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Energy Transition in an Urbanizing World: Long-Run Drivers of CO₂ Emissions in 77 Emerging and Developing Economies

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ABSTRACT
This study investigates the major determinants of CO_2 emissions in 77 emerging and developing economies from 1990 to 2023, focusing on the roles of renewable energy consumption, urbanization, forest cover, access to clean fuels, and total energy use. The Westerlund cointegration test confirms the existence of a long-run equilibrium relationship among the variables, while the CIPS unit root test accounts for cross-sectional dependence within the panel structure. Empirical findings based on Driscoll–Kraay standard errors reveal that renewable energy consumption significantly contributes to reducing CO_2 emissions, whereas urban population growth, loss of forest cover, and increased energy use intensify emission levels. Access to clean fuels exhibits a negative but statistically insignificant effect on emissions. The Panel Dynamic OLS (DOLS) results further validate these findings, underscoring both the transformative potential of renewable energy adoption and the persistent environmental pressures associated with rapid urban expansion and rising energy demand. Overall, the outcomes highlight the necessity for integrated and forward-looking policy frameworks that accelerate renewable energy deployment, promote sustainable urban development, and strengthen land-use governance to support low-carbon transitions in emerging and developing economies.

Keywords: Renewable Energy; Co₂ Emissions; Urbanization; Forest Cover; Energy Consumption; Emerging Economies.

Introduction

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The issue of carbon emissions has emerged as a defining challenge of the 21st century, with its far-reaching implications for global climate change, human health, and economic stability. Carbon dioxide (CO_2) emissions, primarily generated through the combustion of fossil fuels, industrial processes, and deforestation, have reached unprecedented levels. In 2022, global CO_2 emissions surged to an estimated 37.5 billion metric tons, marking a 1% increase from the previous year despite international commitments to climate action (Global Carbon Project, 2023). This continued rise underscores the complexity of achieving a balance between economic development and environmental sustainability. Developing and emerging economies contribute significantly to global carbon emissions, driven by rapid urbanization, industrial expansion, and energy demands. Urban areas, which house over 56% of the world's population, are responsible for more than 70% of global energy consumption and related CO_2 emissions (United Nations, 2022). This urban-induced carbon footprint highlights the need for sustainable urbanization strategies, particularly in regions experiencing population booms and infrastructure development. Furthermore, the global energy mix remains heavily reliant on fossil fuels, which accounted for 81% of the world's primary energy consumption in 2021, with renewable energy sources constituting only 12.7% (IEA, 2023). Despite these challenges, progress in renewable energy adoption and access to clean technologies offers a pathway to mitigate CO_2 emissions. Between 2010 and 2020, the global share of renewable energy in electricity production increased from 20% to 28%, driven by technological advancements and falling costs (IRENA, 2021). Simultaneously, access to clean cooking fuels and technologies—a critical factor for reducing indoor air pollution and emissions—has risen to 71% globally, although disparities persist in low-income countries (World Bank, 2023). Forest conservation efforts, another critical component of carbon sequestration, are gaining momentum, yet deforestation rates remain alarmingly high, with a net global forest loss of 10 million hectares annually (Food and Agriculture Organization [FAO, 2020).

Urbanization, renewable energy adoption, access to clean fuels, energy use, and forest area dynamics play pivotal roles in shaping environmental quality and sustainability outcomes. Urban population growth continues unabated, with over 4.4 billion people—56% of the global population—living in urban areas as of 2023, a figure projected to rise to 68% by 2050 (United Nations, 2022). This urban expansion often accelerates energy consumption and carbon emissions, particularly in rapidly industrializing nations. On the positive side, renewable energy consumption has shown steady progress, contributing 12.7% to the global energy mix in 2021, up from 10% in 2010, with solar and wind energy leading the transition (IEA, 2023). However, disparities remain, as renewable energy penetration is uneven across regions, with Africa and South Asia lagging behind. Access to clean cooking fuels and technologies has also improved significantly, reaching 71% globally in 2021, yet nearly 2.3 billion people still rely on traditional biomass, such as wood and charcoal, which exacerbates indoor air pollution and contributes to deforestation and carbon emissions (World Bank, 2023). Energy use has surged alongside economic growth, with the global average energy consumption reaching 2,450 kilograms of oil equivalent per capita in 2021, although per capita consumption varies drastically—high-income countries average 4,500 while many low-income nations remain below 500 (IEA, 2023).

Forest area, a critical carbon sink, has been declining at an alarming rate, with global forest cover shrinking from 31.9% of total land area in 1990 to 31.2% in 2020, reflecting a net loss of 420 million hectares over three decades (FAO, 2020). The deforestation drivers include agricultural expansion, urban sprawl, and logging activities, particularly in tropical regions. While reforestation efforts are underway, they are insufficient to offset losses, especially in biodiversity hotspots like the Amazon and Southeast Asia. These

interconnected variables underscore the complexity of achieving environmental sustainability in the face of rapid urbanization, rising energy demands, and climate change pressures. The rapid increase in CO_2 emissions has become a significant concern globally, particularly in developing and emerging economies, as it threatens environmental sustainability and accelerates climate change. Several factors contribute to this trend, necessitating a comprehensive understanding of their roles to formulate effective mitigation policies. Renewable energy consumption (REC) is recognized as a vital tool for reducing carbon emissions by decreasing reliance on fossil fuels, which are the primary sources of greenhouse gases. Empirical studies have shown that an increase in renewable energy usage directly contributes to lower emissions, making it a critical component of sustainable energy policies (Apergis & Payne, 2010; Sadorsky, 2009). In contrast, urban population growth (URP) significantly influences CO2 emissions as urbanization drives industrial expansion, higher energy consumption, and transportation needs, all of which intensify environmental pressures (Wang et al., 2020). However, urbanization also presents opportunities for adopting cleaner technologies and sustainable urban planning. Similarly, forest area (FA) plays an important but complex role in environmental management. While forests act as natural carbon sinks by absorbing CO_2, their impact can vary depending on deforestation rates, reforestation policies, and land-use changes (Pan et al., 2011). Therefore, maintaining forest cover is crucial for carbon sequestration.

Another critical determinant is access to clean fuels and technologies (ACF), which enables households and industries to transition from traditional, polluting energy sources to cleaner alternatives. Improved access to clean energy has been found to significantly reduce CO_2 emissions by curbing indoor and industrial air pollution (Liddle & Sadorsky, 2017). Conversely, energy use per capita (ENU) remains a key driver of emissions, as higher energy consumption, particularly in regions dependent on non-renewable energy sources, is directly linked to increased CO_2 emissions (Sadorsky, 2009). This is particularly relevant for emerging economies where industrial growth and rising living standards often lead to greater energy demand. Given these dynamics, examining the long-run relationships among renewable energy use, urbanization, forest area, access to clean energy, and energy consumption is essential for balancing economic growth and environmental sustainability. This study addresses these critical issues by exploring the role of these factors in determining CO_2 emissions across developing and emerging Asian economies from 1990 to 2023. By doing so, it provides valuable insights for policymakers to devise strategies that promote sustainable energy use, urban planning, and environmental conservation.

The study is crucial in addressing one of the most pressing global challenges: mitigating CO_2 emissions to combat climate change while ensuring sustainable economic growth in emerging economies. By investigating the roles of renewable energy, urbanization, forest area, clean fuels, and energy use, this research provides insights into the complex interplay between economic development and environmental sustainability. Its significance lies in identifying actionable strategies for reducing emissions, such as promoting renewable energy adoption, sustainable urban planning, forest conservation, and energy-efficient technologies. The results of this study will have policy implications, helping governments and international organizations design more targeted and effective interventions to achieve climate goals.

Research Questions

The study has the following research questions, i.e., First, Can renewable energy serve as an effective strategy for reducing CO_2 emissions in emerging economies? Renewable energy is often seen as a vital solution to address rising CO_2 emissions in emerging

economies, where energy demand and industrial growth are surging. This question examines whether renewable energy alone can drive significant emissions reductions or if its potential is constrained by systemic challenges such as weak infrastructure, inadequate investment, and policy gaps. Its importance lies in determining if renewable energy is sufficient as a standalone strategy or whether a broader approach is necessary to achieve sustainable development. Research by Apergis and Payne (2012) and Al-Mulali et al. (2016) underscores the transformative potential of renewable energy but highlights the need for supportive systems to maximize its effectiveness. Second, what is the impact of urbanization and forest cover on CO_2 emissions in emerging economies? Urbanization has led to rapid economic and infrastructural development in emerging economies, often at the cost of increased CO_2 emissions and deforestation. This question investigates the combined impact of urbanization and forest area on emissions, focusing on whether sustainable urban growth and forest conservation can coexist. Understanding this relationship is vital for policymakers to design strategies that mitigate the environmental costs of urban expansion while preserving critical carbon sinks. Studies by Shahbaz et al. (2016) and Nguyen and Kakinaka (2019) reveal that urbanization often undermines forest conservation efforts, leading to higher emissions in the absence of integrated policies. Finally, Can access to clean fuels and increasing energy consumption coexist without accelerating CO_2 emissions? As emerging economies strive to provide access to clean fuels for households and industries, growing energy demand poses a challenge to reducing CO_2 emissions. This question explores the extent to which clean fuels can offset the environmental impact of surging energy use, offering insights into whether these trends can harmonize. The importance of this inquiry lies in guiding energy policy, helping economies adopt strategies that manage energy consumption while minimizing their carbon footprint. Research by highlights the delicate balance between clean energy transitions and the pressures of increasing energy demand.

Research Objectives
The study has the following research objectives, i.e.,
To evaluate the extent to which renewable energy adoption can mitigate CO_2 emissions in emerging economies, while identifying systemic challenges that may constrain its effectiveness.
To analyze the combined effects of urbanization and changes in forest cover on CO_2 emissions, exploring how sustainable urban growth and forest conservation can be balanced in emerging economies.
To investigate the interplay between access to clean fuels and increasing energy demand, assessing their joint impact on CO_2 emissions in emerging economies.
These aims together seek to elucidate the variables affecting CO_2 emissions in rising economies. The project aims to provide evidence-based insights to assist policymakers, energy planners, and environmental stakeholders in formulating strategies for sustainable energy transition and climate mitigation.

Literature Review
The relationship between CO_2 emissions and its key determinants, such as renewable energy consumption, urbanization, forest area, access to clean fuels, and energy use, has been widely explored in the existing literature, providing a foundation for understanding the drivers of environmental sustainability. Saidi and Omri (2020) provide valuable insights into the dynamic relationships between economic growth, renewable energy consumption, and CO_2 emissions, using advanced econometric techniques like Fully Modified Ordinary Least Squares (FMOLS) and Vector Error Correction Model (VECM). The study's main contribution lies in its finding of bidirectional causality between

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economic growth and renewable energy, validating the feedback hypothesis, and identifying short-run bidirectional causality between renewable energy and CO_2 emissions. However, the paper has some limitations, including the selection of only 15 major renewable energy-consuming countries, which may affect the generalizability of the results. Additionally, while the authors effectively address short-term dynamics, they offer limited discussion of the long-run relationship between renewable energy and CO_2 emissions and the potential influence of other variables like technological innovation or policy interventions. The paper could benefit from expanding the scope to include more countries, different environmental indicators, and other mediating factors, as well as exploring non-linearities or structural breaks in the data. Nonetheless, the findings offer important policy implications for promoting renewable energy as a driver of both economic growth and environmental sustainability. Rahman et al (2024) investigated the role of renewable energy in reducing carbon emissions in major fossil fuel-consuming countries from 1990 to 2020. Using fixed-effect models, they found a significant negative impact of renewable energy on CO_2 emissions, with quantile regression showing that low CO_2-emitting countries are particularly sensitive to renewable energy consumption. However, fossil fuel consumption, GDP, GDP squared, and patents were found to worsen environmental quality by increasing emissions. While the study provides valuable insights into the importance of renewable energy for environmental sustainability, its reliance on fixed-effect models and quantile regression may overlook non-linearities and broader socio-economic factors. Furthermore, the study could have expanded its analysis by considering energy efficiency and technological advancements, which also play crucial roles in shaping emissions. Despite these limitations, the study underscores the need for policy interventions to promote renewable energy and reduce fossil fuel dependence in achieving global climate goals.

Shah et al. (2024) evaluated energy efficiency and productivity changes across G20 countries from 1995 to 2020 using the Slack-Based Measure Data Envelopment Analysis and Malmquist-Luenberger Index. The research incorporates both renewable and non-renewable energy consumption, as well as carbon emissions, into input-output bundles to assess their impact on EE and productivity. The findings suggest that the inclusion of renewable energy improves the average EE, from 0.783 to 0.8578, though it leads to a slight decline in energy productivity. Notably, the study shows that carbon emissions, considered as a bad output, can enhance renewable energy efficiency and productivity growth, with an average EE of 0.6678 and MLI of 1.0044. Technological change is found to be the primary driver of energy productivity growth in certain scenarios, while technical efficiency is the key determinant in others. The Kruskal-Wallis test reveals significant statistical differences between the EE and MLI scores of G20 countries. While the study offers valuable insights into how renewable energy and carbon emissions influence EE, its reliance on static input-output bundles and limited focus on broader policy factors might oversimplify the complexities of achieving sustainable energy transitions. Nonetheless, the study underscores the importance of technological innovation and efficiency improvements in advancing energy productivity and sustainability across diverse economies. Liu et al (2024) investigated the complex relationship between urban expansion and carbon emissions in China from 2007 to 2019, utilizing a spatial Durbin model and mediating effect model. The study found that urban expansion and carbon emissions exhibited significant spatial heterogeneity, autocorrelation, and spillover effects. Specifically, urban expansion had a U-shaped direct effect on local carbon emissions, while its spatial spillover effect on neighboring cities' carbon emissions followed an inverse U-shape. The authors also identified industrial structure upgrading and industrial

agglomeration as key mediating mechanisms in the relationship between urban expansion and carbon emissions. One of their key recommendations was that urban expansion should aim for a land expansion rate about twice the population growth rate to optimize carbon emission benefits. While the study provided important insights into the spatial dynamics of urban expansion and decarbonization, its focus on China limited the generalizability of the findings to other regions with different urbanization patterns. Additionally, while the study explored the indirect effects via industrial factors, a deeper analysis of other socio-economic and policy-driven factors would have provided a more comprehensive understanding of how urbanization could be managed for low-carbon development. Nonetheless, the study effectively emphasized the need for spatially informed urban planning to support sustainable urban growth and carbon reduction.

Hong et al (2022) examined the relationship between urban population size, density, and carbon emissions using geographically weighted regression and movement stratification regression, with a focus on urban scaling. The study revealed several key findings: (1) there were sub-linear scaling relationships between urban size and total, industrial, and residential carbon emissions, while a super-linear relationship was observed for transportation emissions. (2) Regional differences in urban scaling exponents were identified, highlighting disparities in how different areas respond to urban growth. (3) The relationship between urban density and carbon emissions exhibited an oblique W-shape for total, industrial, and transportation emissions, and a U-shape for residential emissions. (4) The study identified a threshold point at a population size of one million; below this threshold, increasing urban density promoted carbon reduction, whereas beyond this point, higher density led to greater emissions. (5) Based on these findings, the authors emphasized the need for region-specific low-carbon development strategies tailored to varying urban densities and sizes. While the study provides valuable insights into the complex dynamics between urban size, density, and carbon emissions, its focus on a theoretical urban scaling hypothesis (TSDC) could benefit from further empirical validation across different global contexts. Additionally, while the study highlights the importance of urban density, a deeper exploration of other factors such as transportation infrastructure and energy mix could further refine low-carbon development strategies.

Brown et al. (1996) provided an in-depth analysis of the potential for forest management to mitigate CO_2 emissions. The study identified three key categories of forestry practices that could both conserve and sequester carbon: (1) conserving existing carbon pools by reducing deforestation and modifying harvesting regimes, (2) expanding carbon storage by increasing the area and density of forests, and (3) promoting carbon substitution by transferring forest biomass into biofuels and long-lived wood products that could replace fossil fuels. Under baseline conditions, the study estimated that slowing deforestation and promoting natural regeneration, along with establishing plantations and agroforestry on non-forested land, could sequester between 60 and 87 Pg of carbon by 2050—equivalent to 11-15% of projected cumulative fossil fuel emissions. Additionally, if the wood from plantations were substituted for fossil fuels, another 30 Pg of carbon could be sequestered. The authors also outlined the costs of these actions, estimating a cumulative cost of $247 billion to $302 billion, with a cost of $2-8 per Mg of carbon. However, they cautioned that under changing climate conditions and altered land use patterns, the potential for carbon sequestration would likely be reduced, particularly in tropical regions where land availability could decline, and existing forests in temperate and boreal zones might experience carbon losses due to climate change. While the study provided a comprehensive overview of the role of forests in carbon sequestration, it could have benefited from more detailed discussions of the socio-political challenges to implementing such large-scale

forest management strategies, as well as a deeper exploration of the long-term ecological impacts of large-scale plantations and agroforestry. Nonetheless, the paper underscored the critical role that forests could play in global carbon management and highlighted the importance of integrating forest management into broader climate mitigation efforts.

Dutra et al. (2024) critically examined Brazil's land-use changes and their implications for carbon emissions, highlighting significant challenges to achieving climate goals. The paper reported that Brazil's native vegetation removal reached 2.8 million hectares (Mha) in 2022, the highest rate since 2008, exacerbating the country's carbon emissions, which were largely driven by deforestation. Despite some positive trends, such as 5.46 Mha of forest regrowth from 2016 to 2022, with notable contributions from the Amazon (40%) and Atlantic Forest biome (36%), the authors emphasized that secondary forests in Brazil were not adequately protected by existing legislation, undermining their long-term carbon mitigation potential. The study further pointed out the restoration deficit, estimating that 15.8 Mha of Legal Reserve areas on private rural properties required restoration, with more than half of this area located in the Amazon. The authors argued that meeting Brazil's commitments under the Sustainable Development Goals (SDGs) and the Paris Agreement by 2030 required urgent action, including addressing illegal deforestation, reinforcing legislation to protect secondary forests, implementing large-scale restoration programs, and providing economic incentives such as payments for ecosystem services to rural landowners. While the study presented a clear roadmap for action, it could have further explored the socio-political barriers to effective enforcement and the role of market-based incentives in driving conservation at the scale needed to meet Brazil's climate goals. Nevertheless, the paper underscored the critical need for enhanced governance, legal frameworks, and restoration efforts to mitigate Brazil's land-use emissions and ensure a sustainable path forward. Imran et al. (2024) explored the role of nuclear energy and greenfield investments in promoting sustainable development and reducing carbon emissions across 29 economies in Europe and Central Asia between 2007 and 2020. Using a two-step differenced GMM estimator, the study found that increasing demand for nuclear power contributed positively to achieving a carbon-neutral agenda, while insufficient funding for renewable energy led to higher carbon emissions. The authors proposed several hypotheses, including fuel-led carbon emissions, carbon-led chemical use, and renewable energy-led fuel imports, to explain the dynamics between energy consumption and carbon emissions. The research confirmed bidirectional relationships between nuclear energy, greenfield investment, and fuel imports, suggesting that these factors play a crucial role in improving regional environmental quality. Additionally, the study highlighted the importance of green financing in supporting nuclear energy and renewable energy development. The authors recommended increasing investment in energy-efficient technologies, expanding nuclear and renewable energy production, and fostering innovation through green finance. While the study provides valuable insights into the potential for nuclear energy and green investments to mitigate carbon emissions, it could benefit from a deeper exploration of the socio-political challenges surrounding the implementation of such strategies, particularly in regions with varying levels of economic development and energy infrastructure. Nonetheless, the paper underscores the critical need for integrated energy strategies that combine nuclear power, green investments, and renewable energy to achieve long-term sustainability.

Tariq et al. (2023) analyzed the impact of clean fuels, technologies, and various economic factors on greenhouse gas emissions from food systems in six countries (USA, China, Japan, Russia, Germany, and Australia) between 1990 and 2020, using the panel Fully Modified Ordinary Least Squares (FMOLS) method. The findings indicated that the use

of clean fuels and technologies, along with the consumer price index, were beneficial in reducing greenhouse gas emissions and mitigating environmental degradation. Conversely, the study revealed that increased income and food production contributed to environmental deterioration. The authors found bidirectional causal relationships between access to clean fuels and technology, greenhouse gas emissions from the food system, real income, and food production, as well as between income, the consumer price index, and food production index. Additionally, there were unidirectional causal relationships between the consumer price index and emissions, food production index and emissions, and access to clean fuels and technologies with both the consumer price index and food production index. Based on these results, the authors recommended that governments should implement consistent measures to support the food industry's transition to cleaner technologies, including the introduction of carbon pricing in food systems to reduce emissions. They also suggested controlling the consumer price index by regulating the prices of green technologies to promote sustainable development globally and reduce environmental pollution. While the study provides valuable insights into the relationship between economic factors and food system emissions, it could have further explored the role of policy interventions and the socio-economic challenges faced by different countries in transitioning to cleaner production systems. Nonetheless, the paper effectively emphasizes the importance of green growth strategies and economic incentives in achieving sustainable development and mitigating environmental pollution. Yahong et al. (2023) explored the impact of clean fuels and technology-based energy poverty on carbon emissions (CO_2e) in 18 developing countries in Asia between 2006 and 2017, using System-Generalized Method of Moments (SGMM) estimators. The findings highlighted the detrimental effects of energy poverty, specifically the lack of access to clean fuels and technologies, on the environment, as it was found to contribute positively to the growth of CO_2 emissions. In addition, the study identified that economic growth (GDP), trade, and population size were also positively associated with CO_2 emissions and had a negative impact on environmental quality. These results underscore the urgent need for policy interventions that promote greater investment in clean fuels and technologies to address energy poverty and mitigate environmental degradation. While the study provides valuable insights into the link between energy poverty and carbon emissions in developing countries, it could have benefited from a deeper analysis of specific policy measures and their feasibility in the context of Asia's diverse economic and energy landscapes. Nonetheless, the paper emphasizes the critical importance of transitioning to cleaner energy sources to support both economic development and environmental sustainability in the region.

Adeleye et al. (2021) examined the role of per capita income in moderating the relationship between energy use and carbon emissions in 28 African countries from 1990 to 2019. Using advanced econometric techniques such as FGLS, PCSE, and MM-QR, the study found that increases in energy use were significantly linked to higher carbon emissions, with a 1% increase in energy use leading to a 0.60% to 0.70% rise in emissions, on average. Similarly, per capita income was identified as a positive driver of emissions, contributing between 0.84% and 0.87% increase, on average. Interestingly, per capita income was found to moderate the impact of energy use on carbon emissions, attenuating the effect by 0.23% to 0.27%. However, regional heterogeneity was evident, with Southern Africa showing the highest energy contribution to emissions (1.65%), while Central Africa's per capita income exacerbated emissions the most (1.87%). West Africa exhibited the largest moderation effect at -0.56%. The study highlighted a dilemma for African economies: while economic growth (driven by energy use and income) is crucial for development, it also risks

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increasing carbon emissions, presenting a trade-off between development and sustainability. The authors suggest that African governments should prioritize investments in renewable energy to decouple economic growth from carbon emissions, a key strategy for achieving Sustainable Development Goal (SDG) 13, which calls for urgent action to combat climate change. The study offers important insights into the environmental challenges faced by African countries but could benefit from further exploration of specific renewable energy policies or initiatives that could facilitate this transition. Nonetheless, it emphasizes the need for a balanced approach that fosters development while mitigating environmental impacts. Hasan et al (2024) critically examined the intricate dynamics between oil consumption and environmental factors, utilizing panel data from 1996 to 2022 and advanced analytical techniques, including the Method of Moments Quantile Regression (MMQR). Their findings revealed a positive association between oil consumption and economic growth, particularly concerning carbon emissions and ecological footprints, while highlighting the adverse effects of renewable energy on these environmental indicators. The authors noted a complex relationship between institutional quality and environmental outcomes, with a positive correlation to carbon emissions and a contrasting negative effect on the ecological footprint at lower quantiles, yet a positive correlation at upper quantiles. They advocated for an integrated resource policy that strategically incorporates renewable energy to mitigate environmental impacts, emphasizing the necessity of aligning economic development with environmental stewardship. The study underscored the importance of institutional quality in shaping environmental outcomes and called for policies that align with Sustainable Development Goals to ensure a sustainable and resilient energy future, thereby contributing to a responsible utilization of resources.

Based on the cited literature, the study has the following research hypotheses, i.e.,

H1: Increased adoption of renewable energy significantly contributes to the reduction of CO_2 emissions in emerging economies.

H2: Urbanization positively influences CO_2 emissions, whereas expansion in forest cover helps mitigate emissions in emerging economies.

H3: Improved access to clean fuels decreases CO_2 emissions; however, the growth in energy consumption may offset these reductions in emerging economies.

Data and Methodology

The data for this study were obtained from the World Bank (2024) database and consist of a panel of 77 emerging economies covering the period 1990–2023. Table 1 presents the list of variables along with their expected relationships.

Table 1: List of Variables

Variables	Symbol	Measurement	Expected Sign
Dependent Variable			
Carbon dioxide (CO_2) emissions	CO_2	CO2e/capita	-----
Independent Variables			
Renewable energy	REC	% of total final	Negative

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Variables	Symbol	Measurement	Expected Sign
consumption		energy consumption	
Urban population	URP	% of total population	Positive
Forest area	FA	% of land area	Negative
Access to clean fuels and technologies	ACF	% of population	Negative
Energy use	ENU	kg of oil equivalent per capita	Positive

Cross-Section Dependence (CSD) Test
The cross-section dependence (CSD) test is a crucial diagnostic tool in panel data analysis, particularly when dealing with datasets involving multiple cross-sectional units (e.g., countries, industries) over time. It examines whether unobserved common factors or shocks affect multiple cross-sections simultaneously, potentially leading to biased or inconsistent estimates if ignored. CSD often arises in economic data due to globalization, shared economic policies, or regional dependencies. Ignoring cross-section dependence may invalidate the results of standard panel data techniques, such as fixed or random effects models. The Pesaran Cross-Section Dependence (CD) test is widely used to detect such dependence, based on the average correlation of residuals across cross-sections.

CIPS Unit Root Test
The CIPS (Cross-Sectionally Augmented Im-Pesaran-Shin) unit root test is a widely used method in panel data analysis to test for stationarity, particularly when dealing with cross-sectional dependence across units. Unlike traditional unit root tests that assume cross-sectional independence, the CIPS test accommodates the possibility that individual cross-sections (e.g., countries or regions) may be influenced by common factors. The test augments the standard unit root procedure by incorporating the cross-sectional averages of the variables as additional regressors, thereby controlling for cross-sectional dependence. This makes the CIPS test particularly useful in studies where economic, environmental, or social shocks can affect multiple units simultaneously. The null hypothesis of the CIPS test is that the variable contains a unit root (i.e., it is non-stationary), while the alternative hypothesis suggests that the variable is stationary. If the variable is found to be non-stationary, it may require differencing or transformation before proceeding with further analysis

Westerlund Panel Cointegration Test
The Westerlund Panel Cointegration Test is a widely used method for determining the long-run equilibrium relationship between variables in panel data settings, particularly when dealing with multiple cross-sectional units over time. Unlike traditional cointegration tests (such as the Engle-Granger or Johansen tests) that are designed for time

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series data, the Westerlund test is specifically designed to handle panel data and accounts for potential cross-sectional dependence and heterogeneity across units. The test examines whether a cointegrating relationship exists between the dependent and independent variables, implying a stable long-term relationship despite short-term fluctuations. Westerlund's approach includes two main statistics: the group-mean statistic and the panel-statistic, both of which are used to test for cointegration under the null hypothesis of no cointegration. This test is advantageous because it provides more robust results in the presence of cross-sectional dependence and heterogeneity, common in economic data across countries or regions. The existence of cointegration suggests that a long-term relationship exists among the variables, allowing researchers to explore dynamic interactions, such as those between economic growth, energy use, and environmental outcomes.

Driscoll-Kraay Standard Errors

The Driscoll-Kraay Standard Errors test is a robust statistical method used in panel data analysis to address issues of heteroskedasticity and autocorrelation in the error terms across both cross-sectional units and time periods. When conducting econometric analysis with panel data, it is essential to account for potential correlations in the error terms, as these can lead to biased and inconsistent coefficient estimates. The Driscoll-Kraay standard errors are particularly useful in this context, as they provide heteroskedasticity- and autocorrelation-robust standard errors, even in the presence of cross-sectional dependence. This method adjusts the covariance matrix to ensure valid statistical inference, especially when there are short time dimensions (T) and large cross-sectional dimensions (N) in the panel. By using this approach, researchers can obtain more reliable estimates for the regression coefficients, enabling more accurate hypothesis testing and policy implications. The test is especially beneficial when the residuals exhibit cross-sectional dependence or serial correlation, common in economic and financial data.

Panel Dynamic Ordinary Least Squares

DOLS is an advanced estimation technique used in panel data analysis to model the long-run relationship between variables while accounting for potential endogeneity issues, such as simultaneity or omitted variable bias. This method is particularly useful when dealing with panel data where both short-term dynamics and long-term equilibrium relationships need to be analyzed. Unlike traditional OLS, which may suffer from bias when endogenous variables are present, Dynamic OLS corrects for endogeneity by incorporating lags and leads of the independent variables into the regression model. In the panel setting, Dynamic OLS allows for both cross-sectional and time-series variation, making it ideal for studying long-run relationships in heterogeneous data across countries or regions. The technique improves the consistency and efficiency of the estimators, making it a robust approach when working with data that might exhibit serial correlation, cross-sectional dependence, or other forms of dynamic behavior.

Results and Discussion

Table 2 shows the descriptive statistics of the variables.

Table 2: Descriptive Statistics

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Methods	CO2	REC	URP	FA	ACF	ENU
Mean	3.341467	35.05237	52.2796	30.12532	61.23227	1381.168
Maximum	28.19383	98.3	94.941	92.21725	100	14228.58
Minimum	0.032602	0	8.854	0.007862	0.3	114.9325
Std. Dev.	3.981141	30.31501	19.15388	21.97934	36.73799	1598.408
Skewness	2.360451	0.571136	0.0281	0.36554	-0.41992	3.963628
Kurtosis	10.22936	1.999245	2.245391	2.185988	1.591041	26.48069
Jarque-Bera	8132.232	251.5784	62.46038	130.5828	293.4888	66997.27

The descriptive statistics provide an overview of the key variables. The mean values indicate average levels for the panel data, where CO_2 emissions average 3.34 metric tons per capita, while renewable energy consumption stands at 35.05%, and energy use per capita shows a significantly high mean of 1381.17 kg of oil equivalent. Median values, such as 1.95 for CO_2 and 28.1 for REC, highlight the central tendency of the data, often lower than the mean due to skewness. The maximum and minimum values reflect wide variations across the sample, with CO_2 emissions ranging from 0.03 to 28.19, and energy use per capita exhibiting the largest spread (114 to 14,228), signaling considerable heterogeneity. The standard deviation highlights variability, with energy use per capita (1598.40) and renewable energy consumption (30.31) showing significant dispersion. Skewness values reveal the data's asymmetry; CO_2 emissions (2.36) and energy use per capita (3.96) are highly positively skewed, indicating most observations are concentrated near the lower end, while ACF has a mild negative skew (-0.41). The kurtosis further underscores this asymmetry, with CO_2 emissions (10.22) and energy use per capita (26.48) exhibiting extreme peaks, suggesting heavy-tailed distributions. The Jarque-Bera test for normality confirms that all variables are non-normally distributed, as evidenced by p-values of zero or near zero. Table 3 shows the CSD test for ready reference.

Table 3: Cross-Section Dependence (CSD) Test Estimates

Variables	CD-test	p-value	corr	abs(corr)
CO_2	44.24	0	0.14	0.52
REC	28.22	0	0.089	0.495
URP	178.92	0	0.567	0.8
FA	-----	-----	-----	-----
ACF	-----	-----	-----	-----
ENU	69.18	0	0.219	0.565

The results of the cross-section dependence test indicate significant dependence among the variables analyzed, as evidenced by the low p-values (all equal to 0) for each variable, suggesting that the null hypothesis of no cross-sectional dependence can be rejected. The

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CD-test statistics for variables such as CO_2 (44 .24), REC (28.22), URP (178.92), and ENU (69.18) further confirm this, with URP showing the highest test statistic, indicating a strong correlation (0.567) and absolute correlation (0.8). The other variables, CO2 and REC, exhibit lower correlations (0.14 and 0.089, respectively), but still indicate some level of dependence. Overall, these results suggest that the variables are interrelated, which may have implications for further analysis and modeling in the context of the study. Table 4 shows the CIPS unit root test estimates.

Table 4: CIPS Unit Root Test Estimates

Level Estimates												
Variables	**NOC** Critical Values				**Constant** Critical Values				**Constant & Trend** Critical Values			
	CIPS	10%	5%	1%	CIPS	10%	5%	1%	CIPS	10%	5%	1%
CO_2	-1.800	-1.440	-1.520	-1.630	-2.243	-2.020	-2.080	-2.170	-2.796	-2.510	-2.560	-2.650
REC	-1.689	-1.440	-1.520	-1.630	-2.109	-2.020	-2.080	-2.170	-2.368	-2.510	-2.560	-2.650
URP	-1.471	-1.440	-1.520	-1.630	-1.413	-2.020	-2.080	-2.170	-1.261	-2.510	-2.560	-2.650
FA	-1.020	-1.440	-1.520	-1.630	-1.164	-2.020	-2.080	-2.170	-1.079	-2.510	-2.560	-2.650
ACF	0.406	-1.440	-1.520	-1.630	-1.297	-2.020	-2.080	-2.170	-1.265	-2.510	-2.560	-2.650
ENU	-1.891	-1.440	-1.520	-1.630	-2.906	-2.020	-2.080	-2.170	-2.863	-2.510	-2.560	-2.650
First Difference Estimates												
Variables	**NOC** Critical Values				**Constant** Critical Values				**Constant & Trend** Critical Values			
	CIPS	10%	5%	1%	CIPS	10%	5%	1%	CIPS	10%	5%	1%
CO_2	-4.647	-1.440	-1.520	-1.630	-4.776	-2.020	-2.080	-2.170	-5.146	-2.510	-2.560	-2.650
REC	-4.974	-1.440	-1.520	-1.630	-5.171	-2.020	-2.080	-2.170	-5.281	-2.510	-2.560	-2.650
URP	-1.151	-1.440	-1.520	-1.630	-1.369	-2.020	-2.080	-2.170	-2.395	-2.510	-2.560	-2.650
FA	-	-	-	-	-	-	-	-	-	-	-	-

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Level Estimates												
Variables	**NOC**				**Constant**				**Constant & Trend**			
	Critical Values				**Critical Values**				**Critical Values**			
	CIPS	**10%**	**5%**	**1%**	**CIPS**	**10%**	**5%**	**1%**	**CIPS**	**10%**	**5%**	**1%**
	1.842	1.440	1.520	1.630	1.963	2.020	2.080	2.170	2.199	2.510	2.560	2.650
ACF	-1.765	-1.440	-1.520	-1.630	-1.765	-2.020	-2.080	-2.170	-1.478	-2.510	-2.560	-2.650
ENU	-4.360	-1.440	-1.520	-1.630	-4.818	-2.020	-2.080	-2.170	-5.015	-2.510	-2.560	-2.650

The results of the Pesaran CIPS unit root test indicate the presence of unit roots in the level series for most variables, as their CIPS values are greater than the critical values at the 10%, 5%, and 1% significance levels. The results of the Pesaran CIPS unit root test indicate that the variables CO_2, REC, URP, and ENU are stationary at level, as their CIPS values are less than the critical values at the 10%, 5%, and 1% significance levels, suggesting that these variables do not have a unit root and are mean-reverting. In contrast, the variables FA and ACF are non-stationary at level, as their CIPS values exceed the critical values, but they become stationary after taking the first difference, as evidenced by their CIPS values falling below the critical values at all significance levels. Table 5 shows the Westerlund cointegration estimates.

Table 5: Westerlund Cointegration Test Estimates

Statistic	Value	Z-value	P-value	Robust P-value
Gt	-3.196	-8.604	0	0
Ga	-8.151	4.083	1	0.16
Pt	-23.054	-5.355	0	0
Pa	-9.35	-1.455	0.073	0

The Westerlund cointegration test results for panel data show mixed evidence of cointegration among the variables. The Group statistic (Gt) indicates strong cointegration, with a p-value of 0, suggesting rejection of the null hypothesis of no cointegration. However, the Augmented Group statistic (Ga) has a p-value of 1, indicating no cointegration at the augmented group level. The Panel statistic (Pt) provides strong evidence of cointegration, with a p-value of 0, rejecting the null hypothesis of no cointegration. Lastly, the Augmented Panel statistic (Pa) has a p-value of 0.073, which is slightly above the usual 5% significance level, indicating weak evidence for cointegration. Overall, the results suggest significant cointegration at the group and panel levels, while the evidence at the augmented group and panel levels is less definitive. Table 6 shows the Driscoll-Kraay standard errors test estimates.

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Table 6: Driscoll-Kraay Standard Errors Estimates

Variables	Coef.	Std. Err.	t	P>t	[95% Conf.	Interval]
REC	-0.03861	0.004504	-8.57	0	-0.04778	-0.02945
URP	0.007888	0.003314	2.38	0.023	0.001146	0.014629
FA	0.045084	0.007162	6.29	0	0.030512	0.059656
ACF	-0.00793	0.00232	-3.42	0.002	-0.01265	-0.00321
ENU	0.001853	0.000122	15.15	0	0.001604	0.002102
Constant	0.850835	0.463215	1.84	0.075	-0.09158	1.793252

The Driscoll-Kraay standard errors regression results for carbon emissions (CO_2) in emerging and developing countries highlight the complex relationship between various socio-economic and energy-related variables.The negative coefficient of -0.03861 for renewable energy use (p <0.001) indicates that as countries increase their share of renewable energy in total energy consumption, carbon emissions tend to decrease. This finding is supported by Mukhtarov et al. (2022), who demonstrated that greater renewable energy consumption correlates with significant reductions in carbon emissions in oil-rich economies. Adebayo et al (2022) also provided evidence showing that countries adopting renewable energy experience a decline in carbon emissions over time. The positive relationship between urban population and carbon emissions (0.007888, p = 0.023) suggests that as urbanization increases, so do emissions. This finding is supported by studies indicating that urban areas, characterized by higher energy consumption and transportation needs, contribute significantly to carbon emissions. For instance, Ali et al (2019) found that urbanization leads to increased energy demand and higher emissions due to concentrated industrial activities and transportation networks. Furthermore, the research by Seto et al. (2014) emphasizes that urbanization is a key driver of global carbon emissions, as cities account for a substantial portion of energy consumption and greenhouse gas emissions. The positive coefficient of 0.045084 for forest area (p < 0.001) indicates that as the area covered by forests increases, carbon emissions also tend to rise. This counterintuitive finding may be attributed to several factors, including land-use changes and the management practices associated with forested areas. The work of Le Quéré et al. (2018) highlights that the dynamics of carbon emissions in forested areas can be complex, as factors such as forest age, type, and management practices significantly influence overall emissions. The negative coefficient of -0.00793 (p = 0.002) for access to clean fuels and technologies indicates that improving access to cleaner energy technologies is associated with lower carbon emissions. This finding aligns with research demonstrating that the adoption of clean energy solutions significantly reduces reliance on fossil fuels, thereby decreasing emissions. For instance, a study by IEA (2020) highlights that increased access to clean cooking solutions and renewable energy sources can lead to substantial reductions in household and community-level carbon emissions. The positive relationship between energy usage and carbon emissions (0.001853, p < 0.001) reflects the well-established fact that higher energy consumption leads to increased CO2 emissions. This finding is consistent with numerous studies that demonstrate the direct correlation between energy use, particularly from fossil fuel sources, and greenhouse gas emissions. For instance, a comprehensive analysis by Waheed et al (2019).found that as energy consumption rises, CO_2 emissions increase significantly, underscoring the reliance on carbon-intensive energy sources. Furthermore, the Global Carbon Project (2022)

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highlights that energy-related emissions are the largest contributor to global CO_2 emissions, reinforcing the notion that increased energy usage is a primary driver of carbon emissions. Table 7 shows the panel dynamic ordinary least squares estimates for ready reference.

Table 7: Panel Dynamic Ordinary Least Squares (DOLS) Estimates

Variables	Coefficient	Std. Error	t-Statistic	Prob.
REC	-0.00713	0.002083	-3.42476	0.00064
URP	0.010588	0.002632	4.023097	6.17E-05
FA	-0.0141	0.003098	-4.54958	6.02E-06
ACF	-0.00198	0.00164	-1.20612	0.228052
ENU	0.002663	4.85E-05	54.94801	5.86E-307
Statistical Test				
R-squared	0.994466	Mean dependent var		2.376789
Adjusted R-squared	0.98923	S.D. dependent var		2.651621
S.E. of regression	0.275178	Sum squared resid		77.1619
Long-run variance	0.065347			

The Panel Dynamic OLS (DOLS) regression results for carbon emissions (CO_2) across 77 emerging or developing countries reveal several significant insights into the relationship between socio-economic and energy variables and carbon emissions. The coefficient for renewable energy use (-0.00713, p = 0.00064) indicates a negative relationship with carbon emissions, suggesting that higher use of renewable energy reduces emissions. This finding is supported by recent research that highlights the effectiveness of renewable energy in mitigating climate change. For example, a study by Li & Wang, (2023) demonstrated that countries increasing their renewable energy share experienced significant declines in carbon emissions, particularly in the electricity generation sector. Additionally, research by Mohamed & Saad (2024) found that investments in renewable energy technologies lower emissions. Furthermore, a meta-analysis by IRENA (2021) emphasized that scaling up renewable energy deployment is crucial for achieving global climate targets, as it directly correlates with reductions in greenhouse gas emissions. The coefficient for urban population (0.010588, p = 6.17E-05) shows a positive relationship with carbon emissions, indicating that as urban populations grow, carbon emissions tend to increase. This result is consistent with the understanding that urbanization often leads to higher energy consumption and greater reliance on fossil fuels for transportation, heating, and electricity. Study by Chen et al (2023) suggests a Kuznets curve relationship between economic urbanization and carbon emissions, indicating that urbanization contributes significantly to increased emissions through energy consumption related to land urbanization. Additionally, Sadorsky (2014) found that higher levels of urbanization correlate with increased carbon emissions across over 80 countries, reinforcing the idea that urban growth leads to higher emissions. Furthermore, Zhang et al (2021) demonstrated that urban expansion and population density are positively correlated with carbon emissions, emphasizing that as urban areas grow, emissions tend to rise. The negative relationship

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between forest area (-0.0141, p = 6.02E-06) and carbon emissions reflects the vital role of forests in carbon sequestration, indicating that as forested areas increase, carbon emissions tend to decrease. This finding is supported by extensive research demonstrating that forests act as significant carbon sinks, absorbing CO_2 from the atmosphere and storing it in biomass and soil. For instance, Pan et al. (2011) highlighted that global forests sequester approximately 2.6 billion metric tons of carbon annually, underscoring their importance in mitigating climate change. Additionally, a study by Piao et al. (2013) found that forest expansion and improved forest management practices can enhance carbon storage, further contributing to emissions reductions. Furthermore, research by Le Quéré et al. (2018) emphasizes that maintaining and restoring forest ecosystems is crucial for achieving global climate targets, as they play a key role in the carbon cycle. The positive relationship between energy usage (0.002663, p < 0.001) and carbon emissions is highly significant, indicating that increased energy consumption leads to higher emissions. This finding aligns with a substantial body of literature that underscores the direct link between energy use and greenhouse gas emissions. For example, research by Ozturk and Acaravci (2010) demonstrated that higher energy consumption, particularly from fossil fuel sources, is a primary driver of CO_2 emissions in both developed and developing countries.

Conclusions and Policy Recommendation

This study examined the key determinants of CO_2 emissions in 77 emerging and developing economies, with a particular focus on the roles of renewable energy consumption, urbanization, forest cover, access to clean fuels and technologies, and overall energy use. A critical component of the analysis involved addressing cross-sectional dependence (CSD) among the variables to ensure robust econometric results. The CIPS test—a second-generation panel unit root test—was employed to account for CSD. Furthermore, the Westerlund Cointegration Test confirmed a long-run equilibrium relationship among CO_2 emissions and the selected explanatory variables, supporting the relevance of long-term policy interventions. To provide reliable empirical evidence, advanced econometric techniques such as Driscoll–Kraay standard errors and Panel Dynamic OLS (DOLS) were utilized. The findings from the Driscoll–Kraay estimates highlight the significant contribution of renewable energy adoption to reducing CO_2 emissions, reinforcing the argument that clean energy transition is a vital pathway for climate mitigation in developing regions. However, the results also indicate that structural barriers—including limited renewable energy infrastructure, financing constraints, and the slow pace of technological transformation—continue to hinder the full environmental benefits of renewable energy in these economies. Urbanization was shown to have a positive and statistically significant impact on emissions, suggesting that rapid urban growth often increases reliance on energy-intensive activities and fossil fuel consumption. Meanwhile, the positive association between forest area and CO_2 emissions indicates ongoing challenges related to land-use change and deforestation, which remain major contributors to environmental degradation in emerging economies. These outcomes underscore the importance of coordinated strategies that jointly address sustainable urban planning, forest conservation, and clean energy expansion. The DOLS results further confirm the long-term role of renewable energy in minimizing emissions, while also demonstrating that rising energy demand continues to be a leading source of carbon output. Although access to clean fuels and technologies was negatively related to emissions, the effect lacked statistical significance, implying that improvements in household-level clean energy access may require complementary national-level reforms to meaningfully influence emission trajectories. Overall, the findings reveal that CO_2 emissions in

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emerging economies are shaped by a complex interplay of demographic, infrastructural, and environmental factors. Therefore, comprehensive and integrated policy frameworks—emphasizing renewable energy deployment, energy-efficiency improvements, sustainable urban development, and forest resource protection—are essential for achieving low-carbon growth and long-term environmental sustainability in rapidly developing regions.

Policy Recommendations

To effectively reduce CO_2 emissions, policymakers should place strong emphasis on accelerating the transition toward renewable energy systems. Financial incentives—such as tax credits, subsidies, and concessional financing—can encourage businesses and households to adopt cleaner technologies. Strengthening environmental regulations on fossil fuel use, alongside promoting energy-efficiency measures across industrial, commercial, and residential sectors, will further contribute to emission reductions. Public awareness initiatives should also be expanded to educate citizens about sustainable energy practices and the benefits of reducing individual carbon footprints. Governments must establish a supportive regulatory environment that facilitates renewable energy development. This includes simplifying permitting procedures, investing in research and development to improve renewable technology performance, and implementing mechanisms such as feed-in tariffs or power purchase agreements to provide reliable returns for clean energy producers. Public–private partnerships can also play a vital role in scaling renewable infrastructure and mobilizing essential investment to reduce dependency on fossil fuels. As urbanization continues to intensify, sustainable urban planning is critical. Policies should prioritize efficient public transport systems to reduce reliance on private vehicles, encourage mixed-use development to promote walking and cycling, and enforce green building standards to improve energy performance in urban infrastructure. Increasing the availability of urban green spaces can improve air quality and enhance the overall environmental well-being of metropolitan populations.

To address forest degradation and promote ecological resilience, governments should strengthen land-use governance and enforce sustainable logging practices. Reforestation initiatives and incentives for community-based forest management can engage local populations in conservation while supporting economic livelihoods. Additionally, enhanced international collaboration and climate financing can strengthen national efforts to protect and expand forest resources. Expanding access to clean fuels and modern technologies is essential for both environmental sustainability and public health. Investment in distribution networks for clean cooking fuels—particularly in rural and low-income communities—along with targeted subsidies can accelerate the transition away from traditional biomass fuels. Public communication campaigns should highlight the environmental and health benefits of clean fuel use, encouraging wider adoption and behavioral change. Finally, managing energy consumption more efficiently is crucial for mitigating CO_2 emissions. Governments should enforce energy-efficiency standards for appliances, buildings, and industrial processes, while offering incentives for retrofits and energy-saving technologies. Encouraging the use of smart energy systems and demand-side management practices can further reduce unnecessary consumption. By cultivating a culture of energy conservation, policymakers can significantly limit the environmental impact of rising energy demand.

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