SYMBIOSIS SCHOOL FOR ONLINE AND DIGITAL LEARNING

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A Project on "**Impact of Renewable Energy on Reducing Energy Inequality**"

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Master of Business Administration
Batch July 2023

Student Declaration

I, Vishwas Khandelwal, hereby declare that the report entitled "**Impact of Renewable Energy on Reducing Energy Inequality**" at "Symbiosis School for Online and Digital Learning (SSODL)" in partial fulfillment of the requirement of the award of the **"MBA in (Business Analytics)"** is my original work.

The findings in this project are based on data collected by me and I have not copied from any other student or any other source. This report has not been submitted by me elsewhere.

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ABSTRACT

Energy inequality continues to be a major impediment to achieving equitable access to electricity, with most pronounced disparity between urban and rural areas. Renewable energy is often considered as one viable solution, although its impact on addressing the energy gap between rural and urban remains questionable due to infrastructure inadequacies, policy failures, or uneven distribution. This study systematically scrutinizes the role of renewable energy in addressing the urban-rural gap on electrification through a review of global and regional datasets deriving from UNSDG datasets (2010-2020). It combines correlation analysis and ordinary least-squares regression to assess whether an increase in the share of renewable energy in total final energy consumption has been significant in addressing electricity disparities between rural and urban areas. The findings of the research indicate that while renewable energy expansion correlates with improved electricity access globally, its effect on energy disparity varies across regions. Hydropower was found to account for the highest share of renewable energy in terms of financial investments and capacity per capita.

Keywords: Energy inequality; Renewable Energy; Urban-Rural Electrification; Electricity access Disparity; Regression Analysis

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INTRODUCTION

Background and Motivation

The move to renewable energy is viewed widely as an important step towards sustainability and climate change mitigation. However, while there has been plenty of literature and discussion lately around renewable energy that has dealt with environmental benefits, its capacity to address energy inequality is now an area of growing concern. Energy inequality means nothing but the disparities of access to modern energy services, affordability, and infrastructure development across different socio-economic groups and regions (*Volodzkiene L & Streimikiene D. 2024*). Renewables, provided that they are deployed optimally, could help lessen the inequalities by making decentralized and affordable energy sources available to rural and underserved communities. (*KK Sen et al. 2024*)

Problem Statement and Research Objective

Despite significant investments and policy efforts to increase renewable energy adoption, the extent to which it affects energy inequality remains unclear. While studies have highlighted that renewable energy can contribute to reducing income disparities and improving energy access (*Volodzkiene L & Streimikiene D. 2024*), concerns remain regarding uneven distribution and the urban-rural divide in Global electrification. (*Sun, Chenzhou et al. 2024*).

The research attempts to analyze the impact of renewable energy on energy inequality. By looking at global and regional trends, the research addresses whether a larger proportion of renewable energy in Total Final Energy Consumption (TFEC) achieved equal electricity access, specifically bridging the urban-rural divide.

Relevance and Research Gap

Previous studies have primarily focused on the environmental and economic benefits of renewable energy but have not extensively examined its direct relationship with energy inequality (*KK Sen et al. 2024*). Many previous studies remain confined to high-income or specific developing nations, lacking a holistic global and regional perspective (*Volodzkiene L & Streimikiene D. 2024*). Additionally, while policy recommendations are being made, very few recent studies have shown the linkage of renewable energy share with measurable reductions in energy disparity across multiple regions. This study fills these gaps by providing a data-driven evaluation of the role of renewables in energy equality. Although there is substantial literature linking renewable energy to economic growth, few studies have quantitatively assessed its direct impact on reducing energy disparities (urban-rural divide). Many discussions remain theoretical, with limited empirical validation (*Emami Meybodi et al. 2024)* This study aims to bridge these gaps by doing regression-based analyses on a global and regional scale.

LITERATURE REVIEW

Energy inequality remains a major global issue, defined by disparities in electricity access across different geographic, economic, and demographic groups (*Volodzkiene L & Streimikiene D. 2024*). Access to electricity is widely recognized as a fundamental driver of economic and social development, yet millions of people, particularly in rural and low-income regions, remain without reliable energy sources. While urban areas benefit from advanced energy infrastructure and investments, rural areas often face barriers such as high transmission costs, lack of electrification projects, and limited financial access. These disparities contribute to energy poverty, restricting economic opportunities, education, and healthcare services in underserved regions (*Volodzkiene L & Streimikiene, D. 2023*).

The transition toward renewable energy sources has been identified as a potential solution to bridging the electricity access gap, particularly in rural areas where traditional grid expansion is not economically viable (*Jawad Abbas et al. 2023*). Decentralized renewable energy systems, such as solar microgrids and small-scale wind farms, have been deployed in regions with limited grid connectivity, offering an alternative path to electrification. Studies indicate that countries with a higher share of renewables in Total Final Energy Consumption (TFEC) tend to experience improved electricity access overall (*Daniel Adu et al. 2024*). But, the extent to which renewable energy adoption contributes to reducing energy inequality remains uncertain, with varying outcomes across different regions (*Sun, Chenzhou et al. 2024*).

Empirical research analyzing the relationship between renewable energy penetration and urban-rural energy disparities has produced mixed results. While some studies indicate a positive correlation between renewable energy expansion and electricity access improvement (*Mehmood U et al. 2022*), others highlight that renewable adoption has not necessarily translated into equitable energy distribution (*Erna Farina Mohamed et al. 2024*). In some cases, renewable energy investments have been concentrated in urban and industrial areas, reinforcing existing inequalities rather than alleviating them (*Leire Urkidi Azkarraga et al. 2024*). These findings suggest that while renewable energy may increase overall electricity generation, its direct role in reducing disparities in access requires further investigation.

Regional disparities in renewable energy effectiveness have also been widely discussed in the literature. While Europe and Eastern Asia have demonstrated successful renewable energy integration with improved energy access across urban and rural areas, regions such as Sub-

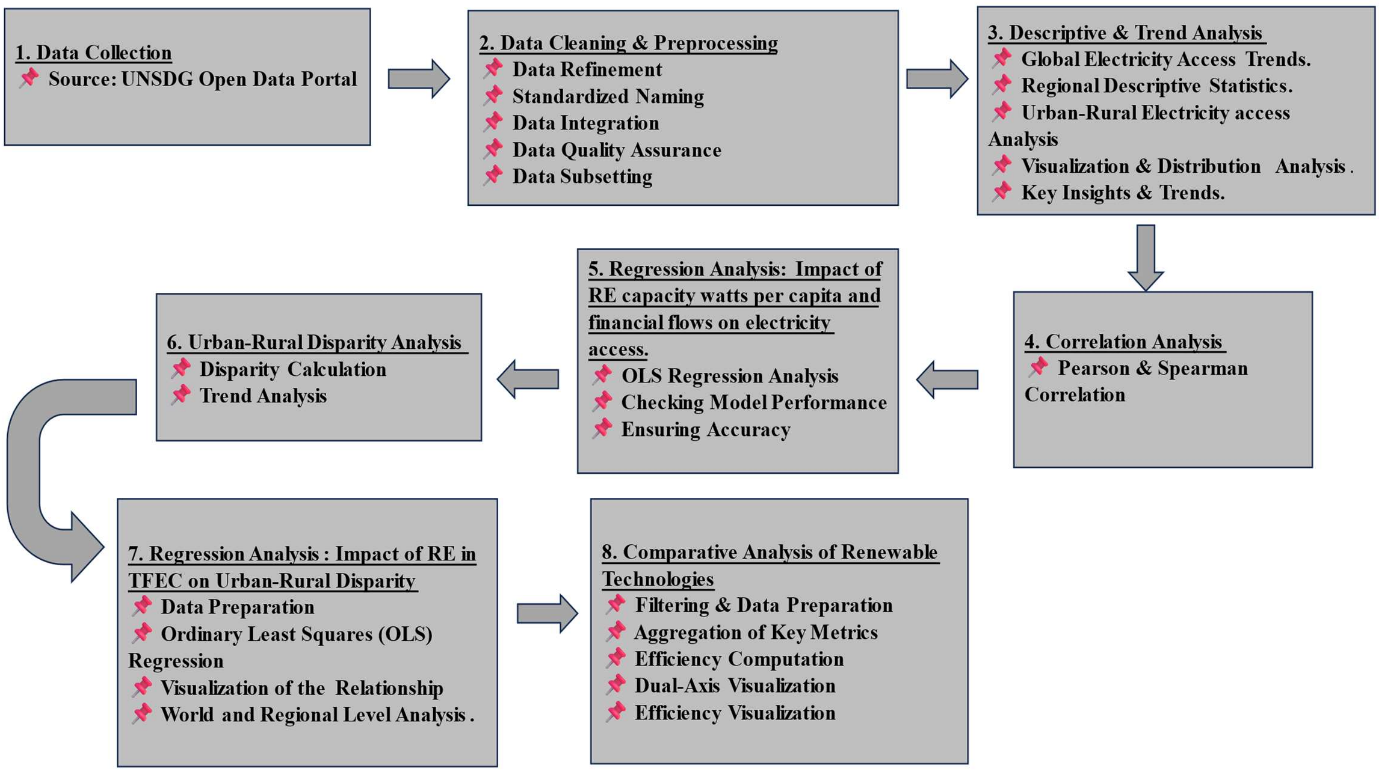
Sub Saharan Africa and South Asia continue to experience high energy inequality despite renewable energy investments (*Emami Meybodi et al. 2024)*. Some researchers argue that differences in infrastructure development, energy policies, and economic factors contribute to these variations. However, a direct, data-driven analysis of how increasing renewable energy share in TFEC impacts energy disparities remains limited in existing research, highlighting the need for further empirical investigation.

This study builds on the existing literature by conducting regression-based analyses to examine whether an increase in renewable energy share in TFEC correlates with reductions in urban-rural electricity access disparities. By evaluating global and regional trends, this research seeks to provide empirical insights into the extent to which renewable energy plays a role in addressing energy inequality or energy disparity.

RESEARCH METHODOLOGY

This section outlines the data sources, statistical models, analytical tools, and frameworks used in the study to assess the impact of renewable energy on reducing energy inequality. The methodology ensures a structured and data-driven approach to examine the relationship between renewable energy share in Total Final Energy Consumption (TFEC) and disparities (Rural- Urban Divide) in electricity access.

RESEARCH DESIGN



Data Collection

The source of the dataset used in this research is the open-access UNSDG datasets website, Dataset used are under Goal 7 (Affordable and Clean Energy). The key datasets used are:

1. Proportion of Population with Access to Electricity (7.1.1): It represents the percentage of the total population with access to electricity, including urban and rural breakdowns.

2. Renewable Energy Share in Total Final Energy Consumption (TFEC) (7.2.1): It represents the proportion of renewable energy in the total final energy consumption of a country or region.
3. International Financial Flows to Developing Countries for Clean Energy (USD) (7.a.1): It represents financial investments and support directed towards clean energy research, development, and production.
4. Installed Renewable Energy-Generating Capacity (7.b.1): Measures the renewable energy capacity per capita (watts per person) of a country or a region.

The **Renewable Energy Share in Total Final Energy Consumption (TFEC)** is the proportion of renewable energy used in a country's or region's total energy consumption. It shows the extent to which clean energy sources like solar, wind, hydro, and bioenergy are integrated into the overall energy mix. A higher TFEC share indicates a stronger transition toward sustainable energy and reduced reliance on fossil fuels and traditional sources of energy.

The **Installed Renewable Energy-Generating Capacity** measures the per capita availability of renewable energy infrastructure in watts. This highlights potential for clean energy generation but does not necessarily indicate actual energy consumption. While higher installed capacity suggests better infrastructure, it does not always ensure equitable energy distribution or access.

For analyzing **rural-urban energy disparity**, Renewable energy in TFEC is more relevant as it measures actual energy **consumption** rather than just availability. It helps assess whether renewable energy is effectively reducing electrification gaps between rural and urban areas. A higher TFEC share suggests that renewables are not only just installed but also actively contributing to rural electrification, making energy access more equitable.

Data Cleaning and Preprocessing

The dataset was refined by removing redundant and irrelevant columns, ensuring cleaner data. Column names were standardized for consistency and readability. Four separate CSV files were merged into a single dataset. It was followed by data quality checks to identify and handle missing or duplicate values. Countries and regions that were not needed were excluded. Only the relevant regions and overall world data were selected for analysis.

Analytical Framework

In order to have conclusive results about the impact of renewable energy adoption and energy disparities, a combination of statistical techniques was employed. These methods enabled the study to measure associations, quantify disparities, and determine causal relationships between renewable energy indicators and electricity access. The primary statistical tools used included Correlation analysis and Ordinary Least Squares (OLS) regression. Each method was selected based on its ability to address specific aspects of the research question, ultimately ensuring a comprehensive analysis of the impact of renewable energy on reducing energy disparities.

Correlation Analysis

Correlation analysis is a statistical method used to measure the strength and direction of the relationship between two continuous variables. In this study, correlation analysis was conducted to determine the extent to which renewable energy capacity, financial investments, and electricity access are correlated. This study utilized Pearson's correlation coefficient and Spearman's rank correlation coefficient to capture both linear and non-linear associations between variables.

In the research, **Pearson correlation** was used to check the strength of relationships between renewable capacity per capita, financial flows to clean energy and electricity access. A high positive correlation would indicate that an increase in renewable energy deployment corresponds to improved electricity access, given that electricity access and renewable energy indicators exhibit continuous trends.

However, financial flows to clean energy and electricity access may not always have a strict linear relationship, as investments may take time to showcase their impact into increased electricity access, or external policy and infrastructure factors may also play their role. Therefore, **Spearman's correlation** was also used to capture monotonic relationships (A monotonic function is one that either never increases or never decreases as its independent variable increases), which may not be perfectly linear but still indicate a directional trend. Its interpretation is similar to that of Pearson's, e.g. the closer it is to +1 the stronger the monotonic relationship, unlike Pearson's correlation, there is no requirement of normality and hence it is a nonparametric statistic.

The results of the Correlation analysis provided an initial assessment of how strongly these factors were related. But correlation does not imply causation, which necessitated further examination using regression analysis.

Ordinary Least Squares (OLS) Regression

The most commonly used method used for regression analysis is called ordinary least squares (OLS). It provides a systematic approach to fitting a line that best represents the relationship between the independent variables and the dependent variable by minimizing the sum of the squared residuals. Before applying OLS regression, a multicollinearity test was also done to examine whether our independent variables were highly correlated or not. To detect and address multicollinearity, we employ the **Variance Inflation Factor (VIF).** A VIF value greater than 5 suggests the presence of moderate multicollinearity, with higher values indicating stronger multicollinearity. Since in the analysis all independent variables have a VIF < 5 (VIF ~ 1), we can confidently proceed with Ordinary Least Squares (OLS) regression without worrying about multicollinearity.

OLS Regression was used to evaluate the impact of renewable capacity watts per capita and financial flows to clean energy on electricity access. The dependent variable in the regression model was electricity access percentage, while the independent variables were renewable energy capacity per capita and financial flows towards clean energy in USD. The estimated regression equation was as follows:

$$Electricity\ Access\ (\%) = \beta_0 + \beta_1(Renewable\ Capacity\ Per\ Capita) + \beta_2(Financial\ Flows\ to\ Clean\ Energy) + \epsilon$$

where β_0 is the intercept, β_1 and β_2 the estimated coefficients, and ϵ is the error term.

The key statistical indicators evaluated in the OLS regression included **R-squared (R^2), p-values, and regression coefficients**.

Urban-Rural Disparity Analysis

In this research, we have defined energy inequality as the gap in electricity access between urban and rural areas. To quantify this gap, disparity analysis was conducted using the difference between urban and rural electricity access percentages. This metric was defined as:

$$Disparity = Electricity\ Access\ (Urban) - Electricity\ Access\ (Rural)$$

Trend analysis was performed to observe how the disparity evolved over time across different regions and for the world. Additionally, regression analysis was applied to assess whether increasing renewable energy in total final energy consumption contributed to reducing this disparity. The independent variable in this model was renewable share in total final energy consumption (TFEC), while the dependent variable was the urban-rural disparity percentage. The findings from this analysis provided insights into whether renewable energy in total final energy consumption had an impact on reducing Energy Disparity.

$$Disparity = \beta_0 + \beta_1(Renewable\ Energy\ Share\ in\ TFEC) + \epsilon$$

where β_0 is the intercept, β_1 and β_2 the estimated coefficients, and ϵ is the error term.

The same technique was applied to see the cases of different regions like South East Asia, Europe, Sub Saharan Africa etc.

Comparative Analysis of Renewable Technologies

The study also examined the relative efficiency of different renewable energy technologies, including solar, wind, hydropower, and bioenergy, in terms of financial investment and capacity generation. A comparative analysis was conducted to determine which technologies provided the highest capacity per unit of financial investment.

For this analysis, financial flows and renewable capacity per capita were aggregated by renewable technology type. The efficiency of each technology was calculated using the metric:

$$Efficiency\left(\frac{Watts}{USD}\right) = \frac{Average\ Renewable\ Capacity\ Per\ Capita\ (Watts)}{Average\ Financial\ Flows\ (USD)}$$

This allowed for an assessment of which renewable technologies were the most cost-effective in reducing energy inequality, providing empirical evidence for prioritizing investments in specific technologies.

Software and Tools Used

- Programming Language and Libraries used: Python (pandas, NumPy, statsmodels, matplotlib, seaborn)
- Visualization Tools: Matplotlib, Seaborn (for correlation heatmaps, trend analysis, and disparity analysis)
- Research Design Implementation: Python (Jupyter Notebooks) was used for Data preprocessing, statistical modeling, and visualization.

Limitations of the Study

- The research considers urban-rural electricity access disparity as a measure of energy inequality, which may not reflect other aspects like affordability or quality of energy. Energy inequality is characterized by an uneven distribution of access to energy resources. It is important to recognize that the term energy inequality is often associated with the concept of (in)security as this issue is an integral part of the broader concept of energy justice (*Volodzkiene L, Streimikiene D, 2024*). However, our research strictly focuses on urban-rural electricity access disparity as a measure of energy inequality.

- The analysis relies on regional and country-level data. More detailed, disaggregated data could provide deeper insights but was unavailable. Although, the research focuses on data from 2010 to 2022, providing a comprehensive analysis of trends and relationships over this period. Regions of interest are Eastern Asia, Europe, South-Eastern Asia, Southern Asia, Sub-Saharan Africa, Western Asia, along with the overall World data.
- The research applies OLS regression and correlation analysis. Advanced techniques like time-series modeling, panel regression, Long Short-Term Memory (LSTM) models might offer a more comprehensive understanding.
- Research does not consider the varied energy policies and infrastructure that existed all around the world. Implementation strategies across regions could significantly influence the observed trends in energy inequality and renewable energy adoption.
- The focus is solely on renewable energy, excluding the impact of traditional energy sources.

RESULTS AND ANALYSIS

Descriptive Statistics:

Global Trends

Descriptive statistics was observed for a comprehensive summary of global trends in electricity access, renewable capacity per capita, renewable share in total final energy consumption (TFEC), and financial flows to clean energy from 2010 to 2022. The table below outlines key statistics for each variable:

Metric	Electricity Access (%)	Renewable Capacity (Watts/Capita)	Renewable Share in TFEC (%)	Financial Flows (USD)
Count	13	13	13	13
Mean	87.92	279.30	17.21	15,359.47
Standard Deviation	2.69	79.38	1.04	5,243.12
Minimum	83.60	175.34	16.01	10,085.08
25th Percentile (Q1)	85.80	216.20	16.52	12,329.42
Median (Q2)	88.20	268.46	16.91	12,825.86
75th Percentile (Q3)	90.20	328.54	17.69	17,680.26
Maximum	91.40	424.14	19.05	28,454.13

Table 1

Key Observations (Table 1):

Electricity Access:
Global electricity access exhibited a consistent trend, with an average of 87.92% across the observed years. The low variability (standard deviation = 2.69%) reflects steady progress toward universal access.

Renewable Capacity per Capita:
Significant variability was observed in renewable capacity, ranging from 175.34 to 424.14 watts per capita, with a mean of 279.30 watts. This indicates uneven adoption and growth of renewable energy infrastructure worldwide.

Renewable Share in TFEC:
Renewable energy contributed an average of 17.21% to global total final energy consumption (TFEC) since 2010. The narrow range (16.01% to 19.05%) suggests moderate progress in increasing renewable energy's share in the global energy mix.

Financial Flows to Clean Energy:

Financial flows to clean energy varied significantly, with the maximum investment peaking at $28,454 million USD in certain years. This variability highlights the inconsistent nature of global investments in clean energy projects.

Regional Trends

Descriptive statistics was observed for a comprehensive summary of regional trends in electricity access, renewable capacity per capita, renewable share in total final energy consumption (TFEC), and financial flows to clean energy from 2010 to 2022. The data was observed for the following regions: Eastern Asia, Europe, South-Eastern Asia, Southern Asia, Sub-Saharan Africa, Western Asia. The table below outlines key statistics for each variable:

Metric	Electricity Access (%)	Renewable Capacity (Watts/Capita)	Renewable Share in TFEC (%)	Financial Flows (USD)
Count	104	104	104	104
Mean	88.51	253.75	25.05	1,405.04
Standard Deviation	18.61	262.81	19.28	1,545.16
Minimum	33.20	23.65	3.44	47.10
25th Percentile (Q1)	89.20	59.98	11.88	329.68
Median (Q2)	96.25	129.76	18.73	892.37
75th Percentile (Q3)	99.38	386.43	31.38	1,959.17
Maximum	100.00	1,025.53	70.88	9,872.53

Table 2

Key Observations (Table 2):

Electricity Access:

The median electricity access is 96.25%, but the data shows high variability. Some regions have near-universal access, while others lag significantly behind, with access as low as 33.20%. This indicates stark disparities in electricity access across the regions mentioned.

Renewable Capacity Per Capita (Watts):

The average renewable capacity per capita is 253.75 watts, with values ranging from 23.65 to over 1,025.53 watts. The distribution is skewed, reflecting a few regions with significantly high renewable capacities, while others remaining far below average.

Renewable Share in TFEC:

The average renewable energy share in total final energy consumption (TFEC) is 25.05%. However, there are major disparities, with values ranging from 3.44% to 70.88%, which indicates an uneven integration of renewable energy across regions.

Financial Flows for Clean Energy:

Financial flows for clean energy vary significantly, with an average of 1,405.04 USD. While some regions receive as little as 47.10 USD, others benefit from financial flows nearing 10,000 USD, likely due to differences in resource availability and level of development.

Urban- Rural Electricity Access Analysis:

Global Trends (Figure 1)

Key Observations:

Urban electricity access has consistently remained higher than rural access globally.

Urban Access: 95.9% in 2010, improving to 97.7% in 2022.

Rural Access: 72.9% in 2010, improving to 84% in 2022.

Insight:

The gap between rural and urban areas has narrowed but rural areas still face significant challenges in achieving universal electricity access globally.

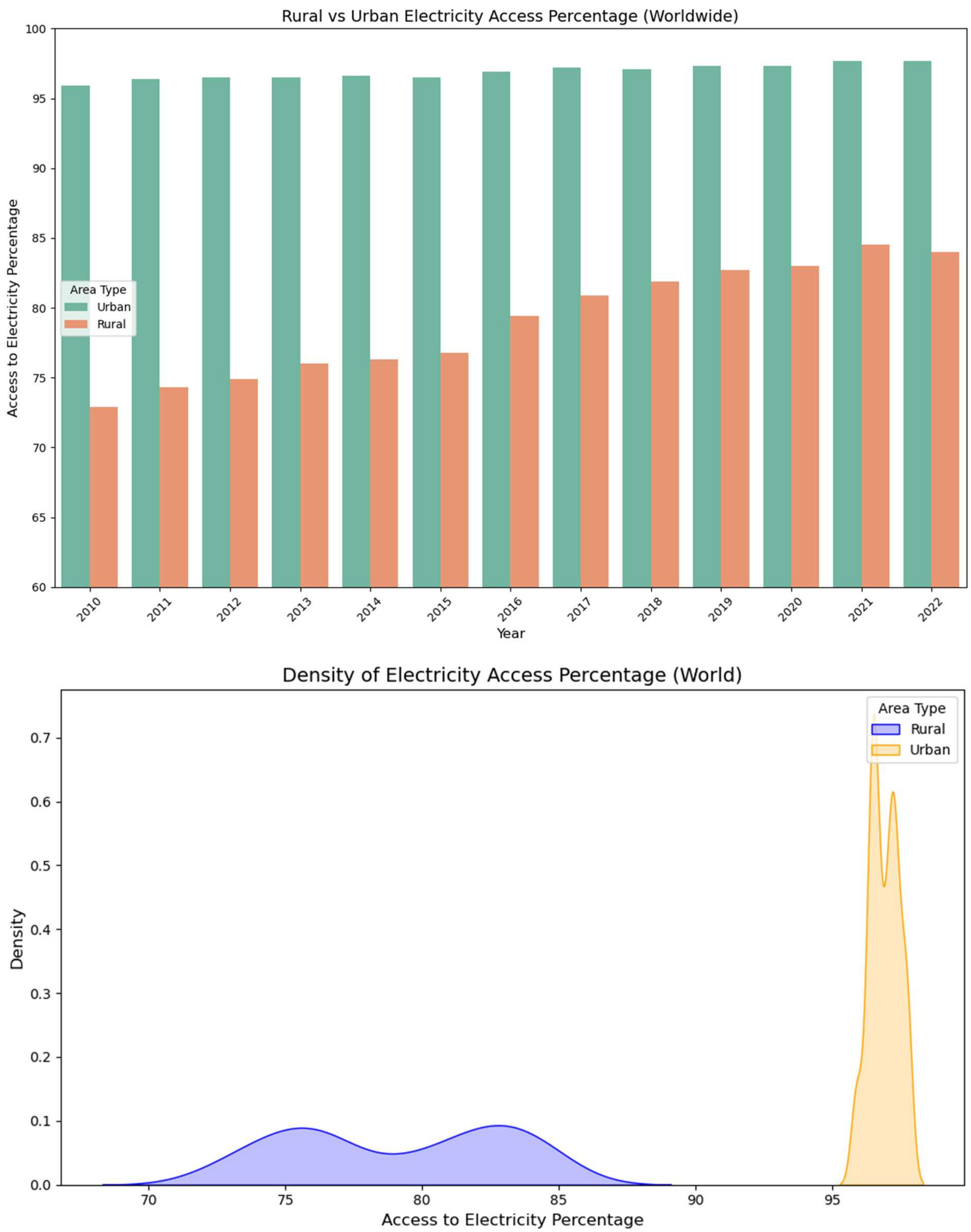

Rural vs Urban Electricity Access Percentage (Worldwide)
Access to Electricity Percentage
Year
Area Type
Urban
Rural
100
95
90
85
80
75
70
65
60
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
Density of Electricity Access Percentage (World)
Density
Access to Electricity Percentage
Area Type
Rural
Urban
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
70
75
80
85
90
95

Figure 1

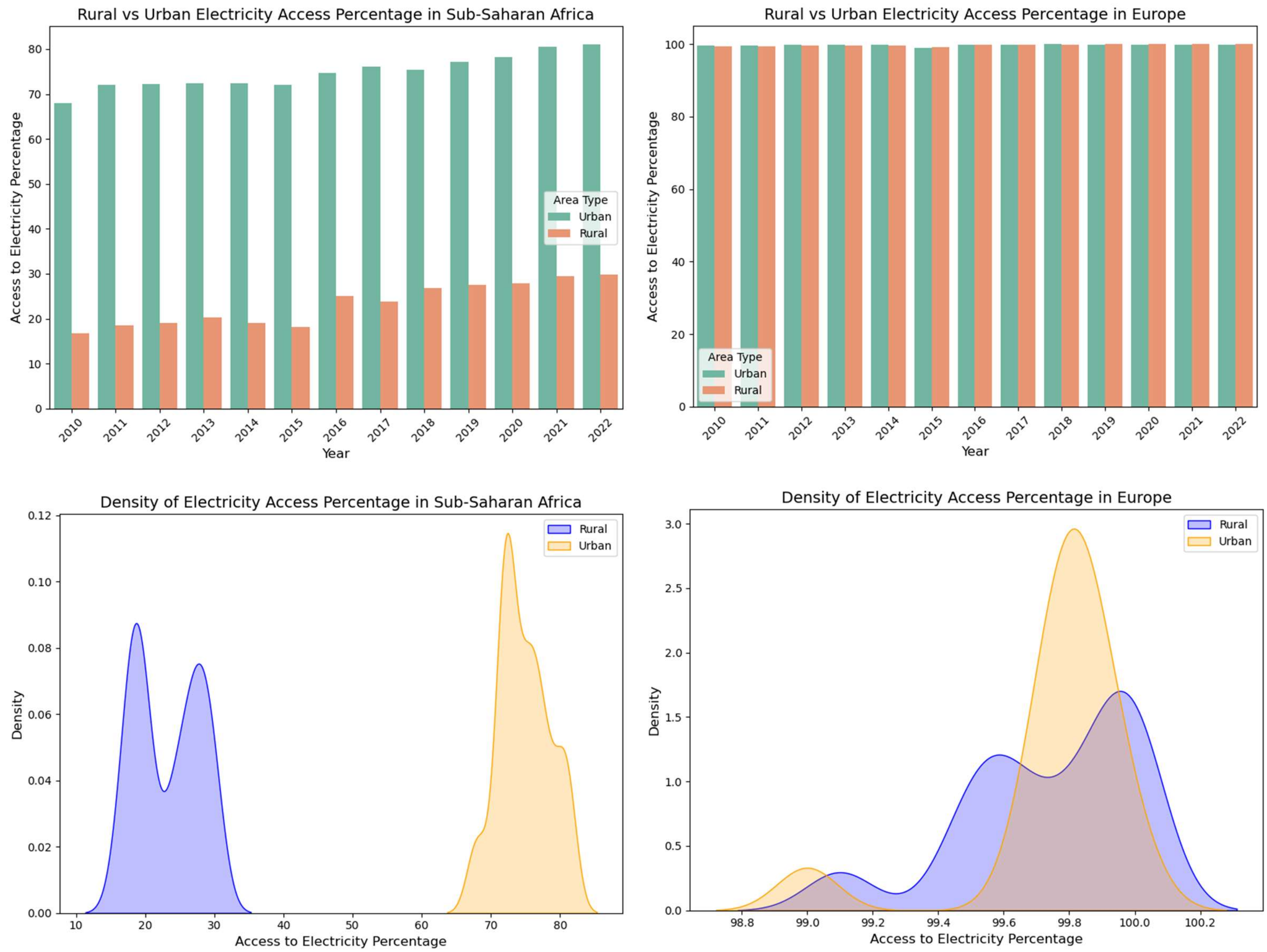


Figure 2

We observed and plotted the urban and rural electricity access over time for each of the following regions: Eastern Asia, Europe, South-Eastern Asia, Southern Asia, Sub-Saharan Africa, Western Asia. The aim was to assess the evolution of electricity access between urban and rural areas across these diverse regions.

Regional Trends (Figure 2)

Eastern Asia - Both rural and urban areas maintained near 100% electricity access throughout the period.

Europe - Both rural and urban areas maintained near 100% electricity access throughout the period.

South-Eastern Asia - Rural electricity access showed a significant improvement from around 80% in 2010 to nearly 94% by 2022, while urban access remained consistently high between 98% and 99% throughout the period.

Southern Asia - Rural electricity access was at ~ 67% in 2010 and improved significantly to around 98% by 2022, while urban access remained consistently high at nearly 95% throughout the period and improved from 94% to ~ 100 % by 2022 throughout the period.

Sub-Saharan Africa - Rural electricity access has stagnated between 15% and 30% over the years, while urban access saw an improvement from around 65% in 2010 to nearly 80% in 2022. It is the region with the largest rural-urban gap in electricity access which still persists.

Western Asia - Rural electricity access was at ~ 84% in 2010 and improved steadily to around 88% by 2022, whereas urban access remained consistently high at nearly 99% throughout the period.

Insights from Figure 3:

Electricity Access Over Time (Worldwide)

The global electricity access has steadily improved from 2010 to 2022, rising from approximately 84% to over 91%. This steady growth reflects global efforts to enhance energy accessibility

Renewable Share in Total Final Energy Consumption

The renewable energy share in total final energy consumption increased from 16% in 2010 to 17.31% in 2019, peaking at 19% in 2020 before stabilizing around 18.7% by 2022.

Renewable Capacity Per Capita and Financial Flows

Renewable energy capacity per capita has shown continuous growth worldwide, rising from around 175 per capita watts in 2010 to over 400 watts in 2022. Financial flows towards clean energy have seen high volatility, with a massive peak in 2016 and a notable dip in 2019 and 2020.

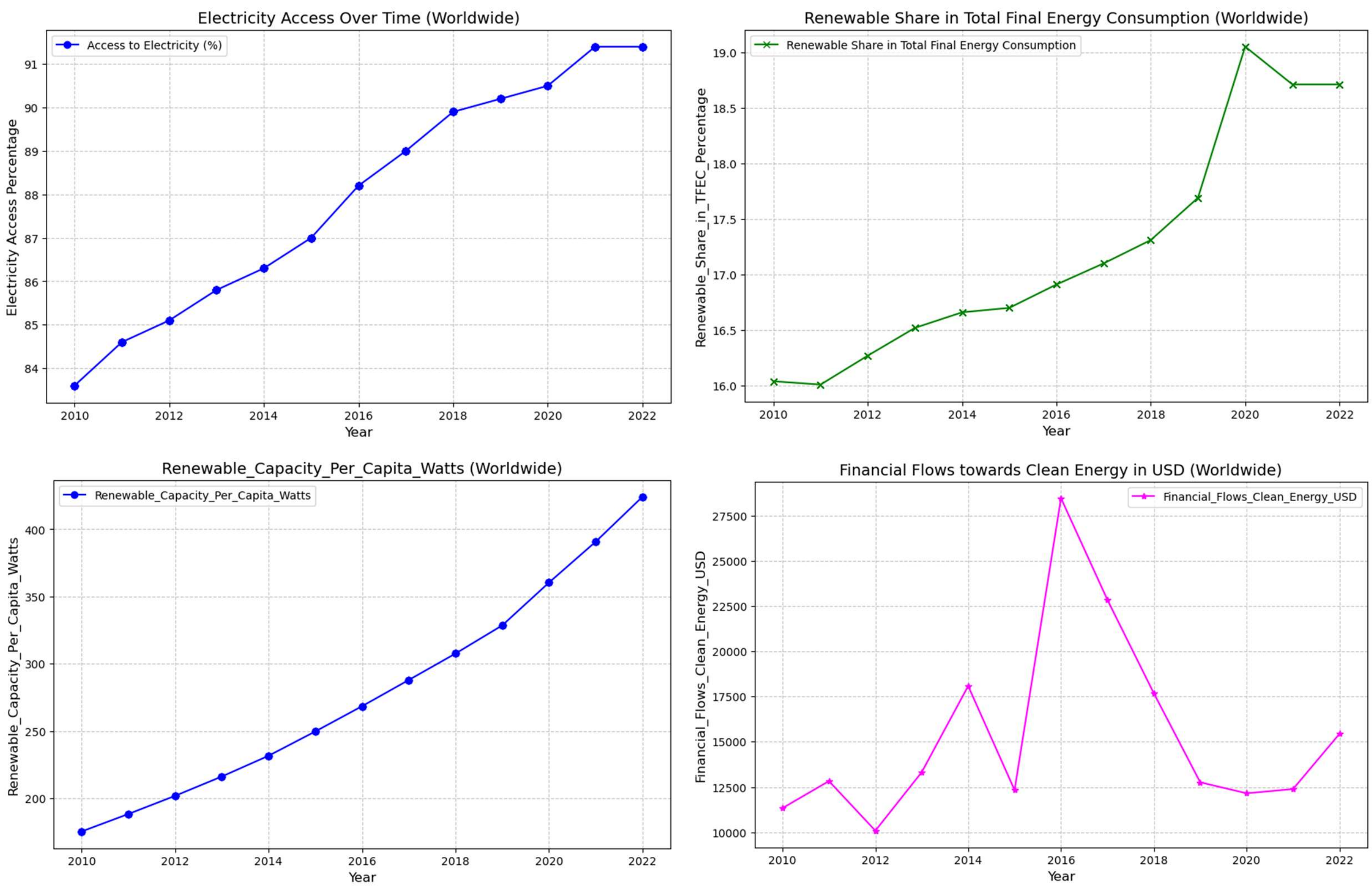


Figure 3

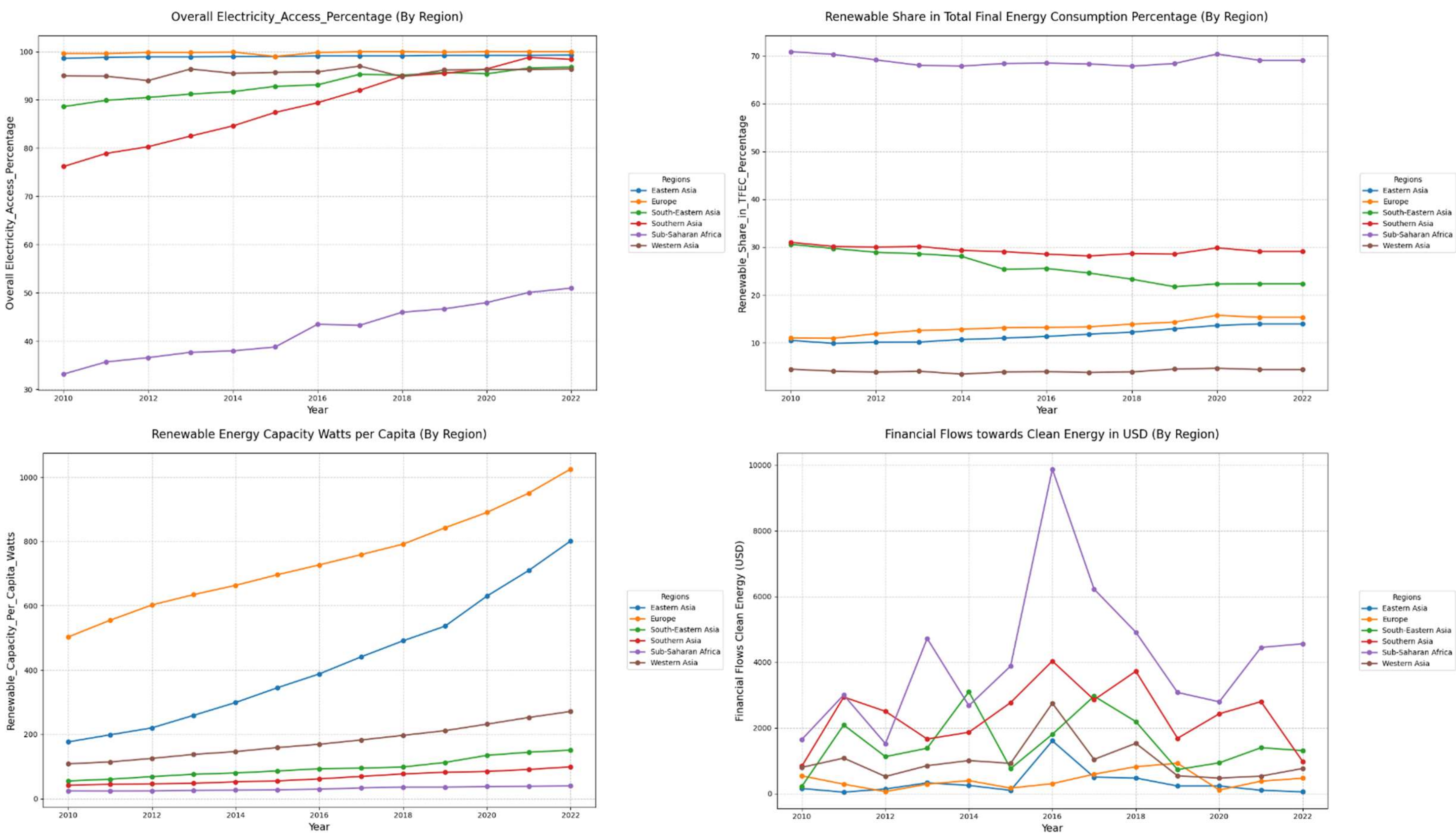


Figure 4

<u>Insights from Figure 4:</u>

Overall Electricity Access Percentage (By Region)

Regions like Eastern Asia, Europe, and South-Eastern Asia have achieved near universal electricity access ~100% over the observed period. Southern Asia made substantial progress, increasing from around 76% in 2010 to almost 98% by 2022. Sub Saharan Africa is one region where electricity access crossed 50% just recently (2020), from approximately 30% in 2010 to around 51% in 2022, indicating a grave issue.

Renewable Share in Total Final Energy Consumption (By Region)

Sub-Saharan Africa stands out with the highest renewable energy share (~70%), mainly due to its reliance on traditional renewable sources. Southern and South-Eastern Asia showcases moderate renewable shares (~30%), while Western Asia and Europe maintain lower shares in the range of 10–15%.

Renewable Energy Capacity Per Capita (By Region)

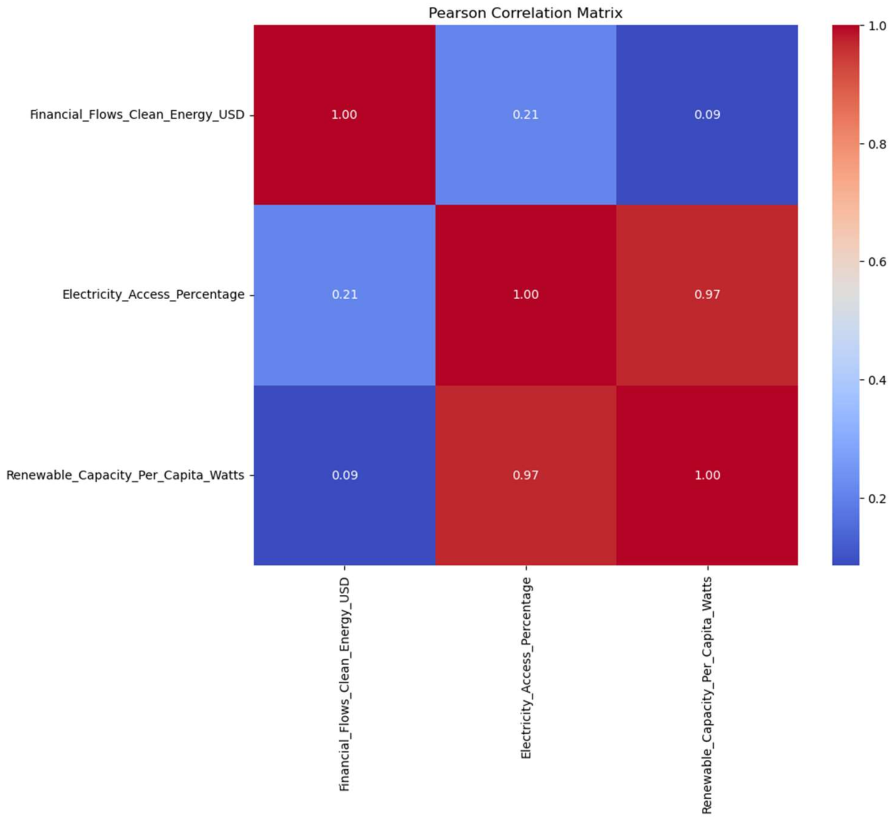
Europe leads in renewable capacity, surpassing 1000 watts per capita by 2022. It reflects Europe's strong investment and infrastructure. Eastern Asia also demonstrates substantial growth, reaching approximately 800 watts per capita by 2022. In contrast, Sub-Saharan Africa show minimal growth and remain at the lowest levels of renewable capacity per capita ~ 40% by 2022, highlighting the need for increased investment and policy focus in the region.

Financial Flows Towards Clean Energy (By Region)

Sub-Saharan Africa leads in financial flows toward clean energy with a significant investment in 2016, followed by a significant decline and a partial recovery by 2022. Southern Asia shows consistent peaks with minor fluctuations after 2016, stabilizing by 2022. Regions such as Europe, Eastern Asia, and South-Eastern Asia exhibit modest but steady financial flows throughout the period. In contrast, Eastern Asia records the lowest level of financial investments, indicating limited focus on clean energy initiatives in that region.

The descriptive analysis established a baseline understanding of global and regional energy disparities, revealing patterns in electricity access, renewable capacity, and financial flows. It aligned with our goal by highlighting rural-urban gaps and regional differences. However, to move beyond patterns and explore relationships, we transitioned to correlation analysis.

<u>Correlation Analysis</u>


Pearson Correlation Matrix
Financial_Flows_Clean_Energy_USD
Electricity_Access_Percentage
Renewable_Capacity_Per_Capita_Watts
1.00
0.21
0.09
0.21
1.00
0.97
0.09
0.97
1.00
1.0
0.8
0.6
0.4
0.2

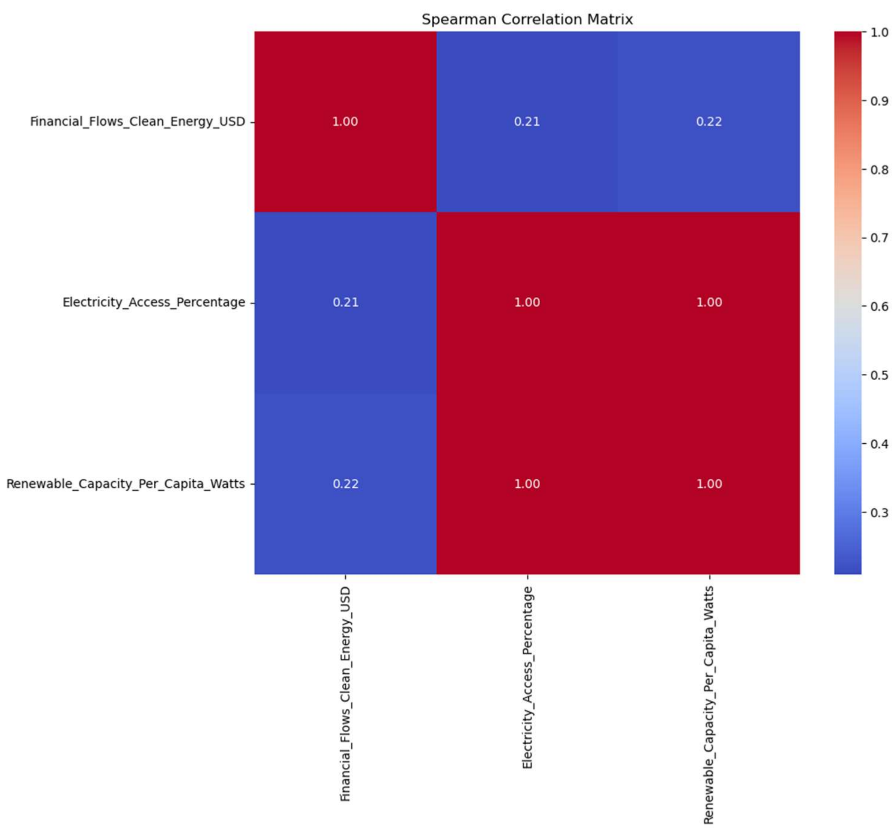

Spearman Correlation Matrix
Financial_Flows_Clean_Energy_USD
Electricity_Access_Percentage
Renewable_Capacity_Per_Capita_Watts
1.00
0.21
0.22
0.21
1.00
1.00
0.22
1.00
1.00
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3

Figure 5

Pearson Correlation Results (Figure 5)

- Electricity Access Percentage and Renewable Capacity Per Capita (Watts)
  - Correlation Coefficient: 0.97 (strong positive correlation)
- Financial Flows towards Clean Energy and Electricity Access Percentage
  - Correlation Coefficient: 0.21 (weak positive correlation)
- Financial Flows towards Clean Energy and Renewable Capacity Per Capita (Watts)
  - Correlation Coefficient: 0.09 (very weak positive correlation)

Spearman Correlation Results (Figure 5)

- Electricity Access Percentage and Renewable Capacity Per Capita (Watts)
  - Correlation Coefficient: 0.99 (near-perfect monotonic correlation)
- Financial Flows towards Clean Energy and Electricity Access Percentage
  - Correlation Coefficient: 0.21 (weak monotonic correlation)
- Financial Flows towards Clean Energy and Renewable Capacity Per Capita (Watts)
  - Correlation Coefficient: 0.22 (weak monotonic correlation)

The **strong correlation between renewable capacity per capita and electricity access highlights renewables as a key driver of energy equity**, emphasizing the need for expanded renewable infrastructure. However, **financial investments show weak correlations with both electricity access and renewable capacity**, suggesting inefficiencies in fund allocation and deployment. While these correlations provide valuable insights into the relationships between key variables, they do not establish causation.

The correlation analysis was an important step in identifying the strength and nature of relationships between key variables renewable capacity, electricity access, and financial flows. We know that Correlation is not Causation. To have a solid understanding and have deeper insights, we moved to regression techniques, specifically Ordinary Least Squares (OLS) regression.

Ordinary Least Squares (OLS) regression

VIF Test Results

The Variance Inflation Factor (VIF) test confirmed the absence of multicollinearity, ensuring that the predictors contribute independently to the regression model. The VIF values were as follows:

- Renewable Capacity Per Capita (Watts): 1.007
- Financial Flows to Clean Energy (USD): 1.007

Since both values are close to 1, multicollinearity was not a concern, allowing us to proceed with Ordinary Least Squares (OLS) regression.

OLS Regression Results for World Data

The OLS regression analyzed the impact of Renewable Capacity Per Capita (Watts) and Financial Flows to Clean Energy (USD) on Electricity Access Percentage.

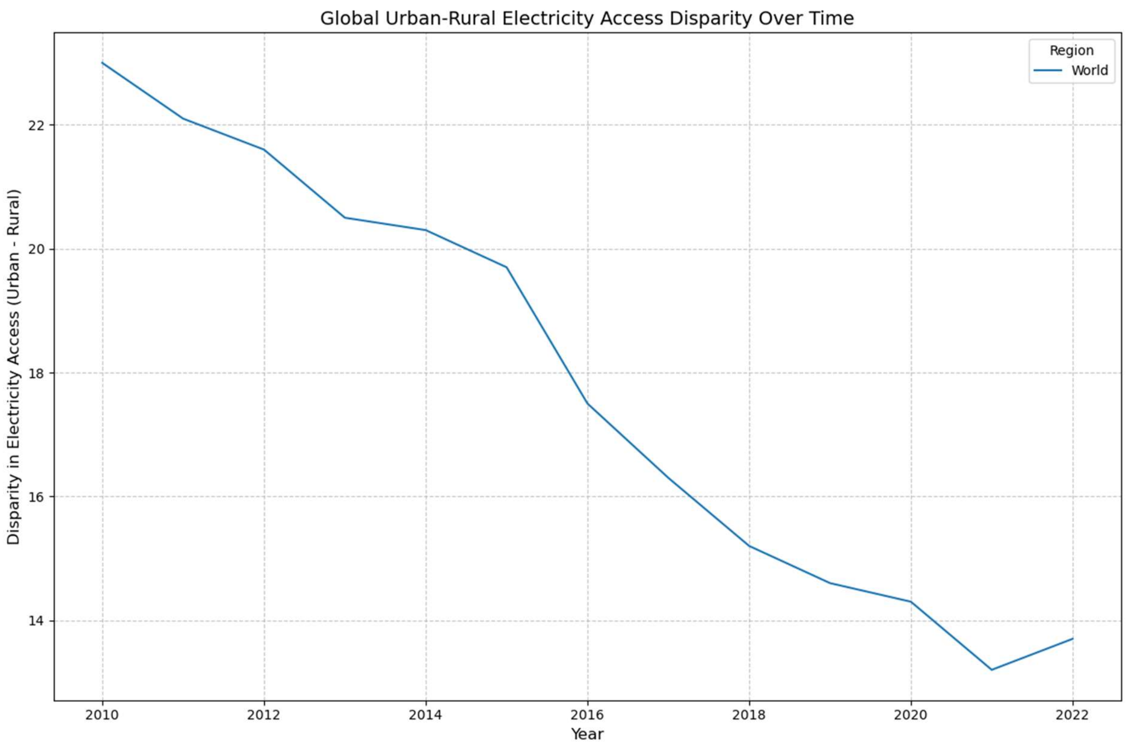
- $R^2 = 0.956$: The model explains 95.6% of the variance in electricity access.
- Adjusted $R^2 = 0.947$: Even after adjustment, the R^2 remains high.
- F-statistic = 107.4 ($p < 0.001$), p-value = 1.74e-07 (close to zero): Indicates that the overall model is statistically significant.

Coefficients:

- Renewable Capacity Per Capita (Watts): Coefficient = 0.0325, $p < 0.001$
- Financial Flows to Clean Energy (USD): Coefficient = 6.545e-05, $p = 0.086$

Before Moving to Disparity Analysis, we found out that **Renewable energy capacity has a statistically significant and strong positive impact on electricity access**. **Financial flows show no direct significant effect, suggesting that effective implementation of strategies is crucial.** The high R^2 value reflects the model's robustness. No multicollinearity issues were detected (VIF Results), confirming the stability of the model. Our goal was to quantify and test the impact of renewable energy on electricity access globally, which OLS was successful in. With the findings established, we moved to the disparity analysis to explore the urban-rural divide in electricity access.

Disparity Analysis



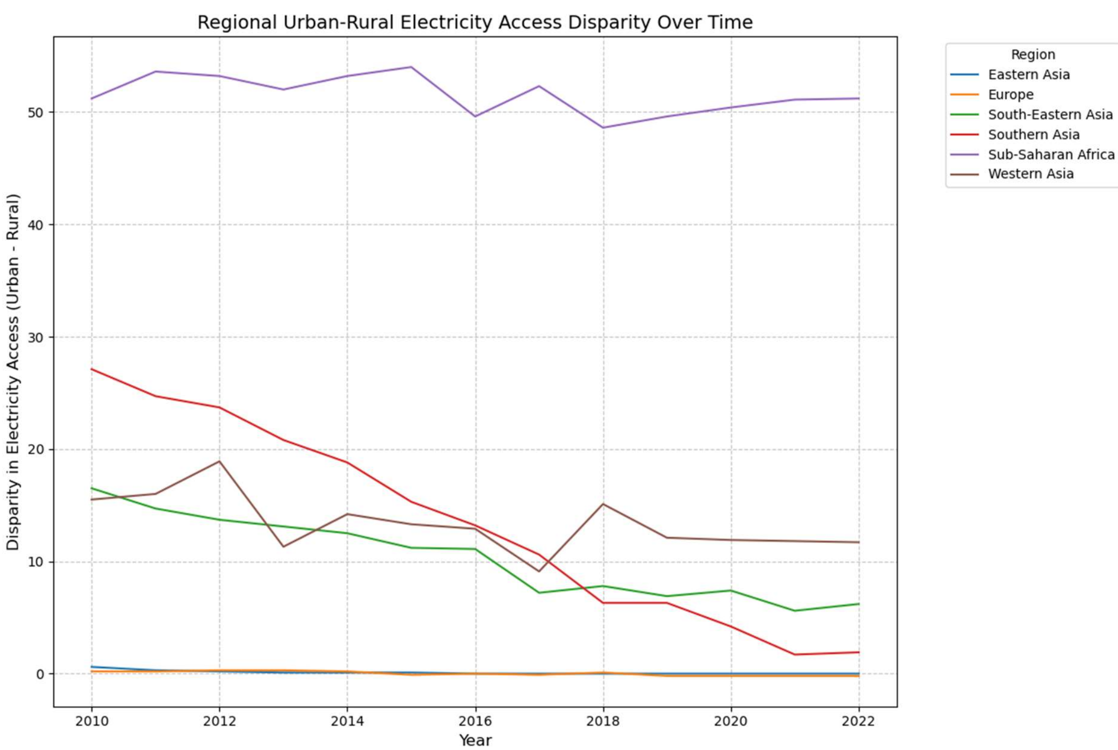


Figure 6

Global Disparity Trend (Figure 6)

- The global disparity in electricity access between urban and rural areas consistently declined from ~ 22% in 2010 to less than 14% by 2022.

Regional Disparities (Figure 6)

- Sub-Saharan Africa: Exhibited the highest and most persistent disparity, starting above 50% in 2010, with gradual improvement but still the largest gap among all regions and remained over 50% in 2022.
- Southern Asia: Significant progress, with disparity reducing from over 25% in 2010 to ~ 1 % by 2022.
- Western Asia and South-Eastern Asia: West Asia saw its lowest disparity in the year 2017 with ~ 9% but it increased afterwards and stands at ~11 % in 2022. South East Asia saw a steady decline from ~16% in 2010 to ~ 6% in 2022.
- Europe and Eastern Asia: Minimal to no disparity throughout the period, reflecting near-universal electricity access.

Following the Urban-Rural Disparity Analysis, an Ordinary Least Squares (OLS) regression model was applied to assess whether increasing Renewable Share in Total Final Energy Consumption (TFEC) contributed to reducing the urban-rural electricity access disparity. This step was crucial to quantitatively evaluate the relationship between the disparity and renewable energy adoption at a global and regional level.

The regression model was built with Urban-Rural Disparity as the dependent variable and Renewable Share in TFEC as the independent variable for World as well as for each Region. This allowed us to determine the extent to which renewable energy adoption impacted the disparity in electricity access over time.

<u>Ordinary Least Squares (OLS) Regression:</u>

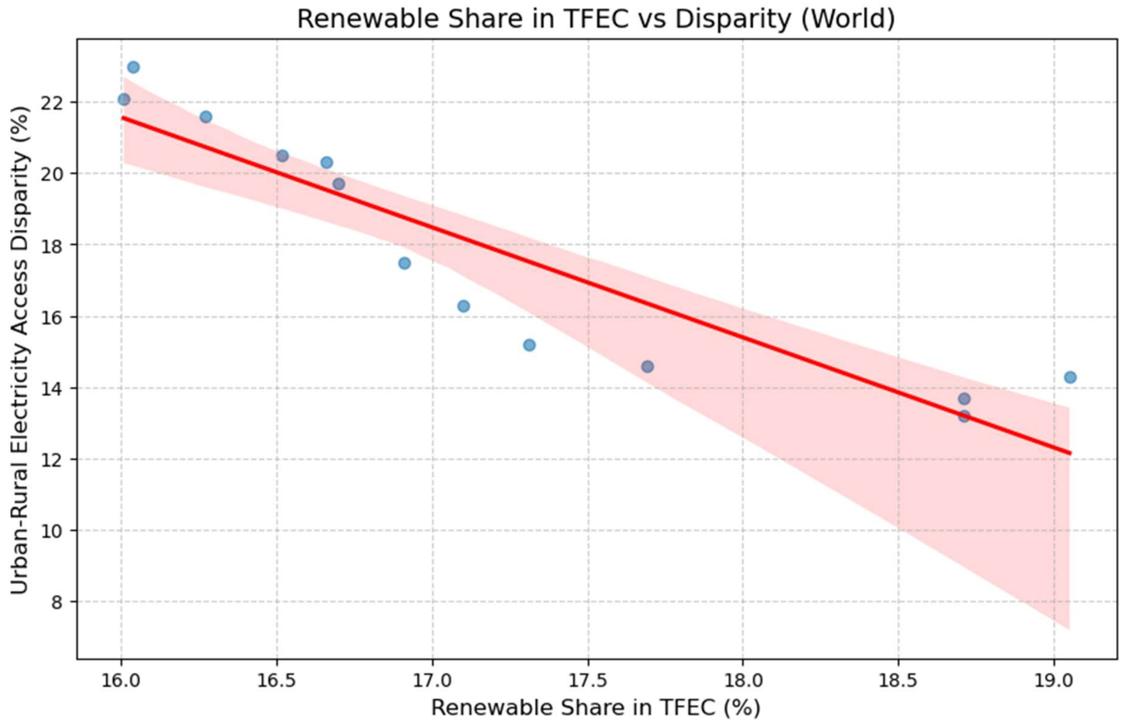


Figure 7

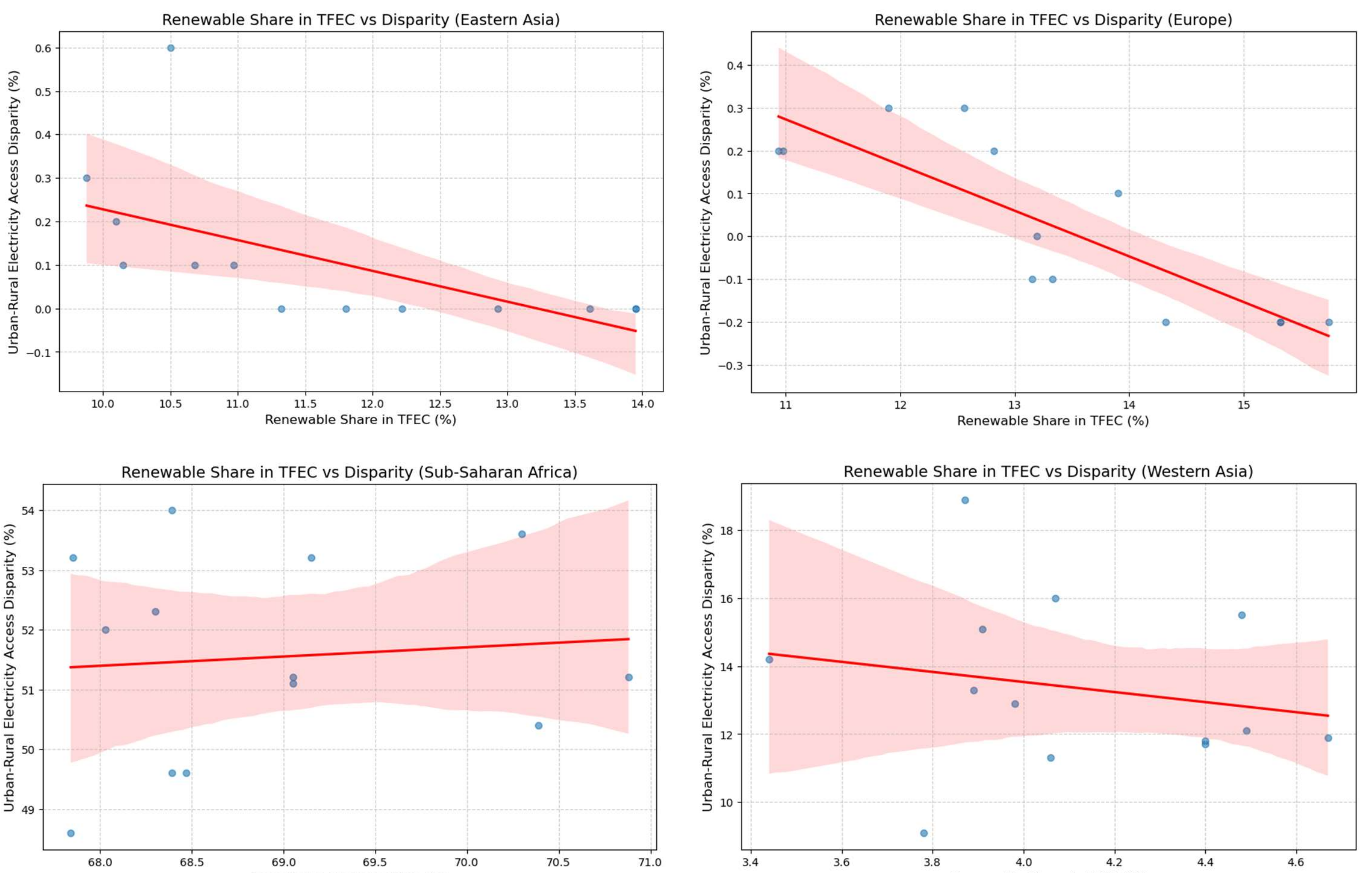


Figure 8

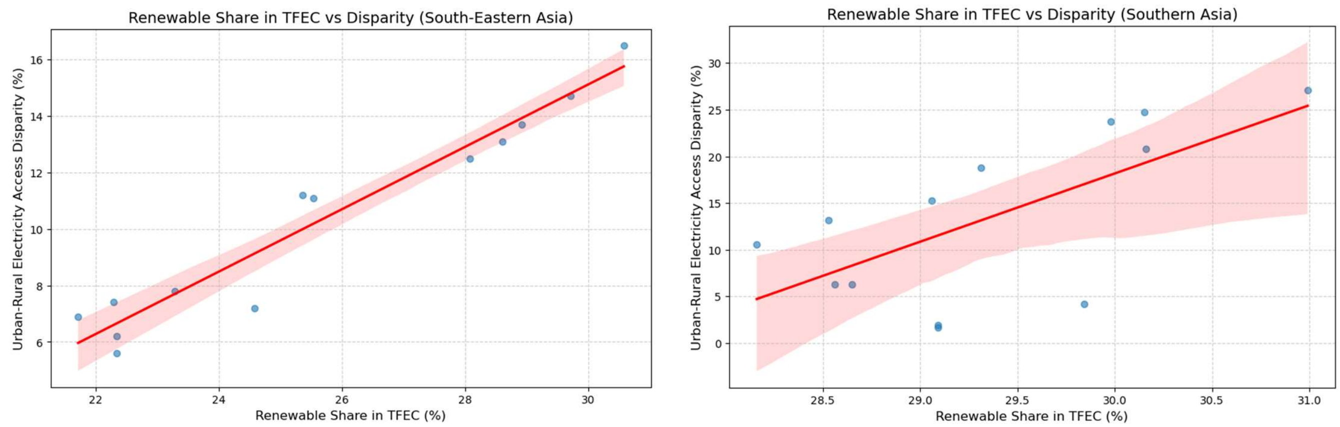


Figure 9

Relationship Between Renewable Share in TFEC & Energy Disparity (Regional & Country-Level Analysis)

Region	R^2 Value	Renewable Share Coefficient	p-value	Trend
World (Global)	0.844	-3.0906	$p < 0.001$	Negative
Eastern Asia	0.367	-0.0708	0.028	Negative
Europe	0.688	-0.1066	$p < 0.001$	Negative
South-Eastern Asia	0.937	1.1047	$p < 0.001$	Positive
Southern Asia	0.443	7.3106	0.013	Positive
Sub-Saharan Africa	0.009	0.1549	0.764	No relation
Western Asia	0.042	-1.4804	0.501	No relation

Table 3

Global & Europe-Level Analysis Confirmed That Higher Renewable Share Reduces Disparity (Figure 7, Figure 8, Table 3)

- Globally ($R^2 = 0.844$, $p < 0.001$) a strong negative relationship was observed, indicating that a higher renewable share reduces disparity.
- Europe ($R^2 = 0.688$, $p < 0.001$) also had a clear decline in disparity with renewable adoption, providing strong evidence for the trend.

- Eastern Asia ($R^2 = 0.367$, $p = 0.028$) followed the trend, but the effect was weaker, suggesting that increasing renewables still contributes to reducing disparity.

Unexpected Findings: South-Eastern Asia & Southern Asia Showed That Disparity was high when Renewable Energy share in Total Final Energy Consumption was high. (Figure 9)

- South-Eastern Asia ($R^2 = 0.937$, $p < 0.001$): Renewable Energy in TFEC is unexpectedly linked with increased disparity (Positive coefficient = 1.1047).
- Southern Asia ($R^2 = 0.443$, $p = 0.013$): A similar pattern was observed, with a positive coefficient of 7.3106, indicating that higher renewable shares were associated with greater disparity.

No Significant Relationship Found in Sub-Saharan Africa and Western Asia (Figure 8)

- Sub-Saharan Africa ($R^2 = 0.009$, $p = 0.764$): The relationship between Renewable energy in TFEC and disparity was not statistically significant.
- Western Asia ($R^2 = 0.042$, $p = 0.501$): The relationship between Renewable energy in TFEC and disparity was not statistically significant.

Globally, a higher share of renewables in total final energy consumption (TFEC) is associated with reduced energy disparity, as evidenced by the strong negative correlation ($R^2 = 0.844$, $p < 0.001$). Europe follows a similar trend ($R^2 = 0.688$, $p < 0.001$), where well-developed policies and equitable infrastructure have ensured that rural areas benefit from renewable energy expansion. Eastern Asia also shows a negative relationship, a bit weaker, indicating that renewable adoption contributes to reducing the rural-urban electrification gap.

However, in South-Eastern Asia ($R^2 = 0.937$, $p < 0.001$) and Southern Asia ($R^2 = 0.443$, $p = 0.013$), a higher renewable share is linked to higher disparity. We need to understand that Renewable Energy Share in Total Final Energy Consumption was stagnated in Southern Asia having Renewable Energy share in TFEC ~30 % throughout the time period. Whereas, South East Asia actually saw a decline in RE share in TFEC from ~ 30 % in 2010 to ~ 22 % in 2022. Despite this, both the regions saw significant decline in disparity which we have seen in our earlier analysis, so disparity reduction in these 2 cases cannot be purely attributed to

Renewable Energy expansion in total final energy consumption. The case was similar in Sub-Saharan Africa and Western Asia where too there is no significant relationship, emphasizing that other factors such as economic conditions, policy effectiveness, play a more dominant role in reducing Electricity disparity between Urban and Rural regions. To achieve true energy equity, countries must implement policies that ensure the benefits of renewables reach all regions.

Comparative Analysis of Renewable Technologies

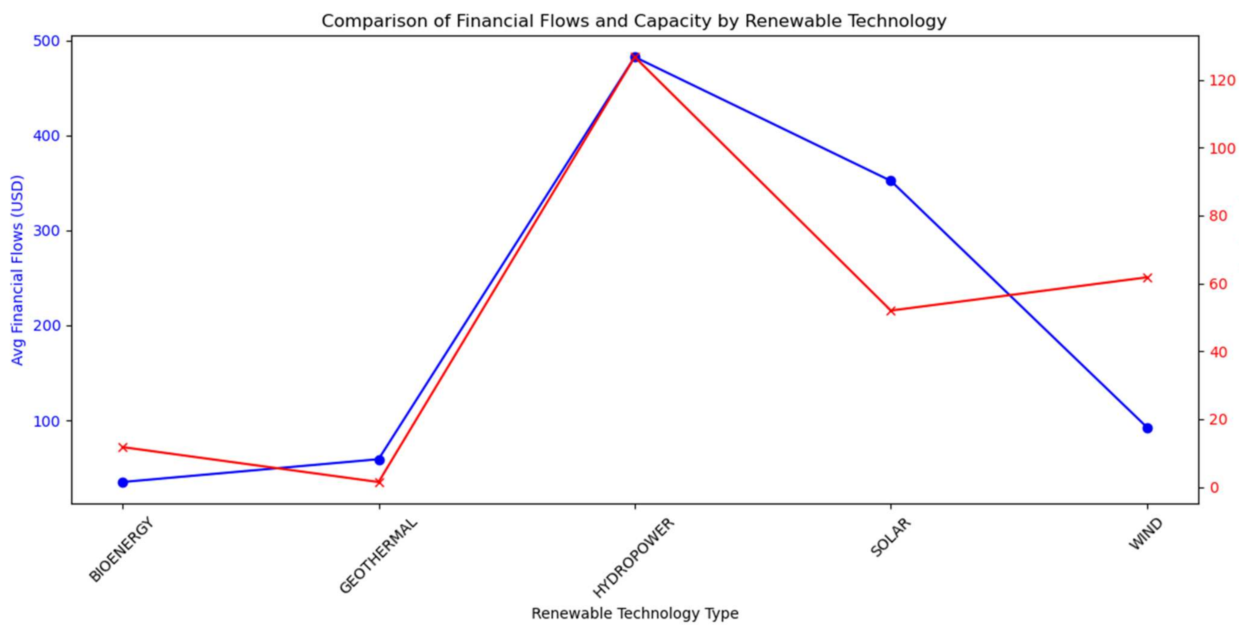


Figure 10

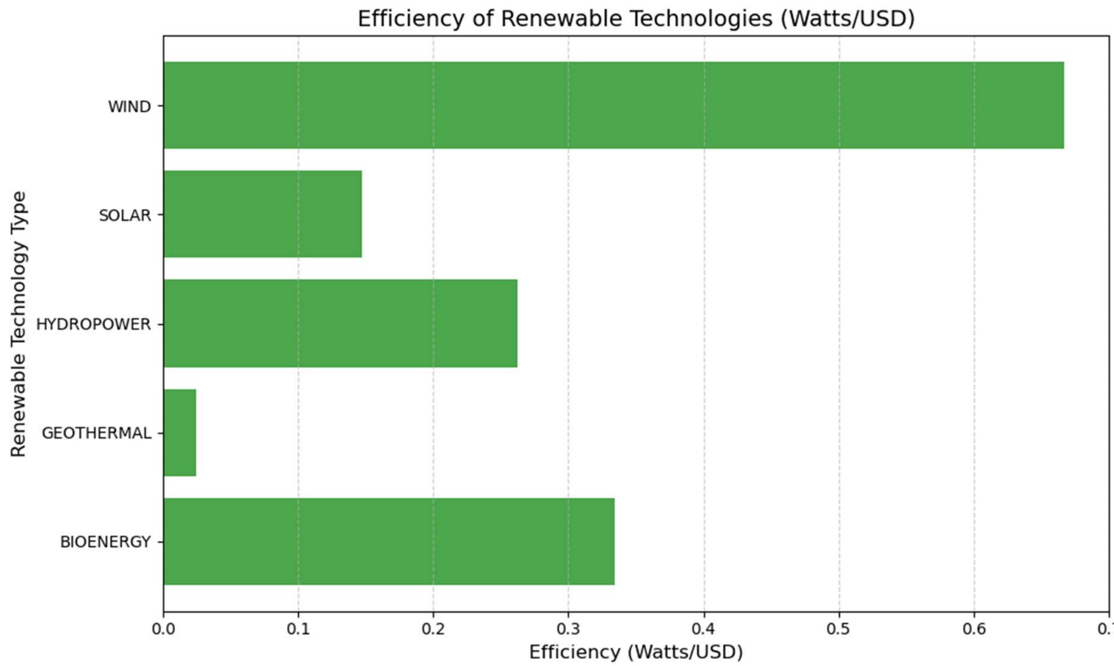


Figure 11

Comparison of Financial Flows and Capacity by Renewable Technology (Figure 10)

Hydropower received the highest financial flows, averaging around USD 482 million, and demonstrated the highest capacity per capita (~126 Watts). This makes it the most significant contributor to renewable energy generation in terms of both funding and output.

Solar and Wind technologies followed Hydropower in terms of financial investment and capacity. Solar had an average financial flow of approximately USD 352 million with a capacity of ~52 Watts per capita. Wind had an average financial flow of USD 92 million and a capacity of ~62 Watts per capita.

Bioenergy exhibited much smaller financial flows (~USD 35 million) and relatively low capacity (~12 Watts per capita) suggesting it might be underutilized or less efficient in large-scale energy generation. Geothermal had the lowest financial flows and capacities, indicating its niche role or lack of widespread adoption.

Efficiency of Renewable Technologies (Watts/USD) (Figure 11)

Wind emerged as the most efficient renewable energy technology, producing approximately 0.67 Watts per USD invested, highlighting its cost-effectiveness in energy generation, Bioenergy ranked second in efficiency (~0.33 Watts/USD), showcasing its potential as a cost-effective solution despite receiving lower financial flows.

Hydropower exhibited an efficiency of ~0.26 Watts/USD, reflecting a balance between cost and output. Solar demonstrated an efficiency of ~0.15 Watts/USD, which, while lower than Wind, reflects its widespread adoption and scalability. Geothermal had the lowest efficiencies ~0.02 Watts/USD, indicating its limited contribution to reducing energy inequality on a cost-to-output basis.

IMPLICATION AND CONCLUSION

Implications of the Research

For Policymakers

Our research confirms that renewable energy has the potential to reduce urban-rural electricity access disparity, but its impact depends on infrastructure, policy support, and fair distribution. In regions like South-Eastern Asia and Southern Asia, where the share of renewable energy stagnated or decreased, electricity disparity still saw a significant decline over time, suggesting that economic growth, targeted rural electrification policies, and infrastructure investments played a crucial role. While renewable energy positively impacts electricity access, financial flows alone do not significantly influence it. So, there is a need for efficient fund allocation along with policy-driven electrification strategies. Hydropower was the most significant contributor to renewable energy generation in terms of both financial investment and renewable energy capacity per capita watts, highlighting its crucial role in energy accessibility. Policymakers must not only focus on increasing renewable energy capacity but also ensure rural areas benefit equally through grid expansion, decentralized sustainable energy solutions, and a mix of high-impact technologies like wind and hydropower to bring tangible improvements in rural electrification.

For Energy Planners

Energy planners should note that the growth in the share of renewables in Total Final Energy Consumption (TFEC) by itself does not guarantee reduced urban-rural electricity disparity. It is evident through our findings that in regions like South-Eastern Asia and Southern Asia, disparity reduction cannot be simply explained by renewable energy expansion. The stagnation or decline in renewable share in these regions suggests that other mechanisms, such as improvements in conventional or traditional energy access and policy-driven electrification programs, contributed to reducing the disparity. For optimal benefits and to maximize the impact, planners should incorporate renewable expansion with targeted rural electrification projects and ensure that infrastructure gaps do not hinder the benefits of renewable energy expansion in energy consumption.

Efficiency analysis revealed that wind energy is the most cost-effective renewable technology, producing the highest energy output per USD invested. Despite receiving major financial flows, solar and hydropower showed lower efficiency, thereby their expansion programs must take into account cost effectiveness in addition to scalability. Energy planners should design investment strategies that optimize financial allocation toward technologies that provide the best return in terms of electricity access, particularly in rural and underserved regions.

For NGOs and Development Agencies

NGOs and Development Agencies working in the area of sustainable energy access must ensure that investments are not only used for renewable energy expansion but also for regional infrastructure needs. Our disparity analysis showed that even in regions with stagnated or declining renewable shares, electricity disparity decreased over time, which suggests that more wide-ranging policy measures and economic development played a crucial role. NGOs and development agencies should advocate for a combination of renewable energy deployment and targeted infrastructure projects to achieve maximum impact. Given that renewable energy’s effectiveness in reducing disparity depends on infrastructure preparedness and policy effectiveness, initiatives should focus on extending the rural grid, decentralized renewable schemes in communities, and capacity development programs. More importantly, financial flows toward clean energy should be strategically channeled so that measurable gains in rural electrification levels could be achieved.

For Researchers

This research highlights the complexity of the relationship between renewable energy and urban-rural electricity disparity. The lack of a strong correlation in regions like Sub-Saharan Africa and Western Asia suggests that other structural factors, including economic conditions, policy effectiveness, and governance, play a more dominant role. Future research should explore how different energy transition models and strategies influence urban-rural electrification trends, particularly in developing economies, to develop a more complete understanding of energy inequality. Also, the findings on hydropower's dominance and wind's efficiency suggest the need for region specific deeper studies into their long-term sustainability and scalability. Additional empirical research is required, in order to identify and evaluate the specific factors that exacerbate energy disparity and to evaluate measures to mitigate these gaps.

Future research can explore the application of Long Short-Term Memory (LSTM) models to analyze electricity access trends and predict the impact of renewable energy expansion in TFEC on urban-rural disparity. LSTMs can capture long-term dependencies in time-series data, making them suitable for complex models, non-linear relationships between renewable energy adoption, infrastructure development, and energy inequality. Our findings reinforce the need for a holistic approach that combines renewable energy deployment with strategic investment in rural electrification and sustainable infrastructure.

In conclusion, **Renewable energy is a powerful driver of reducing energy equality which can be seen from the global scenario**, **but its effectiveness depends on addressing infrastructure and policy challenges as seen in the regional studies.**

REFERENCES

1. *Volodzkiene L, Streimikiene D. Towards Energy Equity: Understanding and Addressing Multifaceted Energy Inequality. Energies. (2024); 17(17):4500. https://doi.org/10.3390/en17174500*
2. *Daniel Adu, Du Jianguo, Stephen Ntiri Asomani, Agnes Abbey, "Energy generation and carbon dioxide emission—The role of renewable energy for green development,", ISSN 2352-4847, https://doi.org/10.1016/j.egyr.2024.07.013.*

3. *Sun, Chenzhou; Sun, Shurui; Yue, Xiaolu, "Does the transition to low-carbon energy alleviate urban-rural energy inequality? The case of China," Heliyon, Volume 10, (2024), Elsevier, https://doi.org/10.1016/j.heliyon.2024.e31355.*
4. *Volodzkiene, L.; Streimikiene, D., "Energy Inequality Indicators: A Comprehensive Review for Exploring Ways to Reduce Inequality," Energies, Volume 16, (2023), 6075, https://doi.org/10.3390/en16166075.*
5. *Emami Meybodi, Mehdi & Owjimehr, Sakine. (2024). The nexus of climate policy uncertainty, renewable energy and energy inequality under income disparities. Energy Strategy Reviews. 53. 101381. 10.1016/j.esr.2024.101381.*
6. *Streimikiene, D.; Baležentis, T.; Volkov, A.; Morkūnas, M.; Žičkienė, A.; Streimikis, J., "Barriers and Drivers of Renewable Energy Penetration in Rural Areas," Energies, Volume 14, (2021), 6452, https://doi.org/10.3390/en14206452.*
7. *Julius Alexander McGee, Patrick Trent Greiner, "Renewable energy injustice: The socio-environmental implications of renewable energy consumption," ISSN 2214-6296, https://doi.org/10.1016/j.erss.2019.05.024.*
8. *Mehmood, U.; Agyekum, E.B.; Tariq, S.; Ul Haq, Z.; Uhunamure, S.E.; Edokpayi, J.N.; Azhar, A. "Socio-Economic Drivers of Renewable Energy: Empirical Evidence from BRICS," Int. J. Environ. Res. Public Health (2022), 19, 4614, https://doi.org/10.3390/ijerph19084614*
9. *Mert Topcu, Can Tansel Tugcu, The impact of renewable energy consumption on income inequality: Evidence from developed countries, Renewable Energy (2019), https://doi.org/10.1016/j.renene.2019.11.103*
10. *Leire Urkidi Azkarraga, Mikel Gurrutxaga, "Making space for environmental justice in renewable energy planning," Energy Research & Social Science, Volume 118, (2024), 103806, ISSN 2214-6296, https://doi.org/10.1016/j.erss.2024.103806*
11. *Jawad Abbas, Lisu Wang, Samira Ben Belgacem, Puja Sunil Pawar, Hina Najam, Jaffar Abbas, "Investment in renewable energy and electricity output: Role of green finance, environmental tax, and geopolitical risk: Empirical evidence from China," Energy, Volume 269, (2023), 126683, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2023.126683.*
12. *Sikandar Abdul Qadir, Hessah Al-Motairi, Furqan Tahir, Luluwah Al-Fagih, "Incentives and strategies for financing the renewable energy transition: A review," Energy Reports, Volume 7, (2021), Pages 3590-3606, ISSN 2352-4847, https://doi.org/10.1016/j.egyr.2021.06.041.*
13. *Sławomir Śmiech, Lilia Karpinska, Stefan Bouzarovski, "Impact of energy transitions on energy poverty in the European Union," Renewable and Sustainable Energy Reviews, Volume 211, (2025), 115311, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2024.115311*
14. *Fergus Green, Noel Healy, "How inequality fuels climate change: The climate case for a Green New Deal," One Earth, Elsevier, ISSN 2590-3330, https://doi.org/10.1016/j.oneear.2022.05.005*
15. *Kanchan Kumar Sen, Shahadat Hosan, Shamal Chandra Karmaker, Andrew J. Chapman, Bidyut Baran Saha, "Clarifying the linkage between renewable energy deployment and energy justice: Toward equitable sustainability," Sustainable Futures, Volume 8, (2024), 100236, ISSN 2666-1888, https://doi.org/10.1016/j.sftr.2024.100236.*

16. *Erna Farina Mohamed, Azlina Abdullah, Amar Hisham Jaaffar, Romanus Osabohien, "Reinvestigating the EKC hypothesis: Does renewable energy in power generation reduce carbon emissions and ecological footprint?" Energy Strategy Reviews, Volume 53, (2024), 101387, ISSN 2211-467X, https://doi.org/10.1016/j.esr.2024.101387.*