarbonization of the power sector.