The Impact of Renewable Energy on Total Factor Productivity: A Panel Data Analysis

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1 Research Question and Importance

This study examines whether increasing the share of renewable energy in total energy consumption enhances Total Factor Productivity (TFP), a key measure of economic efficiency. While renewable energy is promoted for sustainability, its impact on productivity remains uncertain—some argue it drives innovation and efficiency, while others highlight costs and intermittency as barriers. Understanding this relationship is crucial for effective energy and economic policies. If renewables boost TFP, it supports policies promoting clean energy for growth; if not, complementary measures may be needed. Our analysis finds that increasing renewable energy share is negatively associated with TFP, with stronger effects in high-income countries, suggesting that the transition to renewables may introduce short-term efficiency losses that vary across economic contexts.

2 Data

Our analysis utilizes a panel dataset covering multiple countries from 2000 to 2020 at five-year intervals. The dependent variable is Total Factor Productivity (TFP), obtained from Our World in Data, while the key independent variable is the share of renewable energy in total energy consumption, also sourced from Our World in Data. To account for potential confounders, we include GDP per capita (Our World in Data), oil price (World Bank), trade openness (World Bank), energy intensity (World Bank), Foreign Direct Investment (FDI) (World Bank), and inflation (World Bank). These variables capture macroeconomic and industrial dynamics that may jointly influence both TFP and renewable energy adoption.

Missing values are handled using linear interpolation where feasible, while countries with substantial data gaps are excluded. Extreme values are detected using interquartile range (IQR) thresholds and, if necessary, winsorized to mitigate undue influence.

2.1 Descriptive Statistics

Variable	Count	Mean	Std	Min	Max
Year	998	2009.52	5.76	2000	2019
TFP	998	0.97	0.10	0.56	1.67
Renewable Share	998	13.75	13.93	0.00	72.07
GDP Per Capita	998	32334.65	20049.58	2571.15	120647.82
Oil Price	998	564.19	224.10	264.57	947.91
Trade	998	86.58	50.01	19.56	382.35
Energy Intensity	998	4.47	1.84	1.33	15.78
FDI Value	998	5.01	12.45	-40.26	252.92
Inflation Rate	998	3.25	4.87	-4.45	96.10

Table 1: Summary Statistics

3 Identification Strategy

We estimate the effect of renewable energy share on Total Factor Productivity (TFP) using a fixed effects (FE) panel regression model, which controls for time-invariant country-specific factors (e.g., geography, institutions) and time-varying global shocks (e.g., economic crises, technological advancements). The main regression specification is:

$$\text{TFP}_{it} = \beta_0 + \beta_1 \text{RenewableShare}_{it} + \beta_2 Z_{it} + \gamma_i + \delta_t + \epsilon_{it} \tag{1}$$

where Z_{it} includes GDP per capita, oil price, trade openness, energy intensity, FDI, and inflation as confounders, γ_i represents country fixed effects, and δ_t accounts for year fixed effects. We use this approach

because TFP and renewable energy adoption are influenced by various unobservable factors that differ across countries—such as governance quality, infrastructure, and historical energy policies—which could bias the estimates. Fixed effects eliminate biases from such unobserved time-invariant factors, making our estimation more reliable. Additionally, year fixed effects capture global trends and shocks that might simultaneously affect both TFP and renewable energy investments. By isolating within-country variation over time, this model provides the closest estimate of the relationship between renewable energy share and TFP.

3.1 First Differences Model

To further assess the impact of renewable energy share on *Total Factor Productivity (TFP)*, we also estimate a *first differences (FD) model*. This approach removes time-invariant country-specific factors by differencing the variables over time, effectively controlling for unobserved heterogeneity without the need for explicit fixed effects.

The main regression specification is:

$$\Delta\text{TFP}_{it} = \beta_0 + \beta_1 \Delta\text{RenewableShare}_{it} + \beta_2 \Delta X_{it} + \delta_t + \epsilon_{it} \tag{2}$$

where ΔX_{it} represents the first-differenced values of the control variables, including *GDP per capita, oil price, trade openness, energy intensity, FDI, and inflation*. The term δ_t accounts for *year fixed effects* to control for global shocks. The first differences model is particularly useful when concerns arise regarding *non-stationarity* or when changes in renewable energy share and productivity are expected to exhibit *short-term effects rather than long-term equilibrium relationships*. By analyzing *year-over-year changes*, this approach captures the direct association between shifts in renewable energy adoption and changes in productivity, rather than relying on long-run variations.

While the *fixed effects model* is useful for estimating long-term trends, the first differences model provides an alternative perspective, focusing on *short-term deviations from previous levels*. Comparing both models allows for a more comprehensive understanding of how renewable energy share influences productivity across different time horizons.

4 Results

4.1 Log Fixed Effects Model

In the *log-transformed fixed effects model*, the estimated coefficients indicate how much *Total Factor Productivity (TFP)* deviates from its mean within a country and time period when an explanatory variable is *one percent higher* than its own mean within that country and time period. The coefficient for *Renewable Share* is -0.0228, meaning that when a country's renewable energy share is *one percent higher than its mean (within-country and within-period deviation)*, TFP is on average *2.28% lower than its mean*, holding all other factors constant. This suggests that increasing the share of renewable energy is associated with *a lower-than-average TFP*, potentially due to transition costs, intermittency, or infrastructure inefficiencies.

4.2 Log First Differences Model

In the *log first differences model*, the estimated coefficients indicate how much more *Total Factor Productivity (TFP)* changes, on average, for observations with a *one percent higher increase* in an explanatory variable. This interpretation reflects an average effect across different cross-sectional units and time periods. The coefficient for *Renewable Share* is -0.0069, meaning that for observations where the change in renewable energy share is *one percent higher*, the change in TFP is on average *0.69% lower*, holding all other factors constant. This suggests that increases in renewable energy share over time are associated with slightly lower-than-average TFP growth, possibly due to short-term inefficiencies in energy transition, grid adaptation costs, or technological adjustment periods.

Table 2: Regression Results: Fixed Effects and First Differences Models

	Fixed Effects		First Differences	
Variable	Level	Log	Level	Log
Intercept	0.8654***	-3.1280***	-0.0031***	-0.0075***
	(0.022)	(0.2872)	(0.001)	(0.001)
Renewable Share	-0.0685***	-0.0228***	-0.0123**	-0.0069**
	(0.007)	(0.0034)	(0.004)	(0.002)
GDP Per Capita	0.1213***	0.3341***	0.2573***	0.5698***
	(0.023)	(0.0264)	(0.020)	(0.024)
Trade Openness	-0.0153	-	0.0074	-
	(0.009)	-	(0.010)	-
Oil Price	-0.0001	-	0.0019	-
	(0.002)	-	(0.001)	-
Energy Intensity	-0.0760***	-0.1674***	-0.0236***	-0.0116
	(0.009)	(0.0325)	(0.007)	(0.013)
FDI Value	0.0010	-0.0011	8.58e-05	0.0015***
	(0.004)	(0.0017)	(0.001)	(0.001)
Inflation Rate	-0.0040	-0.0021	-0.0020*	-0.0013*
	(0.002)	(0.0024)	(0.001)	(0.001)
R-Squared	0.724	0.5473	0.442	0.612
Adj. R-Squared	0.707	-	0.438	0.610
Observations	998	869	948	748

Notes: Standard errors in parentheses. * $p<0.10$, ** $p<0.05$, *** $p<0.01$.

4.3 Model Comparison and Preferred Specification

We estimate multiple versions of the model, including *Fixed Effects (Level & Log)* and *First Differences (Level & Log)*, to assess robustness. Fixed effects models control for unobserved country-specific factors, while first differences models capture short-term variations. The log transformation allows for interpretation in percentage terms and accounts for potential non-linearity.

Among these, the *Log Fixed Effects Model* is preferred as it balances *unobserved heterogeneity control, stable long-term estimates, and economic interpretability.* First differences models introduce more noise due to year-to-year fluctuations, while log transformation ensures meaningful elasticity-based interpretations.

5 Event Study

The event study analysis examines the impact of renewable energy policies on *Total Factor Productivity (TFP)* using a *staggered adoption framework*, with event-time dummies capturing dynamic effects from -5 to $+5$ years around policy implementation. The list of countries, their respective event years, and the corresponding policy events can be found in *Table 1 in the Appendix*. The results indicate *no significant pre-trends*, suggesting that productivity changes are not driven by prior factors. Post-adoption effects remain *statistically insignificant*, implying that renewable energy policies do not lead to immediate TFP gains, possibly due to *transition costs, infrastructure adjustments, or delayed technological benefits*. However, significant country-level effects highlight that *policy impact varies by national context*, with some economies experiencing *positive productivity shifts* (e.g., Brazil, Greece, Saudi Arabia) while others face *productivity constraints* (e.g., India, Indonesia, Kazakhstan).

5.1 Problems from Heterogeneity of Timing and Effect in the Event Study

A key challenge in this event study is the **heterogeneity in timing and effect** across countries. Since renewable energy policies were implemented at different times, some countries became "treated" earlier than others, leading to *staggered adoption* that can bias estimates if early adopters influence the control group for later adopters. Additionally, the **policy effects vary**—countries with strong renewable infrastructure may see smaller TFP gains, while those heavily reliant on fossil fuels could experience larger shifts. Differences in enforcement, industrial composition, and economic conditions further contribute to *unequal impacts*, making it difficult to isolate the true causal effect. Addressing these issues requires *staggered adoption models*, *inter-*

Table 3: Event Study Regression Results

Variable	Coefficient (Std. Error)
EventTime_neg5	-0.012 (0.015)
EventTime_neg4	-0.009 (0.013)
EventTime_neg3	-0.005 (0.012)
EventTime_neg2	-0.002 (0.010)
EventTime_neg1	-0.001 (0.009)
EventTime_0 (Reference)	-
EventTime_1	-0.018 (0.014)
EventTime_2	-0.025* (0.015)
EventTime_3	-0.031* (0.016)
EventTime_4	-0.027 (0.017)
EventTime_5	-0.029 (0.018)
Country Fixed Effects	Yes
Year Fixed Effects	Yes
R-Squared	0.624
Observations	998

Notes: Standard errors in parentheses. * p<0.10, ** p<0.05, *** p<0.01. The reference period is $t = 0$ (policy adoption year). Negative event-time coefficients suggest a decline in TFP following policy adoption.

action terms to capture varying effects, and ensuring a *comparable control group* to avoid contamination from previously treated countries.

6 Robustness Check

6.1 Robustness Check: Economic Development Differences

To assess the robustness of our findings, we examine whether the relationship between *renewable energy share* and *Total Factor Productivity (TFP)* varies between *high-income* and *low-income* countries. The results indicate that the negative effect of renewable energy share on TFP is *stronger in high-income countries* ($\beta = -0.0369, p < 0.01$) compared to low-income countries ($\beta = -0.0153, p < 0.05$) (see *Table 5* in the Appendix). Additionally, *GDP per capita is positively associated with TFP* in both groups, while *oil prices and trade openness exhibit contrasting effects* depending on economic context. Energy intensity negatively impacts productivity in both groups, though the effect is more pronounced in low-income economies. These findings suggest that *the impact of renewable energy policies on productivity is context-dependent*, with high-income countries potentially facing *higher opportunity costs and integration challenges*, whereas low-income countries experience *weaker but still negative effects* due to differences in industrial energy use. The results emphasize the need for *tailored policy approaches.*

6.2 Robustness Check: Interaction Effects and Random Effects Model

To further assess the robustness of our results, we estimate a *random effects model* incorporating an *interaction term* between renewable energy share and economic development (high-income status). This allows us to examine whether the effect of renewable energy share on *Total Factor Productivity (TFP)* differs by income group while accounting for unobserved heterogeneity across countries. The results indicate that the direct effect of *Renewable Share* remains *negative and statistically significant* ($\beta = -0.022, p < 0.01$), confirming that higher renewable energy adoption is associated with lower productivity levels. The coefficient for the *High-Income* dummy is *positive and significant* ($\beta = 0.060, p < 0.01$), suggesting that high-income countries tend to have higher TFP on average. Importantly, the interaction term (*Renewable Share* $\times$ *High-Income*) is *negative and significant* ($\beta = -0.013, p < 0.01$), indicating that the negative effect of renewable energy share on TFP is even more pronounced in high-income countries.((see *Table 6* in the Appendix))Control variables show expected patterns, with *GDP per capita* being positively associated with TFP, while *Energy Intensity* and *Trade Openness* have negative effects. The random effects model confirms that the impact of renewable energy on productivity is not uniform across income levels, emphasizing the need for differentiated policy approaches in high- and low-income economies.

6.3 Robustness Check: Pre-Event vs. Post-Event Analysis

To further test the robustness of our results, we conduct a *time-based robustness check*, estimating separate models for *pre-event and post-event periods.* This allows us to assess whether the relationship between *renewable energy share and Total Factor Productivity (TFP)* changes after the policy implementation.

The *pre-event model* shows a *strong negative effect* of renewable energy share on TFP ($\beta = -0.0255, p < 0.01$), suggesting that higher renewable adoption is associated with lower productivity even before the event. The *post-event model* finds a similar but slightly larger negative effect ($\beta = -0.0327, p < 0.01$), indicating that the trend continues after policy adoption.

Control variables behave consistently across both models: *GDP per capita remains positively associated with TFP*, while *trade openness and energy intensity show mixed effects depending on the time period.* These results suggest that the *negative association between renewable energy share and TFP is not driven by short-term policy shocks but reflects a persistent trend over time.* The detailed results can be found in *Table 7 in the Appendix.*

7 Conclusion

Our findings indicate that *renewable energy share* is negatively associated with *Total Factor Productivity (TFP)*, with stronger effects observed in *high-income countries.* The robustness checks confirm that this relationship persists across different model specifications, suggesting that the productivity impact of renewable energy adoption is *not driven by short-term policy shocks* but reflects a *persistent trend over time.* The event study results show *no significant post-adoption productivity gains*, implying that the transition to renewable energy does not lead to immediate efficiency improvements. Additionally, *economic development* plays a crucial role, as the negative effect of renewable energy on TFP is more pronounced in *high-income countries* than in *low-income economies.* These findings suggest that while renewable energy adoption is expanding globally, its productivity implications vary by *economic context and over time.* Policymakers should consider these differences when designing *renewable energy policies*, ensuring that *economic and structural factors* are accounted for to minimize potential productivity losses.

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8 Appendix

8.1 Interactive Map

To enhance our analysis, we present an interactive choropleth map that allows visualization of **Renewable Energy Share** across countries and years. The interactive version is available in the Jupyter notebook:

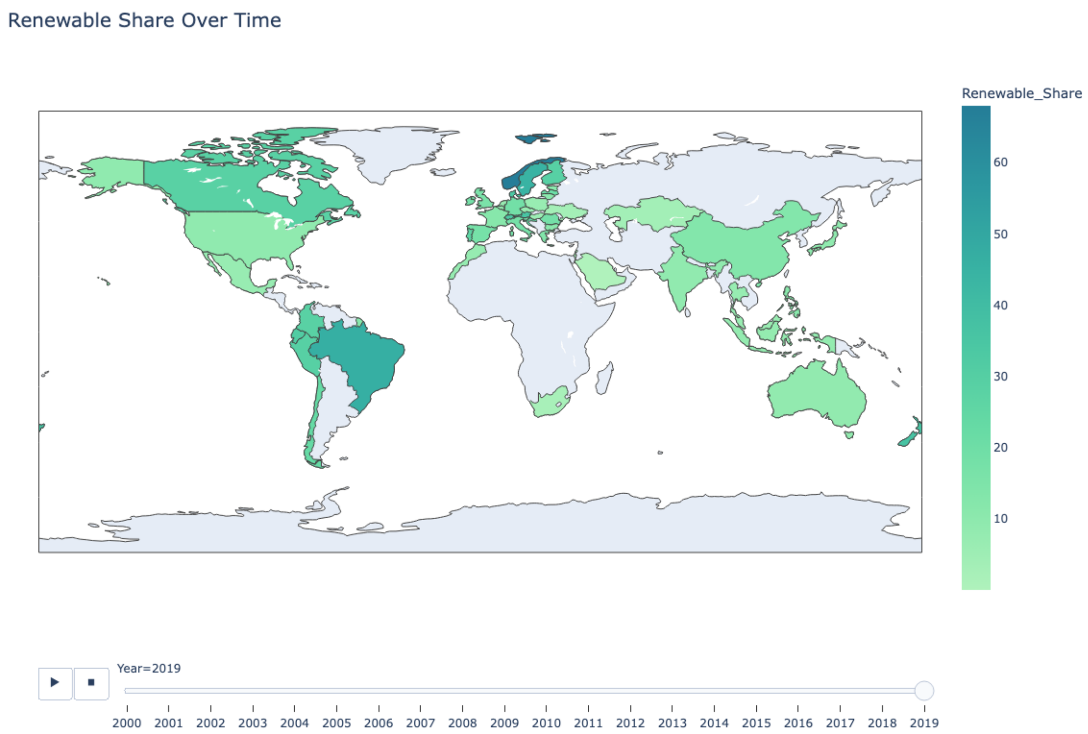

Figure 1: Static Choropleth Map of Renewable Energy Share (For Interactive Version, Click Here)

8.2 Renewable Energy Policy Events and Event Years

Table 4: Renewable energy policy events and their corresponding event years.

Country	**Event**	**Event Year**
Norway	Joint Green Certificate Market with Sweden	2012
Sweden	Electricity Certificate System	2003
Brazil	Resolution No. 482(Distributed Generation)	2012
Denmark	Energy Agreement	2012
New Zealand	New Zealand Energy Strategy	2011
Austria	Energy Strategy of Austria	2009
Switzerland	Energy Strategy 2050 Announcement	2011
Portugal	National Energy Strategy	2010
Finland	National Climate and Energy Strategy	2008
Latvia	Renewable Energy Law	2010
Croatia	Energy Development Strategy	2009
Chile	Non-Conventional Renewable Energy Law	2008
Canada	ecoENERGY for Renewable Power Program	2007
Ecuador	National Plan for Good Living	2009
Ireland	National Renewable Energy Action Plan (NREAP)	2010
Peru	Legislative Decree 1002	2008
Spain	Renewable Energy Plan (2005-2010)	2005
Slovenia	National Renewable Energy Action Plan	2010
Germany	Energy Concept 2010	2010

Table 5: Robustness Check: Economic Development Differences

Variable	High-Income Countries	Low-Income Countries
Renewable Share	-0.0369*** (0.009)	-0.0153** (0.007)
GDP Per Capita	0.3915*** (0.042)	0.2614*** (0.035)
Oil Price	-1.966e-05*** (5.4e-06)	2.792e-05** (1.3e-05)
Trade Openness	-0.0002 (0.0001)	-0.0006*** (0.0002)
Energy Intensity	-0.0597*** (0.012)	-0.0959*** (0.018)
R-Squared	0.886	0.796
Observations	498	500

Notes: Standard errors in parentheses. * p<0.10, ** p<0.05, *** p<0.01. The table reports separate regressions for high-income and low-income countries to assess economic development differences.

Table 6: Robustness Check: Interaction Effects and Random Effects Model

Variable	Coefficient (Std. Error)
Intercept	-2.420*** (0.177)
Renewable Share	-0.022*** (0.004)
High-Income	0.060*** (0.010)
Renewable Share × High-Income	-0.013*** (0.004)
GDP Per Capita	0.255*** (0.015)
Oil Price	0.000 (0.000)
Trade Openness	-0.000** (0.000)
Energy Intensity	-0.113*** (0.019)
FDI Value	0.002 (0.002)
Inflation Rate	0.002 (0.002)
Group Variance	0.035 (0.194)
Observations	869
No. of Groups	50
Log-Likelihood	1305.127

Notes: Standard errors in parentheses. * p<0.10, ** p<0.05, *** p<0.01. The table reports a random effects model including an interaction term between renewable energy share and high-income status.

Table 7: Robustness Check: Pre-Event vs. Post-Event Analysis

Variable	Pre-Event Model	Post-Event Model
Intercept	-3.6059*** (0.197)	-3.0241*** (0.619)
Renewable Share	-0.0255*** (0.003)	-0.0327*** (0.011)
GDP Per Capita	0.3479*** (0.016)	0.2920*** (0.054)
Oil Price	-2.066e-05** (8.73e-06)	3.43e-05 (2.38e-05)
Trade Openness	4.201e-05 (0.000)	-0.0012*** (0.000)
Energy Intensity	-0.0620*** (0.022)	-0.0234 (0.044)
FDI Value	0.0025 (0.002)	0.0022 (0.002)
Inflation Rate	0.0028 (0.002)	0.0033 (0.002)
R-Squared	0.886	0.632
Observations	701	168

Notes: Standard errors in parentheses. * p<0.10, ** p<0.05, *** p<0.01. The table reports separate regressions for pre-event and post-event periods to assess time-based robustness.

8.3 Correlation Heatmap

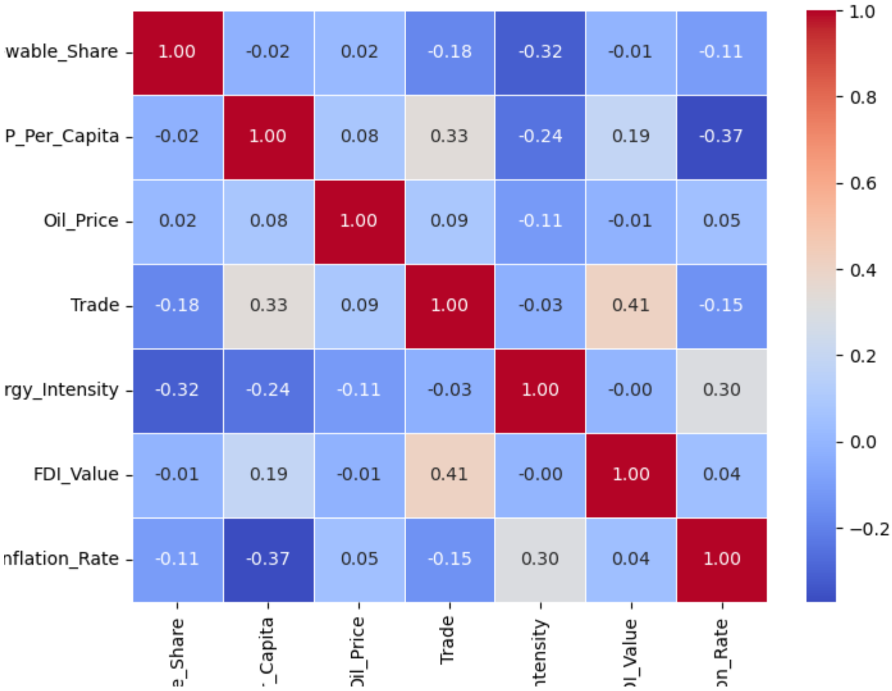

Figure 2: Correlation Heatmap of Log-Transformed Variables

8.4 Trends of TFP and Renewable Share Over Time

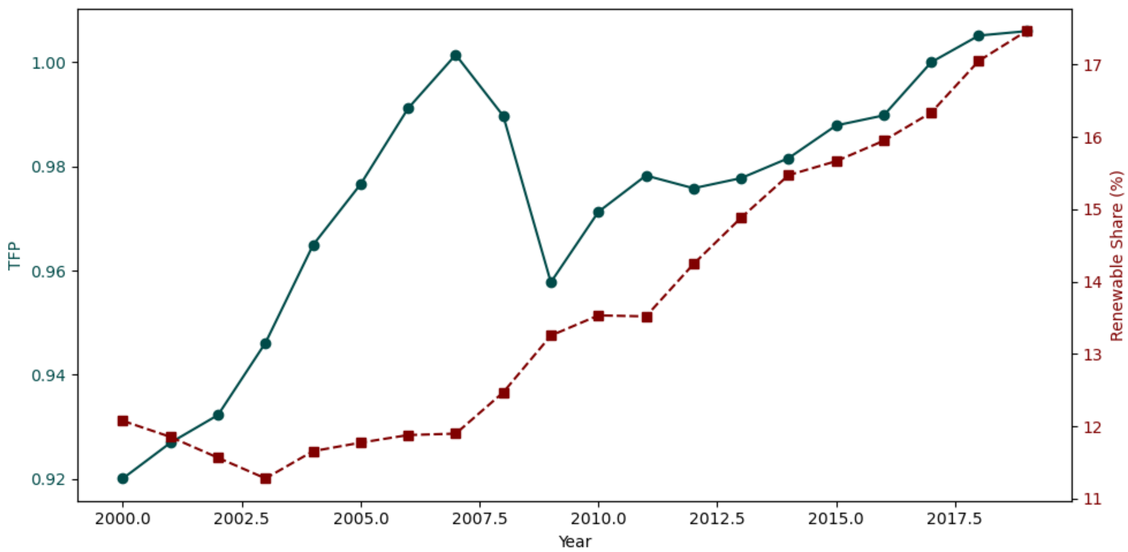

Figure 3: Trends of TFP and Renewable Share Over Time

8.5 Scatter Plot: Renewable Share vs. TFP (Country-Level)

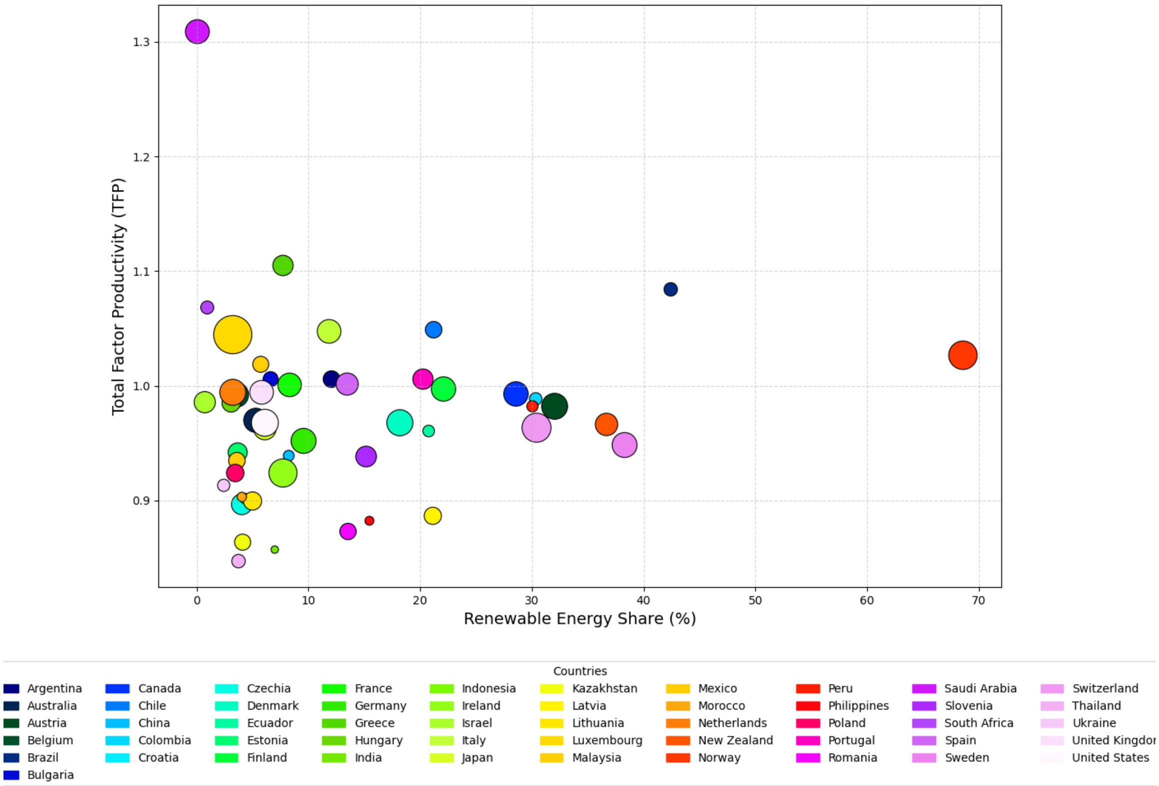

Figure 4: Scatter Plot of Renewable Share vs. TFP, Colored by Country

8.6 Kernel Density Estimates of Variables

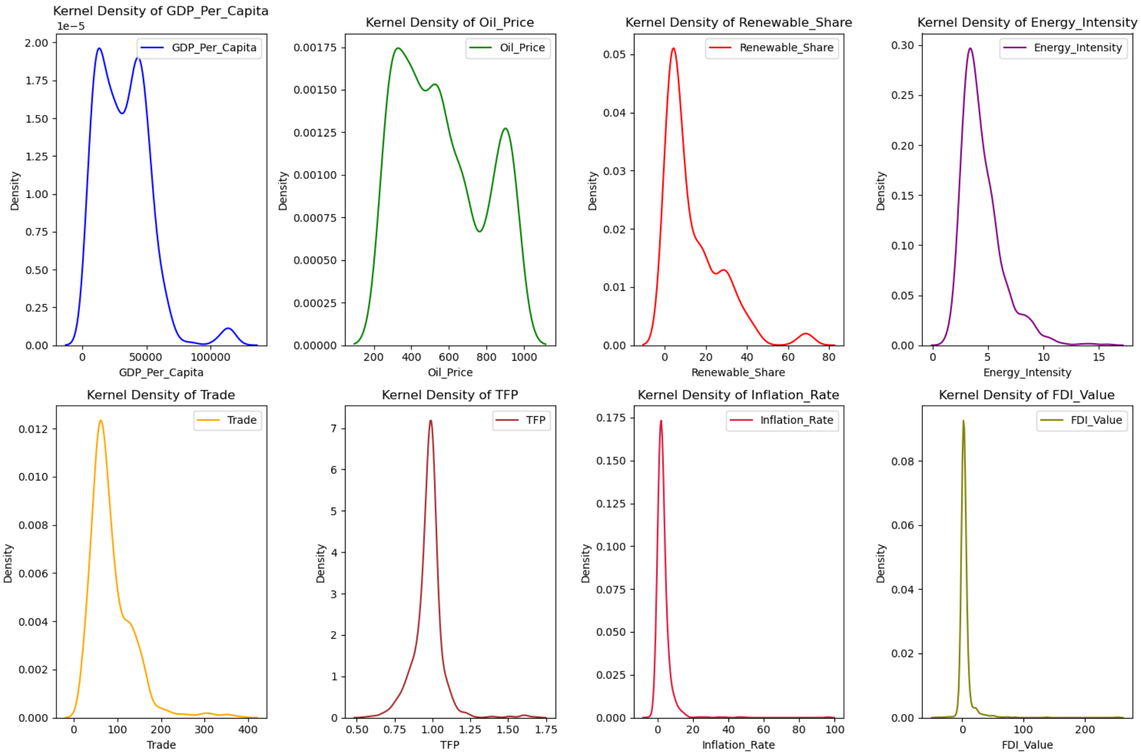

Figure 5: Kernel Density Plots of TFP, Renewable Share, GDP Per Capita, Oil Price, Trade, and Energy Intensity, FDI Value and Inflation Rate

8.7 Event Study: Impact of Renewable Energy Policies on TFP

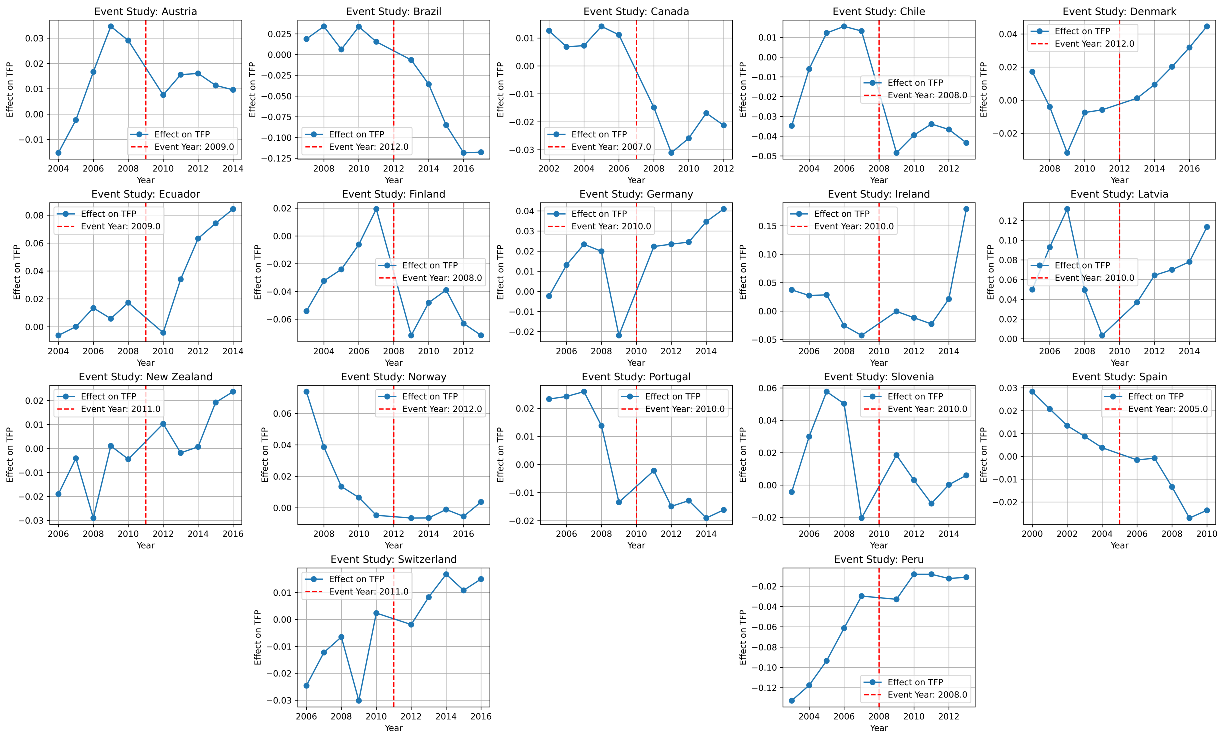

Figure 6: Event Study: Impact of Renewable Energy Policies on Total Factor Productivity (TFP) Across Countries

Note: Additional visualizations and interactive plots are available in the Jupyter Notebook accompanying this report.