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Energy transition in coal-dependent economies: a panel data approach

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Abstract. Renewable energy adoption is shaped by economic, structural, and policy factors, but their relative influence varies across countries. This study examines the roles of Gross Domestic Product (GDP), coal consumption, and national policies in renewable energy deployment in ten countries from 1990 to 2024. Using panel regressions, partial regression plots, and Difference-in-Differences analysis, we evaluate how economic size, energy structure, and policy interventions affect renewable energy shares. Results show that globally, renewable energy shares increased steadily by about 0.35 percentage points per year. GDP has a modest positive effect, while coal consumption is more strongly associated with renewables, reflecting parallel expansion of energy systems in high-demand economies. Country-level analysis reveals significant heterogeneity: Germany, China, the United States, and India consistently exceed predictions, whereas South Africa, Kazakhstan, and Ukraine underperform. Policy interventions are confirmed to have measurable impacts, with early adopters achieving the largest gains. Ukraine, for example, could accelerate adoption by strengthening policies, providing incentives, simplifying approvals, and fostering international cooperation. Overall, renewable energy transitions depend not only on economic and structural factors but also on effective governance and policy frameworks.

1. Introduction

The global energy system is changing quickly as countries work to reduce fossil fuel use and increase renewable energy sources. This change is mainly driven by the need to cut greenhouse gas emissions and fight climate change [1]. Among fossil fuels, coal is the most carbon-intensive fuel and causes a large share of global emissions [2, 3]. Its high carbon content makes it one of the main barriers to decarbonization, despite various methods of burning or processing it [4, 5]. Even though there is growing international pressure to reduce coal use, it still plays a major role in energy systems because it is cheap, widely available, and supports energy security. According to Our World in Data, coal was responsible for more than 35% of global electricity generation in 2022, showing how important it still is in the global energy mix [6, 7].

In many economies, coal is not only an energy source but also a key part of industry and employment [8]. This makes reducing coal use both politically and economically difficult. This challenge is most visible in coal- and mining-based economies such as China, India, South Africa, Indonesia, Australia, Germany, Poland, and many others. For these countries, moving away from coal while supporting economic growth creates a serious policy dilemma. On one hand, these countries need to meet growing energy demand for industrialization and social development. On the other hand, they must meet climate targets and shift toward low-carbon systems. Balancing energy security with emission reduction goals makes the transition more complex in countries that depend heavily on coal.

Renewable energy, including wind, solar, and hydropower, is essential for reducing emissions and achieving climate goals [9]. However, the speed and success of renewable adoption differ a lot between countries. Factors such as economic development, energy policies, market structure, and resource availability all influence the transition process. Countries with higher Gross Domestic Product (GDP) can often invest more in renewable energy technologies and infrastructure. In contrast, economies with strong coal dependence face structural barriers like old coal infrastructure and jobs in coal-related sectors. Previous research shows that economic growth often supports renewable energy adoption because it brings more resources for investment [10]. At the same time, heavy reliance on coal slows down the transition because of economic and social dependence on coal industries [11]. Many studies have looked at global or regional trends, and some have focused on single countries [12-15]. However, there is little research that compares coal-dependent economies over a long period. There are also very few studies that use both data analysis and policy discussion to understand how coal use and economic growth affect renewable energy adoption.

Based on the above, this study aims to fill this gap by analyzing major coal-dependent countries, including China, India, South Africa, Indonesia, Australia, Poland, Germany, Ukraine, USA, and Kazakhstan. These countries show different patterns of energy transition. For example, China is the world's largest coal producer and user, consuming more than half of global coal. It has set ambitious targets like carbon neutrality by 2060, but coal still dominates its energy system [16]. India, the second-largest coal user, relies on coal for more than 70% of its electricity, even though it has expanded solar power under its National Solar Mission [17]. Indonesia depends on coal for both domestic energy and export income, even as it plans to phase out coal by 2050 [18]. South Africa gets more than 80% of its electricity from coal and has introduced the Integrated Resource Plan to add renewables, but progress is slow because of financial problems [19]. Developed economies also face mixed results. Germany introduced the Energiewende policy and plans to phase out coal by 2038, but it increased coal use temporarily after shutting down nuclear plants [20]. Poland remains the most coal-dependent country in the EU and faces strong resistance to reducing coal, even under the EU Green Deal [21]. Ukraine, due to war and coal supply disruptions, is now more interested in renewables as part of its green recovery plan [22]. Kazakhstan still depends on coal for most of its electricity, with limited progress toward 2030 renewable goals [23]. Australia, one of the biggest coal exporters, has recently introduced stronger renewable energy policies, such as the Renewable Energy Target and state-level decarbonization plans [24, 25].

Even though these countries are different in terms of policy, economy, and renewable energy progress, they all face the same challenge: reducing coal dependence while keeping energy security and economic stability. Understanding how economic growth, coal use, and renewable energy adoption are linked is important for making good policies. Panel data analysis is useful here because it can show differences across countries and over time while controlling for country-specific factors. In this study, we use panel data for major coal-dependent countries from 1990 to 2024 to answer three main questions: (1) Does economic growth help increase renewable energy share? (2) Does coal dependence slow down the transition? (3) And which countries do better or worse than expected in renewable energy adoption? This research answers these questions by combining data analysis with policy discussion. The findings will help policymakers and researchers understand what factors matter most for the energy transition in coal-dependent economies and how to balance energy security, economic development, and climate goals. Therefore, the goal of our study is to evaluate how economic, structural, and policy factors influence renewable energy adoption in coal-dependent economies.

2. Methods

To assess the relationship between economic activity, coal dependency, and renewable energy development, we applied a panel data regression framework using annual country-level observations. The dataset was compiled from Our World in Data [26], harmonized into a single panel covering the years 1990-2024 for a selected group of major energy-producing and consuming countries such as Australia, China, Germany, India, Indonesia, Kazakhstan, Poland, South Africa, Ukraine, and the United States. All variables were normalized using z-scored normalization prior to analysis to ensure comparability of coefficients.

The panel regression model was developed using equation (1) [27]:

$$Renew_{it} = \alpha + \beta_1 Coal_{it} + \beta_2 GDP_{it} + \gamma_t + \varepsilon_{it}\ , \tag{1}$$

where $Renew_{it}$ (measured in GWh) denotes the renewable energy share for country *i* in year *t*; $Coal_{it}$ (measured in GWh) captures normalized coal consumption; GDP_{it} (billion USD) represents normalized economic activity (GDP), and γ_t (measured in GWh) denotes year fixed effects that account for global shocks or technological trends common across counties. The error term ε_{it} (in GWh) represents the unexplained residua variation. Coefficient α (in GWh) represents the intercept of the equation, β_1 and β_2 are coefficients for coal and GDP values, respectively. The coefficient β_1 measures the change in renewable energy associated with a one-unit increase in coal consumption. Its unit is the ratio of the unit of $Renew_{it}$ to the unit of $Coal_{it}$. While the coefficient β_2 represents how renewable energy changes for a one-unit increase in GDP. Therefore, its unit is the unit of $Renew_{it}$ divided by the unit of GDP.

The policy effect was estimated using a Difference-in-Difference regression model estimated by equation (2) [28]:

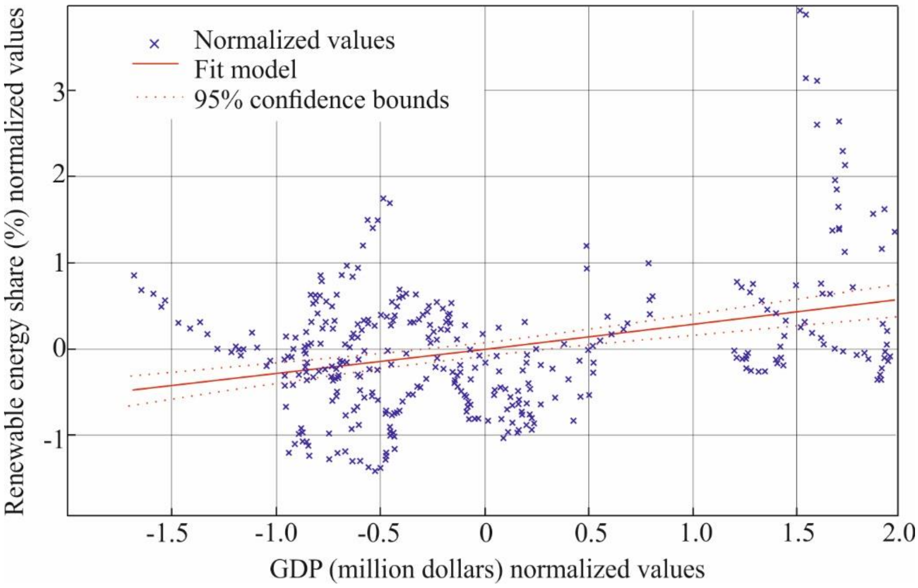
$$RE\_Share_{it} = \alpha + \beta_1 PolicyAdopted_{it} + \beta_2 Post_{it} + \delta\left(PolicyAdopted_{it} \cdot Post_{it}\right) + \gamma_i + \lambda_t + \varepsilon_{it}\ , \tag{2}$$

where RE_Share_{it} (measured in %) represents share of renewable energy in total energy consumption for country *i* in year *t*; $PolicyAdopted_{it}$ indicates whether country *i* had ever adopted the policy by time *t* and takes values 0 (not adopted) or 1 (adopted); $Post_{it}$ indicates whether year *t* falls after adoption and takes values 0 (pre-policy period) and 1 (post-policy period); δ (same units as RE_Share_{it}) captures the Difference-in-Difference estimate (the average treatment effect of policy adoption on renewable energy share; γ_i (same units as RE_Share_{it}) is country fixed effect, and λ_t (same units as RE_Share_{it}) is year fixed effect. The error term ε_{it} (same units as RE_Share_{it}) captures unobserved time-varying factors affecting renewable energy share at country level; coefficient α is intercept of the equation; β_1 is coefficient that represents the difference in renewable energy share between countries that adopted the policy and those that did not, before the policy starts, while β_2 shows how renewable energy share changes over time for all countries, even without the policy. Coefficients α, β_1, and β_2 have the same units as RE_Share_{it}.

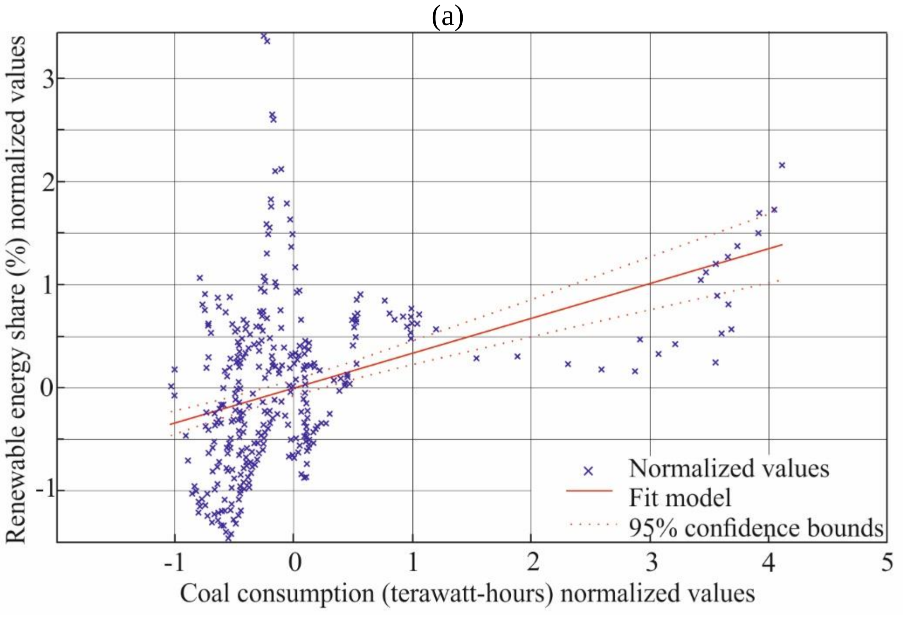
Both models were implemented in MATLAB.

3. Results and discussion

The partial regression plots (figure 1) provide important insights into the drivers of renewable energy deployment. The relationship between GDP and renewable energy share (figure 1a) is characterized by a positive but small slope ($\beta_{GDP} \approx 0.029$), indicating that higher levels of economic activity are associated with a modest increase in renewables once coal use and global time effects are controlled for. Although the confidence interval around the fitted line suggests that the relationship is statistically significant, the strength of the association is weak, and the wide scatter of points around the regression line highlights that GDP alone does not account for much of the cross-country variation in renewable deployment. This suggests that while economic growth can create financial capacity for investment, it is not a strong determinant of renewable uptake in the absence of enabling policies, institutional frameworks, and resource availability.



(a)



(b)

Figure 1. The partial regression plots: (a) GDP vs renewable energy share; (b) coal use and renewables.

The relationship between coal use and renewables (figure 1b) reveals a more surprising pattern. The estimated slope is positive and relatively steep ($\beta_{coal} \approx 0.337$), suggesting that higher coal consumption is systematically associated with higher renewable energy shares. At first glance, this appears unreasonable since coal is typically seen as a competitor to renewables. However, this positive correlation likely reflects structural energy system dynamics rather than a causal promotion effect of coal on renewables. Countries with high overall energy demand often expand both coal and renewables simultaneously, while coal-dependent economies may be actively expanding their energy mix by investing in renewables as part of broader decarbonization or energy security strategies. Large emitters such as China and India exemplify this dual trajectory, where expansion of coal capacity coexists with renewable growth, producing a positive association in the data.

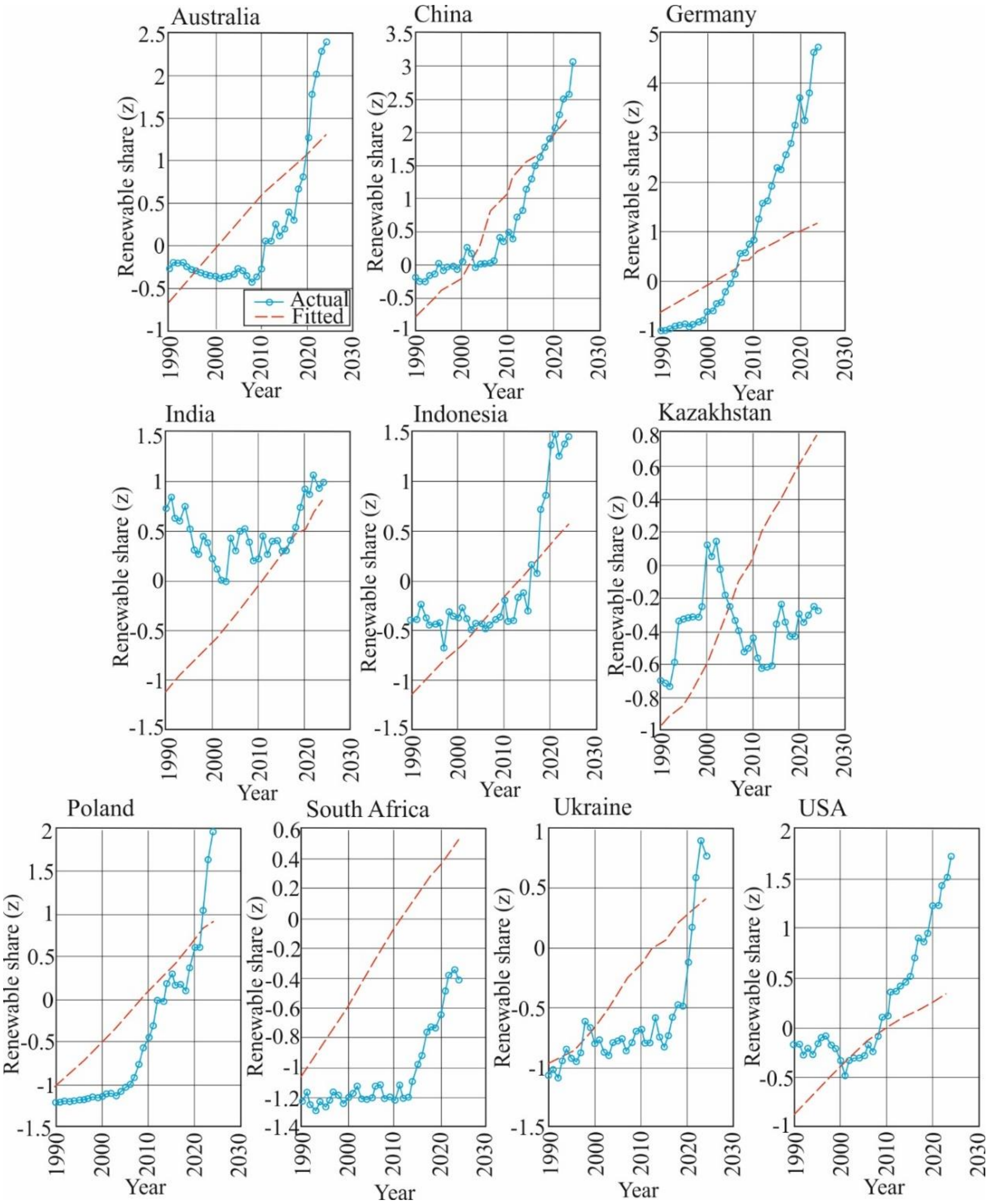


Figure 2. The country-level plots showing the actual renewable energy shares with fitted values from the model.

The country-level plots showed in figure 2 compare actual renewable energy shares with fitted values from the model excluding country fixed effects. A clear pattern emerges: in most countries (e.g., Germany, China, USA, Poland, Indonesia), actual renewable deployment accelerates much faster in recent years than the model predicts, indicating that global drivers like GDP and coal use only partially capture the dynamics of renewable growth. The gap between actual and fitted values is especially large for leaders such as Germany and China, reflecting that such factors as national policies and institutional choices are not captured in the baseline model. Conversely, in countries such as South Africa, Kazakhstan, and India, the model predicts higher renewable growth than what happened, showing that local policies strongly shape outcomes.

When linked back to the earlier partial regression plots (figure 1a and 1b), the connection becomes clear. The GDP-renewables relationship was weakly positive, while coal showed a stronger positive association, reflecting broad global trends. However, the country-level actual vs. fitted plots reveal that these aggregate effects cannot fully explain individual trajectories: countries with similar GDP growth or coal dependence exhibit very different renewable outcomes depending on policy interventions and local contexts.

Figure 3 presents the mean residuals from a panel regression of normalized renewable energy share on coal consumption, GDP, and year fixed effects, excluding country fixed effects. These residuals capture how much each country over- or under-performs in renewable deployment relative to the global baseline predicted by the model. Positive residuals indicate that a country's renewable share is higher than expected given its coal use, economic size, and global temporal trends, whereas negative residuals signal under-performance. The results reveal that India, Germany, and the United States stand out as the strongest positive outliers, with mean residuals of approximately 0.67, 0.56, and 0.41, respectively, suggesting that these countries have significantly outpaced the global average in renewable energy deployment. Indonesia also performs moderately above expectations, indicating a structural shift toward renewables. In contrast, Australia, Kazakhstan, Poland, and Ukraine show slight under-performance, with renewable shares falling below the predicted global trajectory. South Africa emerges as the most pronounced negative outlier, with a mean residual near -0.75, highlighting a substantial lag in renewable energy penetration relative to its economic and coal consumption profile. Together, these results underscore that renewable energy adoption is shaped not only by macroeconomic and energy factors but also by country-specific policies, infrastructure, and investment conditions.

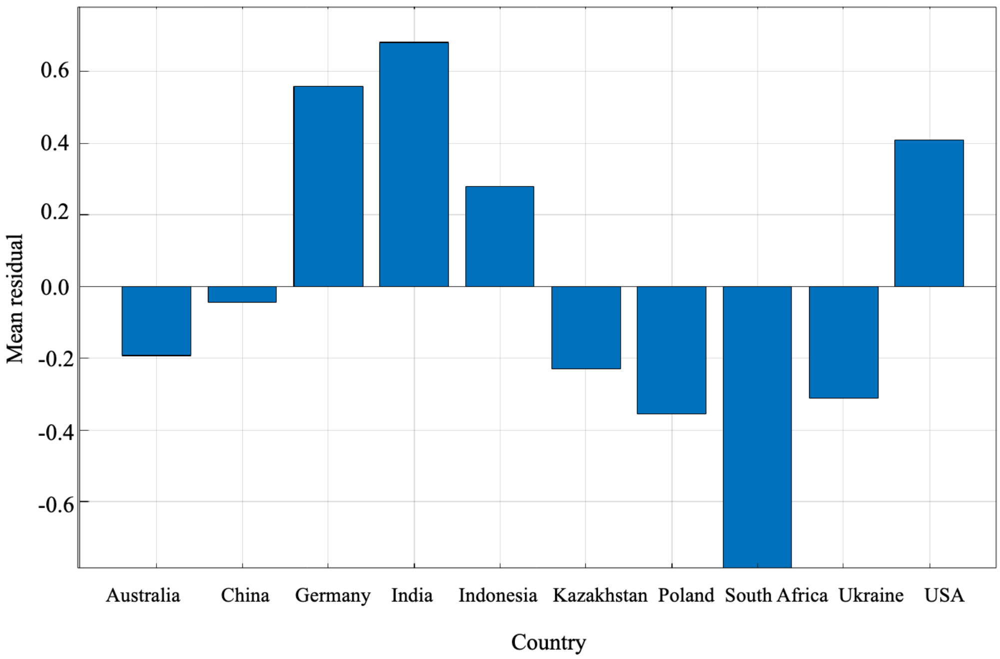


Figure 3. Countries above and below expected renewables.

Table 1 reports the panel regression results without country fixed effects. The model explains around 46% of the variation in renewable energy share (R^2 = 0.46), with all predictors being statistically significant. The standard error (Std. error) shows how precise each coefficient estimate is, with smaller values indicating more reliable estimates. The t-statistic (t-stat) reflects how strongly the data support that the coefficient is different from zero. The p-value indicates the probability that the coefficient has no real effect: very small p-values mean the relationship is statistically significant.

Table 1. Panel regression results (no country fixed effects).

Variable	Coefficient	Std. error	t-stat	p-value
Intercept	-86.77	8.4200	-10.3	<0.001
Year	0.0432	0.0042	+10.3	<0.001
Coal	0.3374	0.0414	+8.16	<0.001
GDP	0.2829	0.0429	+6.59	<0.001

The Difference-in-Difference regression demonstrates a strong model fit ($R^2 = 0.918$), confirming that the chosen specification explains most of the variation in renewable energy share. The coefficient for Year (0.35, p-value is less than 0.001) indicates a consistent upward global trend in renewable energy penetration, reflecting technological advances and broader shifts toward decarbonization. Country effects highlights persistent heterogeneity: Germany (+12.24, p-value is less than 0.001) and China (+3.41, p-value is less than 0.001) show significantly higher renewable energy shares compared to the baseline, while Kazakhstan (-5.09, p-value is less than 0.001) and Ukraine (-3.99, p-value is less than 0.001) remain substantially below average. The modeled and observed policy effects are visualized in Figures 4 and 5. The observed post-policy increases closely align with the modeled policy jumps, confirming that the model effectively captured immediate policy effects. For example, China exhibited the largest effect, with a modelled increase of +5.09 percentage points and an observed increase of +5.45, while Germany recorded +3.71 modeled and +4.60 observed. By contrast, Kazakhstan (+1.41 modeled, +1.37 observed) experienced the smallest gains, consistent with its more modest renewable energy trajectory. The bar chart (figure 4) illustrates these differences across countries. Early policy adopters such as Germany (1991) and Australia (2001) achieved substantial gains, while later adopters, including Indonesia (2014) and Kazakhstan (2013), registered smaller but still positive post-policy increases/ importantly, all ten countries demonstrated measurable positive shifts, reinforcing the assumption that renewable energy policies deliver tangible effects on national renewable energy shares.

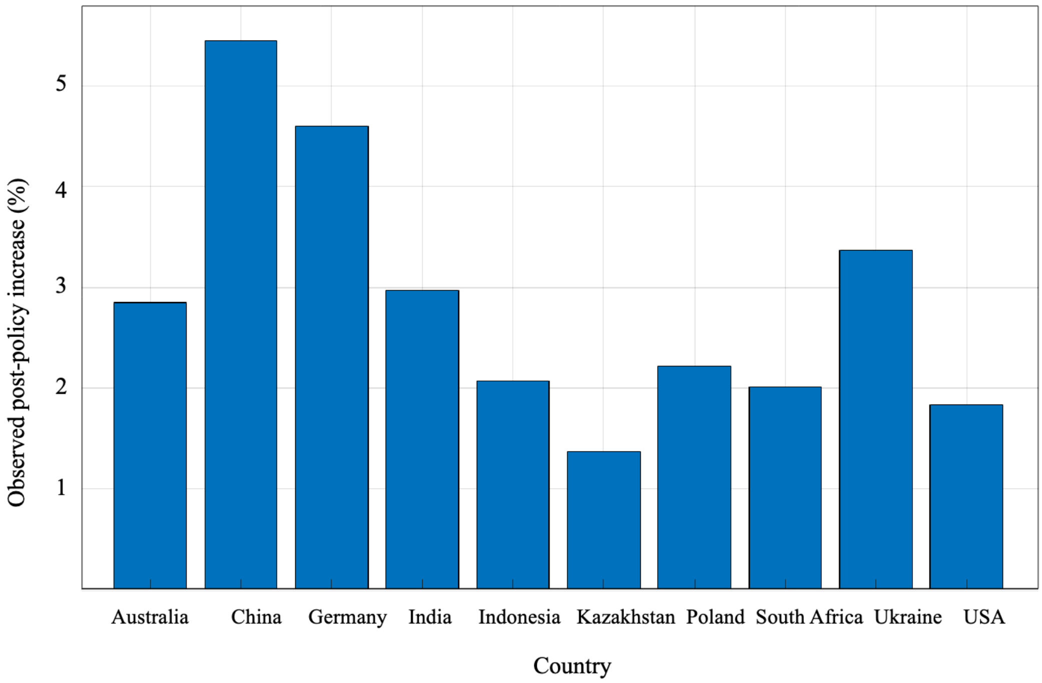


Figure 4. Difference-in-Difference regression of renewable energy share by country (2000 – 2020).

Figure 5 depicts renewable energy share trends from 1990 to 2024, with policy adoption years marked. The trajectories highlight the interplay of underlying growth trends and policy-induced discontinuities. For example, Germany's renewable energy share rose steadily after its 1991 adoption, maintaining the highest levels throughout the period, while China displayed a sharp jump following its 2005 policy and sustained growth thereafter. In contrast, Kazakhstan and Ukraine show flatter profiles, with smaller discrete increases reflecting lower modelled policy effectiveness.

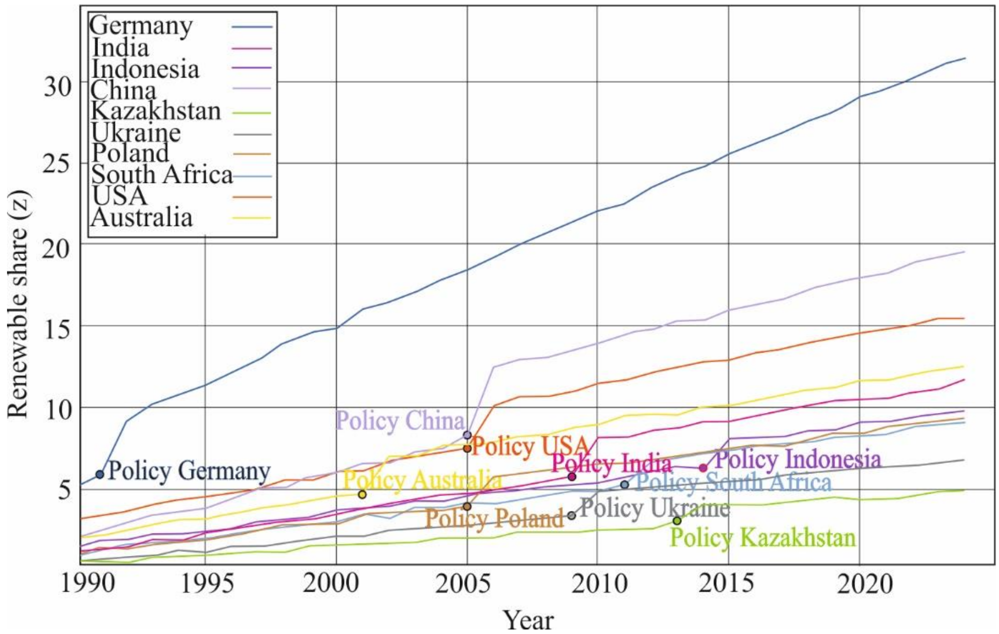


Figure 5. Interaction effects of time and country on renewable energy share.

Our results highlight both global regularities and striking national divergences in the development of renewable energy. At the global level, we find a steady upward trajectory, with renewable energy shares increasing by approximately 0.35 percentage points per year. This reflects a broader technological and institutional momentum toward decarbonization that has been documented in previous studies [29, 30]. However, structural drivers do not operate in a straightforward way. While GDP shows only a weak positive association with renewable deployment, coal consumption is positively related to renewables, suggesting that economies with high energy demand often expand fossil and renewable capacity simultaneously rather than one displacing the other. This finding aligns with the notion of "parallel expansion" in energy transitions, where growing economies diversify their energy portfolios instead of immediately substituting away from coal [31-33].

Beyond these structural factors, country-level effects emerge as decisive. Our analysis shows that Germany, China, the United States, and India consistently outperform global model predictions, whereas South Africa, Kazakhstan, and Ukraine underperform. These deviations indicate that economic size or resource endowments alone cannot account for renewable energy trajectories and that institutional and political contexts play a crucial role [34, 35]. The Difference-in-Differences analysis further confirms the effectiveness of renewable energy policies, showing clear and measurable increases in renewable shares following policy adoption. Importantly, the modeled policy effects closely align with observed post-policy increases, providing strong empirical support for the causal role of policy interventions [36-38]. Early adopters such as Germany and Australia registered the largest cumulative gains, while later adopters, including Indonesia and Kazakhstan, experienced smaller but still positive impacts. Crucially, all ten countries included in the analysis exhibited measurable improvements after policy implementation, reinforcing the conclusion that policy interventions are decisive drivers of renewable transitions, consistent with earlier findings in the policy effectiveness literature [39-41].

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4. Conclusions

Our analysis of renewable energy deployment across ten diverse countries reveals a complex interplay of structural, economic, and policy factors shaping energy transitions. At the global level, we observe a consistent upward trajectory in renewable energy shares, with an average increase of approximately 0.35 percentage points per year, reflecting ongoing technological advancement and broader institutional momentum toward decarbonization. However, structural drivers alone such as GDP and coal consumption do not fully explain the observed patterns. While higher GDP is modestly associated with increased renewable uptake, coal consumption shows a stronger positive correlation, reflecting parallel expansion of energy capacity in high-demand economies rather than direct substitution effects. This underscores that economic size or resource endowments alone are insufficient to account for renewable energy trajectories.

Country-level deviations from global model predictions highlight the critical role of policy contexts. Germany, China, the United States, and India consistently outperform expectations, whereas South Africa, Kazakhstan, and Ukraine stay behind. These patterns demonstrate that national policies, investment strategies, and institutional capacity significantly influence renewable energy adoption. The Difference-in-Differences analysis further confirms the effectiveness of targeted renewable energy policies: modeled policy effects closely match observed post-policy increases, emphasizing the causal impact of policy interventions. Early adopters such as Germany and Australia achieved the largest gains, while later adopters, including Indonesia and Kazakhstan, experienced smaller but measurable improvements.

Overall, our results indicate that renewable energy transitions are driven not only by macroeconomic and energy system characteristics but also by proactive policy measures and country-specific institutional frameworks. This highlights the importance of combining structural capacity with effective governance and policy design to accelerate renewable energy deployment. Policymakers aiming to foster renewable transitions should recognize that enabling policies and institutional support are decisive factors in determining national renewable energy outcomes, complementing global technological and economic trends. Ukraine is currently behind in renewable energy adoption compared to what the model predicts. To catch up, the country could improve its policies and support systems for renewables. Measures like financial incentives, simpler approval processes, and including renewable energy in national planning could help speed up deployment. Working with international partners and using technology transfers could also boost Ukraine’s progress in renewable energy.

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