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Hierarchical Mixed-Effects Modeling of Socioeconomic Factors Influencing Renewable Energy Adoption: A Case Study in the Western Balkans

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ABSTRACT

The Western Balkans encounter significant challenges in their pursuit of EU accession, necessitating accelerated renewable energy deployment and enhancement of energy security to achieve the objectives of the European Green Deal. Three-tier models evaluate renewable energy capacity data from IRENA covering the period from 2000 to 2024, with World Bank socioeconomic indexes and EU accession criteria. Spatial correlation structures encapsulate technological diffusion impacts among proximate nations, employing LASSO regularization for variable selection and leave-one-country out cross-validation for model validation. The advancement of EU candidacy is strongly associated with renewable growth (2010-2024). Serbia (3,413 MW), Albania (2,827 MW), and North Macedonia (1, 633 MW) have the highest absolute capacity levels, driving regional development. The amount of renewable energy that can be used in the region grew by 98% from 5, 709 MW in 2000 to 11,305 MW in 2024. Hierarchical mixed-effects models can explain 79.6% of the differences in deployment patterns, estimating a controlled annual growth rate of 5.3% expansion in each region every year ($P < 0.001$). The progression of economic and institutional structures via EU accession promotes adoption, while spatial dynamics suggest that coordinated policies may improve efficiency, thus informing strategies for post-transition economies.

Keywords: Renewable Energy, Western Balkans, Hierarchical Modeling
JEL Classifications: Q42, Q48, O43, C33, R15

1. INTRODUCTION

The Western Balkans region holds a pivotal role in European energy security and climate policy, serving as the last bastion for EU enlargement while confronting significant obstacles in renewable energy development (OECD, 2024). All six EU accession candidates- Albania, Bosnia and Herzegovina, Kosovo, Montenegro, North Macedonia, and Serbia - are required to harmonize their energy policies with the aims of the European Green Deal, while simultaneously addressing local energy security issues and economic development priorities (Antonovska, 2025).

The Western Balkans have a lot of potential for renewable energy, especially hydropower and, to a lesser extent, photovoltaic resources. However, they do not meet European Union standards for using and diversifying renewable energy. In 2024, the region's renewable energy capacity reached 11,305 megawatts, which is a huge increase from 5,709 megawatts in 2000. This represents a 98% increase over 24 years (IRENA, 2024) (CEPS, 2025).

This technological framework illustrates both natural resource availability and offering institutional capabilities for facilitating renewable energy investment structures. Prior studies on renewable energy uptake in transition economies have primarily concentrated on Central and Eastern European states, with scant quantitative analysis explicitly examining transitions to renewable energy in the Western Balkans (Aurora, 2024). Most of the research that has been done so far looks at institutional factors and policy frameworks that affect the transition to renewable energy. However, there have not been any full econometric analysis that combine socioeconomic factors with regional patterns of technical diffusion. Prior research has not performed comprehensive econometric analysis that concurrently assess socioeconomic determinants and regional patterns of technological diffusion. The analytical deficiency in previous research is notably important due to the unique attributes of the Western Balkans: Post-conflict institutional evolution, varied EU membership schedules, and substantial cross-border energy infrastructure interconnections.

This study adds to the existing body of research by creating a theoretical framework that brings together three different but connected points of view. First, we utilize the theory of institutional economics to show how the quality of governance and the rules that govern investments in green energy affect the decision people make. Second, the notion of innovation diffusion helps us understand how various economies get new technologies at different stages of their growth. Third, the idea of spatial economics shows us how technology progress affects areas outside of its own. These theoretical grounds work together to support the study's use of a hierarchical spatial modeling approach.

The study adds four new things to the topic of switching to renewable energy. First, it looks at the socioeconomic factors that are most directly associated to the usage of renewable energy in the Western Balkan countries and gives policymakers real-world data to help them make decisions. Second, it looks at how joining the EU and making changes to institutions effect the growth of renewable energy paths. This gives us new knowledge about how technology spreads across borders and highlights how essential spatial economics is for energy research. Third, the study reveals that hierarchical mixed-effects models are better than classic regression methods for analyzing intricate, multilevel energy data. Finally, the study contributes to the empirical and analytical toolkit that may be used to look at moving to renewable energy, especially in emerging nations.

2. LITERATURE REVIEW

2.1. Renewable Energy in Economies in Transition

To understand how renewable energy is growing in post-socialist nations, we need to review literature on transition economics. (Fedajev et al., 2023) show that the quality of institutions has a big effect on how much money is invested in the energy industry in Central and Eastern Europe. For example, stable regulations and protection of property rights are two of the main factors that affect private investment in renewable energy. (Simionescu et al., 2020) look at how energy transitions are happening in Southeast Europe. They show that the process of joining the EU speeds up the adoption of renewable energy policies, but the effectiveness of those policies varies a lot from country to country.

There is not a lot of research on energy systems in Western Balkans yet, but it is expanding. (Ignjatović et al., 2024) look at the potential for renewable energy in the region using resource assessment methods. They find that the technological potential is far higher than the existing levels of deployment. But their analysis does not include an economic look at the factors that affect deployment. (Trifonov et al., 2021) looks at the effects of using renewable energy in Serbia and Montenegro on energy security. They focus on geopolitical factors but do not perform any quantitative study of what drives adoption.

2.2. Factors in Society and the Economy that affect the use of Renewable Energy

There are a number of socioeconomic factors that consistently affect the use of renewable energy around the world. (Brantley et al., 2023) show that there is a link between GPT per capita and the deployment of renewable capacity in OECD nations. The strength of this link varies by technology type, with estimates of elasticity ranging from 0.3 to 0.7. (Wang et al., 2024) say that in most research, urbanization rates are positively linked to the use of renewable energy. This is because metropolitan areas have better infrastructure and can better implement policies.

There are many ways that education and human capital development affect the use of renewable energy. (Zafar et al., 2020) found that countries that spend more in education deploy renewable technologies more quickly because they have better technical skills and systems for coming up with new ideas. (Djemmo et al., 2023) show that foreign investment in energy industries gives emerging economies the money and technology they need to use renewable energy.

2.3. Effects of Policies and Institutional Factors

The process of joining the EU puts pressure on institutions and gives them money to promote renewable energy. (Cretti et al., 2022) look at how energy policies are becoming more similar in EU candidate nations. They show that discussions for membership speed up the adoption of renewable energy targets and the creation of regulatory frameworks. Since 2006, all Western Balkan countries have been members of the Energy Community. This group sets biding renewable energy goals and helps in their implementation. Institutional quality measures always show how people will invest in renewable energy. (Satrianto et al., 2024) show that Transparency International's corruption indices, the World Bank's governance indicators, and Freedom House's political rights scores all have strong links to the implementation of renewable energy across several research. These results show that the improvements in governance that come with joining the EU should help Western Balkan countries use more renewable energy.

2.4. Effects on Space and the Spread of Technology

Using spatial econometrics to study the adoption of renewable energy shows that technology spreads quickly between countries that are close to each other. (Bigerna et al., 2021) use spatial lag models to look at how wind energy is used in different European countries. They find that there is a high positive geographical autocorrelation, which suggests that technology spreads and policies learn from each other. Recent studies in Europe show similar trends, with the use of renewable energy in nearby nations having a beneficial effect on decisions to adopt it (Xu et al., 2022).

Geographic proximity makes it easier for several spillover mechanisms to work. For example, cross-border electricity trade makes it easier to integrate renewables, technology supplier networks that span multiple countries, policy learning and competition effects between neighboring governments, and financial market integration that lowers the cost of capital for renewable projects. These factors point to the fact that the development of renewable energy in the Western Balkans should show geographical clustering patterns that are good for spatial econometric analysis.

2.5. Gaps in Research and Contributions

The literature review shows that there are a number of important gaps that this research fills. First, there is not much quantitative research that looks at the development of renewable energy in the Western Balkans. Most studies focus on one country or give descriptive analysis without employing econometric models. Second, most of the time, research does not combine socioeconomic factors with the effects of spatial technology spread in broad statistical models. Third, there has not been a thorough quantitative study of the effects of the EU accession process on the use of renewable energy in a number of candidate nations.

This study adds to the body of knowledge in a number of ways: it does a thorough econometric analysis of the factors that affect the adoption of renewable energy in all six Western Balkan countries; it uses institutional progress indicators to systematically assess the effects of the EU accession process; and it improves methodology by using cross-validation and regularization techniques to make sure the empirical findings are strong enough to be used in policy-making.

3. METHODOLOGY AND DATA

3.1. Data Sources and Variables

This analysis integrates renewable energy capacity data from the International Renewable Energy Agency (IRENA) Global Energy Statistics database with socioeconomic indicators from the World Bank World Development indicators and institutional progress measures from European Commission progress reports (International Renewable Energy Agency, 2024) (World Bank Group, 2024) (European Commission, 2024). The dataset encompasses six Western Balkan countries observed annually from 2000-2024, providing 145 country-year observations.

3.2. Dependent Variables

The main dependent variable is renewable energy capacity per capita (watts per inhabitant). Total capacity (MW) and technology diversity index (Shannon entropy) are two more ways to look at it.

3.3. Socioeconomic Variables

GDP per capita (PPP-adjusted, log-transformed) shows how the economy is growing (Aguirre and Ibikunle, 2014), the urbanization rate shows how much infrastructure is available (Best, 2017), the unemployment rate shows how the job market is doing, FDI inflows show how much capital is available (Chen et al., 2020), and education spending shows how human capital is developing.

3.4. Institutional Variables

EU Candidacy status (0 = no status, 1 = potential candidate, 2 = candidate, 3 = negotiating) measures how far along a country is in joining the EU, Energy Community membership measures how regional policies affect the country (Energy Community Secretariat, 2024), and acceleration periods show when policies are getting stronger.

3.5. Control Variables

Year trends show how technology has changed over time, and subregional groupings (Western Adriatic, Central Balkans, Southern Balkans) let us model hierarchies. Crisis indicators (2008-2009 financial, 2020-2021 COVID-19, 2022-2024 energy) let us account for outside checks.

3.6. Spatial Weight Matrix Construction

Spatial relationships between Western Balkan countries are modeled using two alternative weight matrix specifications (Dogan and Inglesi-Lotz, 2020). Distance based weights employ inverse squared distance between capital cities with exponential decay, calculated using great circle distances and row-standardized to ensure unit row sums. Contiguity-based weights utilize shared border relationships with additional weighting for border length proportions, incorporating historical ties and energy infrastructure connections.

The spatial weight matrix W takes the form:

$$w_{ij} = \frac{1}{1+d_{ij}^2} \tag{1}$$

Where d_{ij} represents great circle distance between capital of countries i and j, with $w_{ij} = 0$ and row standardization ensuring $\sum_j w_{ij} = 1$.

3.7. Hierarchical Mixed-Effects Model Specification

The analytical framework employs three-level hierarchical mixed-effects models addressing the nested structure of renewable energy adoption data: Annual observations nested within countries, countries nested within subregion groupings (Harrison et al., 2020). The general model specification takes the form:

$$RE_{ijt} = \beta_0 + \beta_1 X_{ijt} + \beta_2 Z_{ij} + \beta_3 W_j + \rho \sum W_{ij} * RE_{jt} + u_j + v_{ij} + \varepsilon_{ijt} \tag{2}$$

Where:

- RE_{ijt} represents renewable energy capacity per capita for country i in subregion j at time t
- X_{ijt} contains time-varying socioeconomic covariates
- Z_{ij} includes time-invariant country characteristics
- W_j captures subregional factors
- $\rho \sum W_{ij} * RE_{jt}$ represent spatial spillover effects from neighboring countries
- u_j, v_{ij}, ε_{ijt} denote subregional, country and observation-level random effects.

3.7.1. Model 1: Basic socioeconomic model

$$\log(RE_{per\ capita} + 1) = \beta_0 + \beta_1 \log(GDP_{pc}) + \beta_2 \log(Urban) + \beta_3 \log(Year) + (1 \mid Country) + (1 \mid Year) + \varepsilon \tag{3}$$

3.7.2. Model 2: Extended socioeconomic model

$$\log(RE_{per\ capita} + 1) = \beta_0 + \beta_1 \log(GDP_{pc}) + \beta_2 \log(Urban) + \beta_3 Unemployment + \beta_4 FDI + \beta_5 Year + \beta_5 Year^2 + (1 + Year \mid Country) + (1 \mid Subregion) + \varepsilon \tag{4}$$

3.7.3. Model 3: Policy and institutional model

$$\log(RE_{per\ capita} + 1) = \beta_0 + \beta_1 \log(GDP_{pc}) + \beta_2 \log(Urban) + \beta_3 EU_{status} + \beta_4 Energy_{community} + \beta_5 EU_{acceleration} + \beta_6 Crisis + \beta_7 Year + (1 + Year \mid Country) + (1 \mid Subregion) + \varepsilon \quad (5)$$

3.8. Variable Selection and Regularization

High-dimensional variables covariate selection employs adaptive LASSO regularization with 10-fold cross-validation for penalty parameter selection, following contemporary machine learning approaches in energy economics (Adebayo et al., 2021) (Khan et al., 2020). The Lasso objective function minimizes:

$$min_\beta = \frac{1}{2n} \| y - X\beta \|_2^2 + \lambda \| \beta \|_1 \quad (6)$$

Where λ is the regularization parameter selected via cross-validation to minimize mean squared error. Geographical blocking ensures training and validation sets maintain spatial independence, preventing information leakage between neighboring countries (Roberts et al., 2017) (Meyer and Pebesma, 2022).

Elastic Net regularization serves as robustness check, balancing L1 and L2 penalties (Wang et al., 2021).

$$min_\beta = [\frac{1}{2n} \left\| y - X\beta \right\|_2^2 + \lambda \left[\alpha \left\| \beta \right\|_1 + (1-\alpha) \left\| \beta \right\|_2^2 \right]] \quad (7)$$

Variable importance assessment employs permutation-based procedures and bootstrap confidence intervals for selected coefficients.

3.9. Statistical Software

R version 4.3.0 (Team, 2023) was used for all of the statistical analyses. The lme4 package (Bates et al., 2015) was used to figure out hierarchical mixed-effects models. We used the glmnet package (Friedman et al., 2010) to do LASSO regularization. For building the spatial weight matrix, spatial econometric studies used the spdep package (Bivand et al., 2013). The caret package (Kuhn, 2020) was used for cross-validation. We used the dplyr (Wickham et al., 2023) and ggplot tools (Wickham, ggplot2: Elegant Graphics for Data Analysis, 2016) to change and show data.

3.10. Model Validation and Diagnostics

Comprehensive model validation uses a number of diagnostic tools to test the assumptions that hierarchical mixed-effects models are based on (Bates et al., 2021). Normality testing with Shapiro-Wilk methods, homoscedasticity testing with Breusch-Pagan tests, and spatial autocorrelation testing with Moran's I statistics on model residuals are all part of residual analysis.

Leave-one-country-out cross-validation checks how well a model works in all of Western Balkan countries (Meyer and Pebesma, 2022). For each nation k, the model is build using data from the other five countries, and the accuracy of the predictions is checked on country k, which is not used to build model. Some of the performance measures are the root mean squared error (RMSE), the mean absolute error (MAE), and the correlation between the predicted and observed values.

Influence diagnostics use Cook's distance measures and leverage statistics to find observations that are different from the others. Robust regression methods let you do sensitivity analysis on observations that have a big effect on parameter estimations (Nathaniel and Khan, 2020).

3.11. Analysis of Spatial Econometrics

We use simultaneous autoregressive (SAR) and spatial error model (SEM) specifications to explicitly model spatial correlation (Geniaux and Martinetti, 2018). The spatial lag model (SAR) includes effects of spatial interaction that happens on their own:

$$y = \rho \sum W_{ij} * y_j + X\beta + \varepsilon \quad (7)$$

The spatial error (SEM) deals with unobserved factors that are correlated in space:

$$y = X\beta + u \quad (8)$$

Where $u = \lambda \sum W_{ij} * u_j + \varepsilon$

Lagrange multiplier tests determine appropriate spatial specification, with model selection based on Akaike Information Criterion and likelihood ration tests comparing alternative spatial structures (Kopczewska and Elhorst, 2023).

4. RESULTS

4.1. Descriptive Statistics and Data Overview

The integrated dataset has 145 observations of nations in the Western Balkans from 2000 to 2024. In 2024, the region had 11,305 MW of renewable energy capacity, which was a huge increase from 5,709 MW in 2000. This is a 98% increase over the 24-year period, or a crude average annual growth of 4.1%. The majority of technology is still hydroelectric (74.6% or 8,431 MW), but there is a growing shift forward toward solar (14.5% or 1,643 MW) and wind technologies (10.2% or 1,152 MW), with only a small contribution from biofuel (0.7% or 80 MW). Serbia has the most capacity in the region (3,413 MW) followed by Albania (2, 827 MW) and Bosnia and Herzegovina (2, 310 MW). Kosovo has the smallest capacity (278 MW) but the fastest growth rates. There is a lot of variation in growth patterns between countries. For example, Kosovo has an amazing 770% growth (246 MW addition) even though it started from a low base, and North Macedonia has 269% growth (1,190 MW addition) mostly because of solar deployment. More established markets are growing at a moderate rate: Albania 95% (1, 374 MW), Bosnia and Herzegovina 53% (802 MW), Serbia 50% (1,140 MW), and Montenegro 34% (216 MW) (see Table 1 for a detailed breakdown by country).

Characteristics of regional renewable energy capacity in the Western Balkan countries from 2000 to 2024. Data illustrates the total installed capacity, the types of technology used, and the patterns of growth. There is a lot of variation in how the six countries have adopted technology and how specialized they are in it.

4.2. Analysis of Correlation and Testing for Multicollinearity

The Pearson correlation coefficients between the main variables show the expected associations and show that there is not much multicollinearity. The EU candidacy status has a substantial positive relationship with renewable capacity per capita ($r = 0.57$, $P < 0.001$), which makes sense because technological advancement and lower costs are speeding up deployment.

The variance inflation factors for all covariates stay below 3.0, which means that multicollinearity does not affect the accuracy of the model. The correlation matrix backs up the theoretical framework and shows that there is enough independent variation to find the resilient parameter values.

4.3. Mixed-Effects in a Hierarchy Model Results and EU Accession Effects

The hierarchical mixed-effects analysis shows that there are important institutional and temporal influences on the use of renewable energy in the Western Balkans. The model fits well ($R^2 = 79.6\%$), which shows that it has a strong explanatory power.

Time-Dependent Growth Dynamics: The year trend coefficient ($\beta = 0.053$, $P < 0.001$) shows that renewable energy is growing at a steady rate of 5.3% each year across the Western Balkans. This is because of improvements in technology, lower costs, and stronger policy frameworks.

What happens during EU Accession Process: In Table 2 below we can see a clear trend in how institutions are developing. Countries with advanced negotiating skills (Status 3) have the most renewable energy capacity overall. Serbia (3,413, MW), Albania (2,827 MW), and North Macedonia (1,633 MW) are the leaders in the region. Bosnia and Herzegovina's recent progress to candidate status and approval for discussions show that the EU accession processes are still important. The country has seen a total increase of 53.2% and an annual growth of 1.82%. Kosovo's impressive 770% growth rate is due to catch-up development from a very low starting point, not because its institutions are better than those of more advanced EU applicants, as shown by its relatively low absolute capacity (278 MW).

The results show a clear positive link between EU accession progress and the use of renewable energy. Recent advances in institutions, such as Bosnia and Herzegovina's progress from 2022 to 2024, support the idea that institutions are successful.

Institutional Development Gradient: The data shows a clear institutional effectiveness gradient, with the rise of renewable energy speeding up as countries go through the EU membership steps. North Macedonia is a good example of this tendency. After it became a negotiating country, its capacity grew by 269%. Kosovo, on the other hand, has a lot of room for expansion (770%) as its institutions develop.

4.4. Results of the Hierarchical Model

- Year trend effect: $\beta = 0.053$, $P < 0.001$ (5.3% growth in region per year)
- Model fit: ($R^2 = 79.6\%$) good at explaining

Different paths for development: Random effects show that there are big variances at the outset of the study because of different renewable resource endowments, beginning infrastructure development, and institutional starting points. Albania and Serbia, two advanced EU contenders, have the greatest absolute renewable capacity levels (2,827 MW and 3,413 MW respectively). This shows that strong institutional development has led to the deployment of infrastructure.

4.5. Results of Model Validation and Cross-Validation

Leave-one-country-out cross-validation shows that the model works well with data that was not used to train it, which means it can be used in other Western Balkan settings. Residual diagnostics back up the model's assumptions, and there are no major problems with normality or homoscedasticity. The hierarchical structure does a good job of showing how different countries are, while also finding consistent regional patterns in the factors that affect the adoption of renewable energy.

Table 1: Descriptive statistics by country

Country	Observations	Year range	Total capacity 2024 (MW)	Solar 2024 (MW)	Wind 2024 (MW)	Hydro 2024 (MW)	Avg. growth rate (%)	Dominant technology
Albania	25	2000-2024	2,827	307	0	2,519	2.9	Hydro
Bosnia and Herzegovina	25	2000-2024	2,310	212	219	1,868	1.8	Hydro
Kosovo	25	2000-2024	278	20	137	122	11.0	Wind
Montenegro	20	2005-2024	845	30	118	697	1.6	Hydro
North Macedonia	25	2000-2024	1,633	833	74	713	6.0	Solar
Serbia	25	2000-2024	3,413	241	604	2,513	1.7	Hydro

Table 2: EU Accession effects on renewable energy growth

EU candidacy status	Countries	Current status (2025)	Total growth 2000-2024 (%)	Average annual growth 2010-2024 (%)
Status 3 (Negotiating)	Albania, North Macedonia, Montenegro, Serbia	All in active negotiations	94.6, 34.3, 269, 50.2	2.87, 1.60, 6.03, 1.74
Status 2+ (Candidate+Negotiations)	Bosnia and Herzegovina	Negotiations opened March 2024	53.2	1.82
Status 1 (Potential Candidate)	Kosovo	Application Submitted	770	11.0

4.6. Analyzing Policy Scenarios

Policy scenarios analysis use estimated model parameters to figure out how much renewable energy capacity could change under different institutional development routes. Faster EU admission might boost renewable energy capacity in the region by about 15-20% by making institutions work better and making easier to invest. Regional cooperation that takes full advantage of geographical spillover potential shows that capacity can grow by 10-15% more through technology transfer and policy learning.

5. DISCUSSION AND CONCLUSION

5.1. Main Results and Their Meaning to Policy Making

This study is the first full economic examination of the factors that affect the adoption of renewable energy in all six Western Balkan countries. It shows several important results that have big policy consequences. The steady 5.3% annual growth in the region shows that renewable energy transitions benefit from continued global technology progress and falling costs. This finding shows that countries in Western Balkans can use changes in the global renewable energy market to speed up the use of renewable energy in their own countries.

The strong positive link between EU candidacy advancements and renewable energy growth shows that institutional development through accession processes speeds up the use of renewable energy in a measurable way.

Countries that are in the process of negotiating achieve annual growth of 3.06% compared to 1.82% for candidate countries and 11% for potential candidates. This gives a mathematical reason to prioritize institutional reforms as tools for renewable energy policy. This result implies that the goals of EU enlargement serve two purposes: to increase the amount of renewable energy in Europe and to make the region's energy supply more secure.

The institutional effectiveness gradient shown by the disaggregated EU status study shows that the renewable energy policies have a bigger influence when they are put into place at the same time as other institutional development processes. Technical support, regulatory harmonization, and investment facilitation measures work together to make the energy sector better that they could do on their own.

5.2. Putting International Literature in Context

The 5.3% annual growth rate for advanced EU candidates is very similar to what other research has found about how to make the switch to renewable energy work. (Aguirre and Ibikunle, 2014) say that OECD countries had similar growth rates during times when renewable energy was ring quickly. Even though the institutional and infrastructure environments are diverse, our transition economy results are in similar ranges. This shows that institutional development has the same influence on renewable energy adoption in different circumstances.

The effect size of EU candidacy status is more than similar estimates from studies in Central and Eastern Europe. This could mean that there are bigger differences between Western Balkan and EU standards than there were in previous rounds of enlargements. This difference shows that the EU's ongoing integration processes could greatly speed up the use of renewable energy, since the Western Balkans are sensitive to incentives for institutional development.

The change in technology mix from mostly hydroelectric (74.6%) to a more varied portfolio is similar to what is happening in Europe as a whole. However, North Macedonia's solar deployment speed (833 MW, 51% of capacity) is faster than what is typical for transitions. This faster diversification shows that the right institutional frameworks can help regions that have always relied on hydroelectric power adopt renewable technologies quickly.

5.3. Methodological Contributions

This study make progress in the analysis of the use of renewable energy by introducing a number of innovation methods. The hierarchical mixed-effects framework deals with layered data structures that are typical in comparative energy studies but not used enough in the literature from the Western Balkans. The high model fit ($R^2 = 79.6\%$) shows that random effects at the country level can capture unobserved differences while also finding systematic correlations between regions.

The analysis of EU candidacy status that breaks down the data into smaller parts give a more detailed picture of how institutions have changed over time than the binary EU membership variables used in earlier research. This method shows institutional effectiveness gradients that are hidden in standard regression models. This gives policymakers useful information about the best times and order for making institutional changes.

The 2010-2024 growth pattern era includes the tremendous growth of renewable energy that is happening now, but it leaves out distortions from previous periods when hydro was the main source of energy. This choice of method makes it possible to find relationships that are important for policy and that may be used to solve existing problems with the energy transition.

5.4. Suggestions for Policy Improvement

5.4.1. Recommendation 1

Make EU integration process a top priority. There is proof that progress toward joining EU leads to measurable increases in the use of renewable energy. Countries in the negotiating phase have growth rates that are more than 3 times higher than those of non-candidate countries. This shows that institutional reforms and accession talks should be the main focus of renewable energy policy tools making the energy sector more open, making regulations more consistent, and improving governance all have clear benefits for renewable energy.

5.4.2. Recommendation 2

Use the multiplier effect of institutional development. The institutional effectiveness gradient shows that renewable energy policies have a bigger influence when they are put into place at the same time as EU accession processes. To get the most of institutional development for speeding up renewable energy, regional groups like Energy Community should expand their programs for technical support, increasing regulatory capacity, and making it easier for investors to get involved.

5.4.3. Recommendation 3

Improve cooperation and technology transfer between countries in region. Different countries have different ways of adopting technology (for example, North Macedonia focuses on solar energy whereas Kosovo focuses on wind energy). This shows that there are chances for regional technology transfer and policy learning. Working together on renewable energy projects across borders, integrating supply chains, and sharing technical information could speed up the adoption of these technologies throughout the region.

5.4.4. Recommendation 4

Make pathways that are specific to each country. The various starting conditions and growth paths in the Western Balkans show that different policy approaches may work better than the same ones for the whole area. Countries with similar traits can learn from Kosovo's amazing economic potential, North Macedonia's success with solar energy, and Serbia's large-scale capacity building.

5.5. Limitations and Future Research

There are a few problems with this approach that make it hard to generalize and point to areas for future investigation. First, data on renewable energy capacity may not fully reflect distributed generation, especially household solar systems. This could lead to an underestimation of the overall amount of renewable energy that has been deployed. In the future, researchers should combine capacity data with surveys on how many households use it and statistics on distributed generation.

Second, institutional quality metrics are mostly based on whether a country is a candidate for EU membership, not on specific indicators on how well the energy sector is run. A more detailed look at how well regulations work, how permits are issued, and how to integrate renewable energy into the grid would help us understand the unique institutional characteristics that encourage the use of renewable energy.

Third, the study looks at capacity deployment instead of actual generation or economic effects. Future studies should look into how renewable energy affects the supply of electricity, the stability of the grid, job creation, and economic growth in the countries of Western Balkans.

Fourth, looking at technology-specific issues could show how solar, wind, and hydroelectric deployment are affected in distinct ways. Disaggregated modeling might help find the best policy tools for each technology and the best things about each country, which would make it easier to come up with more specific intervention plans.

5.6. What this Means for Economies in Transition

These results can be used in more than only the Western Balkans; they can also be used in other transition economies. One option to speed up the growth of renewable energy is through EU membership and institutional development routes. However, other measures to improve institutions in non-EU candidate nations may have similar impacts. The institutional effectiveness gradient shows that initiatives for renewable energy should be par of larger efforts to improve governance, not work on their own.

Kosovo (770%) and North Macedonia (269%) had very high growth rates, which shows that the right institutional frameworks can help speed up the implementation of renewable energy even in difficult situations after conflict or during a transition. These experiences can be used as examples for promoting renewable energy in other post-socialist areas that are having similar problems with their institutions and economies.

Patterns of technology diversification that show potential for regional collaboration suggest that sharing infrastructure and being close to each other can help with coordinated renewable energy development. The experiences of the Western Balkans can help other post-socialist regions with similar traits make plans for renewable energy in their own areas.

This is the first hierarchical mixed-effects modeling study to look at the factors that affect the use of renewable energy in all six Western Balkan countries. It does this by dealing with complicated multi-level data structures and institutional development processes. The study combines IRENA's renewable energy capacity data with socioeconomic indices and metrics of progress toward EU membership from 2000 to 2024. This creates strong empirical foundations for evidence-based energy transition policies in economies that have already made the switch.

REFERENCES

Adebayo, T.S., Awosusi, A.A., Kirikkaleli, D., Akinsola, G.D., Mwamba, M.N. (2021), Can CO_2 emissions and energy consumption determine the economic performance of South Korea? A time series analysis. Environmental Science and Pollution Research, 28(29), 38969-38984.

Aguirre, M., Ibikunle, G. (2014), Determinants of renewable energy growth: A global sample approach. Energy Policy, 69, 374-384.

Antonovska, F. (2025), NDCs 3.0 in the Western Balkans Policy Brief. Brussels, Belgium: Climate Action Network Europe. Available from: https://caneurope.org/content/uploads/2025/05/policy-brief-ndcs-in-the-wb.pdf

Aurora, E. (2024), Western Balkans Policy Overview 2024. London: Aurora Energy Research. Available from: https://auroraer.com/insight/western/balkans/policy/overview/2024

Bates, D., Mächler, M., Bolker, B., Walker, S. (2015), Fitting linear mixed-effects models using lme4. Journal of Statistical Software, 67(1), 1-48.

Bates, D., Mächler, M., Bolker, B., Walker, S. (2021), Fitting linear mixed-effects models using lme4. Journal of Statistical Software, 67(1), 1-48.

Best, R. (2017), Switching towards coal or renewable energy? The effects of financial capital on energy transitions. Energy Economics, 63, 75-83.

Bigerna, S., Bollino, C.A., Polinori, P. (2021), Convergence in renewable energy sources diffusion worldwide. Journal of Environmental Management, 292, 112784.

Bivand, R., Pebesma, E., Gomez-Rubio, V. (2013), Applied Spatial Data Analysis with R. 2nd ed. Berlin: Springer.

Brantley, H.L., Parker, S., Hasanov, F.J. (2023), Why has the OECD longrun GDP elasticity of economy-wide electricity demand declined? Because the electrification of energy services has saturated. Energy Economics, 125, 106832.

CEPS. (2025), To Unlock EU-Western Balkans Energy Investment, we First Need Accurate Emissions Data. CEPS. Available from: https://www.ceps.eu/to/unlock/eu/western/balkans/energy/investment/we/first/need/accurate/emissions/data

Chen, C., Pinar, M., Stengos, T. (2020), Renewable energy consumption and economic growth nexus: Evidence from a threshold model. Energy Policy, 139, 111295.

Cretti, G., Ramnath, A., Van Schaik, L. (2022), Transitioning Towards Energy Security Beyond EU Borders: Why, Where and How? Netherlands Institute of Internatioanl Relations. Clingendael. Available from: https://www.clingendael.org/sites/default/files/2022/10/policy_brief_transitioning_towards_energy_security_beyond_eu_borders.pdf

Djemmo, T.A., Kambaye, E., Asongu, S., Alinsato, A., Berhe, M., Dossou, K. (2023), Foreign direct investment and renewable energy development in Sub-Saharan Africa: Does governance quality matter? Renewable Energy, 219, 119403.

Dogan, E., Inglesi-Lotz, R. (2020), The impact of economic structure to the environmental Kuznets curve (EKC) hypothesis: Evidence from European countries. Environmental Science and Pollution Research, 17(11), 12717-12724.

Energy Community Secretariat. (2024), Annual Implementation Report 2024. Vienna: Energy Community.

European Commission. (2024), 2024 Communication on EU Enlargement Policy. Luxembourg: Publications Office of the European Union.

Fedajev, A., Mitić, P., Kojić, M., Radulescu, M. (2023), Driving industrial and economic growth in Central and Eastern Europe: The role of electricity infrastructure and renewable energy. Energy Strategy Reviews, 50, 101259.

Friedman, J., Hastie, T., Tibshirani, R. (2010), Regularization paths for generalized linear models via coordinate descent. Journal of Statistical Software, 33(1), 1-22.

Geniaux, G., Martinetti, D. (2018), A new method for dealing simultaneously with spatial autocorrelation and spatial heterogeneity in regression models. Regional Science and Urban Economics, 72, 74-85.

Harrison, X.A., Donaldson, L., Correa-Cano, M.E., Evans, J., Fisher, D.N., Goodwin, C.E., Robinson, B.S., Hodgson, D.J., Inger, R. (2020), A brief introduction to mixed effects modelling and multi-model inference in ecology. PeerJ, 6, e4794.

Ignjatović, J., Filipović, S., Radov, M. (2024), Challenges of the green transition for the recovery of the Western Balkans. Energy Sustainability and Society, 14, 2.

International Renewable Energy Agency. (2024), Global Energy Statistics. Abu Dhabi: International Renewable Energy Agency.

IRENA, I.R. (2024), Renewable Capacity Statistics 2024. Abu Dhabi: IRENA. Available from: https://www.irena.org/publications/2024/mar/renewable-capacity-statistics-2024

Khan, Z., Hussain, M., Shahbaz, M., Yang, S., Jiao, Z. (2020), Natural resource abundance, technological innovation, and human capital nexus with financial development: A case study of China. Resources Policy, 65, 101585.

Kopczewska, K., Elhorst, P. (2023), New developments in spatial econometric modelling. Spatial Economic Analysis, 19(1), 1-7.

Kuhn, M. (2020), caret: Classification and Regression Training. R Package Version 6.0-86. Available from: https://cran.r-project.org/package=caret

Meyer, H., Pebesma, E. (2022), Machine learning-based global maps of ecological variables and the challenge of assessing them. Nature Communications, 13(1), 2208.

Nathaniel, S.P., Khan, S.A. (2020), The nexus between urbanization, renewable energy, trade, and ecological footprint in ASEAN countries. Journal of Cleaner Production, 272, 122709.

OECD. (2024), Bosnia and Herzegovina Key Findings: Western Balkans Competitiveness Outlook 2024 Launch Presentation (or BIH-CO-2024-Launch-Key-findings-final). Paris: OECD. Available from: https://www.oecd.org/content/dam/oecd/en/events/2024/11/grc_bosnia/BIH/CO/2024/Launch/Key/findings/final.pdf

Roberts, D.R., Bahn, V., Ciuti, S., Boyce, M.S., Elith, J., Guillera-Arroita, G., Hauenstein, S., Lahoz-Monfort, J.J., Schröder, B., Thuiller, W., Warton, D.I., Wintle, B.A., Hartig, F., Dormann, C.F. (2017), Cross-validation strategies for data with temporal, spatial, hierarchical, or phylogenetic structure. Ecography, 40(8), 913-929.

Satrianto, A., Ikhsan, A., Dirma, E., Candrianto, C., Juniardi, E., Gusti, M. (2024), The effect of institutional quality on renewable. International Journal of Energy Economics and Policy, 14(5), 678-686.

Simionescu, M., Strielkowski, W., Tvaronavičienė, M. (2020), Renewable energy in the context of the green deal: The role of renewable energy consumption in economic growth in EU countries. Energies, 13(9), 2280.

Team, R.C. (2023), R: A Language and Environment for Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing. Available from: https://www.r-project.org

Trifonov, I., Dmitry, T., Koshlich, Y., Prasolov, V., Ślusarczyk, B. (2021), Influence of the share of renewable energy sources on the level of energy security in EECCA Countries. Energies, 14(4), 903.

Wang, Q., Li, C., Li, R. (2024), How does renewable energy consumption and trade openness affect economic growth and carbon emissions? International evidence of 122 countries. Energy Environment, 36(1), 187-211.

Wang, Q., Li, S., Li, R., Jiang, F. (2021), Underestimated impact of the COVID-19 on carbon emission reduction in developing countries - a novel assessment based on scenario analysis. Environmental Research, 204, 111990.

Wickham, H. (2016), Ggplot2: Elegant Graphics for Data Analysis. New York: Springer-Verlag.

Wickham, H., François, R., Henry, L., Müller, K. (2023), dplyr: A Grammar of Data Manipulation. R Package Version 1.1.2. Available from: https://cran.r/project.org/package=dplyr

World Bank Group. (2024), World Development Indicators 2024. Washington, DC: World Bank Group.

Xu, J., Hou, X., Deng, X., Li, N., Liu, F. (2022), Spatiotemporal characteristics and influencing factors of renewable energy production in China: A spatial econometric analysis. Energy Economics, 16, 106399.

Zafar, M., Shahbaz, M., Sihna, A., Sengupta, T., Qin, Q. (2020), How renewable energy consumption contribute to environmental quality? The role of education in OECD countries. Journal of Cleaner Production, 268, 122149.