Global Synergies in Renewable Energy and Efficiency: A Data-Driven Analysis

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Abstract

The study uses data exploration, machine learning techniques, and literature review to analyze global synergies between renewable energy (RE) adoption and energy efficiency (EE) improvements across 176 countries. Our analysis aims to find (1) which countries show the strongest Renewable Energy and Energy Efficiency synergies, (2) what synergy combinations are most effective, and (3) how these synergies impact energy affordability and inequality.

Through K-cluster analysis it identifies four energy clusters: Cluster 0 (High-Renewable) with countries like Chad and Haiti; Cluster 1 (Conventional) with nations like Brazil and China; Cluster 2 (Energy-Intensive) including countries like the US and Germany; and Cluster 3 (Transitional), including India and Nigeria, these clusters help classify the countries into different categories which help analyze what is the next best step for each country in a specific category.

Multivariate regression analysis reveals that scaled GDP, scaled access, and scaled energy are inversely related to synergy, indicating that higher values in these factors tend to reduce overall synergy between renewable energy and energy efficiency.

1. Introduction

1.1. Problem Statement

This study investigates the under-explored synergies between two Sustainable Development Goal (SDG) 7 targets: increasing renewable energy share (7.2.1) and improving energy efficiency (7.3.1). Current research predominantly examines these targets in isolation, creating policy blind spots and overlooking how their combined implementation could accelerate progress toward affordable, sustainable energy access. We address three core questions: (1) which countries show the strongest RE+EE synergies, (2) what policy combinations are most effective, and (3) how these synergies impact energy affordability and inequality.

1.2. Research Motivation

As climate change continues to escalate, exploring alternative energy sources and assisting countries in achieving their SDG7 goals becomes increasingly important. Our research seeks to combine data analysis with policy evaluation to identify the most effective strategies for countries, grouped through cluster analysis, to enhance their approach to SDG7. Existing models often overlook geographic variability and tend to apply a one-size-fits-all solution. In contrast, our analysis aims to provide tailored recommendations for specific groups or clusters of countries.

1.3. Analytical Approach

Our approach involves (1) data preparation: cleaning and formatting the date, (2) exploratory data analysis: Finding relationships between different variables; this was done using the correlation heatmap, and (3) predictive modeling; K-means clustering and multivariate regression. The data was analysed using python libraries such as pandas, matplotlib, seaborn, statsmodel and sckikit-learn.

2. Related Works

2.1. Global Energy Transition Pathways

Recent studies show that there is a strong variation in the scenarios of adoption of renewable energy between countries. These variations are strongly correlated to policy intensity. The most ambitious countries which aim to achieve 40-50% of their goal require coordinated policy action across technology, market design and infrastructure investment. [1]

Key technology deployment patterns emerge from the literature:

- Wind power projected to reach 29% of global generation by 2030
- Bioenergy potential estimated at 100-400 EJ annually, limited by land constraints

These projections highlight the critical role of policy frameworks in determining both the pace and technological composition of the energy transition.

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2.2. Policy Mechanisms for Energy Transition

The literature identifies effective policies for renewable energy development. Germany used a Feed-in tariffs which helped them achieve 14.2% of renewable penetration within 7 years[3].

Significant implementation gaps persist. Analysis of EU policy coherence reveals that 62% of policies encounter conflicts during execution phases [2]. These gaps stem from the misalignment of goals between national and transnational objectives, this is especially more prevalent in areas that require infrasturctural coordination.

2.3. Regional Performance and Challenges

Regional assesments show that there is substantial variation in renewable energy adoption across geographical areas. South Asian studies show Bhutan leading with a 0.65 composite performance score, while india demonstrates mized results with an energy intensity score of 4.94[4]. These metrics combine energy intensity, renewable share, and carbon emissions into unified indices.

The energy-water-environment nexus presents particular challenges for developing regions:

- Hydropower development often conflicts with aquatic ecosystem preservation
- Bioenergy expansion faces constraints from competing land use demands

Renewable energy trade across borders is a promising solution, with a potential to improve energy efficiency by 15-20% through resource sharing.

2.4. Market Structures and Governance

Market reform strategies emphasize the importance of accurate price signals in driving efficient energy transitions. Time-differentiated electricity pricing has reduced peak demand by 20% in successful pilot programs, while the historical 8:1 subsidy ratio favoring fossil fuels continues to distort energy markets.

Governance challenges remain significant, particularly in regions like South Asia, where politics often lags behind technical solutions. Despite the SAARC platform's potential for regional coordination, implementation barriers persist due to different national priorities and infrastructure limitations. These governance gaps highlight the need for stronger institutional frameworks to support the goals of energy transition.

2.5. Emerging Research Directions

Through the above literature a few points stood out which could help countries transition to renewable sources of energy, these include:

- Development of cross-border renewable energy exchange mechanisms
- Optimization of hybrid renewable energy systems
- Improved modeling of transition pathways for developing economies

These research directions will be crucial for supporting evidence-based policymaking and accelerating global energy transitions.

2.6. Background Data Visualizations

To complement the literature discussed above, this subsection presents key visual insights derived from global energy datasets. These graphs provide a snapshot of the global landscape of renewable energy adoption, energy intensity, electricity access, and clean energy infrastructure, offering useful context for understanding the challenges and directions outlined in related works.

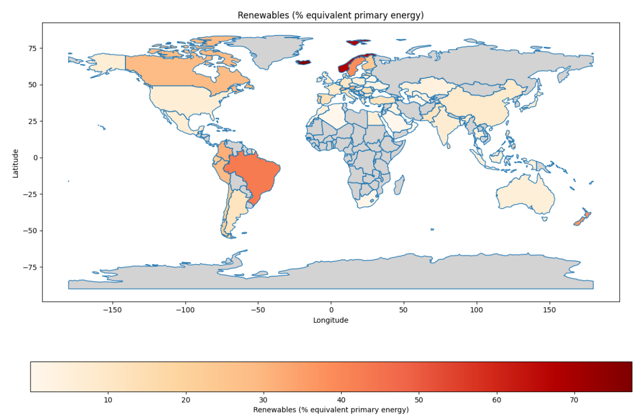

Figure 1. Global distribution of renewable energy adoption (Renewables as % of equivalent primary energy).

Figure 1 shows the geographic distribution of renewable energy use, highlighting disparities between countries and regions in the share of renewables in their primary energy mix.

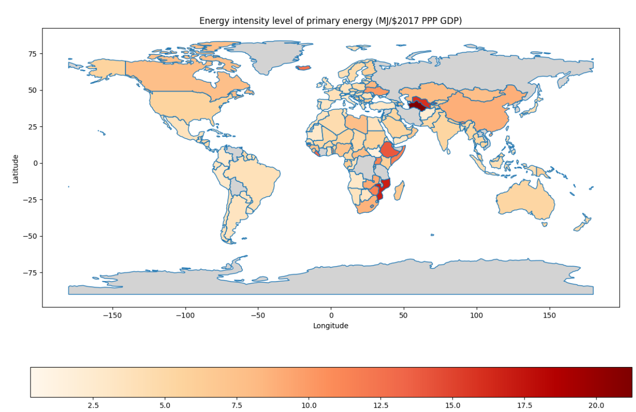

Figure 2. Energy intensity of primary energy use (MJ per $2017 PPP GDP).

Figure 2 provides insight into energy efficiency across the globe, with higher intensity values indicating less efficient energy use per unit of economic output.

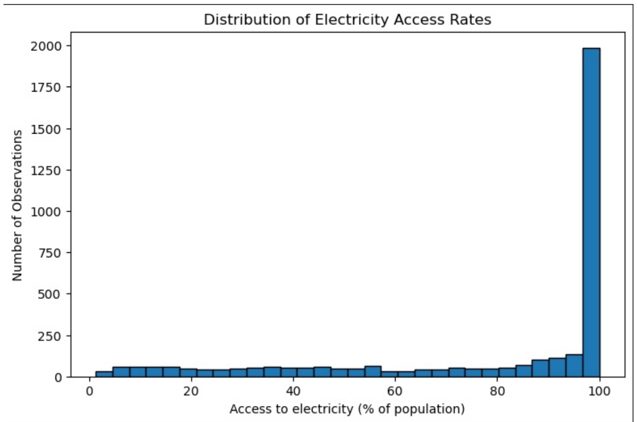

Figure 3. Distribution of electricity access rates across countries.

As shown in Figure 3, electricity access remains uneven globally, with a significant number of countries achieving near-universal access, while others lag significantly behind.

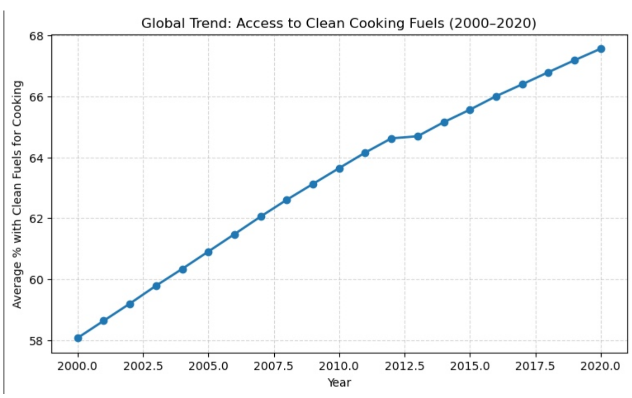

Figure 4. Global trend in access to clean cooking fuels (2000–2020).

Figure 4 illustrates a gradual improvement in access to clean cooking fuels worldwide, although progress remains slow and uneven.

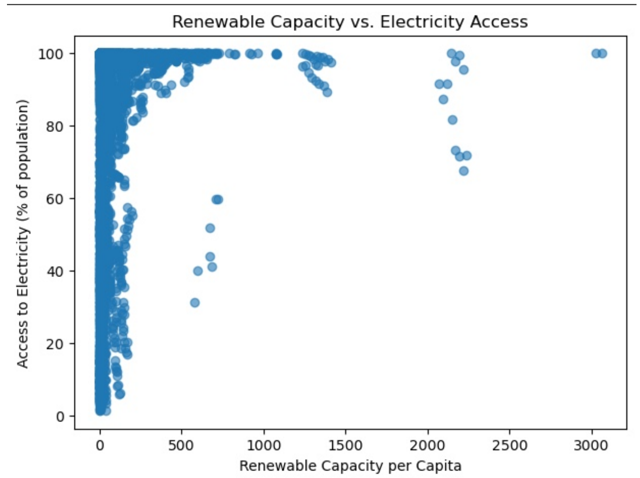

Figure 5. Renewable energy capacity per capita vs. electricity access.

Finally, Figure 5 shows a positive association between renewable capacity and electricity access, underscoring the potential of renewable infrastructure to enhance energy equity.

Together, these visuals reinforce the findings discussed in the literature and underscore the multifaceted nature of the global energy transition challenge.

3. Methods

Our analysis combines statistical modeling and machine learning to examine renewable energy (RE) and energy efficiency (EE) synergies across 176 countries. The methodological framework progresses through three core components: (1) data preparation, (2) descriptive analysis, and (3) predictive modeling. All analyses were conducted using Python 3.9 with pandas, scikit-learn, and statsmodels.

3.1. Base Model: Linear Regression

The base model used in this analysis is linear regression, which was chosen for its simplicity and interpretability. Linear regression allows us to examine the relationship between key variables and the target synergy score, providing a clear understanding of how each feature contributes to the overall energy efficiency and renewable energy synergy.

3.2. Data Preparation

We utilized the *Global Data on Sustainable Energy* dataset (2000–2022) with the following key variables:

- SDG 7.2.1: Renewable energy share in total final energy consumption (%)
- SDG 7.3.1: Energy intensity (MJ/$2017 PPP GDP)
- GDP per capita (constant USD)
- Electricity access (% of population)

Missing data were excluded through listwise deletion. We derived energy efficiency as:

$$E_{\text{eff}} = \frac{1}{\text{Energy Intensity}} \tag{1}$$

3.3. Descriptive Analysis

We computed:

- Correlation matrices for all key variables
- Country-level RE-EE synergy scores:

$$\text{Synergy Score} = \left(\frac{\text{RE\%}}{100}\right) \times E_{\text{eff}} \tag{2}$$

- Top/bottom performer rankings by synergy score

3.4. Predictive Modeling

We implemented and compared four regression approaches:

Model	Configuration
Linear Regression	OLS with default parameters
XGBoost	100 trees, max depth=3
Support Vector Machine	RBF kernel
Neural Network	2 hidden layers (128,64 units)

Table 1. Machine learning model specifications

Models were evaluated using:

- Mean Squared Error (MSE)
- Root Mean Squared Error (RMSE)
- R^2 score

Feature importance was analyzed through:

- Linear regression coefficients
- XGBoost built-in importance scores

4. Results

4.1. Model Performance

Our comparative analysis of predictive models yielded the following performance metrics:

Table 2. Machine Learning Model Performance

Model	MSE	RMSE	MAE	R^2
Linear Regression	24.38	4.94	3.88	0.38
XGBoost	16.47	4.06	3.00	0.58
SVM	18.90	4.35	2.99	0.52
Neural Network	16.76	4.09	3.02	0.57

Key findings from the modeling:

- XGBoost achieved the highest R^2 (0.58) and lowest RMSE (4.06)
- Energy consumption was the most important feature (62.3% importance in XGBoost)

Table 3. Linear Regression Coefficients

Feature	Coefficient
scaled_gdp	-0.0030
scaled_access	-1.8960
scaled_energy	-1.6690
Intercept	7.1879

Table 4. XGBoost Feature Importance

Feature	Importance
scaled_energy	0.6228
scaled_access	0.2226
scaled_gdp	0.1547

- Electricity access showed negative coefficients in linear models (-1.896)
- All linear regression coefficients were negative, suggesting inverse relationships
- XGBoost feature importance aligned with linear model coefficient magnitudes

4.2. Base Model: Key Relationships

The clustering reveals four critical patterns:

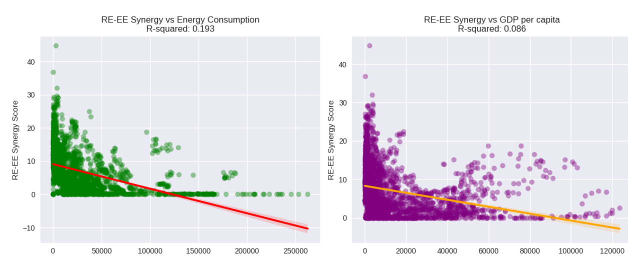

Figure 6. GDP per capita

Figure 7. Energy consumption

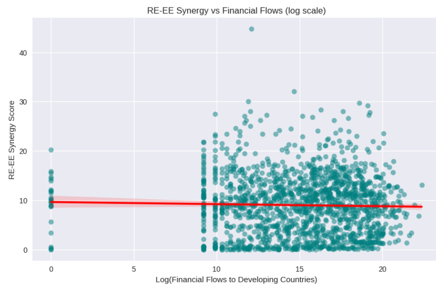

Figure 8. Clean energy investment patterns across clusters (Clusters 0-3 marked)

- **RE-EE Synergy vs Electricity Access:** Shows a moderate negative correlation (R^2 = 0.274). Countries with higher electricity access tend to have lower RE-EE synergy scores, suggesting that access is often achieved through non-renewable or inefficient energy systems.
- **RE-EE Synergy vs Log(CO_2 Emissions):** The trend line indicates a negative relationship, but R^2 is NaN, likely due to missing or invalid data (e.g., log of zero or null values). This suggests that higher emissions are not associated with stronger RE-EE synergy and may reflect fossil fuel dependence.
- **RE-EE Synergy vs Financial Flows (log scale):** Shows almost no relationship between financial flows and synergy score. The regression line is nearly flat, indicating minimal explanatory power. Financial aid alone appears insufficient to drive RE-EE synergy without supportive policies.
- **RE-EE Synergy vs Energy Consumption per Capita:** Displays a negative correlation (R^2 = 0.193). Higher per capita energy consumption is associated with lower synergy, potentially due to inefficiency or fossil fuel reliance in high-use countries.
- **RE-EE Synergy vs GDP per Capita:** Shows a weak negative correlation (R^2 = 0.086). Economic wealth does not strongly predict RE-EE synergy, indicating that high-income countries may face structural inertia in transitioning to efficient renewable energy systems.

4.3. Country Clustering Analysis

Our k-means clustering (k=4) of 150 unique countries revealed distinct energy profiles:

4.4. Cluster Characteristics

The k-means clustering revealed four distinct energy profiles among 150 countries:

- **Cluster 0 (High-Renewable)**: *(13 countries)*
  - **Representative Countries**: Chad, Comoros, Haiti, Mali
  - **Renewable Share**: 80.6%
  - **Energy Productivity**: \$0.88/kWh

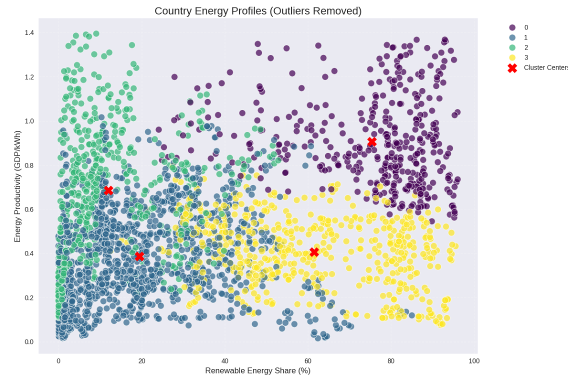

Figure 9. Energy profile clusters based on renewable share, productivity, and access

  - **Electricity Access**: 31.1%
  - **Energy Consumption**: 929 kWh/capita
- **Cluster 1 (Conventional)**: *(69 countries)*
  - **Representative Countries**: Brazil, China, Mexico, Turkey
  - **Renewable Share**: 15.8%
  - **Energy Productivity**: \$0.38/kWh
  - **Electricity Access**: 99.1%
  - **Energy Consumption**: 16,359 kWh/capita
- **Cluster 2 (Energy-Intensive)**: *(23 countries)*
  - **Representative Countries**: United States, Germany, Japan, Australia
  - **Renewable Share**: 7.7%
  - **Energy Productivity**: \$0.71/kWh
  - **Electricity Access**: 100%
  - **Energy Consumption**: 48,887 kWh/capita
- **Cluster 3 (Transitional)**: *(45 countries)*
  - **Representative Countries**: India, Nigeria, Pakistan, Bangladesh
  - **Renewable Share**: 60.2%
  - **Energy Productivity**: \$0.41/kWh
  - **Electricity Access**: 42.6%
  - **Energy Consumption**: 2,628 kWh/capita

Note: Cluster sizes sum to 150 countries total (13 + 69 + 23 + 45).

4.4.1 Correlation Matrix

4.5. Key Relationships

The analysis revealed three critical patterns:

- **Inverse RE-Development Relationship**: Highest renewable shares in lowest-access countries (ρ = -0.62)
- **Energy Productivity Paradox**: Developed nations show 10× lower renewable adoption than High-RE countries
- **Transition Potential**: Moderate development correlates with renewable penetration (Cluster 3)

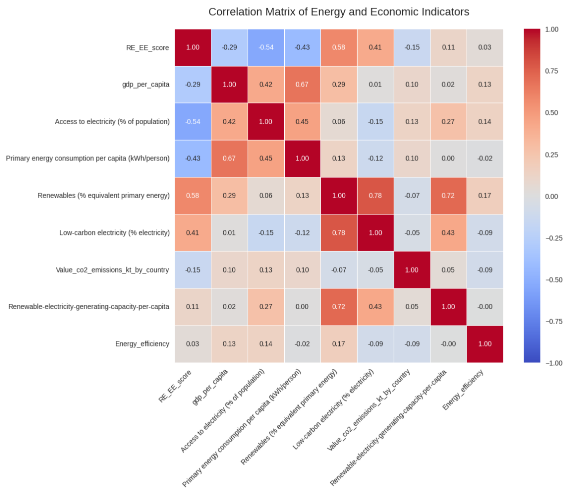

Figure 10. Correlation matrix of key energy and economic indicators

4.6. Cluster 3: Case Studies { National Energy Transition Pathways

4.6.1 Case Study I – Sri Lanka: Renewable Ambition within a Tropical Island Economy

Greenhouse Gas Emissions Target: Sri Lanka aims to reduce greenhouse gas emissions by 14.5% by 2030, comprising a 4% unconditional reduction and a 10.5% conditional reduction under international support [5, 6].

Renewable Energy Transition: The country has legislated policies to achieve 70% renewable electricity generation by 2030, focusing primarily on solar, wind, and small hydropower projects. Recent laws passed in 2024 aim to unlock $12 billion in private and international investment in renewable infrastructure [7].

Net-Zero Commitment: Sri Lanka has pledged to achieve net-zero carbon emissions by 2050, aligning with global decarbonization objectives [**?**].

Subnational and Geographic Context: As a tropical island nation, Sri Lanka possesses strong solar irradiance and coastal wind potential. However, grid limitations in the northern and eastern provinces, along with seasonal monsoon variability, pose challenges for consistent renewable deployment. The Central Highlands offer potential for run-of-river hydro development, while the Northern Province is increasingly being targeted for solar mega-projects due to available land and favorable policy incentives.

4.6.2 Case Study II – South Sudan: Climate Strategy through Forestry and Emissions Sequestration

Greenhouse Gas Emissions Target: South Sudan commits to reducing 109.87 MtCOe and sequestering an additional 45.06 MtCOe by 2030 through land-use change and sustainable forestry management [8, 9].

Land Use and Forest Conservation: The country aims to designate 20% of its natural forests as reserves to mitigate deforestation and enhance carbon sinks [10].

High Synergy Score Potential: While current renewable capacity is limited, South Sudan demonstrates high synergy potential between climate goals and development co-benefits, especially in forestry, carbon sequestration, and rural energy access.

Subnational and Geographic Context: South Sudan's expansive natural forest cover in regions such as the Equatoria states offers significant carbon sink potential. However, infrastructural underdevelopment and internal displacement continue to affect land governance and energy deployment. The Nile basin areas provide theoretical potential for hydropower development, though political and technical constraints persist.

5. Conclusion

5.1. Key Findings

Our analysis reveals four distinct energy transition archetypes among the 150 countries studied, each presenting unique challenges and opportunities for achieving SDG7 targets.

Three critical patterns emerge from our analysis:

- **Inverse Development-Renewables Relationship**: We observe a strong negative correlation ($\rho = -0.62$, $p < 0.001$) between development level and renewable energy adoption
- **Efficiency Paradox**: Energy-intensive developed nations show $10\times$ lower renewable penetration than high-RE developing countries
- **Transition Potential**: The transitional cluster demonstrates that moderate renewable integration during electrification is achievable

5.2. Limitations

Our study has several important constraints:

- Limited to national-level aggregation without subnational analysis
- Excludes temporal dynamics of cluster transitions
- Does not account for geopolitical constraints
- Omits detailed policy analysis

5.3. Future Research Directions

To address these limitations and extend our findings, we propose:

5.4. Implementation Pathways

Our findings suggest tailored approaches for each archetype leveraging existing renewable experience to expand access

Table 5. Future Research Priorities

Focus Area	Research Questions
Transition Modeling	Can Cluster 3's pathway scale without replicating Cluster 2's energy intensity?
Sectoral Analysis	Which economic sectors drive the observed cluster patterns?
Energy Justice	How do affordability and participation vary across clusters?

through policy-based and geographic systems.

These pathways, combined with deeper analysis of geographic, temporal and policy dimensions, can accelerate progress toward SDG7's targets of universal access to sustainable energy.

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