Technological Sustainability

Climate finance, green technologies, energy transition and load capacity factor in MINT economies: assessing the environmental sustainability and validity of LCC hypothesis

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Abstract

Purpose – This study aims to evaluate the interplay of climate finance, green technologies, and energy transition in shaping environmental sustainability within the MINT economies (Mexico, Indonesia, Nigeria, Turkey), using the load capacity factor (LCF) as a comprehensive ecological indicator.

Design/methodology/approach – The study adopts the Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) approach, capturing periods from 2000 to 2021. The robustness of the findings is subsequently reinforced through the application of Common Correlated Effects Mean Group and Dynamic Common Correlated Effects Mean Group (DCCEMG) estimators.

Findings – The results reveal that climate finance significantly enhances the LCF, affirming its role in promoting environmental sustainability through targeted investments in renewables. Energy transition exerts a short-term negative impact on LCF, reflecting the "transitional paradox," where reliance on energies temporarily exacerbates ecological strain. However, green technologies show no statistically significant effects, likely due to fragmented adoption in MINT economies. Lastly, the study explores the U-shaped trajectory proposed by the LCC (load capacity curve) hypothesis and finds that it is not statistically validated for MINT economies.

Practical implications – Climate finance should prioritize high-impact renewables over transitional fuels to accelerate long-term sustainability. Moreover, energy transition timelines must account for short-term ecological costs; for instance, MINT nations could pair gas flaring reduction with decentralized solar grids to mitigate transitional harm. Policymakers should consider implementing targeted financial instruments to channel investments into sectors with the highest environmental returns.

Originality/value – This study introduces pioneering contributions to climate finance and sustainability research by developing a first-of-its-kind climate finance index, which captures the pragmatic energy transition strategies of emerging economies by integrating both renewable and transitional fuel investments.

Keywords Climate finance, Energy transition, Green tech, Environmental quality

Paper type Research article

1. Introduction

The modern-day world is facing a growing climate crisis, mainly due to the excessive use of fossil fuels like coal, oil, and gas (Johnsson *et al*., 2019; Kreps, 2020). These energy sources release large amounts of greenhouse gases (GHGs), most especially carbon dioxide (CO_2), into the atmosphere, which leads to global warming and extreme weather conditions inherent in environmental stress (Yoro and Daramola, 2020). However, in an attempt to prevent further environmental damage, countries have recently been putting several efforts toward transitioning to cleaner and more sustainable energy sources, such as solar, wind, and hydropower. Within this context, climate finance (CLF), green technologies and energy transition have emerged as critical mechanisms for mitigating environmental degradation and fostering a more sustainable development trajectory (Li *et al*., 2023; Strielkowski *et al*., 2021). If these mechanisms are properly put in place, they will go a long way in helping toward the decline of global carbon emissions and consequently slow down climate change (IPCC, 2022). However, the process is complex and requires strong policies, long-term planning, and international cooperation to ensure that clean energy is both accessible and affordable (Bletsas *et al*., 2022).



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Within the developing world, the economies of Mexico, Indonesia, Nigeria and Turkey, collectively known as the MINT economies, with their rapidly expanding economic force, harness substantial energy demands. This is coupled with their considerable potential for renewable energy development, thus positioning them as crucial players in the global effort to combat climate change (Akram *et al*., 2022). Notably, several key factors are intricately connected in shaping the energy transition within the MINT economies. CLF cannot be underemphasized in the sense that it plays a cogent role in providing the necessary capital for investments in green technologies and the development of renewable energy infrastructure (Han and Jun, 2023; Lee, 2020). However, in order to address the pressing challenges of climate change, the collective aspiration of developing nations, including the MINT economies, is confronted by a substantial CLF gap (Cadman and Sarker, 2022; Omukuti, 2024). The United Nations Conference on Trade and Development (UNCTAD) estimates that developing nations will require approximately $1.1tn annually in climate financing by the year 2025, and this figure in the future is projected to escalate to $1.8tn by 2030. Consequently, this immense financial need buttresses the enormous investment required to facilitate the transition toward cleaner energy sources and to implement necessary adaptation measures.

While developed nations have made pledges to provide financial support to their developing counterparts, the current commitments are often perceived as inadequate in the face of the monumental needs (Live Mint, 2025). The pledge made by wealthy countries to provide $300 billion annually by 2035, although a threefold increase from previous targets, represents only a fraction of the $1.3tn per year that developing countries assert is necessary to effectively combat climate change (Live Mint, 2024). Though this discrepancy stands as a fundamental point of contention in global climate negotiations, it portrays the ongoing struggle to bridge the financial divide between developed and developing nations in addressing this shared global challenge. Nonetheless, all these indicate that CLF is critical to bolstering environmental sustainability and addressing challenges such as the load capacity factor (LCF) in MINT economies. This is believed to be efficient when the development and modernization of renewable energy infrastructures are being funded (Moskwa-Bęczkowska and Moskwa, 2022; Strielkowski *et al*., 2021).

The adoption and widespread deployment of green technologies, such as solar, wind and energy storage solutions, are fundamental to achieving issues surrounding environmental sustainability whilst reducing the reliance on carbon-intensive fossil fuels (Alabi, 2025; Guo *et al*., 2020; Li *et al*., 2023). These technological innovations help stabilize the grid and maximize the consistent use of renewable power. For instance, advancements in energy efficiency and the development of supportive policies not only lower GHG emissions but also ensure that the intermittent nature of renewable energy is better managed, which leads to an improved LCF and a more resilient energy infrastructure (Salkuti, 2022). Inherently, CLF serves as a vital catalyst for enabling the development, deployment and scaling up of green technologies within the MINT economies. Increased availability of green financing mechanisms can play a significant role in neutralizing environmental pollution by providing crucial support for the consumption of renewable energy sources and fostering innovation in energy technologies (Habiba *et al*., 2022; Shan *et al*., 2021; Tan *et al*., 2021). More so, shifting to renewable sources such as wind, solar, and hydropower is believed to reduce GHG emissions. This decline in emissions can improve air quality and contribute to a healthier environment (Dam and Sarkodie, 2023; Kreps, 2020).

Importantly, in order to accurately assess environmental sustainability, it is crucial to employ indicators that capture the complex relationship between human activities and the natural environment (Guloglu *et al*., 2023). The LCF serves as such an indicator, calculated as the ratio of a region's biocapacity to its ecological footprint. Biocapacity represents the productive area of land and water available to meet human needs, while the ecological footprint measures the human demand on these biologically productive areas (Awosusi *et al*., 2022; Pata and Samour, 2023). An LCF value greater than or equal to 1 signifies that the environment has sufficient capacity to support the level of human activity, indicating

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environmental sustainability. Conversely, an LCF value below 1 suggests that human demand exceeds the environment's regenerative capacity, indicating an unsustainable situation (Caglar *et al*., 2023). This by contextualization considers both the supply of natural resources and the demand placed upon them, which offers a more comprehensive environmental assessment compared to indicators that focus solely on ecological footprint or carbon emissions (Awosusi *et al*., 2022).

This study pioneers the development of a novel, robust and comprehensive CLF index that quantifies public investments across renewable energy sources (hydropower, wind, geothermal, primary solid biofuels and nuclear) and transitional energy systems (natural gas and fossil fuels). Unlike existing studies that often rely on aggregated green finance data or focus on single energy sources, this index captures the multidimensional nature of climate financing by integrating both green technologies and transitional fuels. The index's unique weighting of investments based on their carbon intensity and alignment with national energy transition goals ensures its robustness, making it the first of its kind to holistically reflect the interplay of policy priorities, financial flows and environmental outcomes in MINT economies. This granularity is vital for MINT economies, where fiscal constraints and energy security concerns often necessitate a mixed approach to financing. In addition, this study tests the validity of the load capacity curve (LCC) hypothesis in MINT economies, offering fresh evidence on whether economic growth can coexist with ecological regeneration in rapidly industrializing contexts. The integration of CLF and energy transition dynamics into the LCC framework extends the theoretical discourse beyond the environmental Kuznets curve (EKC), which narrowly focuses on income–emissions relationships. This novel integration reveals how targeted financial allocations to renewables and transitional technologies can bend the LCC upward, enabling MINT nations to achieve environmental sustainability without sacrificing development. However, it should be noted that while the LCC hypothesis is explored in this study, similar explorations have been attempted in other contexts and this limitation is acknowledged in our analysis.

The remainder of the study is sectioned into different parts. The next section presents the literature review, while the third section explains the theoretical framework. The methodology and data were discussed in the fourth section. The fifth section presents the results and discussion of the findings, and lastly, the study ends with a section revealing the conclusion and policy recommendations.

2. Literature review

This study on environmental sustainability in the context of CLF, green technologies, and energy transition provides a full-fledged view of how each of these individual mechanisms affects the LCF, whilst validating the LCC hypothesis across MINT economies. These relationships can sometimes be a bit complex and sometimes counterintuitive. For instance, CLF and green technologies are crucial toward promoting environmental sustainability, yet their impacts vary across contexts. Ali *et al*. (2023) offered a foundational framework for understanding the interplay between CLF, green technologies and energy transition in MINT economies. Their finding indicated that renewable energy and clean energy access improve the LCF while non-renewable energy and certain aspects of technological innovation lower it. This provides a starting point for evaluating environmental sustainability measures. Complementing this view, Lee *et al*. (2023) emphasize that green finance can accelerate energy transition, though its effectiveness is moderated by regional climate risks. This suggests that the supportive role of CLF may be context-specific, contingent upon regional socioeconomic and environmental conditions. Conversely, Sethi *et al*. (2023) reported that green finance and innovation increased CO_2 emissions in developing countries, suggesting implementation inefficiencies or misaligned policies. These contradictions portray the importance of contextual factors, such as policy frameworks and technological readiness, in determining outcomes (Zhang *et al*., 2022; Lee *et al*., 2023). Recent literature has also

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highlighted the risks of technological myopia in the context of sustainability. Crowther (2023) argues that while technological innovations such as renewables are essential for decarbonization, their adoption is often driven by immediate economic benefits without sufficient consideration of long-term, system-wide and intergenerational impacts. The author emphasizes that even green technologies can have unintended consequences, and that a holistic, life cycle-based evaluation is necessary to ensure that present solutions do not create future sustainability challenges. This perspective reveals the importance of integrating broader social and environmental assessments into CLF and policy frameworks, moving beyond short-term economic justifications (Crowther, 2023).

Green finance accelerates energy transition in China, yet climate risk undermines its efficacy (Lee *et al*., 2023). Similarly, Afshan *et al*. (2023) found that green finance reduces ecological footprints asymmetrically, with greater impacts at higher environmental stress levels. However, Tekin *et al*. (2024) reported that CLF paradoxically reduces LCF in OECD countries, possibly due to misallocation or short-term trade-offs. More so, Aydın *et al*. (2024) and Anas *et al*. (2023) illustrate that investment freedom and green finance, respectively, can lead to improvements in LCF; however, these effects are heterogeneous across countries. For instance, while investment freedom enhances environmental quality in Latvia, it has the opposite effect in New Zealand (Aydın *et al*., 2024). Similarly, green technological innovation, which is generally associated with a reduction in environmental degradation, can have varying effects. In some contexts, such as in Germany and Singapore, the direction of impact diverges (Aydın and Degirmenci, 2023; Sethi *et al*., 2023). This proves that the translation of technological advances into sustainability outcomes is mediated by country-specific institutional and economic factors. In the same vein, Çağlar *et al*. (2024) observed that green technology and renewable energy enhance LCF in top renewable economies.

Methodologically, previous studies span an array of econometric techniques, from the Driscoll–Kraay standard error estimator (Ali *et al*., 2023) and panel cointegration tests (Aydın and Degirmenci, 2023) to the use of CS-ARDL, AMG, and CCEMG approaches (Ali *et al*., 2023; Anas *et al*., 2023; Tekin *et al*., 2024). This methodological diversity not only reinforces the robustness of the findings but also contributes to an ongoing debate regarding the validity of the LCC hypothesis. For instance, while Aydın *et al*. (2024) and Bekun *et al*. (2024) report mixed evidence, with some countries confirming and others refuting the LCC hypothesis, others, like Özkan *et al*. (2023) and Alola *et al*. (2023), find support for an inverted U-shaped relationship between economic growth and LCF. These conflicting findings suggest that the relationship between economic development and environmental sustainability is highly sensitive to the underlying energy portfolio and technological adoption. Notably, the impacts of economic growth and financial development also appear to be double-edged. For instance, while economic growth tends to exacerbate ecological degradation by increasing the ecological footprint (Adebayo *et al*., 2022; Yang *et al*., 2023), several studies indicate that robust environmental policies and green investments can mitigate these effects. Ali *et al*. (2023) and Javed *et al*. (2024) show that environmental taxation and policy stringency, when combined with green investments, can significantly reduce carbon emissions and improve the LCF. Moreover, Afshan *et al*. (2023) and Han *et al*. (2024) provide evidence that green finance and eco-innovation have quantile-dependent impacts on environmental outcomes. Studies by Zhang *et al*. (2022) and Inuwa *et al*. (2024) reveal bidirectional relationships among renewable energy consumption, environmental pollution and climate change, which indicates that technological advancements can both promote renewable energy adoption and curb CO_2 emissions. However, contrasting evidence from Awosusi *et al*. (2022) and Uche and Ngepah (2024) illustrates that the effects of technological innovation on the LCF may vary considerably depending on factors such as resource rents and the broader economic context. This signals that while technological innovation holds promise for environmental sustainability, its benefits may be contingent upon supportive policy frameworks and the complementary use of renewable energy sources.

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Recent contributions (e.g. Dai *et al*., 2025; Voumik *et al*., 2024) further stress the importance of incorporating emerging drivers in finance and technology into the sustainability discourse. These studies illustrate that while green finance and fintech innovations promote sustainable growth, they also introduce new challenges that require dynamic risk management strategies. Additionally, research focusing on top renewable economies (Çağlar *et al*., 2024) and developed countries (Tekin *et al*., 2024) calls for an integrated policy mix that leverages green technology and renewable energy to address trade-offs between economic growth and environmental quality. Economic growth often conflicts with sustainability. In MINT and BRICS nations, growth correlates with higher ecological footprints and lower LCF (Adebayo *et al*., 2022; Yang *et al*., 2023). Natural resource rents further strain environmental quality, as seen in South Africa (Uche and Ngepah, 2024) and Egypt/Turkey (Zhu *et al*., 2024). However, Awosusi *et al*. (2022) validated the EKC hypothesis in South Africa, indicating that growth's negative impacts may diminish over time with targeted policies. This divergence highlights the need for policies that decouple growth from resource extraction, such as green fiscal reforms (Ali *et al*., 2023; Ramzan *et al*., 2022).

It is thus evident that the effectiveness of green finance and technology is highly context-dependent, and the literature reveals both supportive and contradictory findings. For example, green finance tends to be most effective under strong institutional frameworks, robust policy support, and when targeted at sectors with high environmental impact. Conversely, in contexts with weak governance or misaligned incentives, green finance may have limited or even adverse effects. This study responds by integrating a novel CLF index and advanced econometric methods to address these gaps. Furthermore, this study builds on the foundational works of Dasgupta *et al*. (2002) and Grossman and Krueger (1995) with respect to the EKC hypothesis, which posits an inverted-U relationship between environmental degradation and income, and provides a critical backdrop for interpreting the LCC hypothesis and the empirical findings of this study.

In synthesizing these studies, several critical arguments and gaps emerge, which this current study intends to bridge. First, while there is a general consensus on the positive role of renewable energy and green finance in enhancing the LCF, the heterogeneity of findings, especially regarding the impact of technological innovation and economic growth, indicates that a one-size-fits-all policy may be inadequate. Second, the mixed evidence on the LCC hypothesis across different national contexts highlights the need for further research into the conditions under which economic growth might eventually lead to environmental restoration. Finally, the integration of advanced econometric techniques across these studies enriches the understanding of dynamic relationships in the energy–environment nexus, yet also highlights the persistent challenges in reconciling conflicting empirical results.

3. Theoretical framework

This study evaluates the LCC hypothesis in an attempt to investigate the impact of CLF, green technologies, energy transition and the LCF. The theoretical underpinnings of the LCC hypothesis are closely linked to the concepts of the scale effect, the composition effect and the technique effect. In the early phases of economic development, the scale effect dominates, where increased production and consumption, driven by economic growth, lead to greater environmental pollution and resource depletion (Pata and Samour, 2023). As economies progress, the composition effect comes into play, with a shift from polluting industries toward cleaner manufacturing and service sectors (Awosusi *et al*., 2022). Simultaneously, the technique effect emerges, characterized by the adoption of more environmentally friendly and resource-efficient technologies, which further contributes to reducing environmental degradation (Guloglu *et al*., 2023; Han and Jun, 2023).

The LCC hypothesis suggests that in the initial stages of economic development, environmental degradation tends to increase, leading to a decrease in the load capacity, primarily due to the dominance of industrialization and resource-intensive activities

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(Aydın and Degirmenci, 2023; Zhu *et al.*, 2024). However, as economies mature and income levels rise beyond a certain threshold, further economic growth can lead to an improvement in environmental quality and an increase in the load capacity. This turnaround is attributed to factors such as the adoption of cleaner technologies, coupled with the implementation of stringent environmental regulations (Anas *et al.*, 2023; Javed *et al.*, 2024). The U-shaped relationship inherent in the LCC as presented in Figure 1 was inspired by Kuznets' (2019) study on income inequality and economic growth. However, in this context, whilst validating the LCC hypothesis, the study examines how CLF, green technologies and energy transition influence LCF, which is a measure of environmental sustainability (Ali *et al.*, 2023; Inuwa *et al.*, 2024).

4. Data, model, and methodology

4.1 Data

This study examines the relationship between CLF, green technologies, energy transition and LCF in MINT countries, considering annual data covering periods between 2000 and 2021. These periods were considered based on data availability for all the modelled variables. The LCF was utilized as a proxy for environmental sustainability (Siche *et al.*, 2010). The detailed information about the selected variables is described and presented in Table 1. In order to obtain reliable and consistent results that will address any possible heteroscedasticity and serial correlation issues, the parameters, except for the generated CLF index, are converted to natural logarithm forms.

With respect to the CLF variable, while the majority of previous literature utilized investments in green bonds as a measure of CLF, this study considered a more robust and inclusive approach in consideration of public financial investments on renewable hydropower, wind energy, primary solid biofuels, geothermal energy, nuclear, natural gas and fossil fuels (Klepacki *et al.*, 2021; Murgas *et al.*, 2021). Due to the pragmatic realities faced by emerging economies, the study included transitional fuels such as natural gas and fossil fuels in the CLF index. While these fuels are not strictly "green," their inclusion reflects the transitional pathways many MINT emerging countries must follow to balance energy security, affordability and gradual decarbonization. This approach acknowledges that a sudden shift to 100% renewables is often not feasible due to infrastructure, economic, and social

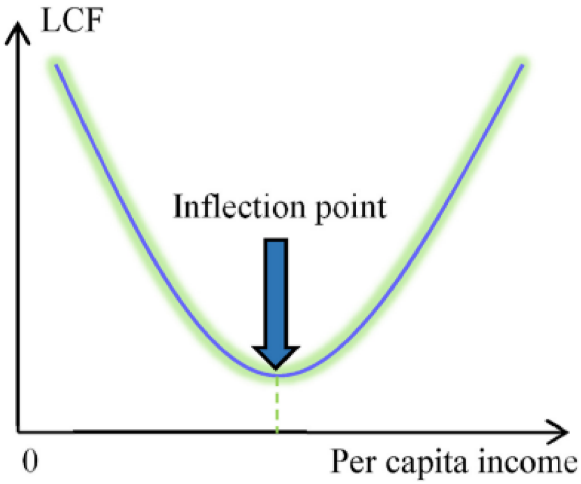


Figure 1. Graphical visualization of the LCC hypothesis. Source: Adopted from Pata and Samour (2023)

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Table 1. Description of variables

Variables	Symbol	Measure	Mean	Std. Dev.	Source
Load capacity factor	LCF	Biocapacity/ecological footprint	−0.226	0.106	Global Footprint Network
Climate Finance	CLF	Developed index of public investments on renewable hydropower, wind energy, primary solid biofuels, geothermal energy, nuclear, natural gas and fossil fuels (2021 million USD)	0.004	1.346	OECD, IRENA Public Finance Database
Green Tech	GRT	Patents on environment technologies (percentage)	−0.046	0.188	OECD
Energy Transition	EnerTr	Traditional fossil fuel to renewable energy transition	1.686	0.146	UNCTAD
Gross domestic product	GDP	Gross Domestic Product per capita (constant 2015 US dollar)	11.82	0.215	World Bank
Natural Resources	NARS	Natural resources rents % of GDP	0.51	0.585	World Bank

Source(s): Authors' own work

constraints. By capturing investments in both renewables and transitional fuels, the index provides a more accurate and policy-relevant picture of CLF flows in real-world contexts.

This study thus employed a weighted CLF index to determine CLF indicators employing each of the aforementioned seven proxies. In line with the studies of Abdi and Williams (2010) and Dai *et al.* (2021), this study established this index for the concerned MINT economies utilizing the principal component analysis (PCA) technique. The results of the PCA are presented in Table 2.

Table 2. Principal component analysis for climate finance

Component	Eigenvalue	Difference	Proportion	Cumulative
Comp1	1.73675	0.465517	0.2481	0.2481
Comp2	1.27123	0.268753	0.1816	0.4297
Comp3	1.00248	0.039763	0.1432	0.5729
Comp4	0.962714	0.087348	0.1375	0.7105
Comp5	0.875366	0.230644	0.1251	0.8355
Comp6	0.644722	0.137977	0.0921	0.9276
Comp7	0.506745	.	0.0724	1

Eigenvectors (loadings)

Variable	Comp1	Comp2	Comp3	Comp4	Comp5	Comp6	Comp7
Fossil ~ fuels	0.2664	0.2295	−0.6293	0.5981	−0.1259	−0.0548	−0.3221
Geothermal ~ En	0.5366	−0.2294	0.1605	0.0376	−0.1477	−0.7491	0.222
Natural ~ gas	0.3882	−0.2975	−0.1101	0.1528	0.7594	0.2815	0.2632
Nuclear	−0.1504	0.1117	0.6495	0.7343	0.0458	0.0329	0.0262
Wind ~ energy	0.2396	0.7367	−0.0097	−0.0771	−0.0806	0.1359	0.6073
Pry ~ solid ~ fuels	0.4872	0.3458	0.3616	−0.265	0.1811	0.0835	−0.6343
Renewable ~ hyd	0.416	−0.3624	0.1157	0.046	−0.5867	0.5745	0.0768

Source(s): Authors' own work

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4.2 Model construction

The study modelled a mathematical and econometric function in order to examine the relationship between CLF, GRT, ENERTR, GDP, GDP2 and NARS on the LCF. However, due to the likely issues of heteroscedasticity and serial correlation, the study transforms the parameters into their logarithmic form, which makes the relationships between the variables more consistent across all the levels of measurement whilst reducing the impact of extreme values (Ximei *et al*., 2025). This is constructed as follows in Eqs. (1) and (2):

$$lnLCFit = f\left(CLFit, lnGRTit, lnENERTRit, lnGDPit, ln\left(GDPit\right)^2, lnNARSit\right) \quad (1)$$

$$lnLCFit = \tau 0 + \tau 1 CLFit + \tau 2 lnGRTit + \tau 3 lnENERTRit + \tau 4 lnGDPit + \tau 5 ln\left(GDPit\right)^2 + \tau 6 lnNARSit + \varepsilon it \quad (2)$$

where *LCF* denotes LCF, GDP^2 represents the quadratic form of *GDP*, the coefficients of *CLF, GRT, ENERTR, GDP and NARS* are represented by $\tau 1,2,3,4,5,6$. $\tau 0$ stands for the constant term, ln indicates the logarithmic form, ε represents the simultaneous error term, *t* represents the periods (2000–2021) and *i* signifies the sampled MINT countries. The study's visual representation in terms of the framework is presented in Figure 2.

4.3 Empirical methods

The study follows an advanced, chronological and robust methodology presented in Figure 2 to achieve the objectives of this study. Before estimating the model's coefficients, the study first conducted a preliminary assessment of the selected variables. This involves an initial examination to understand the dataset's structure, as presented in Table 1, which shows that most of the variables appear relatively stable and within reasonable limits. In simple terms, before running the main analysis, we checked whether the data from different countries were related to each other and whether the relationships between variables were similar or different across countries. We also tested if the data were stable over time. These checks help ensure that the results are reliable and not affected by hidden patterns or differences between countries.

Additionally, the study checks for cross-sectional dependence (CSD) to assess whether shocks in one of the sampled country or unit influence others. This is necessary because panel data models usually assume that error terms are independent across different units (such as countries or firms). However, in some cases, errors may be correlated across these units, which

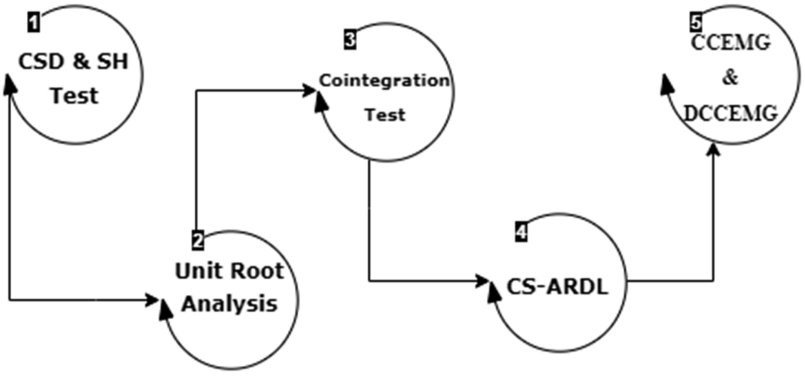


Figure 2. Econometric flowchart. Source: Authors

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translates to observations from different cross-sections influencing each other. Because of this possibility, the study tests whether the data units (or cells) behave as independent entities. To check for CSD, the study applies the Pesaran CD test (Pesaran, 2004), which assesses whether error terms across different cross-sections are correlated. The formula is given as:

$$CSD = \sqrt{\frac{2T}{N(N-1)N}}\left(\sum_{i-1}^{N-1}\sum_{k=i+1}^{N} corr_{it}\right. \tag{3}$$

The study also evaluates slope heterogeneity (SH) to determine if relationships between variables vary across different countries or groups. The findings from these assessments guide the choice between first-generation techniques, which assume no CSD, and second-generation techniques, which account for it. Therefore, the study examines SH using the test developed by Pesaran and Yamagata (2008). This test evaluates whether the relationships (slopes) between variables differ across different cross-sectional units (such as countries or firms). Instead of assuming that all units follow the same pattern, the test accounts for variations by comparing the weighted slopes of individual units. In other words, we wanted to see if the way CLF, green technology and other factors affect environmental sustainability is the same or different in each country. This helps us understand whether a single policy approach would work everywhere or if each country needs a tailored strategy. The SH test equation is presented as:

$$\widetilde{\Delta} = \sqrt{N}\left(\frac{N^{-1}\,S\% - k}{\sqrt{2k}}\right) \text{and } \widetilde{\Delta}_{adj} = \sqrt{N}\left(\frac{N^{-1}\,S\% - k}{\sqrt{\frac{2k\,(T-k-1)}{T+1}}}\right) \tag{4}$$

Further, upon considering SH and cross-sectional dependency, conventional unit root test is required. The study applies the Cross-Sectionally Augmented Im, Pesaran, and Shin (CIPS) test, a second-generation unit root test developed by Pesaran (2007). This test accounts for potential dependencies among cross-sectional units, ensuring more accurate results in determining whether the variables are stationary (i.e. their statistical properties remain constant over time) even in the presence of CSD and SH. This is specified as:

$$CIPS = \frac{1}{N}\sum\nolimits_{i=1}^{N} t_i(N,T) \tag{5}$$

Given the presence of CSD, heterogeneity and stationarity likelihood in the data, the study adopts a heterogeneous estimation approach to test for cointegration. Specifically, it applies Westerlund (2007) and Pedroni (2004) methods, which account for differences in slopes, the coefficient of determination and correlated errors. Put simply, because the countries in our sample are interconnected and may respond differently to changes, we use methods that can handle these complexities. This ensures our findings are robust and meaningful for both researchers and policymakers. The equation is specified as:

$$\Delta Yi,t = \mu' i\,d\,t + \lambda i\,(Yi,t-1-\beta' iXi,t-1) + \sum_{j=1}^{k} \varnothing ij\Delta Yi,t-\mathrm{j} + \sum_{j=1}^{k} yij\Delta Xi,t-\mathrm{j} + \varepsilon i,t \tag{6}$$

In the context of the Westerlund (2007) *Yi* represents the error correction term (ECT), which determines the presence of cointegration.

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In the final step, the study adopted an advanced econometric technique used in handling CSD and heterogeneity in panel data analysis; the CS-ARDL (Cross-Sectional Augmented Autoregressive Distributed Lag) model, developed by Chudik and Pesaran (2015). This method is particularly useful for estimating both short-term and long-term relationships between variables while addressing challenges like endogeneity, non-stationarity, and mixed-order integration. This means that the CS-ARDL model helps us understand both the immediate (short-term) and lasting (long-term) effects of CLF, green technology and energy transition on environmental sustainability, while taking into account the differences and connections between countries. The equation is expressed as:

$$H_{i,t} = \sum_{I=0}^{pw} \gamma I\, i, W_{i,t-1} + \sum_{I=0}^{pz} \boldsymbol{\beta I}\, i, Z_{i,t} - I + \varepsilon_{i,t} \tag{7}$$

Equation (7) presents the ARDL model; however, applying Eq. (2) while not considering CSD may lead to unreliable outcomes. In order to address this, Eq. (10) is modified by incorporating the cross-sectional averages of each explanatory variable individually. This adjustment helps eliminate misleading conclusions regarding the presence of a threshold effect caused by CSD.

$$H_{i,t} = \sum_{I=0}^{aw} \gamma I\, i, H_{i,t-1} + \sum_{I=0}^{az} \boldsymbol{\beta I}\, i, Z_{i,t} - I + \sum_{I=0}^{ax} a_i', I\ddot{\mathrm{X}}_{t-1} + \varepsilon_{i,t} \tag{8}$$

The average values of the dependent and independent variables are computed using the equation:

$$\ddot{\mathrm{X}}_{t-1} = \ddot{\mathrm{H}}_{i,t-1}\, \hat{\mathrm{Z}}_{i,t-1} \tag{9}$$

The lags inherent in the parameters are represented by $a_{w,}\, a_{x,}\, a_z$. $H_{i,t}$ indicates the LCF, while the $Z_{i,t}$ stands for all other explanatory variables in the model. X represents the cross sections in the absence of spill-over trends. The CS-ARDL method determines long-run coefficients whilst relying on short-run coefficients as inputs. This technique ensures that short-term dynamics inform long-term relationships. Further, Eqs. (10)–(12) outline how the mean group (*MG*) predictor is used to derive both long-run and short-run coefficients.

$$\phi_{MG} = \frac{1}{N} \sum_{i=1}^{N} \phi_i \tag{10}$$

$$\phi_{CS-ARDL,i} = \frac{\sum_{i=0}^{pz} \boldsymbol{\beta}_{\boldsymbol{I,i}}^{\boldsymbol{pw}}}{1 - \sum I = 0}\, \gamma I_{,i} \tag{11}$$

$$\begin{aligned} \Delta H_{i,t} =& \phi_i \left[H_{i,t-1} - \phi_i\, Z_{i,t}\right] - \sum_{I=1}^{aw} \gamma I, i\, \Delta_i H_{i,t-1} + \sum_{I=1}^{a_{ws-1}} I, i\, \Delta_i Z_{i,t-1} + \sum_{I=0}^{ax} a_i', I\ddot{\mathrm{X}}_{t-1} \\ &+ \varepsilon_{i,t}\ where\ \Delta_i = t - (t-1) \end{aligned} \tag{12}$$

$$\delta_i = -\left(1 - \sum_{I=1}^{a_w} \gamma I, t\right) \tag{13}$$

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$$\phi_i = \frac{\sum_{i=0}^{az} \boldsymbol{\beta}_{I,i}^{aw}}{\delta_i} \tag{14}$$

$$\phi_{MG} = \frac{1}{N} \sum_{i=1}^{N} \phi \tag{15}$$

Essentially, the MG predictor aggregates individual estimates across cross-sectional units to obtain a reliable overall estimate while accounting for variations among different units. This process helps improve accuracy and robustness in panel data analysis, particularly when dealing with CSD and heterogeneity. More so, in the CS-ARDL approach, an economy reaches equilibrium when the error correction mechanism (ECM) coefficient approaches −1. This indicates that any short-term deviations from the long-run equilibrium are fully corrected in the next period, ensuring a stable adjustment process. The ECM value reflects how quickly an economy returns to equilibrium after a shock, with a value closer to −1, which indicates a faster adjustment and a more stable long-run relationship among the variables.

5. Results

5.1 Pre-estimations

Table 3 presents the results of CSD (Panel A) and SH (Panel B). CSD is tested using t-statistics and correlation coefficients for each variable. The significant results for most variables indicate interdependencies among countries in the panel data. The SH tests (Δ~ and Δ~ *adj*) are also significant, confirming variations in relationships across cross-sectional units.

Table 4 reports unit root test results to assess the stationarity of variables at both levels and first differences. At the level, some variables, such as GDP and NARS, are nonstationary, failing to reject the null hypothesis. However, after first differencing, all variables become stationary at a 1% significance level. This justifies the need for first-difference transformations in further estimations.

Table 5 presents results from Westerlund and Pedroni tests for cointegration. The results confirmed a long-run relationship among variables. While the Westerlund test shows a weak

Table 3. Cross-sectional dependence (CSD) and heterogeneity analyses

Panel A: CSD Variables	t-stats	Corr.
LCF	4.16***	0.354
CLF	2.49***	0.3
GRTIN	−1.68*	−0.152
EnerTr	10.19***	0.887
GDP	11.39***	0.97
NARS	5.15***	0.448

Panel B: Slope heterogeneity	Delta	*p*-value
Δ~	2.768***	0.006
Δ~ *adj*	3.352***	0.001

Note(s): ***, **, * indicate significance at 1, 5 and 10% levels, respectively

Source(s): Authors' own work

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Table 4. Pesaran's CIPS unit root tests

	Level		First difference	
	Constant	Constant and trend	Constant	Constant and trend
LCF	−2.492	−3.616***	−5.453***	−5.604***
CLF	−3.963***	−3.659***	−5.160***	−4.980***
EnerTr	−2.827***	−2.699	−4.674***	−4.582***
GRTIN	−4.345***	−4.279 ***	−5.799***	−5.992***
GDP	−0.932	−1.263	−3.555***	−4.400***
GDP^2	−0.942	−1.269	−3.547***	−4.392***
NARS	−1.686	−2.575	−4.487***	−4.539***

Note(s): *** indicates significance at 1% level
Source(s): Authors' own work

Table 5. Test for cointegration

	Stat.	*p*-value
Westerlund	1.6327*	0.0513
Pedroni	1.7654**	0.0387

Note(s): ***$p < 0.01$, **$p < 0.05$, *$p < 0.10$
Source(s): Authors' own work

significance ($p = 0.0513$), the Pedroni test confirms cointegration at a 5% significance level ($p = 0.0387$). These results suggest that the selected variables maintain a stable long-term equilibrium relationship despite short-term fluctuations.

Notably, all these pre-estimation diagnostics confirm the appropriateness of the second-generation econometric technique, given the presence of CSD, SH, mixed order of integration (I(0) and I(1)), and a confirmed long-run relationship, the CS-ARDL model appears as the most appropriate econometric technique (Mehmood *et al.*, 2022; Voumik *et al.*, 2023). This approach ensures robust estimations in the sense that it addresses cross-sectional dependencies while allowing for heterogeneous responses across panel units. For this fact, the CS-ARDL appears superior to traditional panel ARDL or Fixed Effects models. This in general ensures the robustness and reliability of the estimation in the study's model.

5.2 Estimations and discussions

Table 6 presents the CS-ARDL regression estimates used to assess the long- and short-term effects of CLF, green technologies (GRT), energy transition (ENERTR), GDP, GDP^2 and natural resources (NARS) on the LCF in MINT economies. In the long run, CLF exhibits a statistically significant positive impact on the LCF at the 5% significance level, with a coefficient of 0.0038, which suggests that an increase in CLF inflows in the MINT economies is associated with an improvement in their environmental sustainability over time. Consistently, in the short run, CLF presents a statistically significant positive impact on the LCF at the 5% significance level. Though the coefficient of 0.0062 implies that an immediate increase in CLF is associated with a short-term improvement in environmental sustainability. This therefore mirrors the long-run effect, which pinpoints a consistent positive relationship between CLF and LCF in the MINT economies. This finding aligns with the studies of Afshan *et al.* (2023), Habiba *et al.* (2022), Lee *et al.* (2023), Shan *et al.* (2021) and Tan *et al.* (2021) that emphasize the crucial role of climate and green finance in spurring investments toward environmentally conscious projects. These projects, such as renewable energy initiatives and

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Table 6. CS-ARDL estimation results

Term	Variables	Coefficient	Std. Err.	z-Stat.	Prob.
Long run	CLF	0.0038**	0.0019	2.00	0.045
	LGRTIN	0.0209	0.0211	0.99	0.322
	LEnerTr	−2.5712*	1.4633	−1.76	0.079
	LGDP	−57.805	60.669	−0.95	0.341
	LGDPsq	2.4274	2.5286	0.96	0.337
	LNARS	−0.0369	0.0796	−0.46	0.643
Short run	ECT_{t-1}	−1.772***	0.2066	−8.58	0.000
	ΔCLF	0.0062**	0.003	2.43	0.015
	ΔLGRTIN	0.031	0.035	0.89	0.374
	ΔLEnerTr	−4.5451*	2.436	−1.87	0.062
	ΔLGDP	−102.158	94.254	−1.08	0.278
	ΔLGDPsq	4.1965	3.953	1.06	0.288
	ΔLNARS	−0.085	0.151	−0.56	0.574

Note(s): ***, **, * indicate significance at 1, 5 and 10% levels, respectively
Source(s): Authors' own work

energy efficiency improvements, all of which are essential for transitioning to a green economy and enhancing environmental quality (Aydın and Degirmenci, 2023). However, this finding is contrary to that of Tekin *et al*. (2024), who reported that CLF paradoxically reduces LCF in OECD countries.

Conversely, the impact of green on LCF in the long run is statistically insignificant, as revealed in Table 6. This is astonishing because, despite the widespread expectation in academic discourse that the adoption of green technologies is beneficial toward mitigating environmental degradation, which is evident through cleaner production processes and enhanced resource efficiency, the result of this study does not provide statistically significant evidence of such a relationship in both the long run and short run for the MINT economies. This could potentially indicate delayed adoption or inadequate integration of green technologies in MINT economies; hence, the current levels of green technology adoption are insufficient to yield a significant impact on the overall environmental sustainability (Afshan *et al*., 2023; Çağlar *et al*., 2024; Guo *et al*., 2020; Uche and Ngepah, 2024; Voumik *et al*., 2024).

From the perspective of energy transition, the result demonstrates a statistically significant negative impact on LCF in the long run at the 10% significance level. The coefficient of −2.5712 suggests that the ongoing energy transition processes in the MINT economies are, somewhat counterintuitively, which is associated with a decrease in their LCF in the long term. In the short-run analysis, energy transition likewise exhibits a statistically significant negative impact on LCF, also significant at the 10% level. The coefficient of −4.5451 reinforces the long-run finding, suggesting that the immediate effects of changes related to energy transition in the MINT economies are associated with a decrease in the LCF. This could be due to the initial phases of energy infrastructure development or shifts in energy consumption patterns that might have immediate environmental consequences. The findings imply that while the energy transition toward cleaner and renewable energy sources is generally considered a vital strategy for environmental sustainability, this result might reflect the initial challenges and potential environmental costs associated with the transition process itself, such as the development of new infrastructure or the decommissioning of existing systems (Lee *et al*., 2023; Ramzan *et al*., 2022; Sun and Qamruzzaman, 2025).

This revelation also aligns with the claims of extant studies that have cautioned against an overreliance on technological solutions as inherently sustainable, emphasizing the need for a more critical and holistic evaluation of their long-term impacts. As Crowther (2023) notes, the adoption of new technologies, including renewables, has often been driven by immediate economic benefits, sometimes at the expense of considering potential unintended

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consequences or the broader social and environmental context. While renewable energy investments are central to decarbonization strategies, their deployment must be assessed across their entire life cycle, including resource extraction, land use and end-of-life disposal. Overoptimism that future technological breakthroughs will resolve current sustainability challenges risks deferring responsibility and may inadvertently create new problems for subsequent generations.

In order to validate the LCC hypothesis, the study included the GDP and its square term in the study's model. The coefficient for GDP is −57.805 and GDP^2 is 2.4274, respectively, even though the signs of these coefficients align with the hypothesized U-shaped relationship; however, neither of these coefficients is statistically significant at the conventional significance levels in both the long run and short run models. This implies that within this model and for the MINT economies under consideration, economic growth does not have a statistically significant nonlinear effect on LCF. This indicates that the hypothesized inverted-U relationship (where environmental quality first deteriorates with growth and then improves after reaching a threshold) is not clearly supported in this context. This finding reflects MINT economies' early developmental stages, where income thresholds for sustainability benefits are unmet (Alola *et al*., 2023; Bekun *et al*., 2024). The long-run impact of natural resources on LCF is also statistically insignificant. The coefficient of −0.0369 suggests a negative but statistically weak association between the abundance of natural resources and the LCF for the MINT economies. While Yang *et al*. (2023) and Dai *et al*. (2025) suggest that natural resource abundance can be associated with environmental degradation, the lack of statistical significance in this study indicates that this relationship is not strongly evident in the dynamics of the MINT economies' environmental sustainability as measured by LCF.

5.3 Robustness check

In an attempt to validate the reliability of the study's findings, two advanced panel estimators were employed in line with the studies of Cunha and Lobão (2022) and Zhou *et al*. (2025). These are the Common Correlated Effects Mean Group (CCEMG) and the Dynamic Common Correlated Effects Mean Group (DCCEMG) estimations as presented in Table 7. These methods are ideal for verifying the consistency of results earlier obtained, as they are robust to CSD, heterogeneity and endogeneity. This consideration thus helps mitigate bias that may arise in the model (Chudik and Pesaran, 2015).

Table 7. Robustness estimation results

	Variables	Coefficient	Std. Err.	z-stat.	Prob.
CCEMG	CLF	0.0063*	0.0037	1.69	0.091
	LGRTIN	0.0376	0.0457	0.82	0.41
	LEnerTr	−1.2245**	0.5747	−2.13	0.033
	LGDP	32.873	44.866	0.73	0.464
	LGDPsq	−1.3512	1.8553	−0.73	0.466
	LNARS	0.00055	0.0061	0.09	0.929
DCCEMG	L.LLCF	−0.8431***	0.084285	−10	0.000
	CLF	0.0030**	0.001511	2.00	0.046
	LGRTIN	0.827	0.774	1.07	0.285
	LEnerTr	−0.0220**	0.012	−1.84	0.066
	LGDP	−2.717	5.201	−0.52	0.601
	LGDPsq	0.103	0.223	0.46	0.645
	LNARS	−0.00078	0.001399	−0.55	0.579

Note(s): ***, **, * indicate significance at 1, 5 and 10% levels, respectively
Source(s): Authors' own work

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The results of the CCEMG and DCCEMG estimators both confirm that an increased CLF positively affects the LCF, aligning with the main results in Table 6 where CLF also showed a significant positive impact. For green technologies, the coefficient for green technologies is again positive and also not statistically significant. This mirrors the CS-ARDL findings, where green technologies did not show a statistically significant influence on LCF. The robustness results for energy transition likewise support the earlier finding from Table 6, which indicates that energy transition exerts a negative influence on LCF. This negative relationship suggests that the initial phases of energy transition may be associated with transitional challenges or inefficiencies that reduce environmental sustainability in the short to medium term. Further, across both estimators, the coefficients for LGDP, LGDPsq and LNARS remain statistically insignificant. These results are in line with the baseline regression outcomes, further implying that the hypothesized nonlinear relationship between economic growth and LCF (akin to the inverted-U of the LCC hypothesis) is not strongly supported in this context. This persistent rejection of LCC hypothesis reveals the need for context-specific environmental theories in emerging markets.

6. Conclusion and policy recommendations

This study investigated the impact of CLF, green technologies and energy transition on environmental sustainability, as measured by the LCF, in the MINT economies. The study covered periods between 2000 and 2021. Several pre-diagnostic tests, including the CSD, SH, unit root test, and tests for cointegration, were considered before applying the novel CS-ARDL regression approach to examine both the long-run and short-run relationships. In the final stage, the study employed the CCEMG and DCCEMG estimators in order to buttress the validity, consistency and reliability of the findings. The findings revealed that CLF has a statistically significant positive impact on LCF in both the short and long run, which implies that CLF is an effective mechanism in promoting environmental sustainability. However, energy transition shows a statistically significant negative impact on LCF, which portrays potential challenges or initial environmental costs associated with the transition process in these economies. Likewise, green technologies and natural resources did not exhibit statistically significant long-run impacts on LCF in this model. Regarding the LCC hypothesis, the long-run coefficients for GDP and its squared term, while having the expected signs for a U-shaped relationship, were not statistically significant. Therefore, based on the results, the study concluded that the LCC hypothesis is not statistically validated for the MINT economies.

Given the consistent positive impact of CLF on environmental sustainability, MINT economies should prioritize attracting and effectively utilizing green investments. This can be achieved through the development of robust policy and regulatory frameworks that incentivize green projects and promote innovative green financial instruments. It is crucial to ensure transparency and efficiency in the allocation of CLF toward sustainable initiatives. However, despite the revealed results of the green technologies adoption, the crucial role of green technologies in long-term environmental sustainability cannot be overemphasized. Policymakers in these regions are encouraged to implement targeted incentives, such as tax benefits, subsidies and grants, to encourage the widespread adoption and development of green technologies across various sectors. More so, the observed negative impact of energy transition on the LCF necessitates a careful review and strategic management of the current energy transition pathways in the MINT economies. It is important that policies should focus on ensuring a just and truly green transition, which will prioritize investments in renewable energy sources and enhance energy efficiency across all sectors. This will proactively mitigate any short-term negative environmental consequences associated with the transition. Further, while the LCC hypothesis was not validated in this study, it is paramount to understand the underlying principle of decoupling economic growth from environmental degradation. Therefore, MINT economies should pursue and prioritize sustainable economic development strategies that foster cleaner industries, green technologies and implement stringent

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environmental regulation mechanisms. This study is limited by its focus on MINT economies, which may restrict the generalizability of the findings to other regions with different societal and regional dynamics. For future research, it is suggested that a broader set of emerging and developed economies could be considered to provide a wider perception. For CLF stakeholders, practical tools such as climate risk assessment models, project evaluation scorecards and transparent reporting frameworks are recommended to enhance decision-making and accountability. Future studies should also propose and empirically test specific hypotheses regarding the mechanisms through which CLF and green technologies affect environmental sustainability, using both quantitative and qualitative approaches.

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